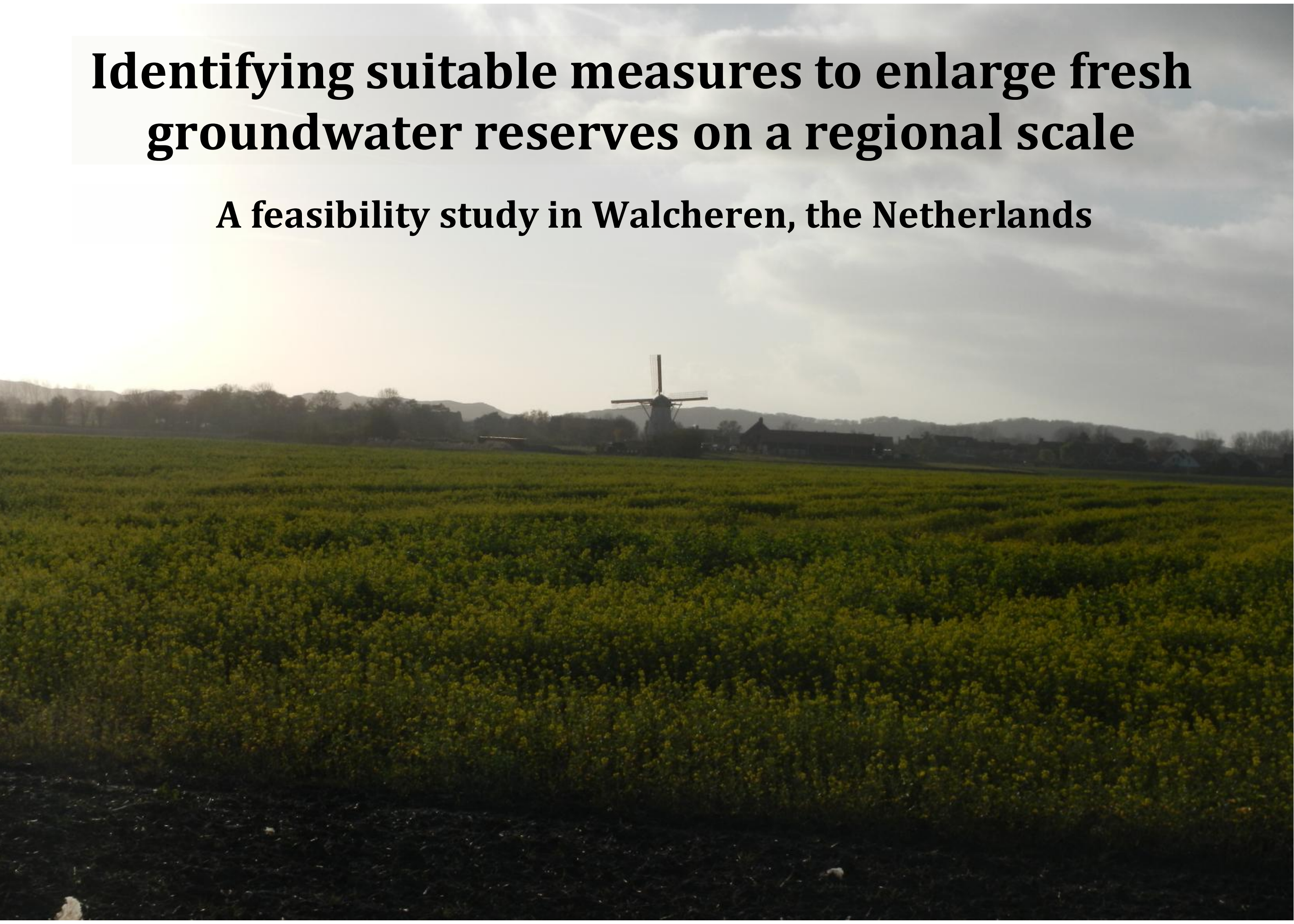
Identifying suitable measures to enlarge fresh groundwater reserves on a regional scale

A feasibility study in Walcheren, the Netherlands



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Hydrology and Quantitative
Water Management

M.J. Sommeijer
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Hydrology and Quantitative Water Management

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Abstract

Creek ridge deposits can store large amounts of fresh groundwater in a predominant saline coastal area. These fresh groundwater reserves can potentially be enlarged for benefit of agriculture. This is of special interest as fresh groundwater in coastal systems is vulnerable to salinisation, even more under future climate change and rising sea levels. As part of the Knowledge for Climate project *GO-FRESH*, this research focuses on creek ridge deposits in Walcheren, the Netherlands. In this research suitable creek ridge deposits for the enlargement of fresh groundwater reserves are localised and the types of measures that could be applied to achieve this enlargement are determined. Based on several geophysical criteria the suitable locations are identified. For these locations, various water management measures are indicated that contribute to the enlargement of fresh groundwater reserves. The proposed measures result from GIS analyses, field analyses, EC-measurements and water system analysis. The measures focus on retention of fresh groundwater in the creek ridge locations, with at some locations even the possibility for infiltration of extra fresh water, and on limitation of the effects of saline (surface) water on the fresh groundwater. With the implementation of these measures significant enlargement of the fresh groundwater reserves can probably be realised.

List of used symbols and abbreviations

BGH – Badon Ghijben - Herzberg

CCD – Composite controlled drainage

CD – Conventional drainage

Cl – Chloride (mg Cl^-/l)

DEM – Digital Elevation Model (m)

EC – Electrical conductivity (mS/cm)

ET_c – Crop evapotranspiration (mm/d)

k – Hydraulic conductivity (m/d)

k_h – Horizontal hydraulic conductivity (m/d)

k_v – Vertical hydraulic conductivity (m/d)

NAP – Normaal Amsterdams Peil (m)

P – Precipitation (mm/d)

$q_{infiltration}$ – Infiltration flux (mm/d)

$q_{seepage}$ – Seepage flux (mm/d)

T – Temperature (°C)

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1. Introduction

Many coastal areas in the world are facing problems with salinisation of surface- and groundwater (e.g. Nicholls, 2011; Oude Essink *et al*., 2010) . As a result of salinisation, fresh groundwater reserves are diminishing which can cause problems for agriculture and drinking water supplies. Also the south-western delta of the Netherlands is facing problems with the salinisation of groundwater. Figure 1.1 shows the depth of the fresh-saline interface[1] in the Province of Zeeland, the Netherlands. The figure shows that at many places salinity occurs at very shallow depths, meaning that fresh groundwater reserves are limited. As a result of autonomous salinisation, climate change, sea level rise and land subsidence fresh groundwater reserves will be under higher pressure in the future (Oude Essink *et al*., 2010). Optimizing fresh groundwater reserves is crucial for agriculture to remain a healthy sector in a future setting with increasing salinisation (Oude Essink *et al.*, 2009).

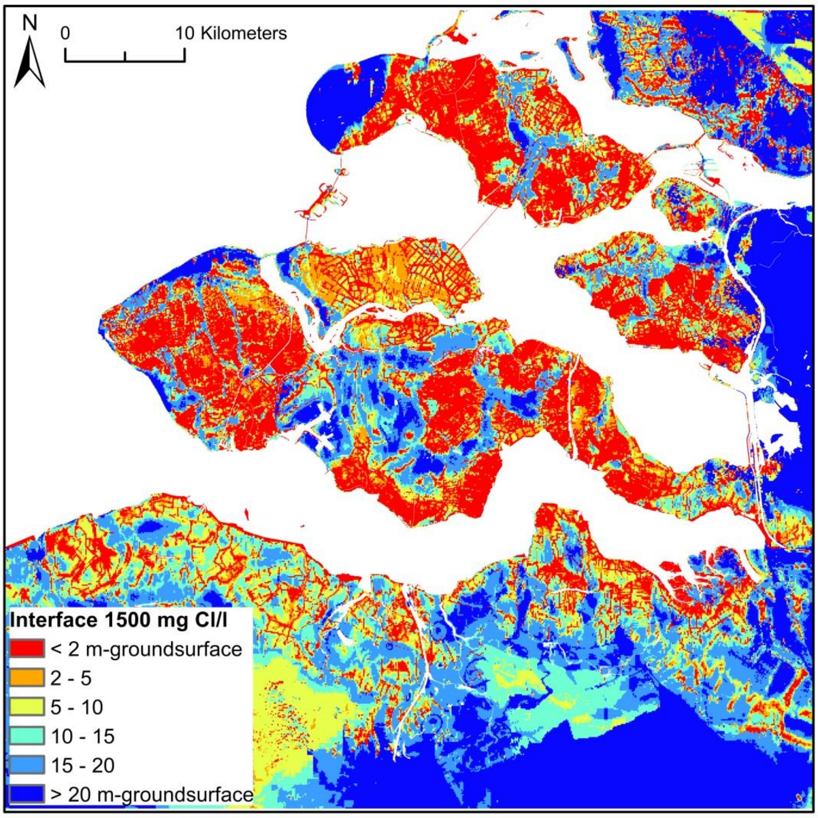

Figure 1.1: Depth of fresh-saline interface (1500 mg Cl/l) in the Province of Zeeland (Van Baaren *et al.*, 2011a).

A consortium works within the Knowledge for Climate Program Tranche 3 on preserving and increasing fresh groundwater reserves to counter salinisation (Oude Essink, 2011). The official title of the project is: *Towards implementation of promising measures for local fresh water supply and salinity control in the Southwestern Delta.* The working title of the project is *GO-FRESH*.[2]

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[1] A chloride concentration of 1500 mg/l is taken as the threshold between fresh and saline water. See section 2.3.1.

[2] More information on the project and the partners in the consortium can be found at: https://publicwiki.deltares.nl/display/ZOETZOUT/GO-FRESH+-Valorisatie+kansrijke+oplossingen+robuuste+zoetwatervoorziening.

Within the project *GO-FRESH*, Deltares is involved in several subprojects in which potentially valuable techniques to optimize fresh groundwater reserves are developed and tested. One of the subprojects concerns fresh groundwater reserves in creek ridge deposits. These fresh water bodies can have thicknesses of tens of meters. Extraction is currently allowed when the thickness exceeds 15 m, for extraction from thinner fresh water bodies stricter rules apply (Waterschap Scheldestromen, 2010). In the winter of 2012 – 2013 a pilot is started on actively enlarging the thickness of a fresh groundwater reserve in a creek ridge deposit by active infiltration of fresh water through a composite controlled drainage system (see section 2.4). With this technique fresh water, resulting from precipitation excess during the winter months, can be stored in the groundwater. This fresh water contributes to the robustness of the fresh groundwater system and may be used during dryer (summer) months. The subproject acts as a showcase for potential measures to counter salinisation by enlarging fresh groundwater reserves. The pilot takes place in the area of Walcheren, the Netherlands.

The focus of this research is on fresh groundwater reserves in creek ridge deposits to be used for agriculture purposes. Agriculture is the main type of land use in Zeeland; it occupies 80% of the surface. Several types of measures can be taken to actively enlarge fresh groundwater reserves in creek ridge deposits. The pilot takes place only at one specific location. Development of measures for other locations is required to significantly enlarge fresh groundwater reserves on a larger scale. The main research questions are therefore: **At which creek ridge locations can the fresh groundwater reserve potentially be enlarged and which measures can be taken to achieve this enlargement?** This will be investigated with a feasibility study for the part of Walcheren located west from the canal ('*Kanaal door Walcheren*'), Province of Zeeland in the Netherlands (Figure 1.2). In this region several projects are in progress and therefore a lot of required knowledge and data is already available.

Sub questions to answer the main research question are the following:

- Which criteria can be used to classify creek ridge locations that are suitable for the enlargement of fresh groundwater reserves?
- Which types of measures to achieve enlargement of fresh groundwater reserves in creek ridge deposits can be identified?
- What methods can be used to identify suitable measures for a specific location?

To answer the main research questions, a thorough understanding of creek ridge deposits and corresponding geohydrological properties is required first. Furthermore, the basics of the composite controlled drainage technique and corresponding boundary conditions need to be well understood. These are described in a theoretical framework in chapter 2. Chapter 3 describes which types of measures could be implemented to enlarge fresh groundwater reserves. Chapter 4 deals with the methodology that will be applied to answer the main research questions. The results are presented in chapter 5, followed by a discussion in chapter 6 and by conclusions and recommendations in chapter 7.

Figure 1.2: Location of the study area Walcheren, within the Province of Zeeland. The canal (*'Kanaal door Walcheren'*) is indicated with the blue arrow.

2. Theoretical framework

This chapter provides background information on aspects that influence the (geo)hydrological properties of the study area. First the geology of Zeeland and the development of creek ridges are described. In this section also the geohydrological properties of creek ridges are described. Secondly the Badon Ghijben and Herzberg theory, concerning fresh water lenses in dunes and creek ridge deposits, is explained. The third section deals with salinity and EC-measurements. Finally, a description of the composite controlled drainage system and active infiltration is given.

2.1. Geology of Zeeland and development of creek ridges

The most important aquifers and aquitards in Zeeland consist of Pleistocene and Holocene deposits[3]. Sands deposited during the Weichselien form the Pleistocene sediments. These sediments dip towards the north-west; in the south-east of Zeeland the top of the deposition is at surface level whereas at the north-west of Zeeland it is located at a depth of 16 m below surface level (Berendsen, 2005). A Holocene covering deposition[4] covers the Pleistocene deposition. This Holocene deposition consists mainly out of marine depositions in combination with peat layers. Relative sea level rise and tidal currents during the Holocene transgressions have determined the geological development largely. The saline groundwater is a result of Holocene transgressions that left saline water in the soil (Post *et al.*, 2003). Finally human influence has had an important impact on the creation of the current landscape, especially the creation of manmade polders (Berendsen, 2005; Oude Essink *et al.*, 2009).

Creek ridges are former tidal channels that are filled up by sandy deposits. The surrounding clay and peat areas have subsided as a result of drainage of these areas. As a result, the creek ridges are now approximately 1 to 2 m higher than the surrounding areas (Berendsen, 2005; Vermaas, 1987). Figure 2.1 graphically shows the development of creek ridges.

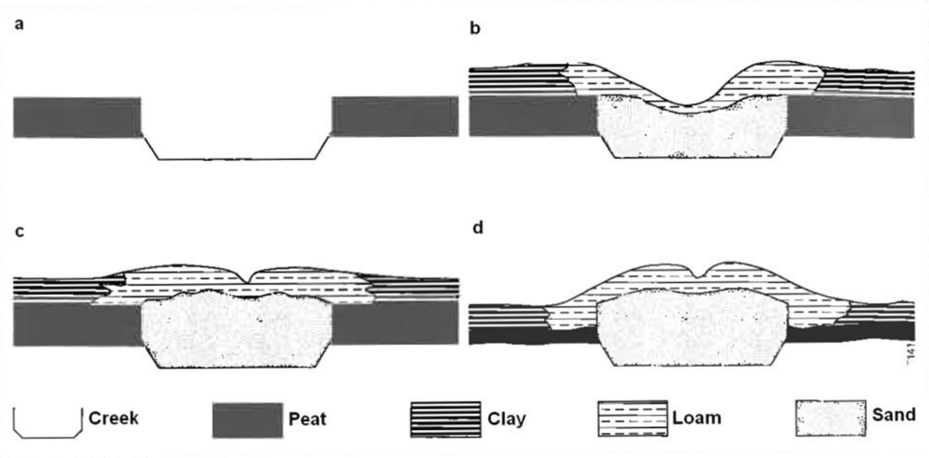

Figure 2.1: Development of a creek ridge, with a: Incision of a creek in a peat layer, b: Filling of the creek and new depositions on the top layer, c: Situation after the area has become land, d: Situation after subsidence and decomposition of the peat layer (Berendsen, 2005).

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[3] The Pleistocene occurred from 2 M BP – 10,000 BP, the ice age Weichselien is part of the Pleistocene and occurred from 80,000 BP – 12,000 BP. The Holocene follows the Pleistocene from 12,000 BP – present.
[4] The Dutch translation for 'covering deposition' is 'deklaag'.

Creek ridge deposits form one of the three main fresh groundwater systems present in Zeeland (Oude Essink *et al.*, 2009). The other systems are dunes and shallow fresh rainwater systems that occur in the reclaimed salt marshes (Figure 2.2). In the sandy soils with, high hydraulic conductivity, of creek ridges thick fresh water aquifers occur with thicknesses of tens of meters, whereas fresh rainwater lenses have thicknesses of only 1 to 2 m. This explains why creek ridge deposits are important features for fresh groundwater reserves in Zeeland. Additionally, the sandy creek ridges form good soils for agriculture and fruit trees (Oude Essink *et al.*, 2009). The phreatic groundwater level is relatively high in creek ridge deposits. This is because of the high infiltration capacity and hydraulic conductivity of the sandy soils and the relative high elevation in the landscape. Therefore these locations do not experience (saline) seepage. Creek ridge deposits are widespread over the Province of Zeeland. Figure 2.2 gives an indication of the appearance of these areas in Zeeland.

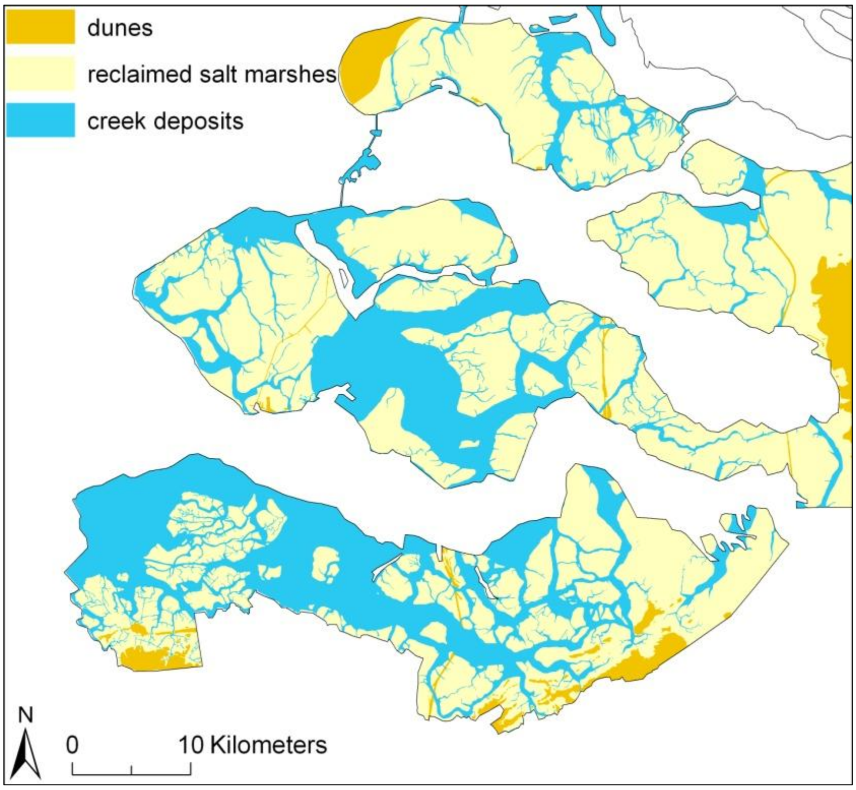

Figure 2.2: Appearance of dunes, reclaimed salt marshes and creek deposits in Zeeland (REGIS, n.d.).

Goes *et al.* (2009) conclude that the depth of fresh and brackish/saline groundwater and landscape type are highly correlated for a large part of Zeeland. However, they also conclude that not all former tidal channels are filled with thick freshwater bodies. This depends on factors and the interdependence of these factors such as elevation, soil type, location from the sea and date of reclamation from the sea. This shows that not every former tidal channel has developed into a creek ridge carrying thick freshwater reserves.

2.2. Fresh groundwater reserves in creek ridges

Badon Ghijben (1889) and Herzberg (1901) both described the theory of the fresh-saline interface in groundwater systems. Nowadays, the Badon Ghijben and Herzberg (BGH) principle is still referred to (e.g. De Louw *et al.*, 2011; Eeman *et al.*, 2011). This theory describes the relation between the phreatic groundwater level and the depth of the fresh-saline interface (Equation 1).

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

Where h is the phreatic groundwater level in relation to mean sea level, ρ_s is the density of salt water, ρ_f is the density of fresh water[5] and H is the depth of the fresh-saline interface (see Figure 2.3).

Equation 1 shows that the phreatic groundwater level and depth of fresh-saline interface are related to each other in a ratio of 1:40 [6] when the salt water has a density comparable to sea water (see Figure 2.3 for a fresh water lens in dunes)(Oude Essink, 2001a). This means that a rise in groundwater level of only 1 m leads to a theoretical increase in lens thickness of 40 m. The saline groundwater underneath creek ridges however, has a lower chloride concentration than pure seawater. This means that the ratio between the phreatic groundwater level and the depth of the fresh-saline interface is smaller. Furthermore, the BGH theory does not account for vertical flow components in the fresh water bodies and therefore cannot be applied directly to the system of fresh water lenses in creek ridges (Oude Essink, 2001a). Nevertheless, the principle that increasing the phreatic groundwater level results in a lowered fresh-saline interface can be applied to fresh water lenses in creek ridges and can be quantified through modelling efforts (e.g. Van Baaren *et al.*, 2011a; Visser, 2012).

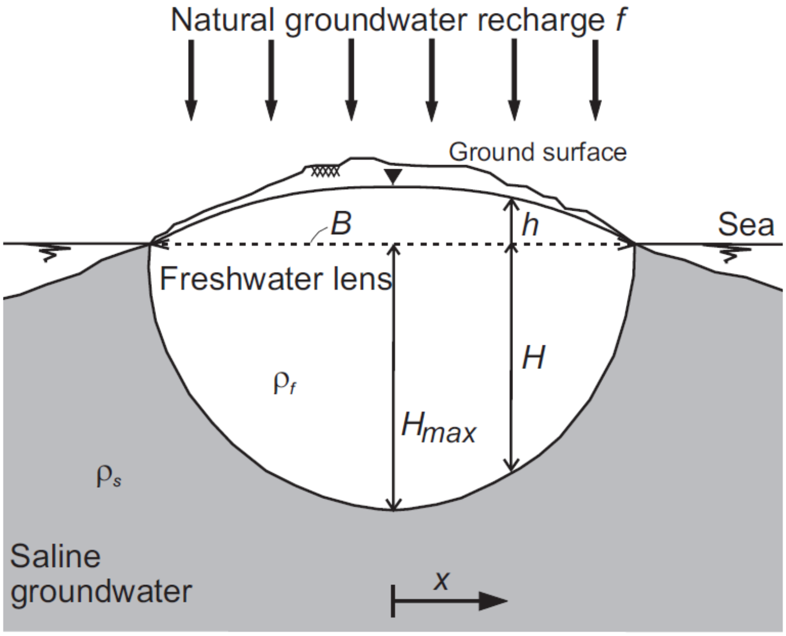

Figure 2.3: Fresh water lens in a dune area (Oude Essink, 2001a).

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[5] The density of fresh water (ρ_f) is 1000 kg/m^3 and the density of sea water (ρ_s) is 1025 kg/m^3.

[6] $\rho_s - \rho_f / \rho_f = 0.025 = 1/40$.

2.3. Salinity and EC-measurements

2.3.1. Salinity

In the Dutch delta, chloride is the major conservative anion and can be used as a proxy for salinity (Pauw, 2011). A higher chloride concentration means more saline water. A common-used characterization of water types based on chloride concentration is developed by Stuyfzand (1986)(Table 2.1).

Table 2.1: Water types based on chloride concentration (Stuyfzand, 1986).

Water type	**Chloride concentration (mg/l)**
Fresh	< 150
Fresh-brackish	150 – 300
Brackish	300 – 1000
Brackish-salt	1000 – 10,000
Salt	10,000 – 20,000
Hyperhaline	>20,000

According to this characterization fresh water hardly exists in Zeeland. In practice even fresh-brackish and brackish water can be used in agriculture without causing too many problems. Therefore the Province of Zeeland has introduced 1500 mg Cl^-/l as a threshold between fresh and saline water (Van Baaren *et al.*, 2011a).

2.3.2. EC-measurements

Electrical conductivity (EC) is a measure for the salinity of the water; the more (chloride) ions in the water, the higher the EC. The EC of water can be measured directly using an EC-meter. An EC-meter makes use of two or four electrodes to measure either the electrical conductivity or resistivity, depending on the type of instrument (Pauw, 2011).

The EC of water changes with temperature variations; a higher temperature induces a higher conductivity. Therefore the measured EC is converted to a temperature corrected EC at 25°C (McNeill, 1980; Pauw, 2011). This is done according to the convention by McNeill (1980):

$$EC_{T=T°\mathrm{C}} = EC_{T=25}(1 + 0.022(T - 25)) \qquad (2)$$

Where $EC_{T=T°C}$ is measured EC, $EC_{T=25°C}$ is temperature corrected EC at 25°C and T is measured temperature.

2.3.3. From EC to chloride concentration

Oude Essink *et al.* (2009) describe various conversions to calculate the chloride concentration from EC (Figure 2.4). The analysis by Van Wirdum (2004) is based on the measured EC (and a correction factor depending on the type of measurement instrument), whereas the analysis by Stavenga (1992) also includes bicarbonate concentration. The analysis by Oude Essink *et al.* (2008) is based on measurements from a field study in the Province of Flevoland.

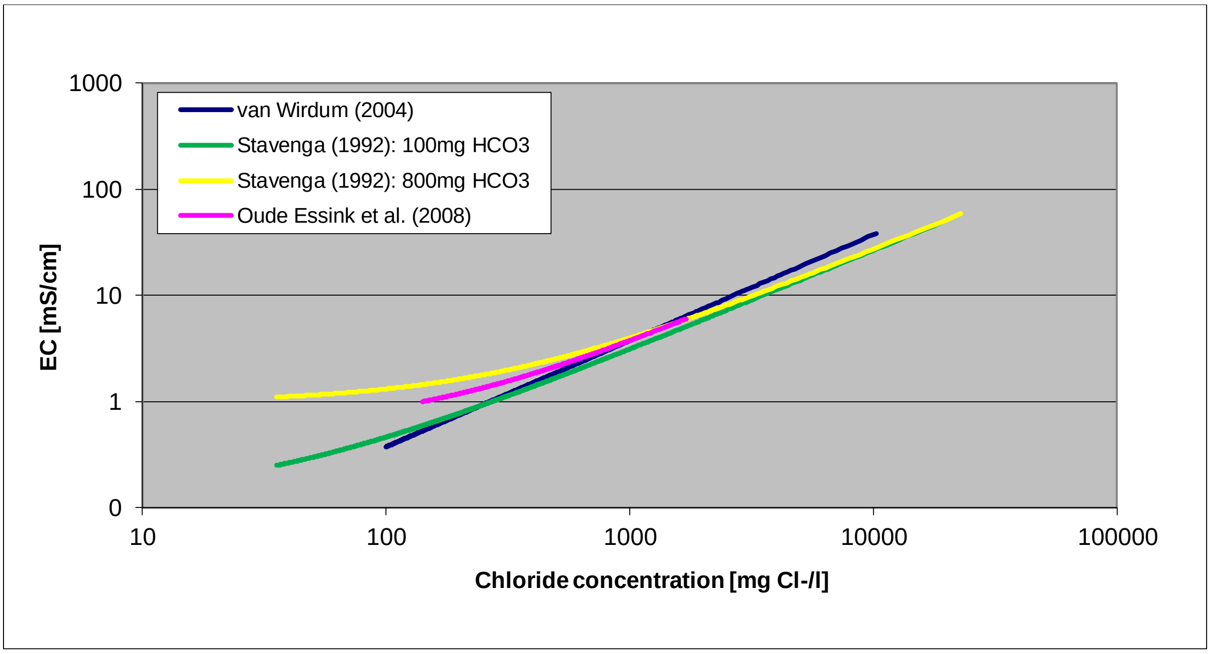

Figure 2.4: Relation between EC and chloride concentrations, calculated with three different conversion methods (Oude Essink *et al.*, 2009).

Figure 2.4 shows that especially for low chloride concentrations (< 1000 mg Cl^-/l) there is high variation in the results of the various conversion methods. Next to chloride, other elements (e.g., bicarbonate, sulfate and nitrate) influence the EC as well (McNeill, 1980). Especially for low salinity the contribution of bicarbonate concentration on the EC is relatively high (Stavenga, 1992). Therefore, not all the measured conductivity can be attributed entirely to chloride. Standard EC-meters only measure the conductivity and not the concentrations of various elements. It is therefore recommended to work with EC-values rather than chloride concentrations. The conversion table (Table 2.2) developed by De Louw *et al.* (2011) based on fielddata from Schouwen Duiveland is commonly used by Deltares to give an indication of the chloride concentrations corresponding to a specific EC. The threshold of 1500 mg Cl^-/l as maintained by the Province of Zeeland has an EC equivalent of approximately 5 mS/cm. Farmers in the area have indicated that water with an electric conductivity lower than 2 mS/cm can be used for irrigation (p.c. Waterhouderij, 2012). However, some even occasionally use water with an EC of 5 mS/cm to prevent drought stress in plants.

Table 2.2: Indication of chloride concentration corresponding to EC values (De Louw *et al.*, 2011).

EC (mS/cm)	**Cl^- (mg/l)**
0 – 0.9	0 – 150
0.9 – 1.5	150 – 300
1.5 – 3.8	300 – 1000
3.8 – 6	1000 – 2000
6 – 12	2000 – 4000
> 12	> 4000

2.4. Composite controlled drainage and infiltration

Phreatic groundwater levels are controlled by dense networks of ditches and by drainage systems (Post *et al.*, 2003). Groundwater levels at field scale can be controlled by means of drainage systems. A distinction can be made between conventional drainage (CD) systems and composite controlled drainage (CCD)[7] systems. CD has a drainage level which is fixed or controlled by the water level in ditches, whereas with CCD the drainage level can vary from field to field (Figure 2.5). With CCD the drainage pipes do not directly discharge in ditches, but the water is collected in a collector drain which discharges in a drainage well of which the water level is controlled (Stuyt *et al.*, 2012). This allows farmers to control the groundwater level at their plots themselves. The drainage levels of ditches are usually controlled by the local waterboard.

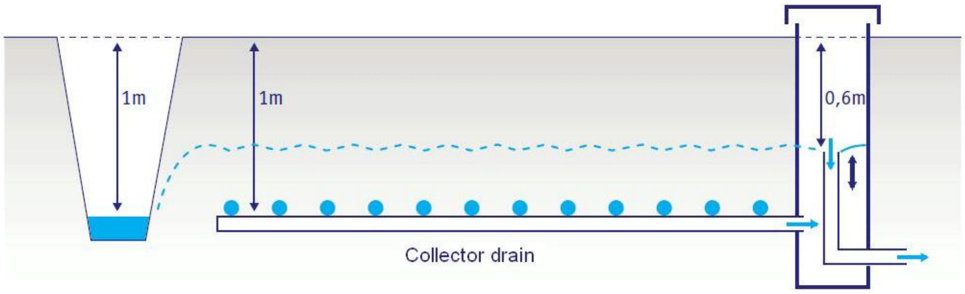

Figure 2.5: Composited controlled drainage system where the groundwater level is variable. The groundwater level is controlled by the level in the drainage well and not by the water level in the ditch (Stuyt *et al.*, 2012).

A pilot of infiltration of fresh water in creek ridges in Zeeland works with a CCD system[8]. An infiltration drain is added to the design of the drainage system (Figure 2.6). Fresh water from an adjacent ditch is fed via an infiltration well into the infiltration drain from which the water is distributed amongst the regular drains. From the regular drains the fresh water can infiltrate into the soil. The excess water is collected in a collector drain and discharged via the drainage well. The groundwater level can be controlled in the drainage well. This type of drainage system also functions as a normal drainage system that drains excess water during times of high precipitation excess to prevent water damage.

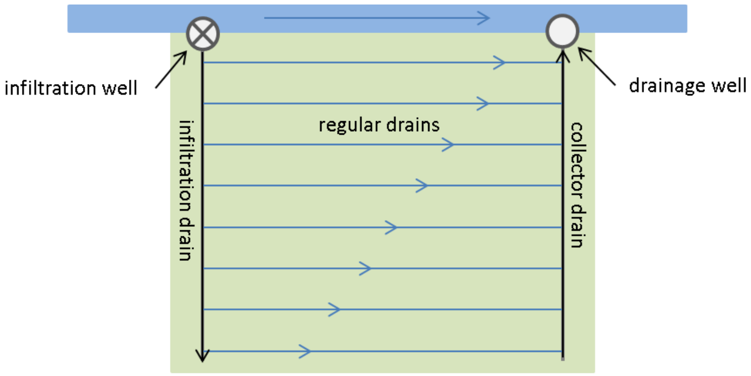

Figure 2.6: Conceptual design of a CCD system with an infiltration well and infiltration drain via which fresh water can be inserted into the regular drains. From the regular drains the fresh water can infiltrate into the soil.

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[7] The Dutch translation for 'composite controlled drainage' is 'samengestelde regelbare drainage' or 'peilgestuurde drainage'.

[8] In Appendix I the location of the pilot and the design of the drainage structure at this specific location are described.

The objective of the pilot is to enlarge the fresh groundwater reserve in a creek ridge (Van Baaren *et al.*, 2011b). The fresh groundwater reserves in creek ridges can be used for extraction of water for irrigation of agricultural land. Current policies allow extraction of water when the thickness of the fresh water lens exceeds 15 m, for extraction from thinner fresh water bodies stricter rules apply (Waterschap Scheldestromen, 2010). With increased fresh water availability and security there might be more water available for extraction and/or policies might be adjusted.

Visser (2012) created a 3-D density dependent groundwater flow model that simulates the development of a fresh water lens in a creek ridge. The model is designed for the specific creek ridge of the pilot location. The modelling results show that with extra infiltration of 1 mm/d in wintertime[9] leads to higher groundwater levels and therefore significant lowering of the fresh-saline interface (Figure 2.7). This is closely related to the BGH theory. In the modelled scenario a deep drain (#1) and a drainage ditch (#2) have been removed; this reduces the upconing of the fresh-saline interface at these locations which explains that at these location the interface in Figure 2.7 lowers the most (Visser, 2012).

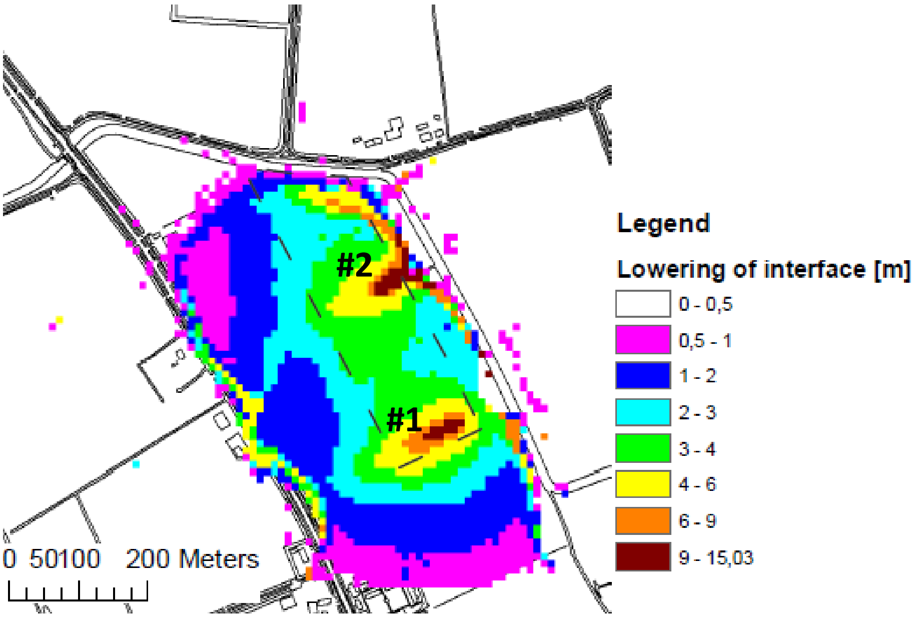

Figure 2.7: Lowering of fresh-saline interface as a result of artificial infiltration (Visser, 2012). #1 corresponds to a deep drain and #2 to a drainage ditch which both have been removed in the modelled scenario.

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[9] Wintertime is from the 1st of October – 31st of March.

3. Measures to enlarge fresh groundwater reserves

Several water management measures can be applied to enlarge fresh groundwater reserves in creek ridges. Four measures are described below.

3.1. Implementation of composite controlled drainage

Composite controlled drainage (CCD) is a special type of drainage system, with which groundwater levels at field scale can be controlled (see section 2.4.). Therefore water can be retained longer at the field (Stuyt *et al.*, 2012). This increases the water availability during dryer periods. Instead of draining the fresh water away immediately it can infiltrate in the soil. According to the BGH theory higher phreatic groundwater levels result in a lowered fresh-saline interface and therefore an enlarged fresh groundwater reserve (see section 2.2). The implementation of CCD systems is therefore an important measure to enlarge fresh groundwater reserves.

3.2. Infiltration of fresh water

When fresh surface water is available around the creek ridge locations, this water can be used to actively infiltrate in the creek ridge via the CCD system. This situation is comparable to the situation as currently tested at the pilot location (see section 2.2 and Appendix I). Modelling results show that with an artificial infiltration rate of 1 mm/d during wintertime, the depth of the fresh-saline interface significantly increases (Figure 2.7)(Visser, 2012). For the specific case study for which the model has been executed the interface lowers with a minimum of 2 m inside the infiltration area (see Figure 2.6) (Visser, 2012).

The drainage pattern of Walcheren is a complex network of ditches. As a result of infiltration and seepage fluxes the salinity of surface water in the area varies. Ditches can be permanent saline, permanent fresh or fresh and saline for some parts in the year. Because of limited elevation differences in the area, flow directions can be controlled using weirs. In this way weirs can be used to separate fresh and saline surface water. The available fresh water can then be guided towards the desired locations (see Figure 3.1 for a schematic example). Of course there are limitations on this, based on the capacity of weirs and waterways, and risks of water damage (p.c. Geschiere, 2012). Fischer (2012) also concludes that it can be very valuable to separate fresh and saline surface water, for instance by use of weirs and other control structures.

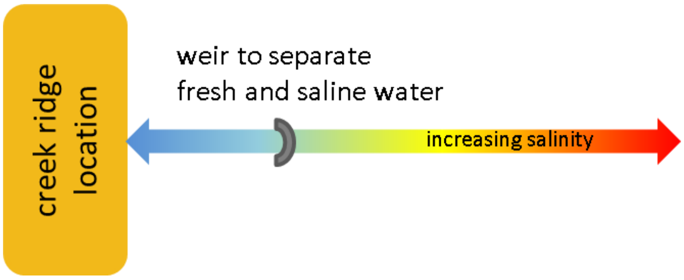

Figure 3.1: Schematic example of how the flow direction can be controlled by the use of weirs. In this case fresh and saline water is separated using a weir. The fresh water is returned towards the creek ridge location (where it might be used for infiltration), instead of being directed towards more saline areas.

3.3. Remove tertiary ditches separating fields

The primary function of tertiary ditches separating fields[10] is to drain water from these fields. Tertiary ditches are the smallest type of ditch and discharge in primary and secondary ditches via which the water is discharged out of the area. Usually the conventional drains of a field discharge into tertiary ditches. These tertiary ditches generally also function as the boundary between different fields. Once CCD has been installed the water is collected in a collector drain instead of the tertiary ditch. Therefore these tertiary ditches are not functional anymore for discharge of drainage water and can be removed or (partly) closed off with a weir (Stuyt *et al.*, 2012). The water collected in a collector drain can be discharged in a primary or secondary ditch.

With the removal of ditches (or raising the water level with a weir) the natural drainage towards these ditches decreases and the relative groundwater level rises resulting in higher phreatic groundwater levels (Figure 3.2). Theoretically the rise in groundwater level results in a deeper fresh-saline interface and therefore enlarges the fresh groundwater reserves in creek ridges significantly (see section 2.2). Furthermore, geophysical measurements leading to 2-D resistivity profiles show that tertiary ditches on creek ridges can result in undesirable upconing of the fresh-saline interface (Figure 3.3).

An additional advantage of the removal of these ditches is that the chance of superficial runoff of nutrients is lowered (Stuyt *et al.*, 2012). However, tertiary ditches can only be removed when they have a draining function, when they do not discharge water from upstream areas and when it does not result in harmful wetness on fields (p.c. Geschiere, 2012; Stuyt *et al.*, 2012).

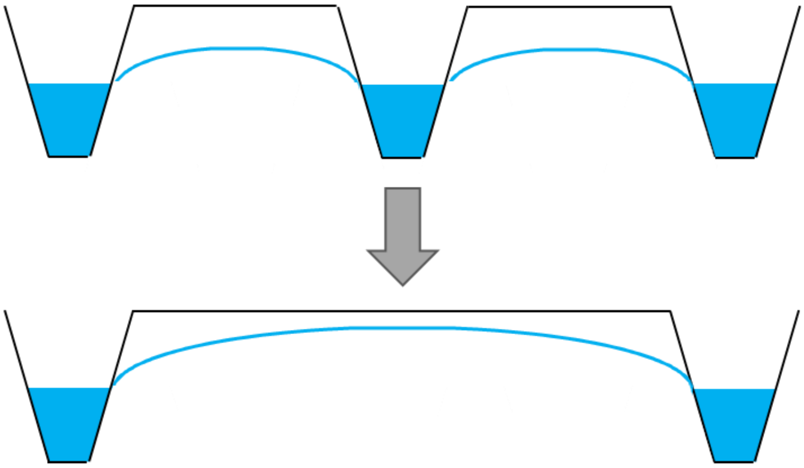

Figure 3.2: The removal of a tertiary ditch leads to a relative higher phreatic groundwater levels.

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[10] The Dutch translation for ‘tertiary ditch separating fields’ is ‘kavelsloot’.

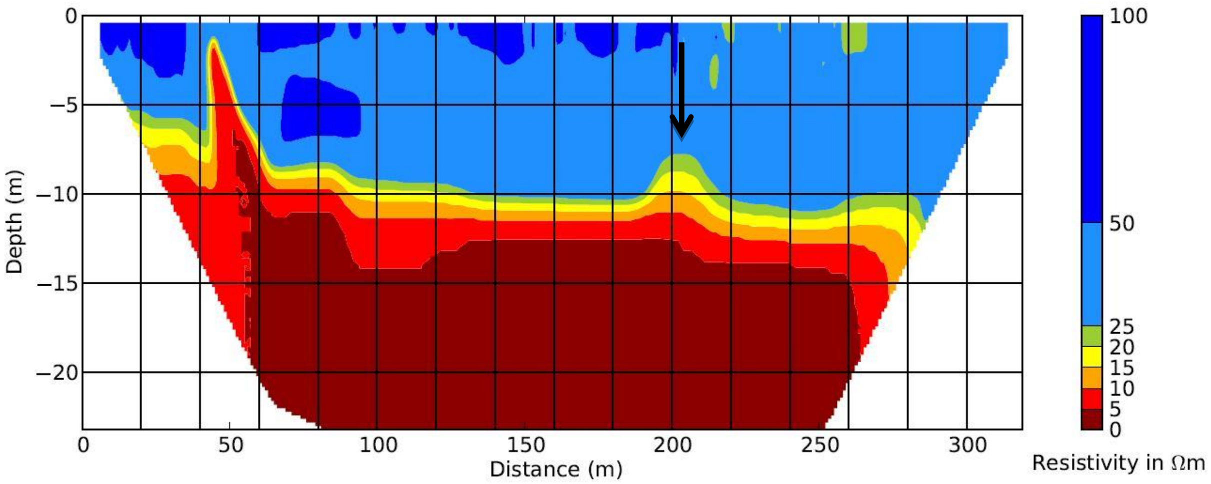

Figure 3.3: 2-D resistivity profile resulting from a CVES transect at a creek ridge (for the location of this transect see figure I.1 in Appendix I). The upconing of the fresh-saline interface indicated at the arrow is caused by a tertiary ditch perpendicular to the cross-section. CVES (continuous vertical electrical sounding) is an electrical resistivity method to measure the resistivity of the subsurface. Fresh groundwater is indicated in blue and saline groundwater in red. (The peak in conductivity on the left side of the picture (at 50 m) is due to an electricity cable in the subsoil.) (Visser, 2012)

3.4. Limit the effects of saline primary ditches

In the study area, several primary saline ditches cross creek ridge deposits. Under draining circumstances, valuable fresh water from the creek ridge deposits is drained into the saline surface water. The ditches influence groundwater levels and therefore limit the enlargement of fresh groundwater reserves. Besides, they are responsible for upconing of the fresh-saline interface underneath the ditch. This is similar to the effects ascribed to tertiary ditches, however, primary ditches cannot be removed as they have a primary function of discharging water out of the area. Furthermore, primary ditches can also be infiltrating. Under these circumstances saline water is intruded into the fresh groundwater.

Measures to limit the effects of saline primary ditches on the fresh groundwater reserves can include adjusting the water levels in these ditches with the use of weirs. The water levels should be adjusted as such that the draining effects are limited, but no infiltration of saline water into the fresh groundwater occurs. Next to that, weirs can be used to divert some of the saline water via other ditches. Modelling results by Visser (2012) show that the upconing effects caused by a primary ditch under draining circumstances can effectively be eliminated when the water level of this ditch (winter level) is raised by 0.5 m (Figure 3.4). The modelling results are for the specific case study at the pilot location (see Appendix I).

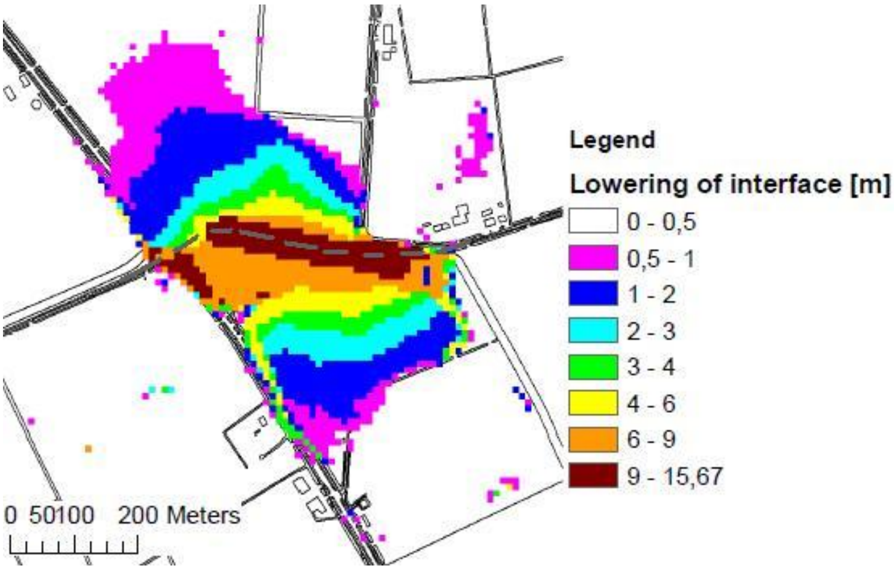

Figure 3.4: Lowering of fresh-saline interface as a result of increasing the water level in (a part of) the primary ditch with 0.5 m (Visser, 2012). The location of the ditch is indicated with dashed grey line.

4. Methodology

4.1. Creek ridge locations with potential for enlargement of fresh groundwater reserves

The creek ridge locations with a potential for enlargement of fresh groundwater reserves are determined based on seven geophysical criteria. The selection of the criteria is based on expert judgement. These criteria, which are explained in detail in the coming subsections, are the following:

1. Ground surface should be at or above NAP[11].
2. Sediment type should contain less than 35% lutum.
3. Land use type is classified as agriculture.
4. The location should be infiltrating (no occurrence of seepage).
5. The depth of the fresh-saline interface (1500 mg Cl^-/l) should be at least 5 m below ground surface.
6. The unsaturated zone should be at least 0.85 m thick.
7. There should be no confining layers within the first 20 m of the subsurface.

The specific criteria are developed and analysed based on map material (the basic map material can be found in Appendices II and III). All criteria are combined in one map displaying suitable and unsuitable locations, where the suitable locations are those locations that score positive on all seven criteria.

4.1.1. Ground surface

Analysis of the ground surface levels in the area is based on the AHN (DEM for the Netherlands) with a resolution of 5 x 5 m (Meetkundige Dienst, 2007). With the development of Zeeland the clay and peat areas have subsided, whereas the sandy creek ridge areas have not. As a result the sandy creek ridge locations currently have a higher elevation in relation to the surrounding areas (see section 2.1). Sensitivity analysis of the AHN shows that the amount of ‘suitable cells’ does not change significantly (<1%) when the suitability threshold varies between 0 and 1 m +NAP. It is therefore chosen to set the threshold at 0 m +NAP.

4.1.2. Sediment type

For the analysis of sediment type[12] in the area a sediment type map covering the entire Netherlands is used (Alterra, n.d.). In the study area, peat, sand, light and heavy clayey sand[13], light and heavy clay, and built-up area comprise the sediment types. Sand, light and heavy clayey sand, and light clay are considered as suitable sediment types for enlarging fresh groundwater reserves. For these sediment types the percentage of lutum is lower than 35%, which means that the hydraulic conductivity is sufficiently high for a freshwater lens to develop (see also section 2.2). For the definition of suitable and unsuitable locations, the locations classified as built-up areas are also considered as suitable. This is because it is assumed that these locations will be filtered out by the

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[11] NAP (Normaal Amsterdams Peil) is the Dutch ordnance datum, which approximately corresponds to mean sea level.

[12] The Dutch translation for ‘sediment type’ is ‘grondsoort’.

[13] The Dutch translation for ‘clayey sand’ is ‘zavel’.

land use type criterion, which is based on a more detailed map indicating the built-up areas (see section 4.1.3).

4.1.3. Land use type

Land use type analysis is based on a detailed land use map of the Netherlands with a resolution of 100 x 100 m (GeoDesk, 2001). On this map, 46 unique land use classes are indicated. As it is only feasible to install drainage systems in agricultural areas, land use classes that can be considered as agriculture are indicated as suitable locations. The suitable land use classes are grass, maize, potatoes, beets, cereals, fruit trees, and ‘other agricultural crops’.

4.1.4. Infiltration and seepage fluxes

Infiltration and seepage fluxes are retrieved from modelling results from the ‘Zeeland model’. This numerical, density dependent groundwater flow and transport model covers the entire Province of Zeeland (Van Baaren *et al.*, 2011a). The model results provide insight in the distribution of fresh and saline groundwater and corresponding fluxes. The model is based on the modelling code MOCDENS3D, which is a variation of MOC3D which has been adapted to model transient density-driven groundwater flow (Oude Essink, 2001b). A map with infiltration and seepage fluxes on a 100 x 100 m grid is one of the modelling outputs. The infiltration and seepage fluxes have been calculated at the bottom of the semiconfining layer on top of the aquifer. This layer is a clay deposition on top of the sand and peat deposits (see Figure 2.1). It is assumed that the fluxes at this location determine eventually the amounts of water that are discharged via the drainage network. In the Zeeland model, separate outputs for the summer and winter season have been generated. For the analysis, the winter results have been used as it is only during the winter season that there is a precipitation excess which can be used to enlarge fresh groundwater reserves. Infiltration fluxes in the model indicate locations where artificial infiltration is possible.

4.1.5. Depth of fresh–saline interface

The depth of the fresh-saline interface is also retrieved from the Zeeland model as described in section 4.1.4. Rather than a sharp boundary between fresh and salt water, a transition zone exists over which on the average the groundwater gradually becomes more saline with depth. It is chosen to use a chloride concentration of 1500 mg/l as a threshold level for saline water as this is the same threshold level as maintained by the Province of Zeeland (Van Baaren *et al.*, 2011a). For the depth of fresh-saline interface no distinction is made between summer and winter situation as it is assumed that seasonal variation is limited.

A minimum depth of the interface of 5 m is chosen to make a distinction between shallow rainwater lenses and fresh groundwater reserves in creek ridges. Besides, one of the goals of the measures is to enlarge the fresh groundwater reserves to such an extent that extraction during (dry) summer seasons becomes possible (now only allowed by law when the fresh water lens exceeds 15 m in thickness). This means that initially at least a couple of meters of fresh water should already be present.

4.1.6. Unsaturated zone thickness

The thickness of the unsaturated zone is calculated as the space between the ground surface and the groundwater table. The map displaying groundwater levels is retrieved from the results of the Zeeland model as well (see section 4.1.4). The groundwater levels are also based on the winter situation. For ground surface a resampled map of the ground surface is used. The map is resampled to a resolution of 100 x 100 m, so that both maps have the same resolution. The ground surface map is the same map as was used as input for the Zeeland model.

There should be some space in the unsaturated zone to be able to raise the groundwater level without bringing damage to fields and crops. It is preferred to have at least 0.5 m of space to increase phreatic groundwater levels. Analysis of the unsaturated zone shows that (in winter) the thickness of this zone is rather limited. It is chosen to be flexible with the criterion and take a rather limited required thickness of 0.85 m. Setting a higher threshold would limit many possible locations (a thickness of 1 m instead of 0.85 m limits 1289 cells extra, which corresponds with 1289 ha) while the acceptable groundwater level at a location varies from location to location and depends on the type of crop and farming practices (p.c. Waterhouderij, 2012). At field scale the accepted (raise in) groundwater level should therefore be defined in agreement with the farmer.

4.1.7. Geohydrological properties subsurface

A combination of the first six criteria (see section 4.1) results in line patterns displaying the creek ridge deposits in Walcheren. Over these line patterns cross sections were drawn along which the hydrological properties of the subsurface up to a depth of 30 m have been investigated (see Appendix III). For the Zeelandmodel, k_v values (vertical hydraulic conductivity) over a depth of 30 m have been computed based on GEOTOP data (Dinoloket-TNO, n.d.). k_h values (horizontal hydraulic conductivity) can be calculated from the k_v values applying an anisotropy factor, see Table 4.1.

Table 4.1: Calculation of k_h values based on k_v values.

Condition	**Calculation of k_h (m/d)**
If $k_v < 7$	$k_h = k_v \times 1.4$
If $k_v >= 7$	$k_h = k_v$

The value of the k_v value is an indication for the sediment type and therefore for the ability of a fresh water lens to develop. Table 4.2 shows the sediment type corresponding with a specific hydraulic conductivity. The combination of the sediment type and the thickness of the specific layer determines whether a specific layer is confining.

The hydraulic conductivity data from GEOTOP have been compared to data from several boreholes available for the specific cross-sections at Dinoloket. The borehole data provide information on the sediment types at a specific location. This comparison is made to clarify striking patterns (e.g. peat or clay layers) and to check the reliability of the GEOTOP data.

Table 4.2: Hydraulic conductivity (k) for specific sedimenttypes (Nonner, 2010).

Sedimenttype	**k (m/d)**
Clay	$10^{-7} – 10^{-3}$
Sandy clay	$10^{-3} – 1$
Fine sand	$10^{-1} – 10$
Medium sand	5 – 70
Coarse sand	50 – 200

4.2. Water system analysis

A water system analysis has been carried out to determine which measures are applicable to enlarge fresh groundwater reserves at the creek ridge locations. The water system analysis was based on analysis of the drainage pattern, EC-measurements of surface water and water balance analyses. Below a description is given of each component of the water system analysis.

4.2.1. Drainage

The drainage system in the area is a complex pattern of primary, secondary and tertiary ditches (Figure 4.1). The entire area of Walcheren located west from the canal ('*Kanaal door Walcheren*') has two outlet pumping stations. This means that all the water is routed to either one of these pumping stations. The water levels in the area are controlled by weirs. The primary function of the drainage system is to discharge water during wet periods (winter) and prevent subsidence and corresponding damage to buildings and infrastructure (summer) (p.c. Geschiere, 2012).

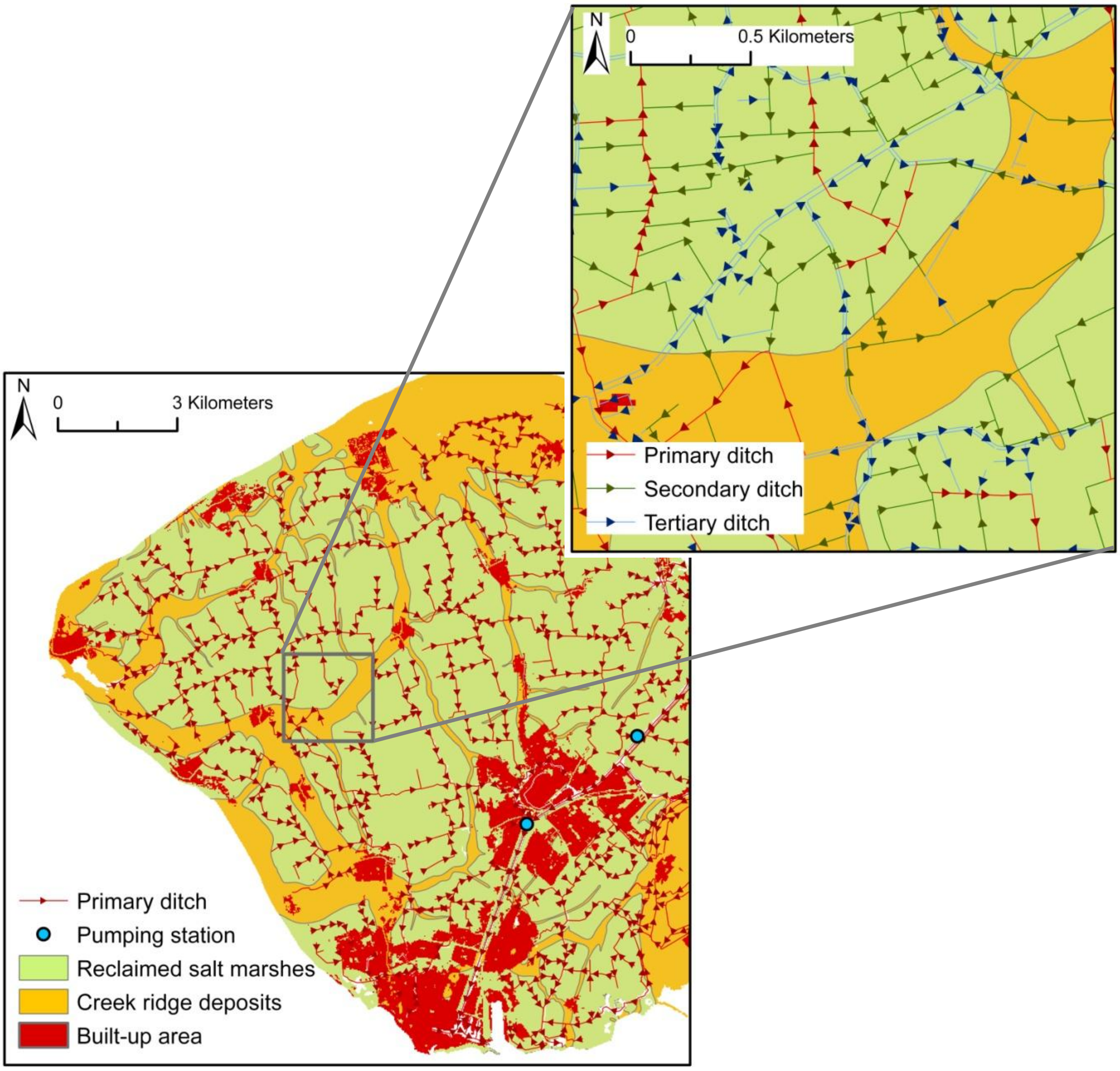

Figure 4.1: Overview of the primary drainage pattern; primary ditches at the entire area of Walcheren and primary, secondary and tertiary ditches for a small area.

The drainage pattern shows which ditches cross the creek ridge locations and may cause upconing of the fresh-saline interface. The drainage pattern also gives an indication which tertiary ditches are located at the creek ridge locations. Once CCD has been installed these ditches may lose their function and may be removed or closed off with a weir.

Furthermore, the drainage pattern indicates the flowpath of surface water and therefore of chloride concentrations. Together with the EC-measurements, the drainage pattern shows which ditches contain enough fresh water for infiltration via the CCD system. Weirs could be used to divert the water towards the desired creek ridge locations.

The findings and proposed measures regarding the drainage pattern are discussed with the area expert of the waterboard Scheldestromen, René Geschiere (p.c. 2012). Within the framework of the primary functions of the drainage system there is some space, although limited, to adjust the system and use weirs (especially manually controlled weirs) to divert water in other directions.

4.2.2. EC-measurements

At 57 locations EC-measurements of the surface water have been taken in November and December 2012[14]. The measurement locations were distributed over the area as such that a good overview of the salinity of the primary ditches and of the smaller ditches close to creek ridge locations is obtained. The measurements are taken at strategic locations where multiple ditches congregate. At these locations the EC is measured of each tributary separately (see Figure 4.2 for an example). For each measurement point the EC is measured twice, once at the water surface and once near the bottom of the ditch (Figure 4.3). For practical reasons the EC of big primary ditches is measured from control structures, weirs or divers, or from the side.

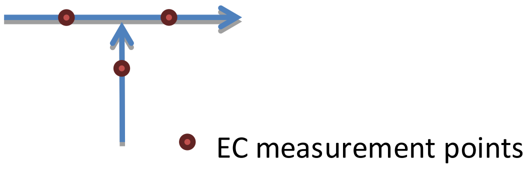

Figure 4.2: Example of EC measurement points at a specific measurement location.

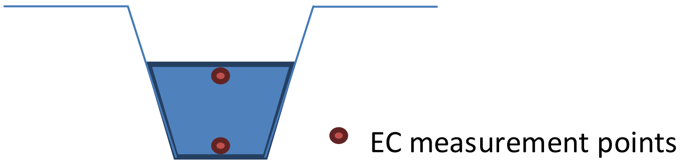

Figure 4.3: Cross-section of a ditch with the position of EC measurements taken at this point.

The EC-measurements give a spatial overview of the distribution of salinity in the area. It shows from which ditches water may be used to infiltrate via the CCD system. It furthermore provides insight in the infiltration and seepage fluxes in the area. A map with an overview of the EC-measurements can be found in Appendix IV.

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[14] Prior to the measurements an extended period of (heavy) rainfall occurred.

4.2.3. Water balance

The amounts of available fresh water for infiltration can be roughly estimated using a water balance. For a specific outlet point of a (fresh water) ditch a corresponding catchment can be drawn based on the drainage pattern. Creek ridge locations are excluded from the catchments as it is assumed that measures, such as CCD, retain all the water and therefore prevent discharge from those locations. For each catchment input and output terms can be quantified resulting in available amounts of water at the outlet point. Average terms of the entire winter season (1st of October – 31st of March) are used to determine average daily availability of fresh water. The available fresh water can be used for infiltration via the CCD system.

In the water balance the following terms are used: precipitation, potential crop evapotranspiration and infiltration/seepage fluxes (Figure 4.4). As the groundwater levels are relatively high and are maintained at a fixed level it is assumed that storage can be neglected.

$$Water\ balance: Q_{out} = \left(P + q_{seepage}\right) - \left(ET_c + q_{infiltration}\right)$$

Figure 4.4: Terms used in the water balance. Where P is precipitation, ET_c is potential crop evapotranspiration, $q_{seepage}$ and $q_{infiltration}$ are the infiltration and seepage fluxes.

For precipitation and evapotranspiration data from the meteorological station of KNMI in Vlissingen have been used (KNMI, 2012). Only the winter data have been used, starting from the 1st of October 2000 until the 31st March 2012. The average daily precipitation and evapotranspiration over this data range have been computed. Precipitation less than 0.05 mm/d could not be recorded accurately and is therefore assumed to be negligibly small. The reference evapotranspiration is converted to potential crop evapotranspiration by multiplying with a crop factor (Allen *et al.*, 1998). Agricultural land, which is most of the time bare during winter, has a crop factor of 0.9 during the winter months (Allen *et al.*, 1998; Bot, 2011). It is assumed that agricultural land comprises most of the area and that the crop factors of the other types of land use can be summarized in the crop factor of agricultural land.

Infiltration and seepage fluxes are based on the modelling results from the 'Zeeland model' (see section 4.1.4)(Van Baaren *et al.*, 2011a). It is assumed that seepage contributes to the water that reaches the outlet of a catchment, whereas infiltration fluxes contribute to groundwater recharge and do not reach the outlet. For each gridcell (100 x 100 m) within a catchment the type of flux (infiltration or seepage) and magnitude is known. In this way the total fluxes for an entire catchment can be calculated. The average drainage/seepage flux for the catchment is calculated and multiplied with the surface area of the catchment.

It is assumed that an infiltration rate of 1 mm/d of extra fresh water during wintertime gives promising results for the enlargement of fresh groundwater reserves in creek ridges (see section 2.4). Based on this infiltration rate and the amounts of extra available fresh water (see the water balance), the total surface over which the available fresh water can be applied can be determined.

5. Results

5.1. Creek ridge locations with potential for enlargement of fresh groundwater reserves

Creek ridge locations with potential for enlargement of fresh groundwater reserves have been determined based on the seven selection criteria (see section 4.1). First a map was created based upon the first six criteria (this map can be found in Appendix III). On this map patterns of the creek ridges appear. Criterion 7 (no confining layers in the first 20 m of the subsoil) is assessed based on cross-sections drawn across the creek ridge patterns (see section 4.1.7). Appendix III shows the positions of the cross-sections, the cross-sections itself and the classification of suitable and unsuitable locations.

The suitable creek ridge locations which are smaller than 200 m in width were removed. These locations were considered too small to be suitable for enlarging fresh groundwater reserves. The remaining individual pixels were manually smoothed to define uninterrupted creek ridge locations. This results in a map displaying the creek ridge locations that are suitable for enlargement of fresh groundwater reserves (Figure 5.1). The suitable creek ridge locations cover 1342 ha. This is 12% of the total area that is used for agriculture in Walcheren located west from the canal ('*Kanaal door Walcheren*').

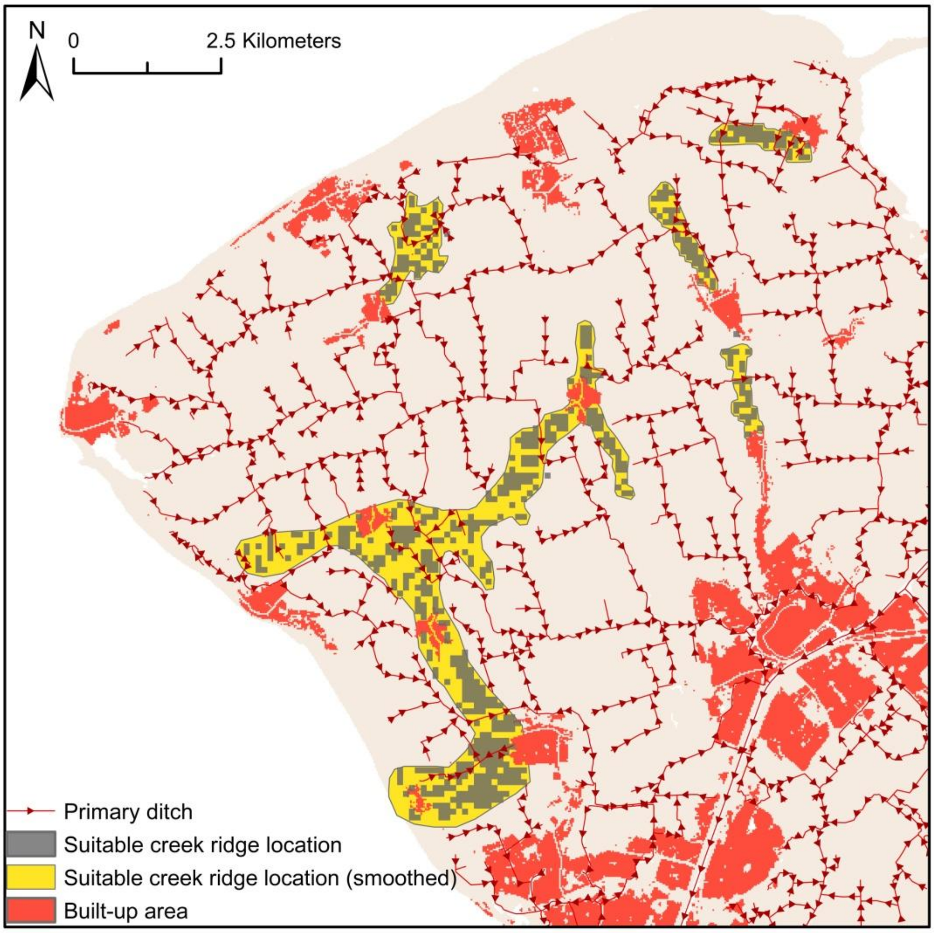

Figure 5.1: Suitable creek ridge locations, with the suitable cells in grey and the result of smoothing in yellow.

5.2. Applicable measures for enlargement of fresh groundwater reserves

The total study area of Walcheren has been divided in five sub areas for which applicable measures for enlargement of fresh groundwater reserves are determined (Figure 5.2). To achieve the enlargement, it is important to retain water as long as possible at all creek ridge locations. It is therefore recommended to install CCD at all the identified creek ridge locations, 1342 ha in total. In addition, applicable water management measures for specific locations were determined based on the water system analysis (section 4.2). In total, it is suggested to remove 40 tertiary ditches, adjust the water levels of 9 existing weirs, place 9 new weirs and change the flow direction of 7 ditches. At 8 locations fresh water is currently also available for infiltration via the CCD system. Furthermore, 7 special measures are suggested. Below, the (special) measures are described per sub area.

Currently the waterboard already takes measures to retain water in the area, by adjusting several weir levels. Generally this can only be done in consultation with the surrounding farmers. In the near future a new water level agreement[15] will be developed, in which water retention will play a more important role (p.c. Geschiere, 2012). This is also encouraged by other parties, such as the Province of Zeeland, who provide subsidies for measures that increase water retention.

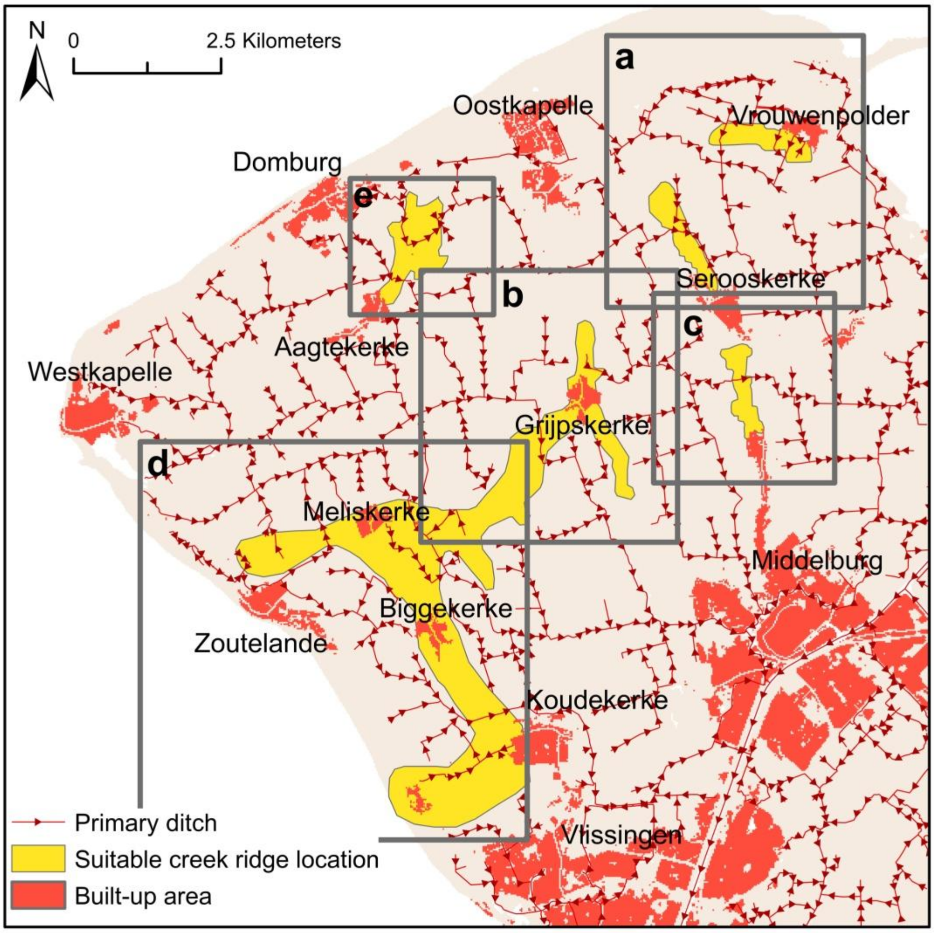

Figure 5.2: Sub areas for which the measures for enlargement of fresh groundwater reserves in creek ridges are determined.

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[15] This is an agreement in which all water levels for the area are documented. It is the job of the waterboard to maintain these levels. The Dutch translation for 'water level agreement' is 'peilbesluit'.

5.2.1. Measures for sub area A

This is the area of the 'Waterhouderij', a cooperation of 13 farmers who work together to achieve better water availability in the area. Hence some measures are already taken, such as adjusting weir levels. In this area the pilot of fresh water infiltration via a CCD system is located (see the red circle in Figure 5.3, Appendix I gives a detailed description of the pilot). Per creek ridge location different measures are identified (Figure 5.3).

For the north-east creek ridge location the measures come down to adjusting the weir levels in such a way that the water is guided towards the primary ditch at the western end of the creek ridge location (#1 in Figure 5.3). In this way the water does not cross the creek ridge location multiple times via primary ditches (#2 in Figure 5.3).

The south-west creek ridge location is very suitable for infiltration of fresh water which is transported via the primary ditch from the north (#3 in Figure 5.3). This fresh water is also intended to be used at the pilot location. An adjustment of the weir level is suggested to raise the water level and lower the flow velocity in this primary ditch and allow the water to infiltrate.

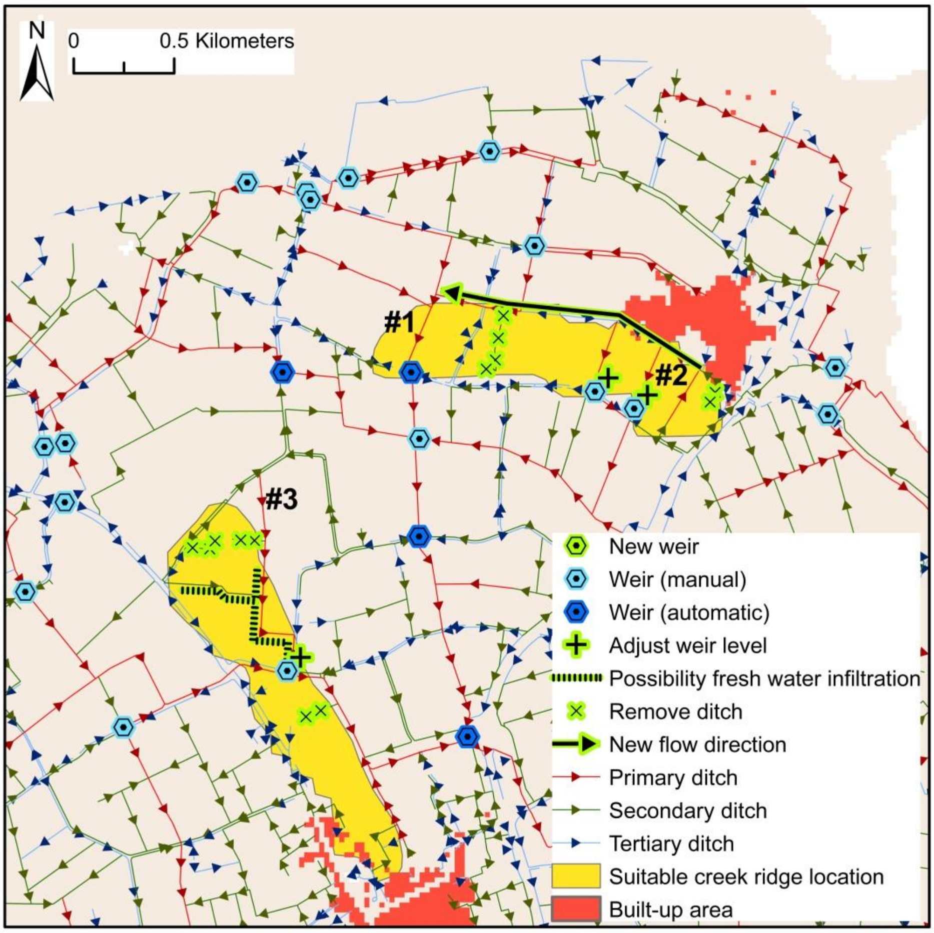

Figure 5.3: Proposed measures to achieve enlargement of fresh groundwater reserves in sub area A. The location of the pilot of fresh water infiltration via a CCD system is indicated with the red circle (see Appendix I for a detailed description of the pilot).

5.2.2. Measures for sub area B

In this sub area several measures can be distinguished that involve the change of flow direction, also two special measures are suggested (Figure 5.4). First of all, in the north part of this creek ridge location fresh water is drained away from the creek ridge location (#4 in Figure 5.4). It is recommended to block this water at the downstream weir and change the flow direction towards the creek ridge where the water can be infiltrated.

Secondly, in the south-east part of the creek ridge a secondary ditch cuts through the creek ridge deposit (#5 in Figure 5.4). It is recommended to block this ditch and divert all the water southwards into a primary ditch. From this primary ditch water can be used for infiltration. As a result of the blocking in combination with CCD at the creek ridge, the secondary ditch loses its function and either can be removed or the water level can be raised.

Thirdly, in the south-west part of the sub area fresh water is drained from the creek ridge and transported north (‘special measure 7’ in Figure 5.4). Away from the creek ridge saline seepage occurs, making the water more saline as it flows downstream. It is recommended to collect the water before it becomes too saline. Placing a weir, e.g. next to the road, blocks this water and changes the flow direction towards the creek ridge where the water can be infiltrated (see Figure 3.1 for a schematic example).

Finally, at the location marked with ‘special measure 1’ in Figure 5.4 a saline primary ditch cuts through the creek ridge location, likely to cause drainage of fresh water from the creek ridge and upconing of the fresh-saline interface. This is the most important waterway of Walcheren and therefore a rise in the water level cannot easily be realised (p.c. Geschiere, 2012). It is therefore recommended to search for alternative measures, e.g. to make the bed of the ditch impermeable.

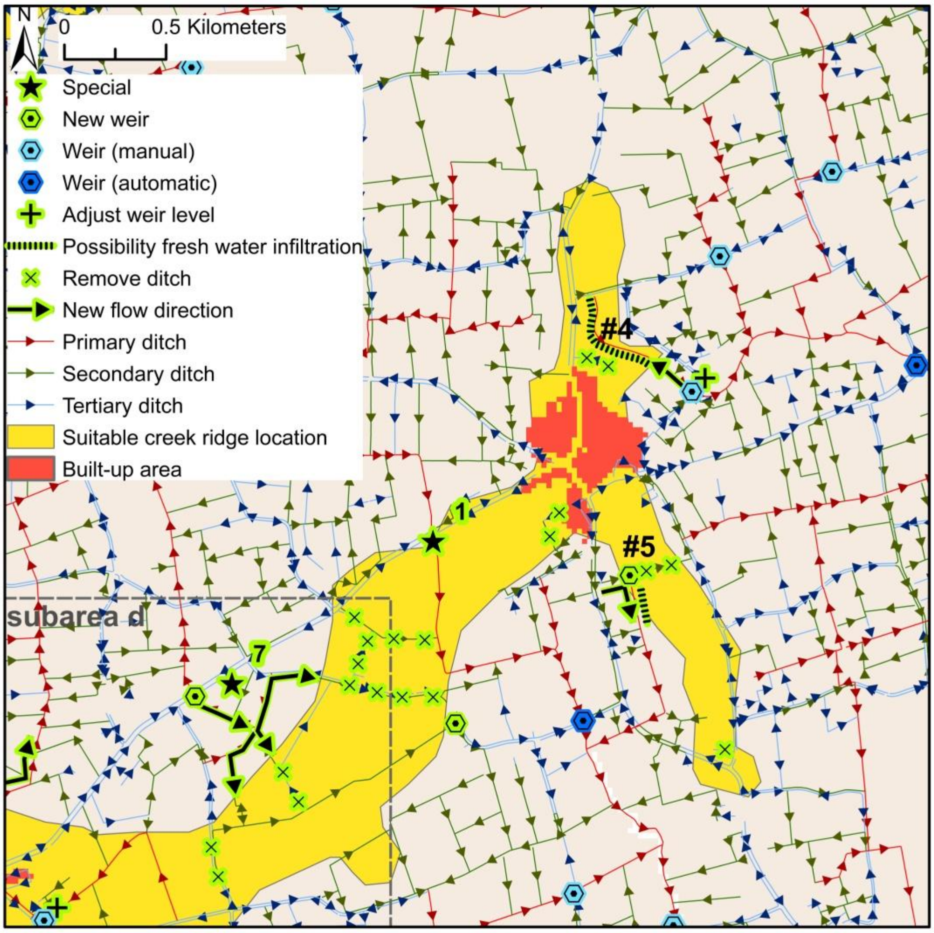

Figure 5.4: Proposed measures to achieve enlargement of fresh groundwater reserves in sub area B.

5.2.3. Measures for sub area C

In this sub area several measures can be distinguished (Figure 5.5). First of all, a saline primary ditch crosses the creek ridge location (#6 in Figure 5.5). To limit the effects of this ditch on the fresh groundwater reserve in the creek ridge two measures are proposed. On the one hand, to reduce the amount of water that flows towards the creek ridge. On the other hand, to raise the water level on the east side of the creek ridge location, by adjusting the weir level. The water level needs to be adjusted as such that drainage towards this ditch is limited, while at the same time infiltration from this ditch is prevented.

Secondly, a secondary ditch runs over the middle of the creek ridge ('special measure 2' in Figure 5.5). It is recommended to limit the draining effects of this ditch by raising the water level and by diverting the water along the edges of the creek ridge.

Finally, some of the tertiary ditches at the south end of the creek ridge location can be removed (#7 in Figure 5.5). With the installation of CCD systems these ditches will lose their functionality (see section 3.3).

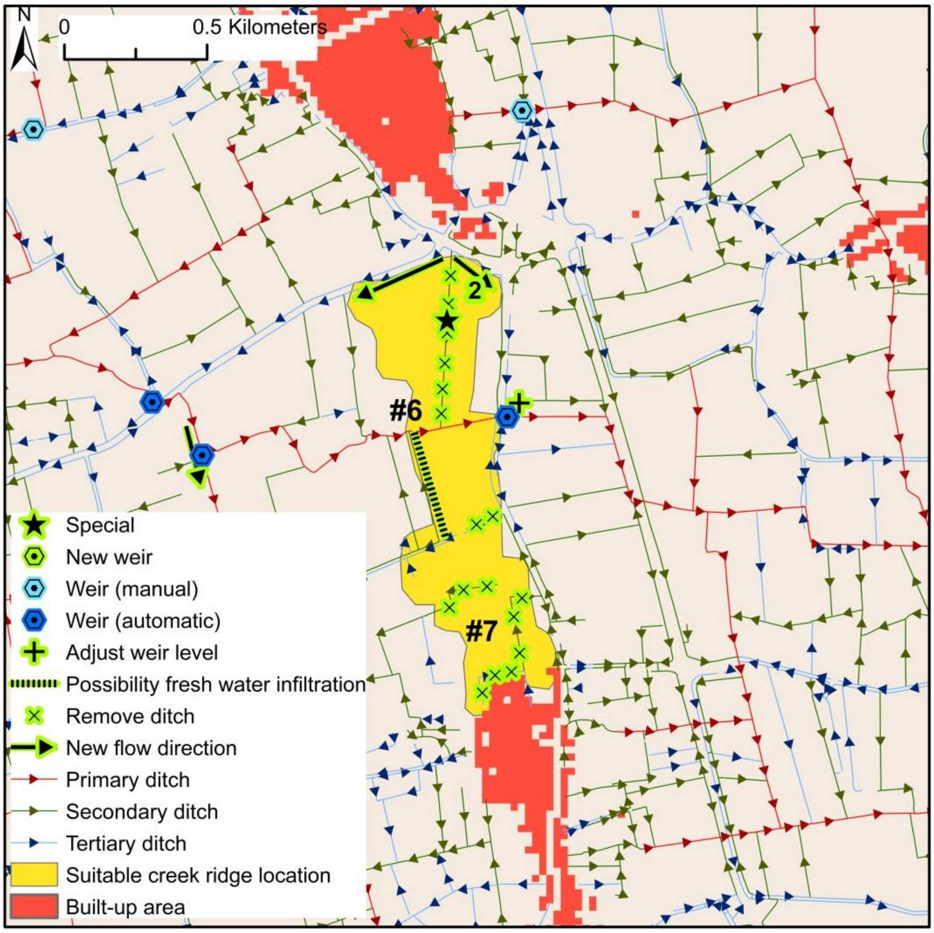

Figure 5.5: Proposed measures to achieve enlargement of fresh groundwater reserves in sub area C.

5.2.4. Measures for sub area D

In this sub area several measures are suggested including some special measures (Figure 5.6). First of all, it is suggested to raise the levels of three weirs and place two new weirs to decrease the draining function of these ditches (#8 in Figure 5.6).

Secondly, at the north side of the creek ridge saline water is transported towards the creek ridge (#9 in Figure 5.6). It is recommended to divert this water via an adjacent primary ditch. Before this can be realised the ditches need to be connected for which the construction of a new part of the ditch is required.

Thirdly, at the location indicated with 'special measure 3' saline water is measured (10 mS/cm). This is probably saline seepage, as the dune ridge is very narrow at this part of Walcheren. This saline water is transported through the entire area of Walcheren before it is discharged via the pumping station 'Boreel' near Middelburg. It is therefore recommended to search for solutions to prevent this saline water from entering the area, e.g. pump it directly back towards the sea. At the location indicated with 'special measure 4' this saline water is divided among two primary ditches. Part of the water flows towards the location indicated with 'special measure 5' (southwards). As the water flows downstream, it becomes less saline. This indicates that the saline water originates from the inlet and is mixed with fresh water from the area. If the amount of saline water that flows towards special location 5 could be reduced, the water at location 5 may become fresh enough for infiltration. However, the capacity of the ditch running eastwards from 'special measure 4' is not sufficient to transport all the water during wet periods (p.c. Geschiere, 2012).

Finally, throughout this sub area tertiary ditches may be removed when they lose their functionality as a result of the installation of CCD systems.

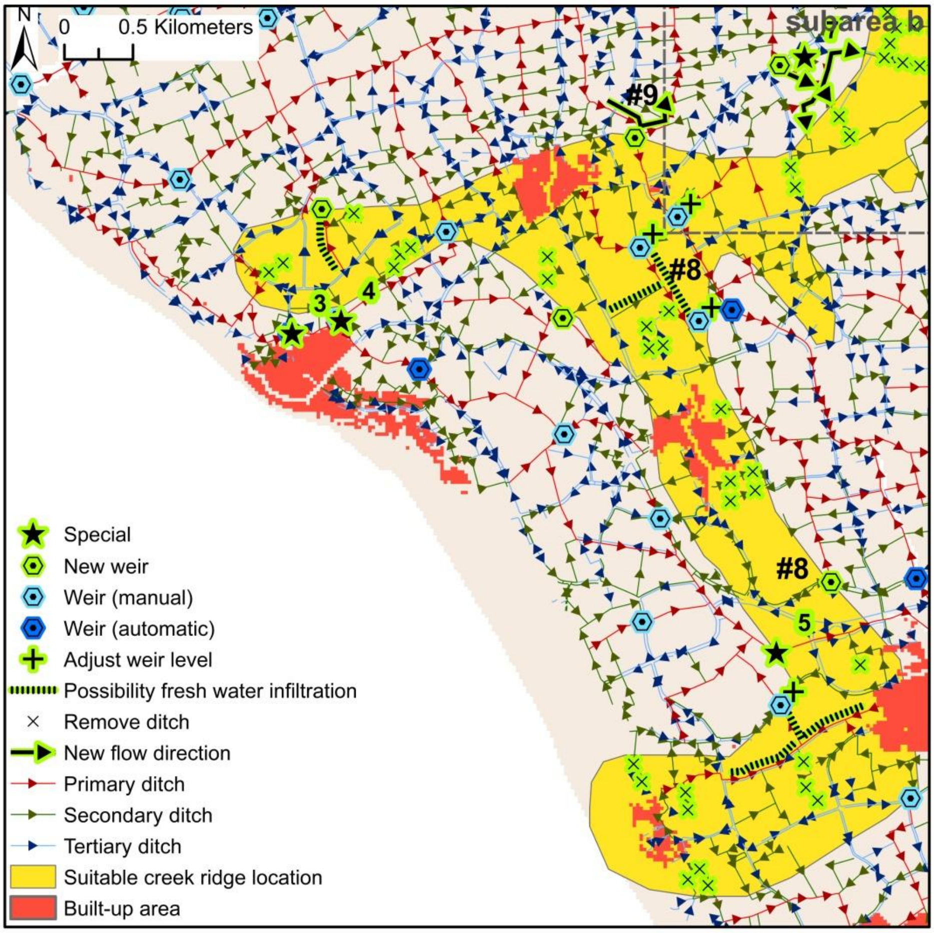

Figure 5.6: Proposed measures to achieve enlargement of fresh groundwater reserves in sub area D.

5.2.5. Measures for sub area E

Sub area E is highly suitable for the infiltration of fresh water (Figure 5.7). It is therefore recommended to place two new weirs in the area to raise the water level and lower the flow velocity in the primary ditches to allow the water to infiltrate.

The salinity of the water at the location of 'special measure 6' was measured to be just above the threshold for infiltration (2 mS/cm). It is therefore recommended to measure the salinity at various moments in time to be able to make a good judgement of the suitability of the surface water at this location for infiltration.

The tertiary ditches that lose their functionality as a result of the installation of CCD systems can be removed.

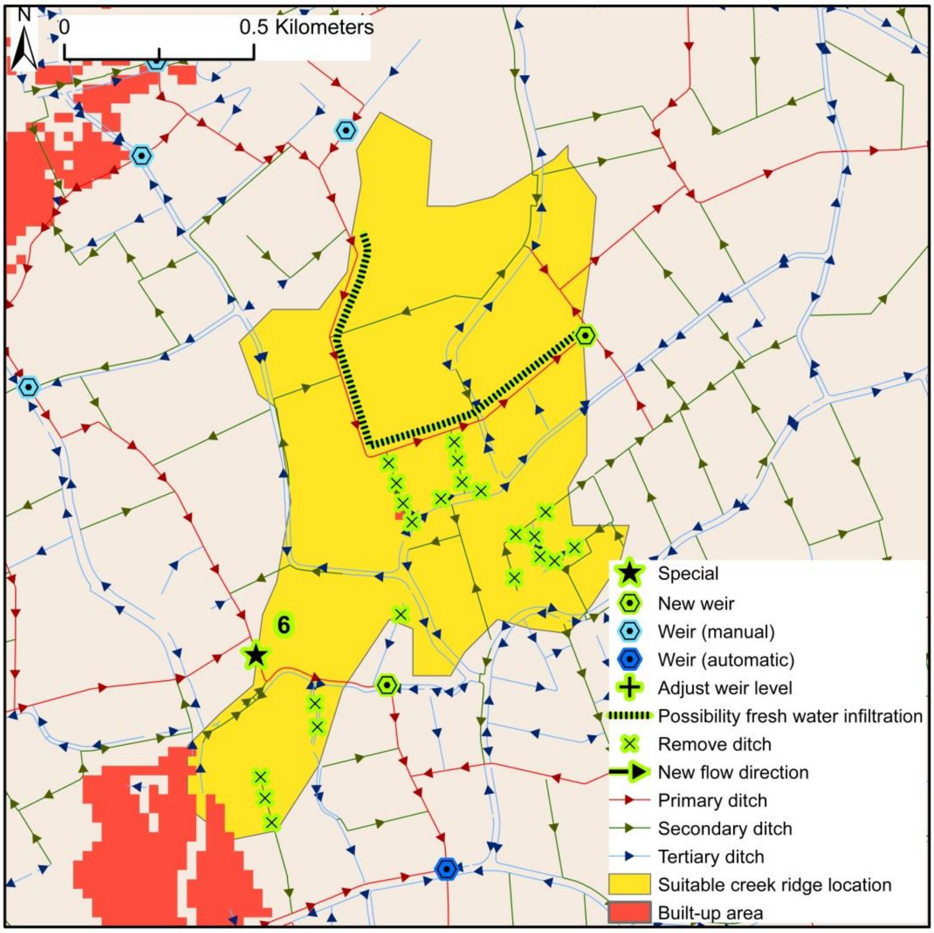

Figure 5.7: Proposed measures to achieve enlargement of fresh groundwater reserves in sub area E.

5.3. Available quantities of fresh water for infiltration

For the locations indicated as suitable for infiltration of fresh water, the quantities of available fresh water have been determined. Based on the drainage pattern, catchments corresponding to the infiltration locations could be identified (Figure 5.8). The creek ridge locations were excluded from water balance calculations as it was assumed that with the recommended measures (see section 5.2) all water is retained at these locations. Some creek ridge locations that are suitable for infiltration on the western side of Walcheren are therefore left out of the calculations. These locations are indicated as suitable for infiltration of fresh water, but the catchments only consist out of creek ridge locations. Theoretically these locations have therefore no extra water available for infiltration.

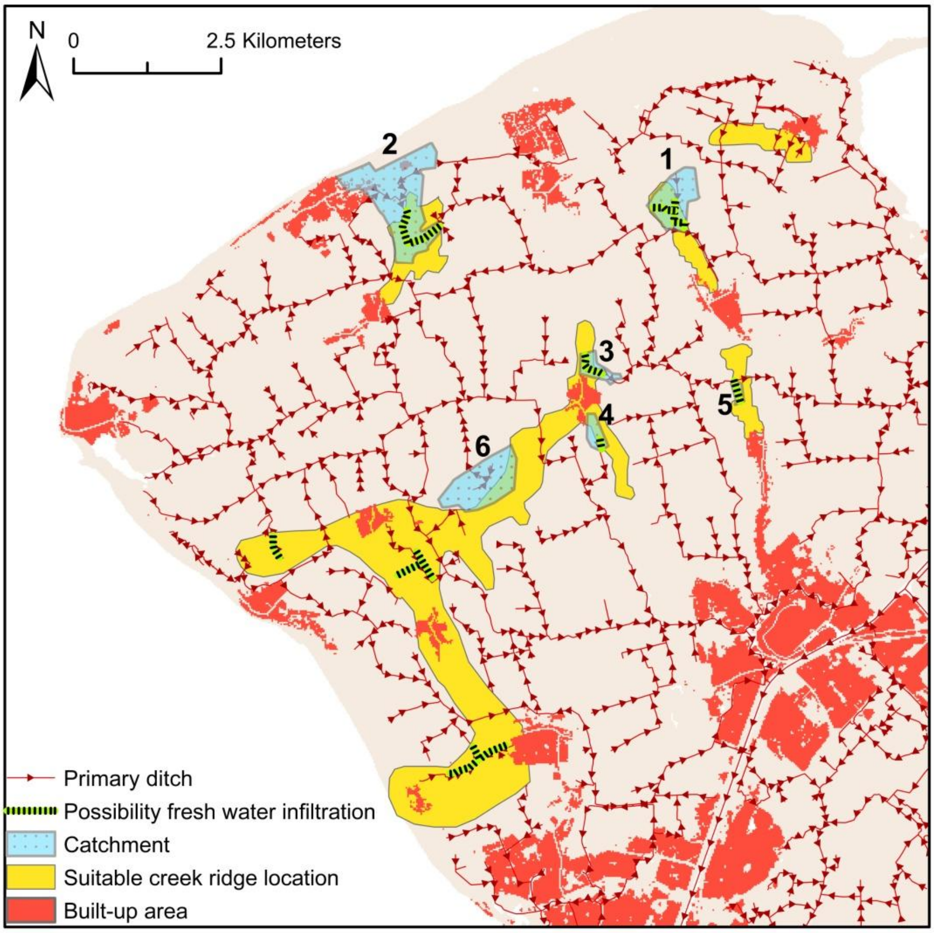

Figure 5.8: Catchments corresponding to locations with a possibility for fresh water infiltration.

By means of water balance analyses (see section 4.2.3) the available quantities of fresh water were calculated per catchment (Table 5.1; see Appendix V for the water balance per catchment). The surface over which this available water could be distributed is determined for an infiltration rate of 1 mm/d (Table 5.1). Figure 5.9 gives an indication of the areas over which the extra infiltration of fresh water may be realised. This comprises a total of 262 ha. At those locations where extra fresh water can be infiltrated the enlargement of the fresh groundwater reserves is significantly bigger.

Table 5.1: Water availability per catchment and the area over which this water can be infiltrated. (The water balances per catchment can be found in Appendix V.)

Catchment	Water availability (m^3/d)	Area for infiltration of 1 mm/d (ha)
1	309	30.9
2	1490	149 (this creek ridge location covers only 112 ha)
3	91	9.1
4	92	9.2
5	19	1.9
6	991	99.1

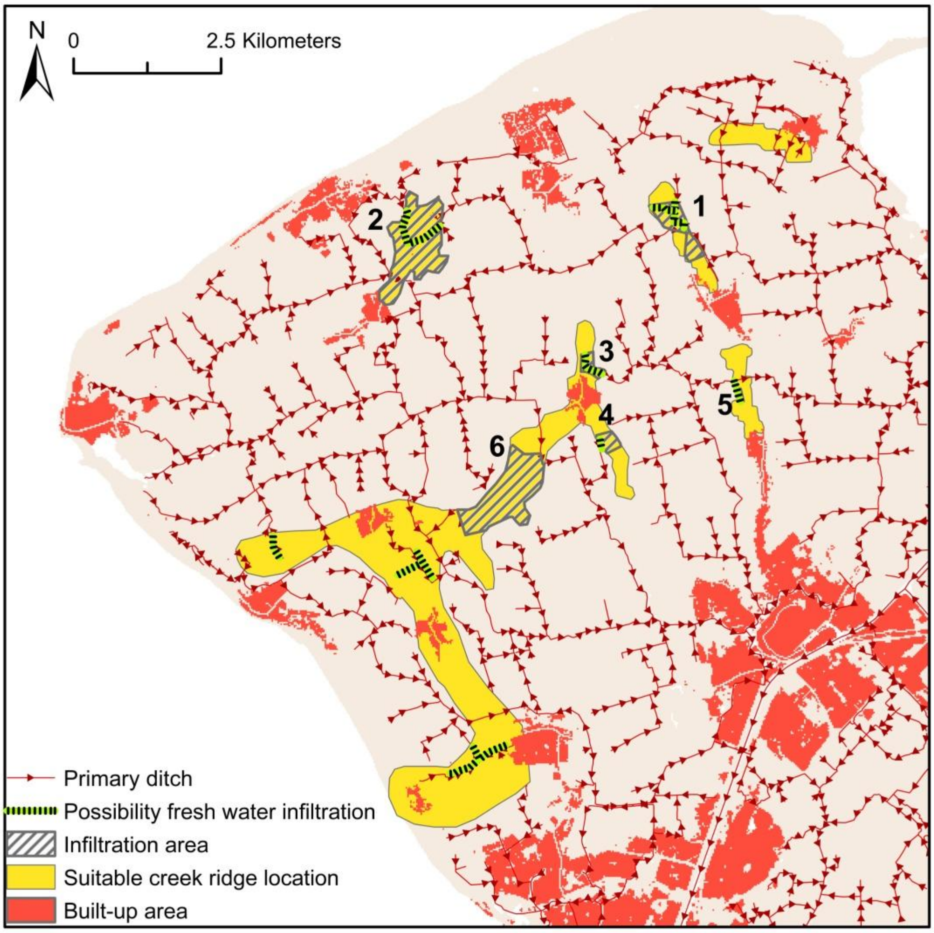

Figure 5.9: Indication of the areas over which extra fresh water can be infiltrated (1 mm/d in wintertime).

6. Discussion

Fresh groundwater reserves in coastal areas and their development are complex systems. The project *GO-FRESH* acts as a showcase for practical solutions and, at the same time, enhances the knowledge and understanding of processes regarding fresh and saline groundwater (Oude Essink, 2011). The development of this knowledge can be valuable for other (vulnerable) coastal areas in the world as well. Especially as fresh groundwater reserves in coastal areas will be under higher pressure with increasing climate change and sea level rise (Nicholls, 2011; Oude Essink *et al.*, 2010; Pauw *et al.*, 2012).

In this research it is assumed that infiltration of fresh water via a CCD system is effective in enlarging fresh groundwater reserves in creek ridges. A pilot study in which this theory is tested is still ongoing and the results are yet to be expected (Oude Essink, 2011). Therefore there are no quantitative statements in this report about the exact enlargement of the fresh groundwater reserves. Besides, the development of fresh groundwater reserves is influenced by complex interactions between (geo)hydrological properties of a specific area. To make predictions about the development of fresh groundwater reserves, detailed modelling is required as well as more detailed field data (especially regarding geology). This was beyond the scope of this research. An example of such a detailed study is done by Visser (2012).

Additional measurements, detailed modelling studies and calculations at field scale are also required to make an estimation of the effects of the proposed measures. This accounts for the influence on both the fresh groundwater reserves as the water management in the area. It must therefore be remarked that the proposed measures are rather suggestive than conclusive. The measures are supposed to achieve the desired results, without causing problems such as water damage. Results of the modelling studies will indicate what practicable (adjustments of) weir and groundwater levels are. It is assumed that with the installation of CCD systems all water is retained at the creek ridge locations and not drained away. Research needs to indicate if this is realistic in practice. When not all water can be retained at the creek ridge locations, this water can be used for infiltration elsewhere. In that case more fresh water might be available for infiltration, also at the suitable infiltration locations on the western side of Walcheren. Furthermore, raised surface- and groundwater levels will have positive effects on the fresh groundwater reserves in creek ridges. However, this also means that there is less space for storage of water. As a consequence the system becomes more sensitive to wetness during high rainfall periods and more adequate reaction is required during these periods to prevent water damage.

It is also important to investigate the feasibility of the measures before implementation. An important aspect that should be taken into account is the presence of infrastructure both above and below the surface. There are, for instance, many pipes and cables in the ground that may interfere with the construction of new ditches and control structures (p.c. Geschiere, 2012). Next to that, the basis of the proposed measures is the construction of CCD at all creek ridge locations. The construction costs for a CCD system are approximately twice the construction costs for a standard CD system. Therefore most farmers currently work with CD systems. Incentives might be needed to make CCD common practice. At the moment it is not the policy of the waterboard to oblige farmers to install CCD systems (p.c. Geschiere, 2012). Another waterboard however, the waterboard Peel en

Maasvallei, has made CCD mandatory since 2008 (Waterschap Peel en Maasvallei, 2009). This shows that with a change in policy it might be possible to make CCD systems mandatory in Walcheren as well. Another important aspect concerning the feasibility of the measures is that it may be difficult to guide fresh water towards creek ridge locations where it can be infiltrated. This is due to the fact that the creek ridge locations, as a result of their development, are generally higher elevated than the surrounding areas. Usually water is drained away from these creek ridge locations towards lower-lying areas surrounding the creek ridges.

The main part of this research is based on analysis of available maps. The accuracy of the results is therefore to a great extent determined by the accuracy of these maps. Some of the criteria for suitable creek ridge locations are tested with the aid of modelling results. As with every modelling study various assumptions are made, which make the results only an approximation of the reality (Van Baaren *et al.*, 2011a). For instance, the geological assessment is based upon a map, which has been created through the interpolation of borehole data. Interpolation also results in an approximation of the reality and the quality improves with higher data resolution. Fieldwork and expert judgement also pointed out that the drainage pattern map has some deviations from reality. Despite the deficiency of the available maps, an approximation of the hydrological situation can be obtained. It, however, also amplifies the need for the collection of more and detailed field data.

The available data from maps have been complemented with EC-measurements. At every location the EC has been measured at only one moment in time, after an extended period of heavy rainfall. It was assumed that the measured EC-values are a good representation of the average EC during the winter season. To get better insight of the variation of the EC over time it might be useful to measure the EC at some places multiple times throughout the year, e.g. with the use of divers. Besides, the measured EC-values are only an indication for the salinity of the water. Not only chloride, but also other elements contribute to the EC of water (McNeill, 1980). Next to the collected EC-data, there were also some salinity data of the study area available. This data, however, were only of limited use for several reasons. First of all, the data did not indicate at which location exactly at a congregation of ditches the measurements were taken (Figure 4.2). Secondly, the data were given in chloride concentration, but it was not indicated which conversion method had been used, which is important to know in case of low EC. Finally, the measurements were taken at a different moment in time (September and March/April) than the EC-measurements of this research.

The water balance analysis is a rough estimate of the available fresh water for infiltration. Only the most important terms are included in this analysis. The precipitation and evapotranspiration data are provided by accurate weather station measurements. However, the infiltration and seepage component is determined from modelling results at a grid size of 100 x 100 m. The latter data are therefore likely less accurate. Furthermore, the suggested areas over which the fresh water can be infiltrated give merely an indication of the possible areas and their sizes. A detailed field study is required to determine the exact locations for infiltration of fresh water.

7. Conclusions & Recommendations

This research can be seen as a starting point for a change in water management in the area of Walcheren. The suggested measures lead to enlarged fresh groundwater reserves with higher resilience to increasing salinisation under changing climates and rising sea levels. Based on seven selection criteria, creek ridge locations that are suitable for the enlargement of fresh groundwater reserves are identified. For these suitable locations water management measures to establish enlargement of fresh groundwater reserves have been identified. The main conclusions of this research are:

- Creek ridge locations that are suitable for the enlargement of fresh groundwater reserves cover 1342 ha. This comprises 12% of the total area of Walcheren located west from the canal (‘*Kanaal door Walcheren*’) that is used for agriculture.
- At 262 ha of the suitable creek ridge locations fresh water can be infiltrated actively to realise extra storage of water and therefore enlargement of the fresh groundwater reserves. This is 20% of the total 1342 ha of suitable creek ridge locations.
- Various water management measures are identified to realise the enlargement of fresh groundwater reserves. Key aspects of the measures are to increase the retention of fresh water on the creek ridge locations, to limit the effects of saline water and to prevent (valuable) fresh water from being discharged into saline ditches.
- Before implementation of the measures, the effects, effectiveness and feasibility of the measures should be investigated and quantified through modelling studies. The results can be used to fine-tune the proposed measures.

Retention of fresh water in the creek ridges can be realised by the implementation of composite controlled drainage systems and the removal of tertiary ditches. With the aid of composite controlled drainage systems groundwater levels at field scale can be controlled with which the unsaturated zone can be optimally used for storing fresh water. The composite controlled drainage systems can (with some adaptations to the drainage design) also be used for the infiltration of extra fresh water at locations where fresh water is available. The effects of saline water on the fresh groundwater reserves can be limited by control structures, such as weirs. Weirs can be used to raise surface water levels to limit the draining effects of a ditch and to guide water via ditches that do not cross the creek ridge locations. Weirs can also be used to separate fresh and saline water in ditches and prevent in this way the (valuable) fresh water from being mixed with saline water.

For the implementation of the proposed measures the following procedure and priorities are recommended. First of all, it is recommended to make the installation of composite controlled drainage systems common practice. It is expected that this type of drainage system has a major impact on the storage of fresh water and therefore the enlargement of fresh groundwater reserves. Secondly, the other proposed water management measures should be fine-tuned based on modelling efforts that determine the effects, effectiveness and feasibility of the measures. Once these have been established the measures can be put into practice. The adjustments of weir levels can relatively easily be adopted in the next water level agreement. After that, the measures can be applied that require construction works, such as the installation of new weirs, removing tertiary ditches and change the course of ditches. At the same time, there should be wide support for the implementation of the measures amongst water managers and users. Practice has shown that in the cooperation of the ‘Waterhouderij’ (fresh) water management is easier and more effective when all stakeholders cooperate. It is therefore recommended to not only focus on the practical sides of the implementation of measures, but also on cooperation and knowledge exchange between stakeholders.

For future research an important aspect should be the detailed modelling of the effects of the measures. Besides, it is very important to monitor the effects of implemented measures in practice. With this learning-by-doing approach, important insights in the hydrological system can be gained. The insights gained by modelling and monitoring efforts can, for instance, be used to develop a tool with which the effects of various methods at field scale can easily be estimated. Especially the effects on groundwater levels and the depth of the fresh-saline interface are important.

The proposed measures focus on creek ridge locations, because these show the highest potential for the enlargement of fresh groundwater reserves based on the (geo)hydrological properties. However, enlargement of fresh groundwater reserves could possibly also be realised outside the creek ridge locations. It is therefore interesting to involve other locations than creek ridge locations in future research on the enlargement of fresh groundwater reserves.

To improve water management planning and modelling efforts it is valuable to collect more field data. Especially the datasets of geological data and EC-measurements should be expanded. For the collection of EC-measurements it is important to pay attention to the moment of measurement. Next to that, it is very important to document the exact location of the measurements accurately.

The knowledge and insights gained for this particular region may be valuable for other (vulnerable) coastal areas in the world. It is therefore worthwhile to devote future research on investigating the possibilities for exportation and application to other areas in the world.

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Appendices

Appendix I – CCD system with infiltration at pilot location

In Walcheren, near Serooskerke, a pilot experiment has been set up to experiment with fresh water infiltration via a CCD system (Figure I.1). The pilot is located at a creek ridge and covers two fields of different farmers. At this location a new CCD system with additional infiltration drains has been installed in the winter of 2012 – 2013 (Figure I.2). A detailed monitoring plan has been designed to monitor changes in groundwater level, the fresh-saline interface and the corresponding development of the fresh groundwater reserve in the creek ridge. This pilot experiment functions as a showcase for this technique and is part of the *GO-FRESH* project.

At this specific pilot location several (geophysical) measurements are done to get more insight in the specific (geo)hydrological properties (e.g. Visser, 2012). Visser (2012) also developed a 3-D density dependent groundwater flow model for this specific pilot location. Some of the measurement and modelling results have been used in this report to illustrate statements. The specific locations of these measurements and modelling efforts are indicated in figure I.1.

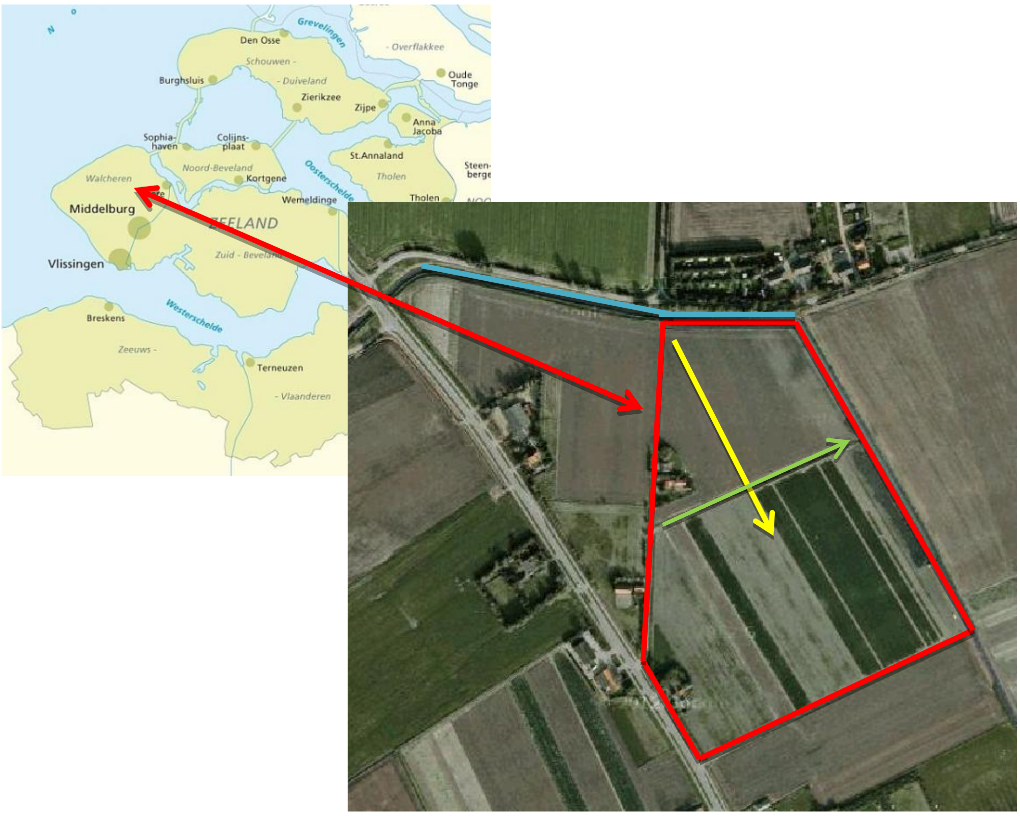
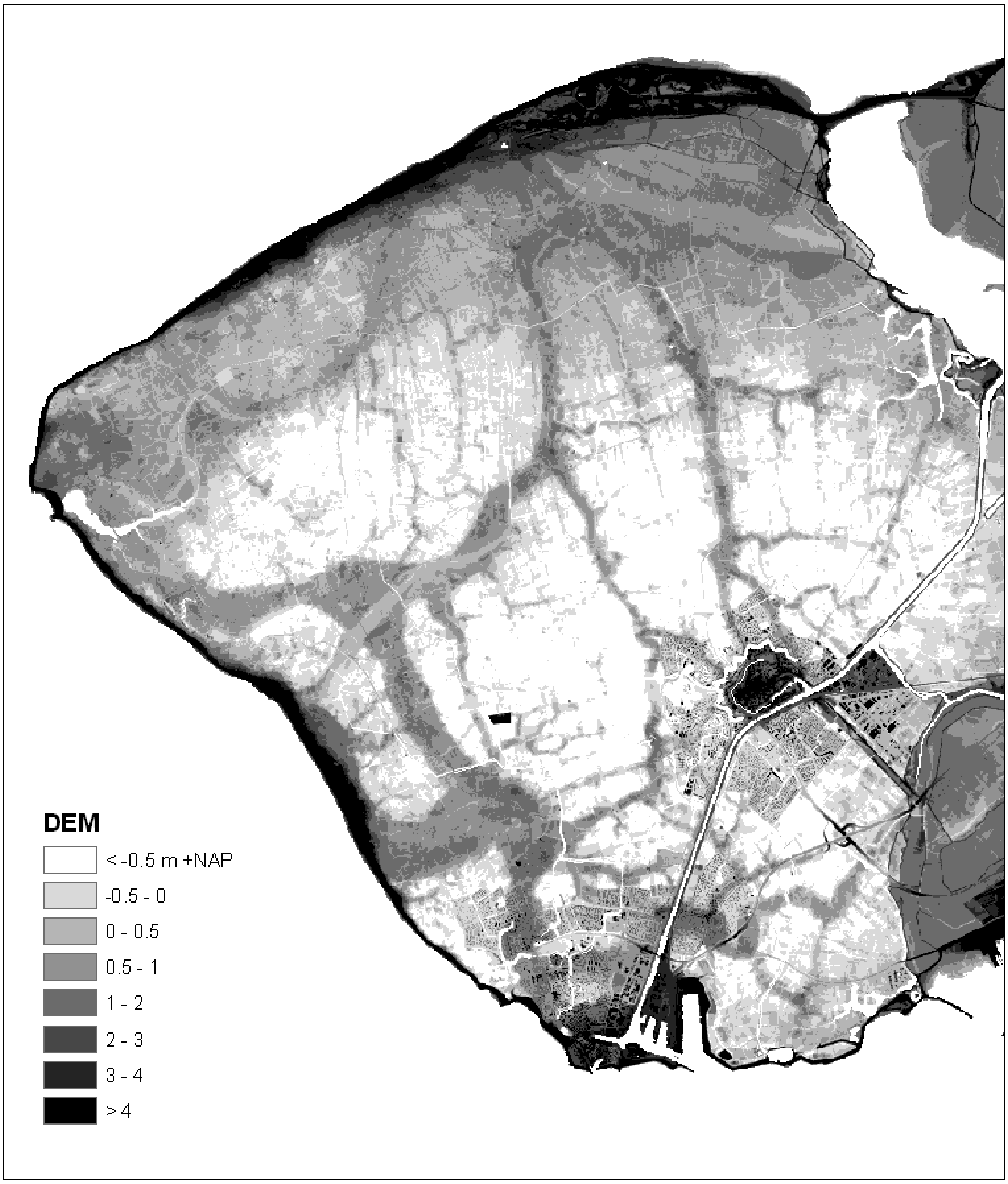


Figure I.1: Location of pilot with infiltration through controlled water level drainage. The pilot location is indicated in the red. The CVES transect is indicated in yellow with the primary ditch which causes upconing in the fresh-saline interface indicated in green (see section 3.3). The primary ditch for which the effects of a water level rise of 0.5 m have been modelled is in indicated in blue (see section 3.4).

Figure I.2: Design of the pilot CCD system with infiltration facilities (Pauw and Van Baaren, 2012).

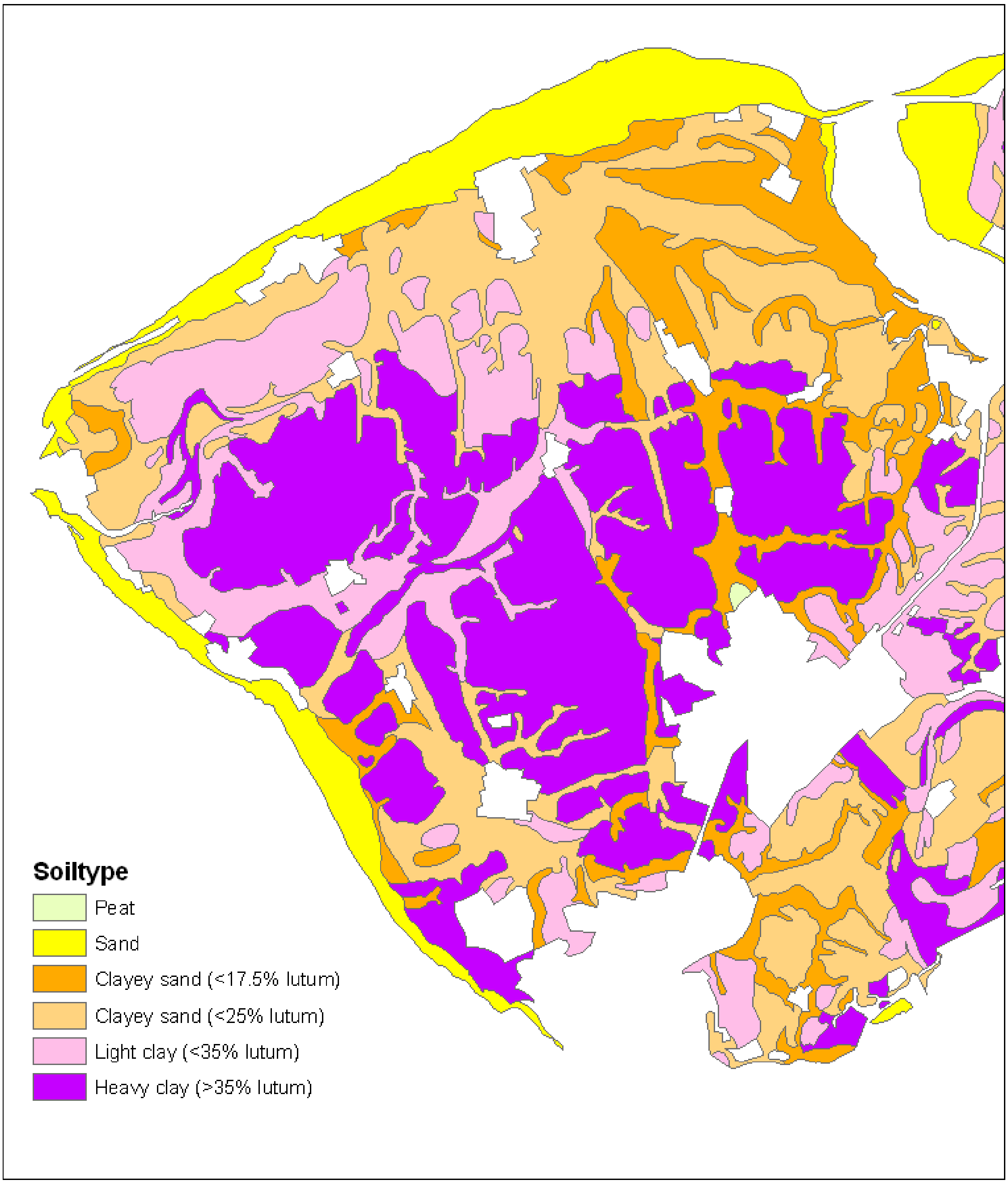
Appendix II – Basic maps

II.A – DEM



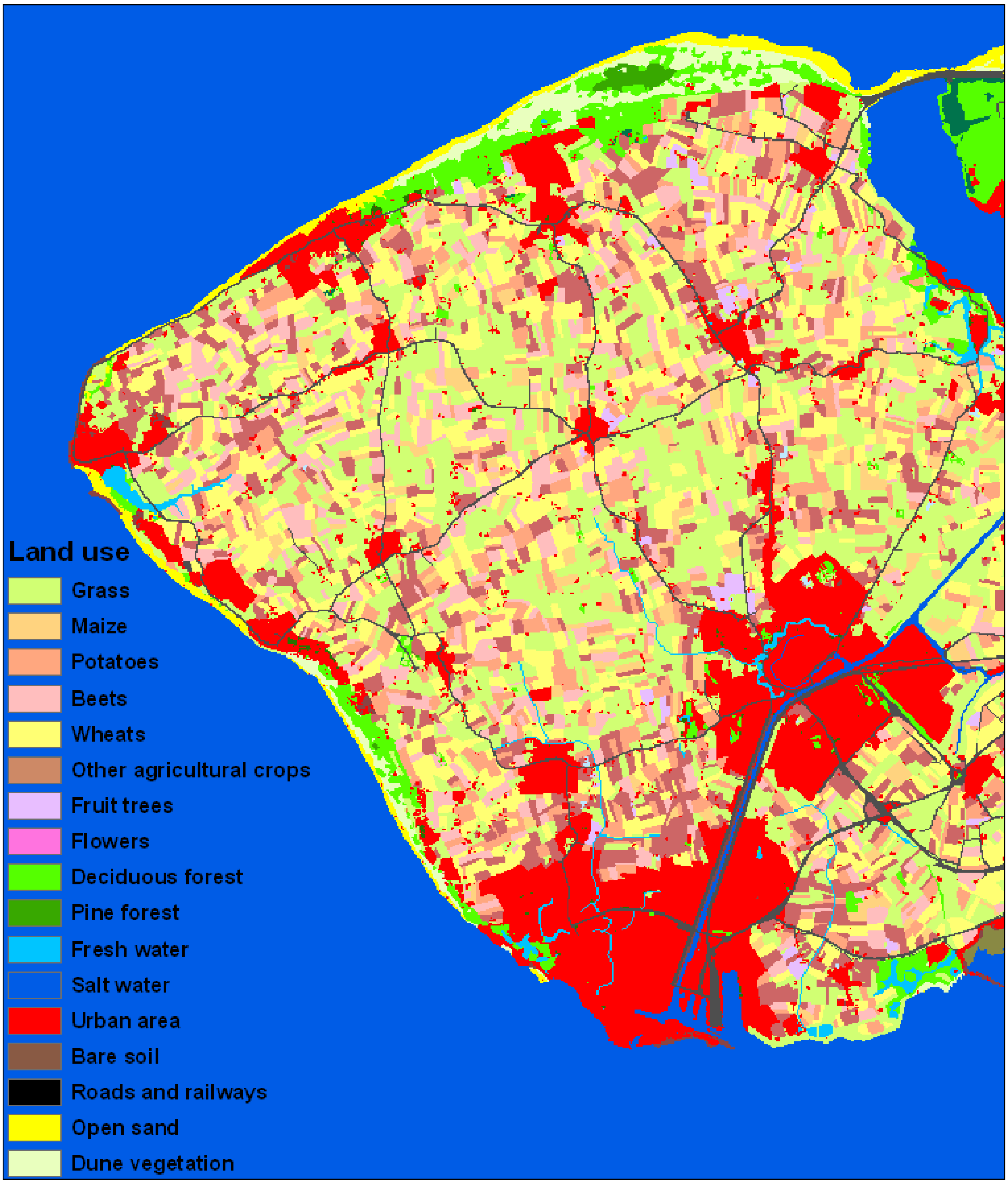
(Meetkundige Dienst, 2007)

II.B – Sediment types



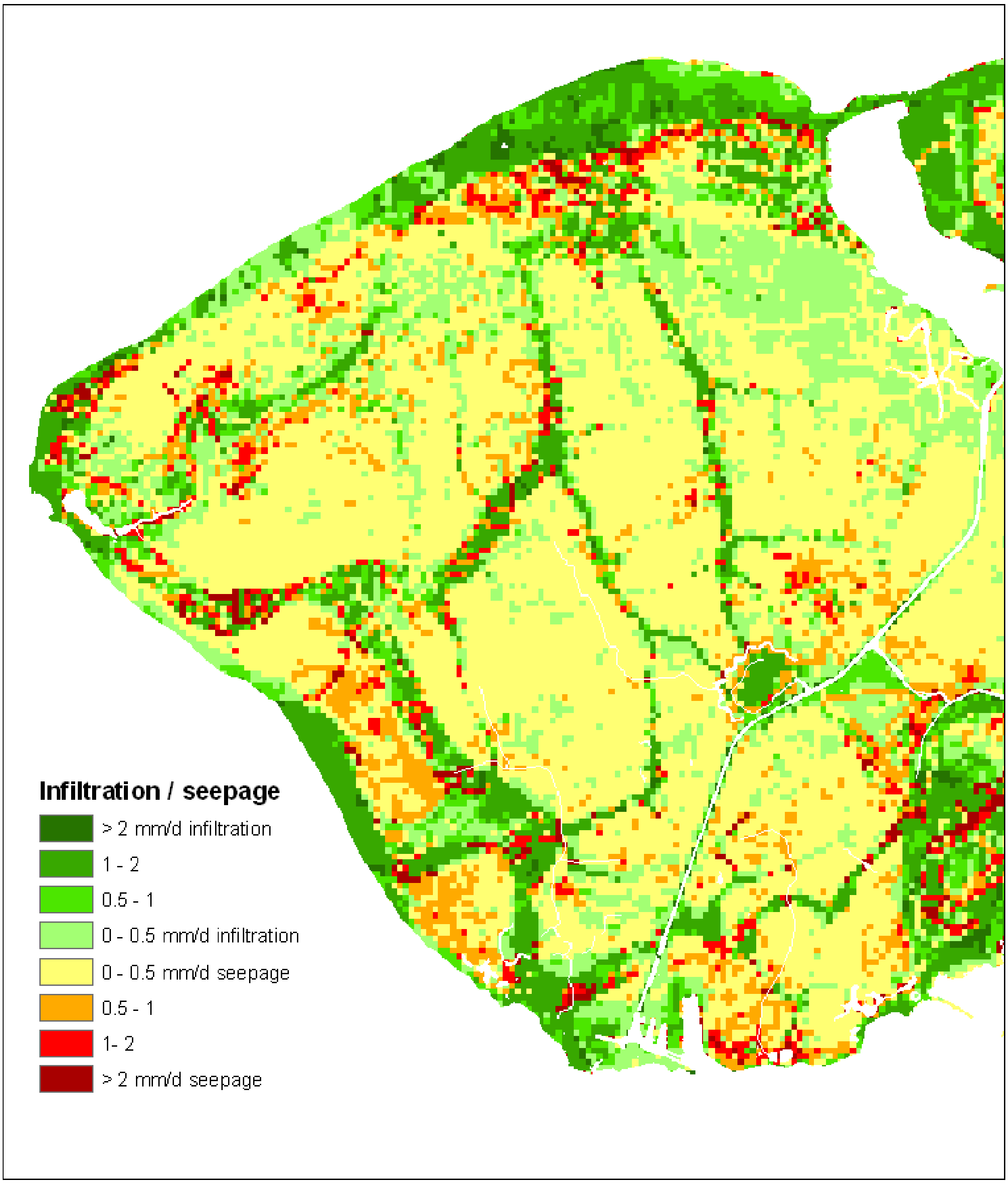
(Alterra, n.d.)

II.C – Land use



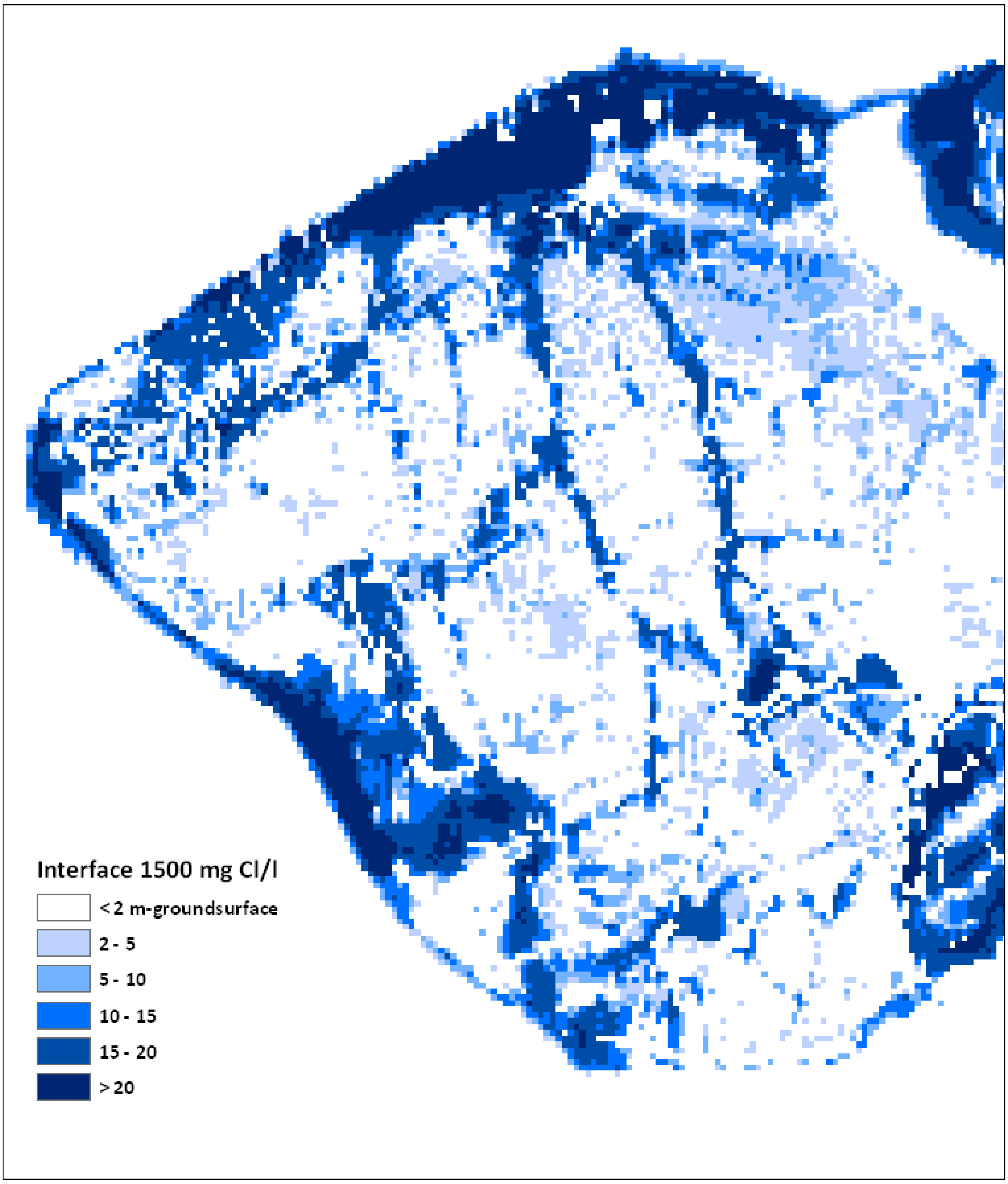
(GeoDesk, 2001)

II.D – Infiltration and seepage



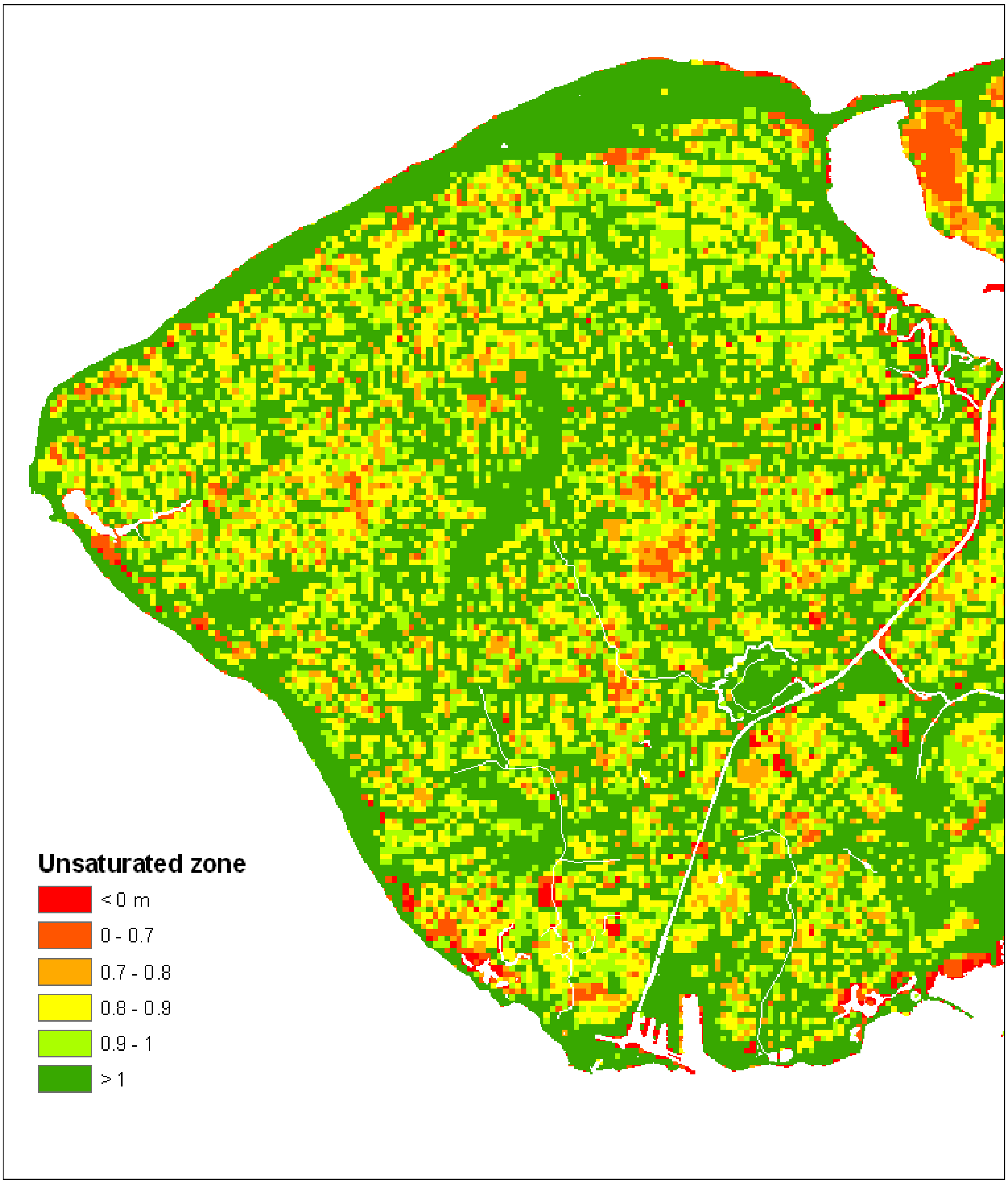
(Van Baaren *et al.*, 2011a)

II.E – Fresh-saline interface



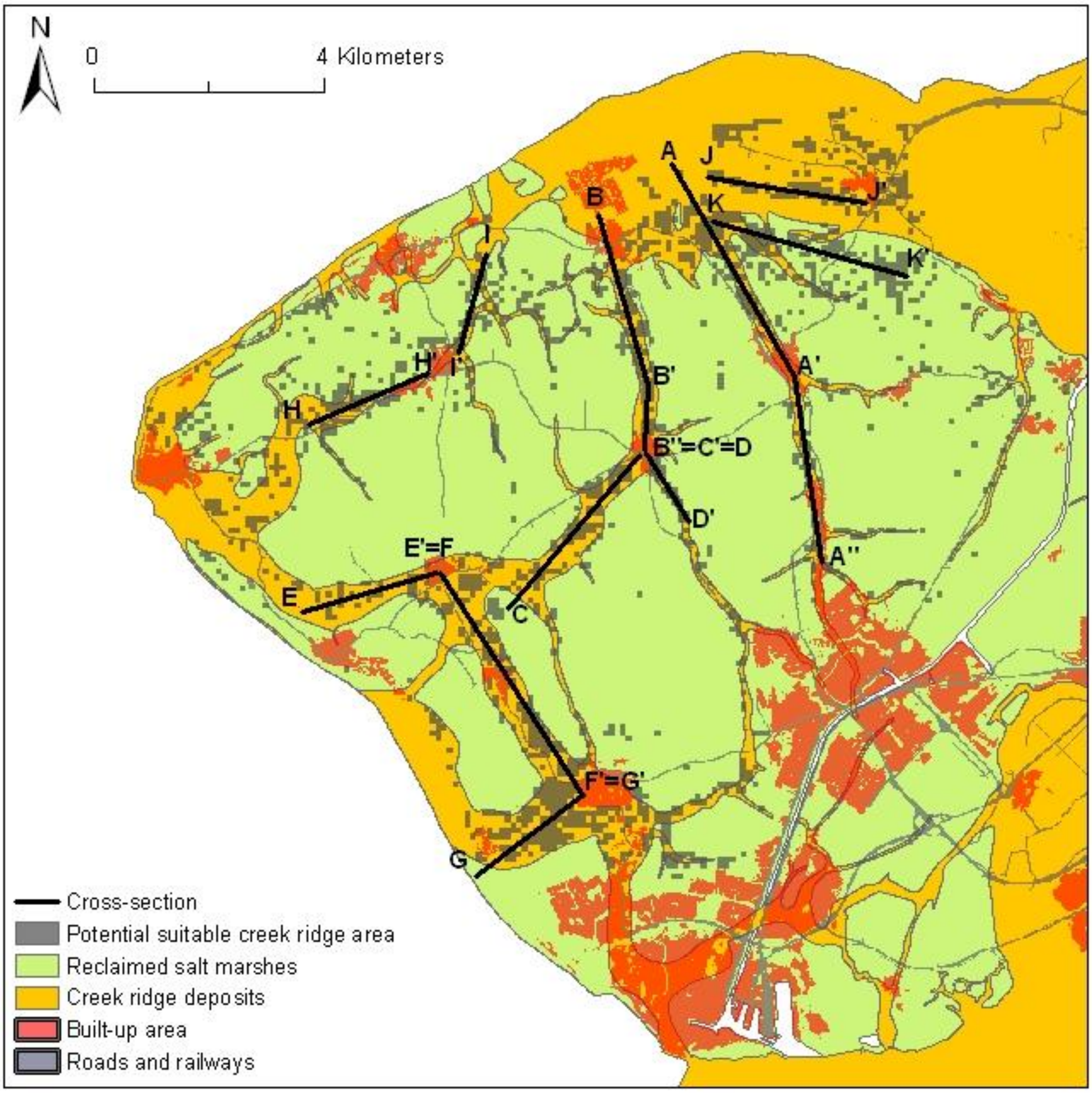
(Van Baaren *et al.*, 2011a)

II.F – Unsaturated zone thickness



Appendix III –Geohydrological properties subsurface

Potential suitable creek ridge locations based on six criteria[16] and the position of cross-sections



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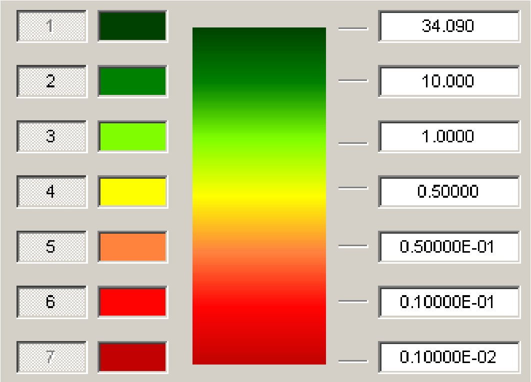
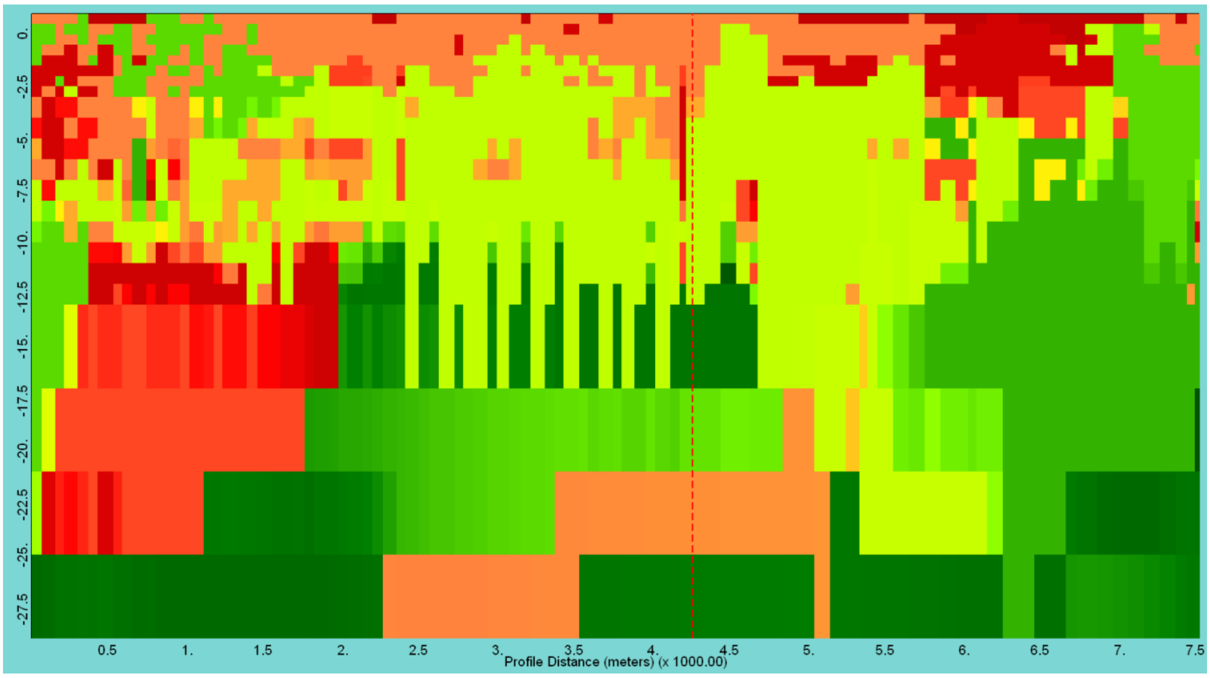
[16] These six criteria are the first six as listed in the selection criteria (see section 4.1).

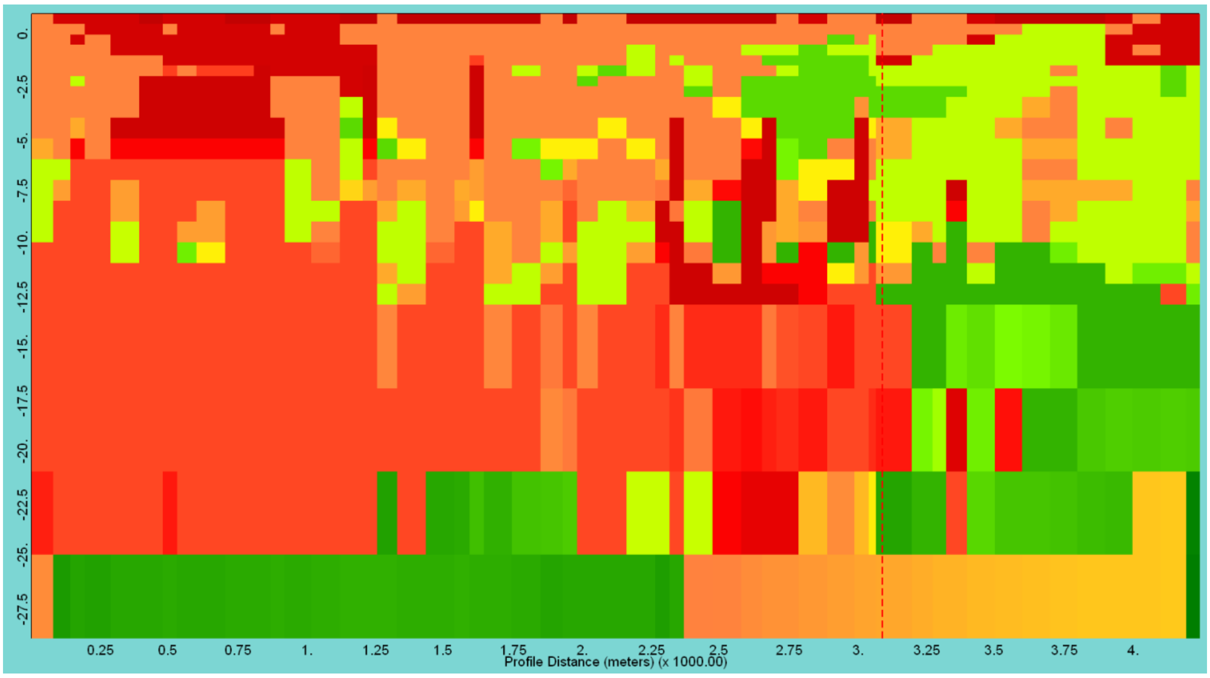
Legend hydraulic conductivity



A-A’-A’’



B-B’-B’’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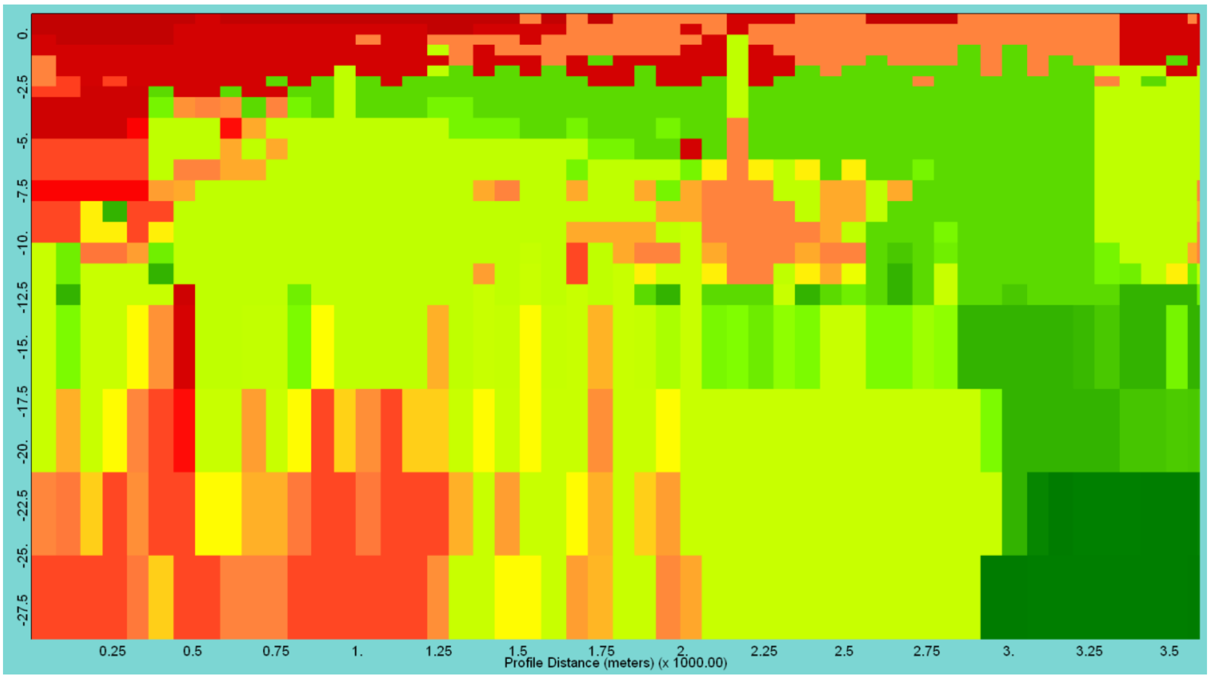
C-C’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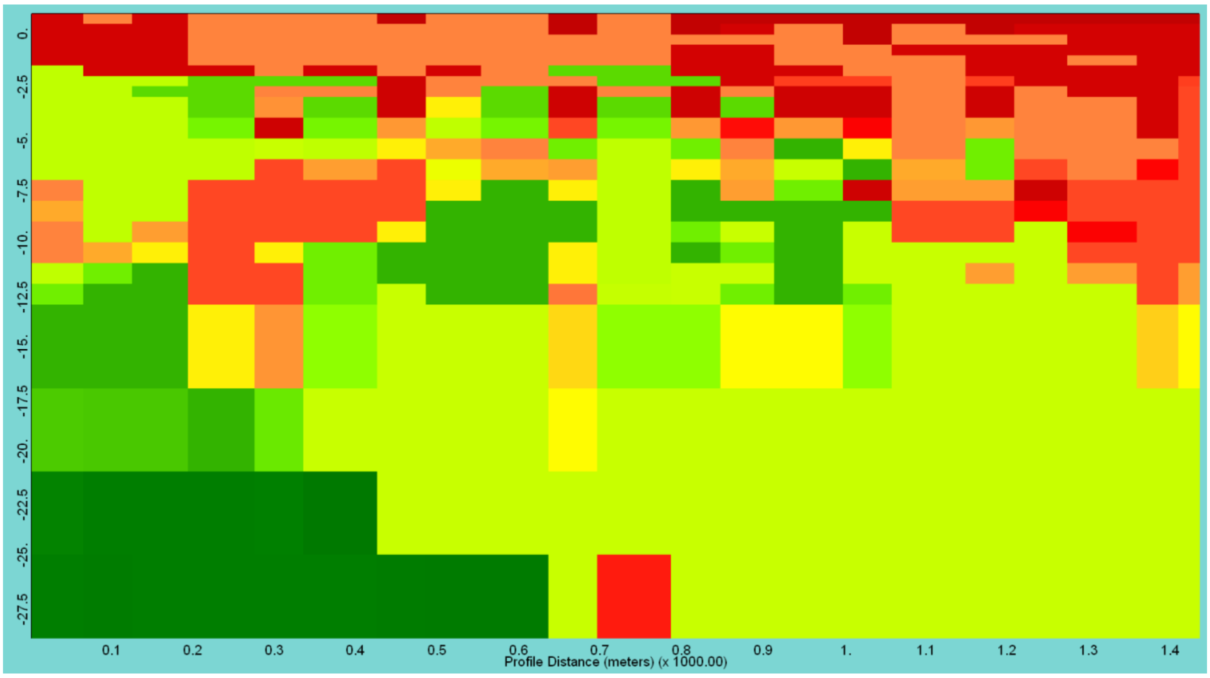
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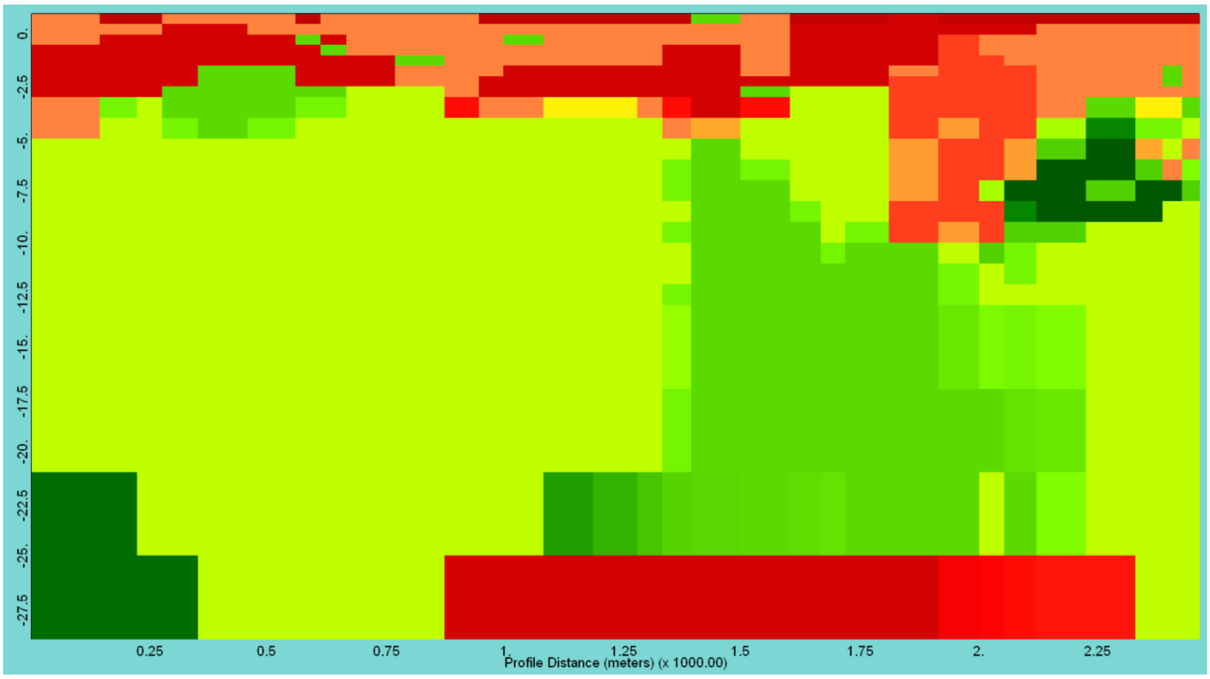
E-E’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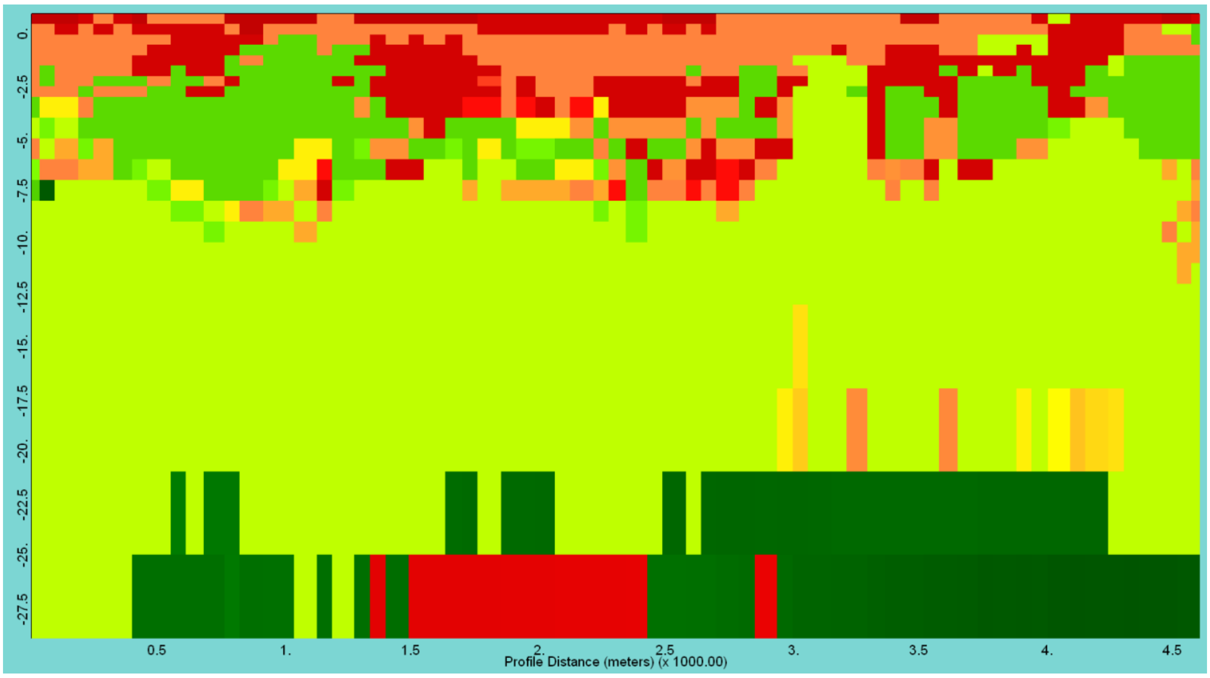
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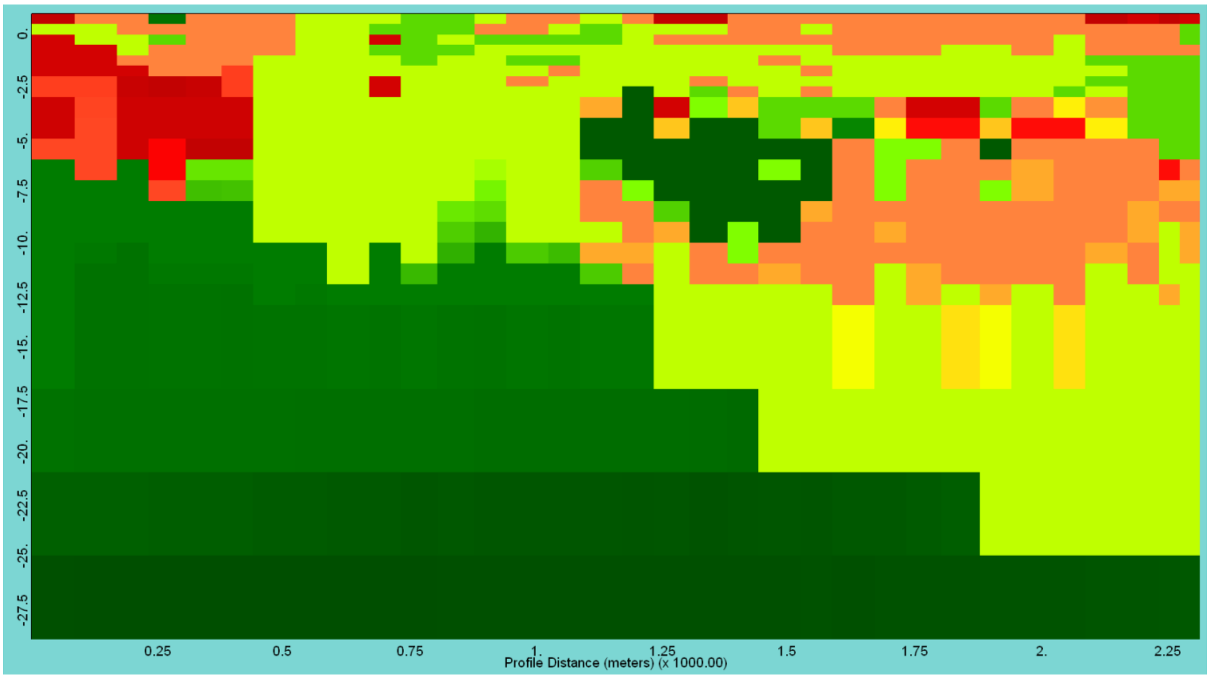
G-G’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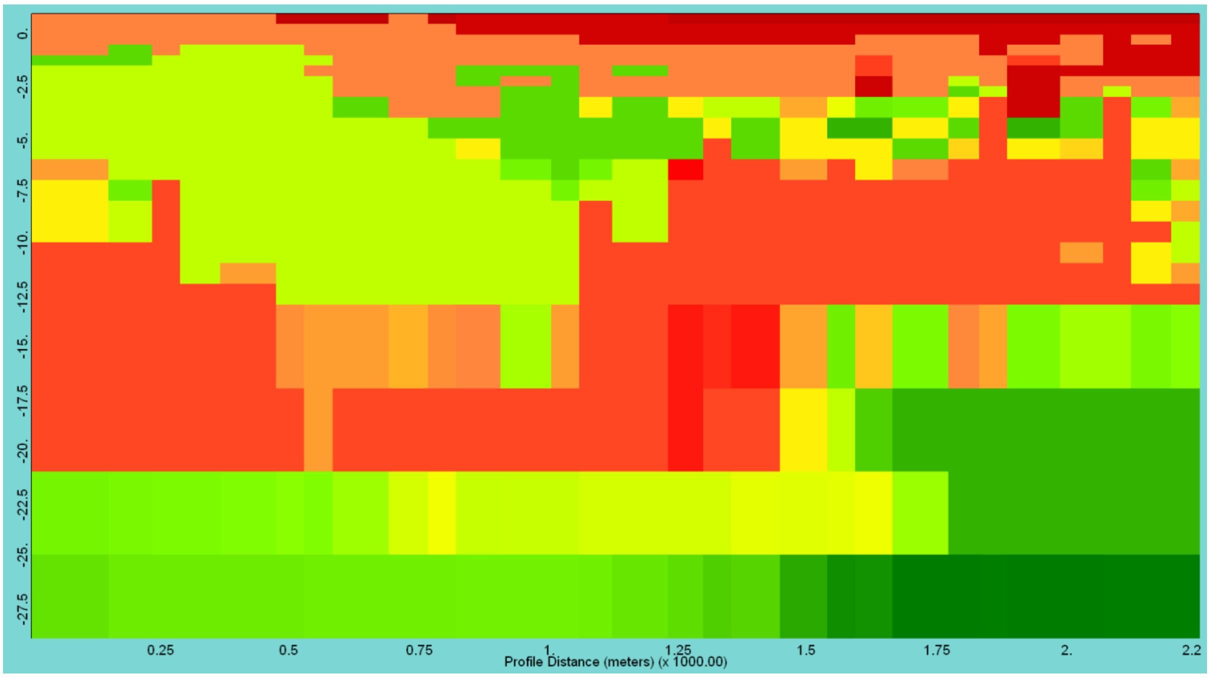
H-H’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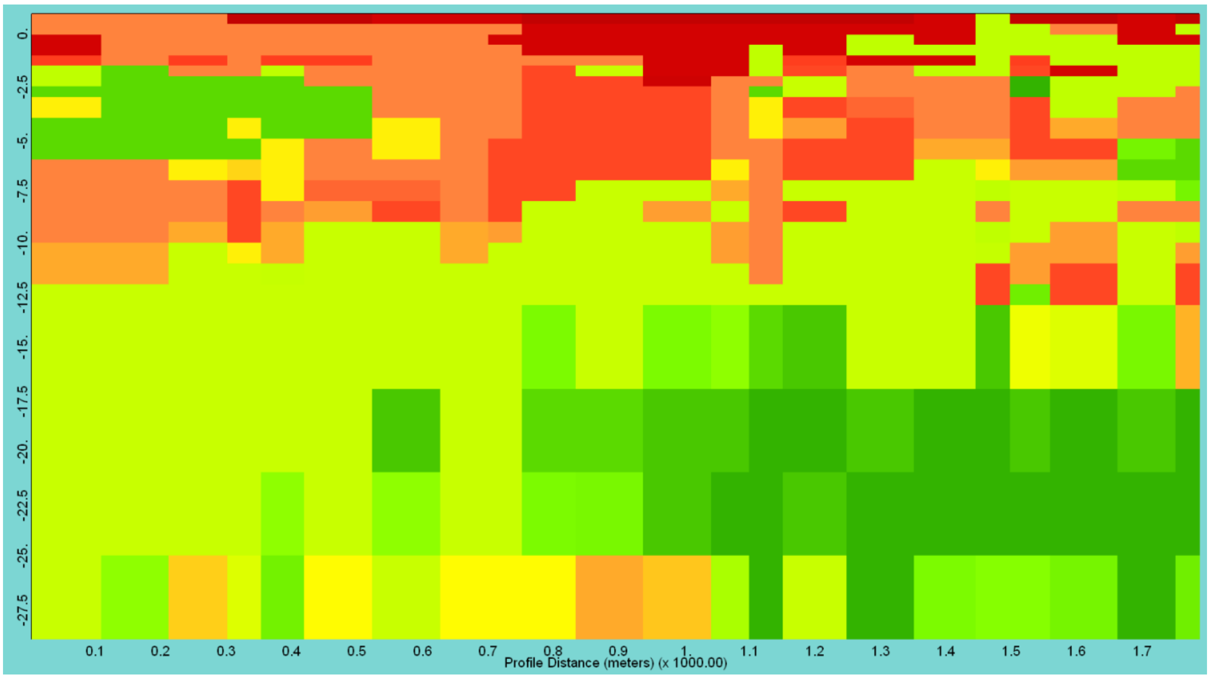
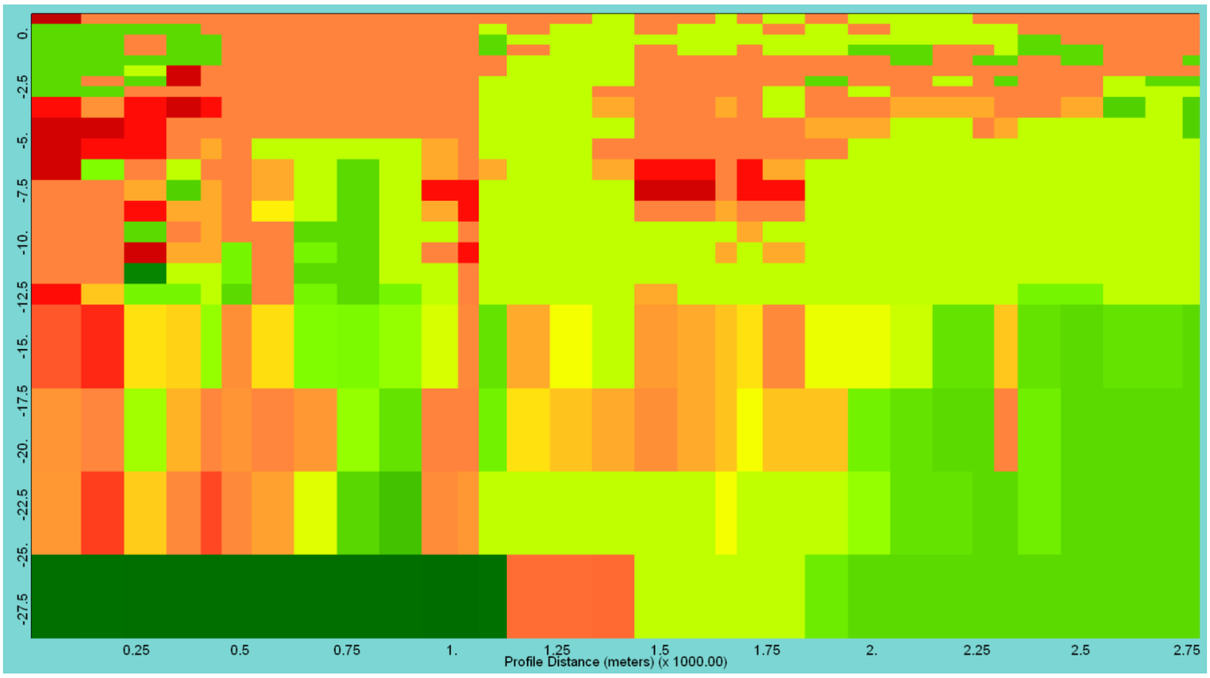
2.
2.2
Profile Distance (meters) (x 1000.00)

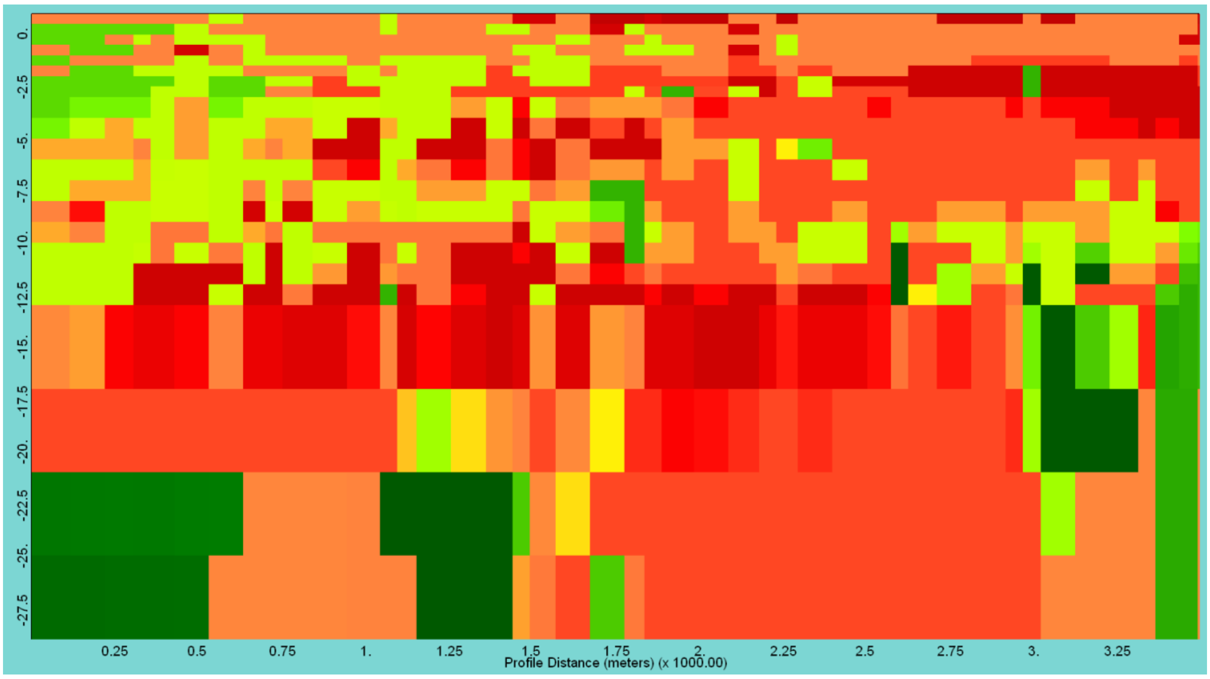
I-I’


0.
-2.5
-5.
-7.5
-10.
-12.5
-15.
-17.5
-20.
-22.5
-25.
-27.5
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
1.6
1.7
Profile Distance (meters) (x 1000.00)

J-J’


0.
-2.5
-5.
-7.5
-10.
-12.5
-15.
-17.5
-20.
-22.5
-25.
-27.5
0.25
0.5
0.75
1.
1.25
1.5
1.75
2.
2.25
2.5
2.75
Profile Distance (meters) (x 1000.00)

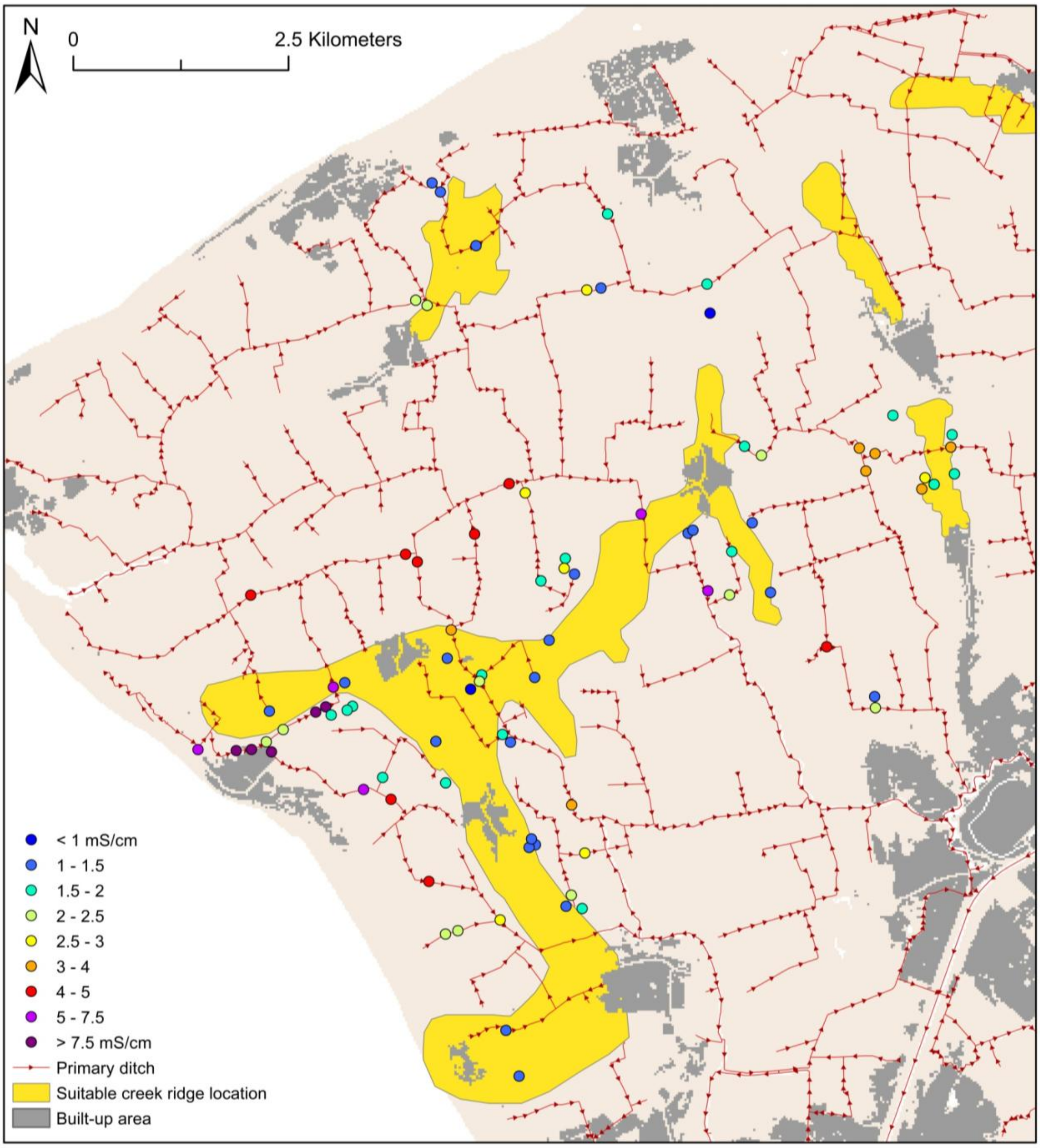
K-K’


0.
-2.5
-5.
-7.5
-10.
-12.5
-15.
-17.5
-20.
-22.5
-25.
-27.5
0.25
0.5
0.75
1.
1.25
1.5
1.75
2.
2.25
2.5
2.75
3.
3.25
Profile Distance (meters) (x 1000.00)

Suitability of the subsoil at the cross-sections

Cross-section	Suitable (Yes/No)
A - 2 km from A	N
2 km from A - A' - A''	Y
B - B'	N
B' - B''	Y
C - C'	Y
D - D'	Y
E - E'	Y
F - F'	Y
G - G'	Y
H - H'	N
I - I'	Y
J – 1 km from J	N
1 km from J – J'	Y
K - K'	N

Appendix IV – EC-measurements



Appendix V – Water balance per catchment

Catchment 1		
Catchment area (without creek ridge location)	25.5	ha
IN		
P	2.10	mm/d
qseepage	0.00	mm/d
OUT		
Etc	0.60	mm/d
qinfiltration	0.29	mm/d
WATER BALANCE (IN-OUT)		
q	1.21	mm/d
Q	309.10	m3/d
Area extra infilration (1mm/d)	30.9	ha

Catchment 2		
Catchment area (without creek ridge location)	101.9	ha
IN		
P	2.10	mm/d
qseepage	0.00	mm/d
OUT		
Etc	0.60	mm/d
qinfiltration	0.04	mm/d
WATER BALANCE (IN-OUT)		
q	1.46	mm/d
Q	1490.47	m3/d
Area extra infilration (1mm/d)	149.0	ha

Catchment 3		
Catchment area (without creek ridge location)	6.8	ha
IN		
P	2.10	mm/d
qseepage	0.00	mm/d
OUT		
Etc	0.60	mm/d
qinfiltration	0.15	mm/d
WATER BALANCE (IN-OUT)		
q	1.35	mm/d
Q	91.17	m3/d
Area extra infilration (1mm/d)	9.1	ha

Catchment 4		
Catchment area (without creek ridge location)	5.2	ha
IN		
P	2.10	mm/d
qseepage	0.28	mm/d
OUT		
Etc	0.60	mm/d
qinfiltration	0.00	mm/d
WATER BALANCE (IN-OUT)		
q	1.77	mm/d
Q	91.76	m3/d
Area extra infilration (1mm/d)	9.2	ha

Catchment 5		
Catchment area (without creek ridge location)	1.0	ha
IN		
P	2.10	mm/d
qseepage	0.30	mm/d
OUT		
Etc	0.60	mm/d
qinfiltration	0.00	mm/d
WATER BALANCE (IN-OUT)		
q	1.80	mm/d
Q	18.70	m3/d
Area extra infilration (1mm/d)	1.9	ha

Catchment 6		
Catchment area (without creek ridge location)	59.1	ha
IN		
P	2.10	mm/d
qseepage	0.18	mm/d
OUT		
Etc	0.60	mm/d
qinfiltration	0.00	mm/d
WATER BALANCE (IN-OUT)		
q	1.68	mm/d
Q	991.15	m3/d
Area extra infilration (1mm/d)	99.1	ha