MASTER THESIS WATER SCIENCE AND MANAGEMENT

# THE ECONOMIC AND SOCIETAL BENEFITS OF LARGE SCALE SUBMERGED DRAINAGE

## *A multi-criteria analysis applied to the Lange Weide polder*


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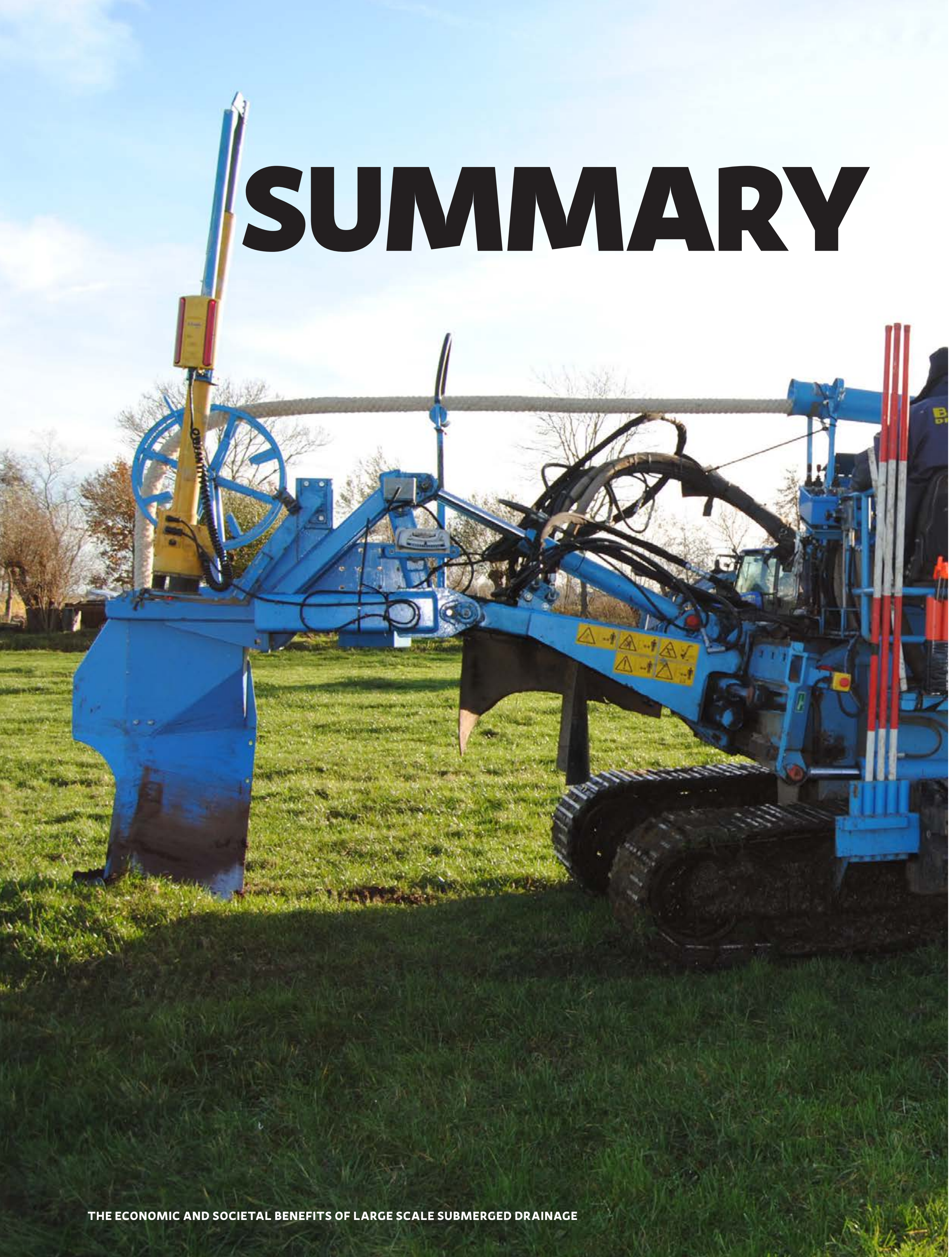
# SUMMARY



All around the world, peatlands suffer from the negative effects of land subsidence. In the Netherlands, the peatlands are mostly used for dairy farming. Submerged drainage and pressure drain infiltration are two technical innovations with the aim to reduce the land subsidence and at the same time have a positive impact on the dairy farming.

These techniques are only tested on a scale of a plot or several plots, hence the focus was on a small scale level. Only for some individual effects, an analysis of large scale use is made. Therefore, in this master thesis a multi criteria analysis (MCA) of large scale use is presented. As a case study the Lange Weide polder is used and six alternatives are determined. The alternatives consist out of different combinations between submerged drainage, pressure drain infiltration and water-level strategies. To assess the different alternatives the following criteria are determined: agricultural effects, greenhouse gas emissions, storage requirements, investment costs and water consumption. The outcome of the MCA is used to give a policy advice about the large scale use of submerged drainage and pressure drain infiltration.

The first three criteria of the MCA are strongly influenced by the land subsidence, and the outcome of the subsidence equation is based on the clay thickness and the Average Deepest Groundwater table (ADG). Hence, it is important to provide the most accurate method in determining the clay thickness and ADG as possible. In order to gain the most accurate input data about the clay thickness different (interpolation) methods are analysed with the principal of validation. The ADG is determined using the outcome of the two existing models.

Kriging with the nearest 5 data points was the most accurate method in determining the clay thickness. The 'karteerbare kenmerken kaart' was most suitable to determine the ADG, because the Hydromedah method had unexplainable deep ground water levels. With this input data and the effect of an alternative the subsidence for 2010-2050 is modelled. After the addition of the different criteria, the five alternatives with submerged drainage and/or pressure drain infiltration had a higher score than the alternative without technical investment. The two alternatives with a combination of submerged drainage and pressure drain infiltration had the highest score.

The MCA showed that the large scale use of submerged drainage and pressure drain infiltration is social and economic beneficial. Therefore the policy advice is given to encourage the large scale use of these techniques.

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# 1 ▸ INTRODUCTION



## 1.1 The social problem of the Dutch peatland areas

In the early middle ages, the Dutch peatland area was located a few meters above sea level. From this period onwards the inhabitants tried to cultivate the peatland area. To do so, the water level needed to be lowered and this was done by digging drainage ditches. The landscape slowly developed to its characteristic narrow plots, stretched ditches, dairy farming and meadow birds (Hoving et al., 2008). Peat consists, for the largest part, of organic material. Through the drainage of the peatland area: oxidation, shrinkage and consolidation occurs (Schothorst, 1967). In most cases the surface water level is lowered with the same rate as the land subsidence. This process is called indexation. Through this process, new peat will oxidize and the land subsidence continues.

In the 1960's the freeboard (the difference between the surface height and the surface water level) was increased to make modern agriculture possible (Kwakernaak et al., 2010). This resulted in an accelerated rate of land subsidence in the peat areas. However, land subsidence also contains several disadvantages:

- High maintenance cost for infrastructure, such as roads and sewers.
- The water management of the area is expensive and complex. The heterogeneity of the peat soil results in differential subsidence rates. This, together with the different water level demands for settlement areas, nature and agriculture, results in compartmentalization into small water-level areas (Van Hardeveld et al., 2014).
- Eutrophication of the local surface water increases (Michielsen, Lamers & Smolders, 2007).
- Large amounts of $CO_2$ and $N_2O$ are emitted (Kwakernaak, et al. 2010).

From the 1980's onwards, environmental awareness and attention for landscape preservation increased. Similarly, the debate about the future of the peatland area gradually started. People began to realize that with the current policy, after some decades the peatland may be gone in several parts of the Netherlands (Jansen et al., 2009a).

The water authorities situated in western part of the Netherlands started to decrease the freeboard. In the area of Stichtse Rijnlanden a freeboard is nowadays 45 to 55 cm. The board of Stichtse Rijnlanden, farmers - & environmental organization consider this the optimum between the interest of the agriculture, environment and social costs. Water authorities are obliged to store a certain amount of rainfall without inundation. A smaller freeboard contains a smaller storage capacity for rainfall, and decreases the economic viability of the dairy farming. Therefore, a smaller freeboard is considered not feasible.

However, a smaller freeboard does constitute a step in the right direction to mitigate land subsidence and its negative consequences. The land subsidence increases through climate change, and the skewed distribution of the costs, mainly paid by the related governments and not by the landowners, encourages the debate about the future of the peatland area anew (Van Hardeveld et al., 2014).

One possible solution for the land subsidence is a change in land use, to paludiculture. This is an agricultural form where crops are cultivated, and whereby the groundwater is always close to the subsurface. The advantage of this method is that the subsidence is reduced to its minimum. In contrast, there are also several disadvantages. One of the disadvantages is that there are unsure market conditions for these types of crops.

The other solution is the use of submerged drainage and pressure drain infiltration. These techniques increase the groundwater table during dry periods and therefore the subsidence rate is decreased. Apart from the higher investments, these techniques provide little to no disadvantages for the practice and returns of dairy farming (Hendriks et al., 2016). At the moment, most politicians and landowners thus prefer the strategy with submerged drainage and pressure drain infiltration.

## 1.2 Problem description

Much research has been done towards the effects of submerged drainage. By now, the first field experiments with pressure drain infiltration have started. These techniques are applied to individual plots, and therefore the focus is generally on the small scale effects. For some individual effects, the effects on large scale use have been modelled. However, a quantitative analysis that weighs all the effects has not yet been done. The lack of this analysis means that policy makers are not sure if they should stimulate the large-scale application of these techniques.

To model the effects of large-scale use of subsurface drainage, a subsidence model called 'Phoenix' can be used. This model calculates the subsidence rate with an empirical relation of van de Akker (2007). Input variables are a climate factor, clay thickness and the average deepest groundwater table (ADG). Geisler (2014) improved the weight of these factors and gave the formula his current form. The equation is sensitive to the clay thickness, therefore it needs to be estimated with the upmost accuracy. However, until today no research has been done in order to investigate the best method for determining the clay thickness.

## 1.3 Research area

An area where the land subsidence contains a strong influence on the governmental policy is polder the Lange Weide. The polder has a relatively high subsidence rate compared to other peatland areas of Stichtse Rijnlanden. The polder is shown in figure 1, the white area refers to the settlement area.

In the 1990s, a separate water-level area for the settlement area was create in order to protect the wooden piles of the old buildings (HDSR, 2011). From that moment onwards, the settlement area has a higher water level than the surrounding agricultural area. Through the difference in freeboard, the subsidence rate of the agricultural area is greater. Therefore, the water level between the grassland area and the linear settlement areas is increasing. When the difference in surface water levels exceeds 50 cm, special constructions are needed to cope with the pressure difference (HDSR, 2011). This requires a large financial investment. Depending on climate change, it is expected that the difference will be 35-45 cm by 2050 (Van Hardeveld et al., 2016).

When a difference of 50 cm is reached there are two options. The first option is to stop the indexation in de agricultural area. This will have a negative impact on the dairy farming (Hendriks et al., 2016). The second option is to start decreasing the surface water in the settlement area. This will however have negative consequences for the wooden foundations in the area (HDSR, 2011).

The local agricultural association of the Lange Weide is aware of this water management problem, and are looking for a solution to continue the dairy farming. In order to postpone the difference of 50 cm, they came up with an initiative to use submerged drainage in the agricultural area. Research has shown that this is an effective solution to reduce the subsidence rate (Hendriks et al., 2016). In order to support this initiative, the Lange Weide serves as a case study for this particular research.

## 1.4 Research Aim

The aim of this research is to analyse the economic and societal benefits of the large-scale application of submerged drainage and pressure drain infiltration in order to provide a policy advice to governments dealing with land subsidence. To support this policy advice, a multi criteria analysis (MCA) will be used. This will be applied to the case: Lange Weide. The MCA includes the analysis of a number of alternatives to determine the optimal design for the sub-


**Figure 1** ▸ Study area of the Lange Weide



merged drainage and/or pressure drainage system. As the majority of the criteria of the MCA are dependent on the land subsidence rate, it is important that the Phoenix model produces accurate results. Therefore, this research also aims to identify the method that predicts the most accurate input data of the model's parameters: clay thickness and ADG.

## 1.5 Research Question

What is the optimal design for the submerged drainage system and/or pressure drainage system in polder Lange Weide in terms of economic and social benefits?

# 2 ▶ THEORY



## 2.1 Physical theory on land subsidence processes

Subsidence in peatland areas can be caused for different processes. Schothorst (1967) ranked these for rural areas from important to less important.

**Oxidation ▸** Peat consists for the largest part of organic material. Organic material is vulnerable for biological decomposition, because organisms mineralize the organic mattering during dissimilation for respiratory functions and during assimilation to build organic matter (van de Akker et al, 2007). This process is happening under aerobic conditions especially (Eq.1). Under anaerobic conditions nitrate acts as the electron receptor (Eq.2), however this process is deemed less efficient:

$$C_6H_{12}O_{(6)} + 6O_2 \rightarrow 6CO_2 + 6H_2O + 2870 \text{ } \textit{KJ per mol glucose} \quad \textbf{(Eq.1)}$$

$$C_6H_{12}O_{(6)} + NO_3^- + 6H^+ \rightarrow 6CO_2 + 9H_2O + 3N_2O + 2280 \text{ } \textit{KJ per mol} \quad \textbf{(Eq.2)}$$

Both equations show an irreversible reaction. Through lowering the water levels new pied layers are exposed to oxygen.. The temperature influences the decomposition rate considerably. The optimal temperature is around 35°C (van de Akker, 2007). Hence, to determine the degree of oxidation the ADG and temperature are key factors (Jansen et al., 2009a).

**Shrinkage ▸** The organic material in the subsoil partly consists of water. When the groundwater level drops, this water is released and shrinkage takes places. When the groundwater rises again swelling takes place. Therefore are peat areas in general higher in wintertime and lower during summertime (Oleszczuk & Brandyk, 2008). However, a part of the shrinkage is irreversible this contributes to the land subsidence.

**Loss of Buoyancy ▸** The soil consist out of soil particles and water, and these are under hydrostatic pressure. The soil particles are lifted through this pressure. When the groundwater is lowered the hydrostatic pressure decreases.

**Consolidation ▸** This process occurs in the presence of an external object, like a house or a tractor.

The weight of the object causes the expulsion of water and pack the soil particles more tightly.

## 2.2 Water management of the rural peatlands

In the Netherlands peatland areas are mostly used for dairy farming. To enter the plots, without damaging the grassland, the agricultural machinery and cows need a certain bearing capacity. The bearing capacity is determined by the groundwater level, soil moisture and soil type. The bearing capacity is sufficient at a groundwater table around 40-50 cm below surface level (van de Akker et al., 2013).

A polder is divided into different water-level areas. The water authorities are responsible for the surface water height and surface water quality in these water-level areas. In most cases the water authorities are lowering the water-level at the same rate as the subsidence rate, which is called indexation. This to sustain the dairy farming. After a certain period the water level is reviewed by the water authorities, and together with the landowners and other stakeholders a new water level is set (HDSR, 2011). However, water authorities differ in their policy. In the northern parts of the Netherlands more attention is put towards the dairy farming, resulting in lower surface water levels comparing to the western parts of the Netherlands. The downside is a higher subsidence rate. In the management area of Stichtse Rijnlanden the freeboard is 45 to 55 cm. This is calculated with the average surface height of a water-level area (HDSR, 2011).

## 2.3 Submerged drainage

The first tests with submerged drainage were done fifteen years ago. These tests and pilot locations results in a lot of knowledge that can still be used today (Hendriks et al., 2016). Submerged drainage changes the groundwater dynamics.

The groundwater level in peatlands is mainly influenced by rainfall and precipitation. In a dry period the groundwater table is lower than the surface water level, so there is infiltration of surface water. Nevertheless, this process has a small influence on the groundwater level through the low permeability of the soil. Submerged drainage increases the permeability and the ADG by 10–20 centimetre. This reduces the oxidation significantly, and therefore also the subsidence by 30–50 percent. Moreover, the submerged drainage also has a drainage effect when the groundwater level is higher than the surface water level. Research has shown that the groundwater peak level is reduced by 20 cm. As a result, the groundwater table becomes more stable during the year (Hendriks et al., 2016). Figure 2 represents the change in groundwater level. Blue refers to the old groundwater level, while dark blue represents the new groundwater level.

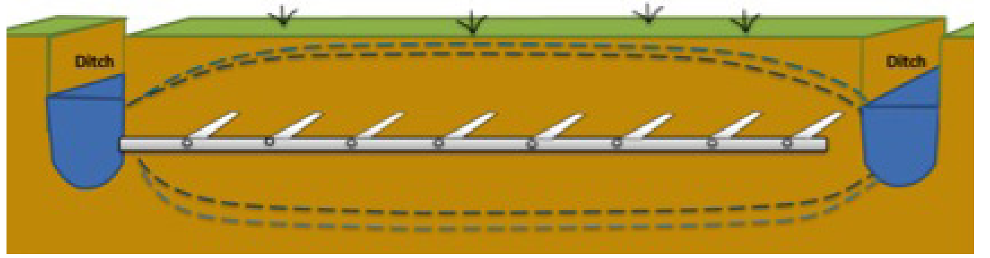



**Figure 2 ▸** The influence of submerged drainage on the groundwater level in summer- and wintertime

The optimal design of submerged drainage is important for its effectiveness. In the literature an infiltration capacity of 3 mm/d is recommended (Massop & van Houwelingen, 2016). This is because 3 mm/d is the average evaporation in summertime. Factors than can influence the infiltration capacity of the system are the distance between the drains and the surface water level. First, the maximum distance between the drains can be calculated with the formula of Hooghoudt. Its outcome is especially dependent on the hydraulic conductivity of the subsoil (Massop & van Houwelingen, 2016). However, van de Akker et al. (2013) advice to use a maximum distance of 6 meters between the drains. Second, the effect of submerged drainage can be stimulated by changing the surface water level in the contra direction of the groundwater level. For example, the increase of the water level stimulates infiltration.

## 2.4 Pressure drain infiltration

A relatively new technique is pressure drain infiltration, in which the drains are connected to a reservoir. The advantage of this technique is that the water level of the reservoir can vary much more and faster in height compared to the surface water level, because the water level in the pressure well is highly adaptable, so that the desired groundwater level of 40-50 is reached in most cases (K. van Houwelingen, personal communication, 2017).

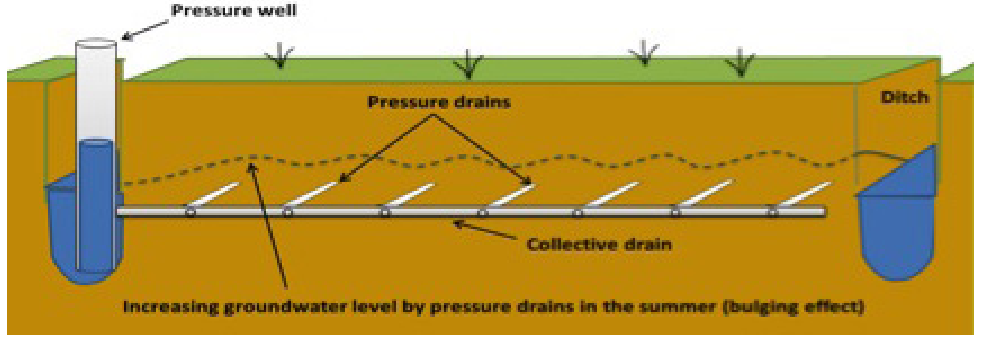
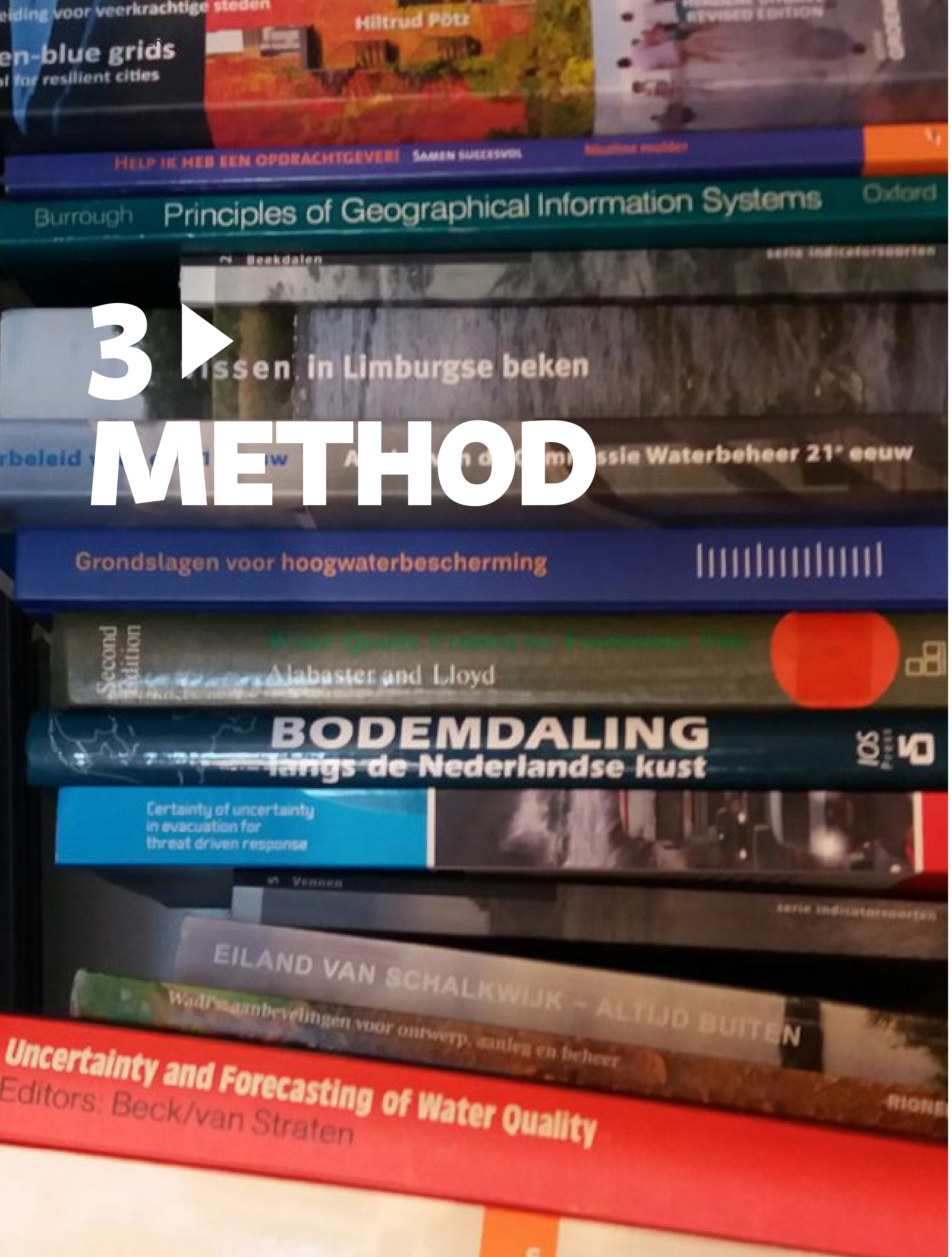



**Figure 3 ▸** Cross-section of a Pressure drain infiltration system (Hak, 2016)

# 3 ▸ METHOD




To assess the societal benefits of subsurface drainage a multi criteria analysis (MCA) MCA is performed. In the first part of the method the different steps of a MCA are explained. Special attention is given towards the subsurface drainage alternatives and the criteria. After the MCA part, the subsidiary models are described: a groundwater model and land subsidence model (Phoenix). As the Phoenix model is sensitive to topsoil clay thickness and the absolute value of the ADG, additional attention is given to the different methods for obtaining these input data.

## 3.1 Multi criteria analysis (MCA)

The MCA method can be applied to compare different options/alternatives based on set criteria. It is a non-monetary comparison. A MCA is usually applied with a common aim: to provide policy makers insight in the conflicting interests outlined in various different alternatives (Hellendoorn, 2001).

All MCA's have, more or less, the same structure. Starting with (1) the introduction of the different alternatives, (2) the formulation of the different objectives and criteria, (3) the standardisation, (4) the weighing of the different criteria, (5) The scores per alternative, and (6) the evaluation of the outcome (Commissie van de milieueffectenreportage, 2002).

### 3.1.1 *Drainage alternatives*

To compare the different alternatives, three different drainage system scenarios and one scenario without drainage system have been created. The two scenarios with submerged drainage (scenarios 2 and 4) will be combined with two different water level strategies, because the water level strategies determine the effectiveness of these systems (Jansen et al., 2009b). This results in 6 different alternatives that will now be assessed:

**Alternative 1 ▸ No pressure drain infiltration or submerged drainage system**
This alternative contains no change in ADG, therefore the basic ADG map will be applied. However there are two basic ADG maps to choose from. The analysis of the ADG will determine which map is the most appropriate for alternative 1 (see section 3.2.2).

**Alternative 2a ▸ A system with submerged drainage with flexible water level**

The flexible water level strategy entails that the water level is lower during dry periods and higher in wet periods. It is therefore a more natural water level. Through the low water level in dry periods, there is a small increase in the ADG. Jansen et al. (2009b) shows the effects of different water level strategies with submerged drainage. Their study reveals that with submerged drainage and a flexible water level, the ADG increases by 10 centimetres. Following this result, the ADG of the basic map will be increased by 10 centimetres.

**Alternative 2b ▸ A system with submerged drainage with dynamic water level**

A dynamic water level strategy increases the surface water in a dry period and lowers the surface water in a wet period. Through the high water level during dry periods the assumption is made that the ADG of the basic map increases by 20 centimetres. This value is also modelled by Jansen et al. (2009b).

**Alternative 3 ▸ A system with pressure drain infiltration**

With this technique it is possible to have a stable groundwater level. An ADG of only 45 cm is possible (K. van Houwelingen, personal communication, 2017). The ADG in this alternative is therefore not calculated with a correction of the base map but is simply 45 cm below the surface height of the particular grid cell.

**Alternative 4a + b ▸ Freeboard as navigator with (a) flexible and (b) dynamic water level**

The subsurface in the Lange Weide is heterogeneous, which gives variance in subsidence rates. Both alternatives aim to make the subsidence rates as equal as possible. The plots with a freeboard less than 40 centimetres will have a pressure drain system and therefore an ADG of 45 centimetres can be assumed. All plots with a freeboard between 40 and 60 centimetre have submerged drainage. In alternative 4a, the ADG is increased by 10 centimetres, whilst following alternative 4b the ADG is increased by 20 centimetres. In both alternatives, no technical investments are done in the case of freeboards larger than 60 centimetres.

### 3.1.2 *Objectives and criteria*

The alternatives have an influence on several social objectives or requirements within these peatland areas. Therefore, this section explains which and how the alternatives affect these criteria. The criteria include climate change, flooding requirements, investment costs, agricultural benefits and water consumption.

**$CO_2$ emission**

The Dutch government wants to decrease the $CO_2$ emission. This is especially the case after the agreements set in Paris. The influence of peat oxidation on $CO_2$ or $N_2O$ is never measured directly. However there are modelled estimations of 2259 kg $CO_2$ per ha per mm (van de Akker et al., 2008) and around 0, 8 kg $N_2O$ per ha per mm (Kuikman et al., 2005). In total $CO_2$ equivalent this is 2506 kg $CO_2$ per ha per mm. With these assumptions the $CO_2$ emission can determined for every alternative.

**Storage requirements to prevent flooding**

In the Netherlands the water authorities are in charge of maintaining the water system in rural areas. Water authorities balance the size of the investment for the water system with the costs that this system is preventing in the case of flooding. Therefore the system is large enough to store the water of a normal rainfall event, but this changes when there is an extreme rainfall event. In the latter case, it is possible that the water level in the system becomes higher than the surface height of the area.

The water system of Stichtse Rijnlanden is evaluated with the following rule: during a T=10 event, less than 10 percent of the rural area should be flooded. In many cases this is the lowest 10 percent of the water-level area. T=10 refers to an event which statistically happens once in 10 years (Velner & Spijker, 2011). The degree to which such an event is able to be stored in the subsoil is determined by the soil accommodation space which is highly dependent on the groundwater level. Therefore there is no fixed rainfall amount at a T=10 event. If the water-level area does not meet this requirement, changes in the water system, like increasing the percentage of surface water, should be made.

By investing in submerge drainage or pressure-drain infiltration in lower areas, these areas will have a lower subsidence rate than average. The indexation level is the same as the average subsidence rate, and therefore the freeboard of these lower areas is increasing. This also results in an increase in the water storage. For every alternative the water level and the surface height of the lowest 10 percent are calculated in 2050. The difference in surface height can be seen as the storage capacity of the system.

**Investment costs**

Currently the water authority Stichtse Rijnlanden works on a pilot with submerged drainage and pressure drain infiltration, from this the investments cost can be extracted.

**Agricultural cost and benefits**

According to the market prices of 2008-2012, the net added value in the Lange Weide is approximately €1840 per ha per year (Van Hardeveld et al., 2014). It is difficult to provide an estimation of the agricultural benefits in 2050, due to the influence of uncertainties such as market prices, the height of the European agricultural subsidy and the environmental regulations.

A program called Waternood (Van Bakel et al., 2002) uses the Help-tabellen to calculate the yield lost through high or low groundwater levels. However this program is only useful to calculate the agricultural benefits for the alternative without submerged drainage or pressure drain infiltration. The investment in those techniques changes the groundwater dynamics and makes the Help-tabellen unusable, see 5.2 for more explanation. Therefore the agricultural benefits of these alternatives will be quantified with a literature study.

**Water consumption**
When submerged drainage or pressure drain infiltration are applied, the groundwater level is higher than the original situation. This increases the evapotranspiration and therefore the water consumption of the area increases. In dry periods, especially in the future, a shortage of water might occur. Then choices about the water distribution should be made.

Jansen et al. (2009b) made a hydrological model of polder 'Zegveld' to quantify the hydrological effects of submerged drainage and different water level strategies. This study will be used to quantify the effects on the extra water consumption of the different alternatives.

### *3.1.3 Standardization*

To compare the different criteria the outcomes should be in the same units. This process is called standardization. After standardization all scores are between 0 and 1. There are a lot of methods to do this but in most MCA the linear transformation procedure is used (Chakhar & Mousseau, 2008).
Within the linear transformation procedures there are again different possibilities like maximum standardization and interval standardization. Interval standardization is advised when the difference between the alternatives is important while maximum standardization is used when the absolute size is important. In almost every MCA some objectives are more appropriate for the interval standardization while other objectives prefer the maximum standardization. However more than one standardization method is not recommended in a MCA (commissie van de , milieueffectenreportage 2002). To show a clear difference between the alternatives the interval standardization is chosen, see equation 3.

$$\text{interval standarization} = \frac{\text{score-minimum score}}{\text{maximum score-minimum score}} \qquad \textbf{(Eq. 3)}$$

### *3.1.5 Scores per alternative*

To determine the optimal scenario, the scores of every objective will be multiplied by their weighting factor. Afterwards they will be summed up. This technique is called weighted summation and is mostly used in MCA (Janssen, 2001). As stated above, here the same weight for each criterion is used.

### *3.1.6 Sensitivity analysis*

The goal of this analysis is to show the sensitivity of the order of the alternatives. Uncertainty is possible within scores, i.e. through sensitivity in the outcome of a criterion or through the used standardization method. Secondly uncertainty is possible due to the weights of the MCA (Janssen et al. 2000).

## 3.2 Subsidence model Phoenix

The subsidence model 'Phoenix' was built to simulate subsidence rates of peatland areas. To apply the model, the study area is divided into calculation points on a regular grid. In this research the smallest grid size of 25 x 25 meter is used. For every point the subsidence can be calculated for a given time period. This calculation is based on an empirical formula of van de Akker (2008). Geisler (2014) verified the formula and changed the value of the constants and brought the formula in the current form.

$$\Delta L = a * ADG + b * K + c \qquad \textbf{(eq. 4)}$$

ΔL = land subsidence [m/y]
a = climate factor [1/y]
ADG = Average deepest groundwater table [m below surface]
b = clay factor (0,01263) [1/y]
K = clay thickness [m]
C = soil composition constant (0,00688) [1/y]

### *3.2.1 Input variable climate factor*

As told in the theory, oxidation increases when the temperature increases. Geisler (2014) came with a formula to determine a new climate factor. The formula is based on the microbial activity formula of van de Akker (2007).

$$CC(T_{i+2000} - T_{1990}) = \frac{\left(\Sigma_i^n F_{oxidation+}\left(Q_{10}\left(\frac{(Ti+2000 - T\,1990)}{10}\right)\right)\right)}{n} \qquad \textbf{(eq. 5)}$$

CC(Ti+2000) = increase in land subsidence to CC [%]
Foxidation = Fraction of land subsidence contributed to oxidation
Q10 = increase in biological activity 10°C
Ti+2000 = temperature in year i + 2000
T1990 = temperature in 1990

The new climate factor is calculated by multiplying CC(Ti+2000) by 0.023537. The Royal Netherlands Meteorological Institute (KNMI) published four climate scenario's in 2006. In this study the WH climate scenario is used, which is the most extreme scenario with a temperature rise of 2.3 °C in 2050 (KNMI, 2006). To have a gradually increase of the temperature, the model is stopped 3 times. This to adjust the climate factor. Moreover the wind pattern is expected to change in the WH scenario which increases the evapotranspiration surplus in summertime (KNMI, 2006). Dik (2008) used MetaSWAP and Modflow to model the effect of this increased evapotranspiration surplus on the ADG. The outcomes of this model are used to adjust the ADG for every modeling period.

### 3.2.2 *Input variable clay thickness (K)*

Up to now the clay thickness has been based on the soil map, scale 1 : 50,000 (De Vries et al., 2014). Using an average value for every soil type. However, it has not been investigated if this is the best way to estimate the clay thickness.

In Dinoloket and from Utrecht University 261, approximately evenly distributed, ground drillings were available in the Lange Weide. At these points the exact clay thickness is known. To identify the best method and assess the uncertainty resulting from the choice of a method, the clay thickness of the whole area is calculated with four different interpolation techniques.

The first interpolation method is interpolation by Thiessen polygons (nearest neighbor interpolation). Around each sample point a polygon is defined, so that any location inside the polygon is closer to that point than any of the other sample points. The points within each point are given the value of the associated sample point (Thiessen, 1911).

The second method is based on (ordinary) kriging. The concept of this interpolation technique is from Krige (1951). Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. The spatial correlation is measured by a semivariogram that is estimated from the data. Values at any location are calculated by a weighted average of the values at the sampling points within a radius of influence, where the weights are calculated with the semivariogram and the locations of the sampling points. In this research a specified number of 5 and 12 points are chosen to determine the output value.

The third method is kriging with external drift. With this method it is possible to improve the Kriging interpolation with an extra auxiliary variable that describes a spatial trend. For instance, Van der Gaast et al. (2006) used the surface height to improve the ADG calculation in the area of Twente. In this case the regression between surface height and clay thickness is used. The regression is made on the assumption that places with a clay layer have a lower subsidence rate and therefore have a higher surface height.

Inverse distance method (IDW) is the fourth method. This method makes a prediction for point I based on the distance between the surrounding points and a weighting factor. As the distance increases the weight decreases. The weighting factor determines how fast the weight decreases as the distance increases (Shepard, 1968). Like with the Kriging method a maximum specified number of 5 and 12 points are chosen.

All four methods are combined with a Thiessen interpolation based on the 'stroombanenkaart' of the University of Utrecht, this map indicates all abandoned riverbeds. In the former riverbeds thick clay and sand layers have been deposited. The lower area around the riverbeds had almost no natural drainage system. Therefore reed, birch and alders were growing which results in the formation of peat. Only at flood events small clay layers were deposed in these areas. (Berendsen & Cortenraad, 1983). The formation of the areas is therefore not equal, whereby the areas are interpolated separately.

To determine the accuracy of the methods validation is used. Validation is a technique whereby independent data points are compared with the model results (Bhunia et al., 2016). In this research the independent data set is created by new ground drillings. To have no influence on the locations, the tool 'Generate Random Points' in ArcGIS is used. In all soil types (Koopveengronden, Weideveengronden & Liedeerdgronden) 14 locations, with a minimum distance between them of 50 meter were selected. The location of the 42 ground drillings is shown in figure 4.

In the validation the root mean square error (eq. 6), mean absolute error (eq. 7) are calculated to evaluate the accuracy of interpolation methods.

$$RMSE = \sqrt{\frac{\Sigma_{i=1}^{N}(O_i - S_i)^2}{N}} \quad \textbf{(eq. 6)}$$

$$ME = \frac{\Sigma_{i=1}^{N}(O_i - S_i)}{N} \quad \textbf{(eq. 7)}$$

**where**

*$O_i$ is observed value*
*$S_i$ is the predicted value*
*N is the Number of samples*

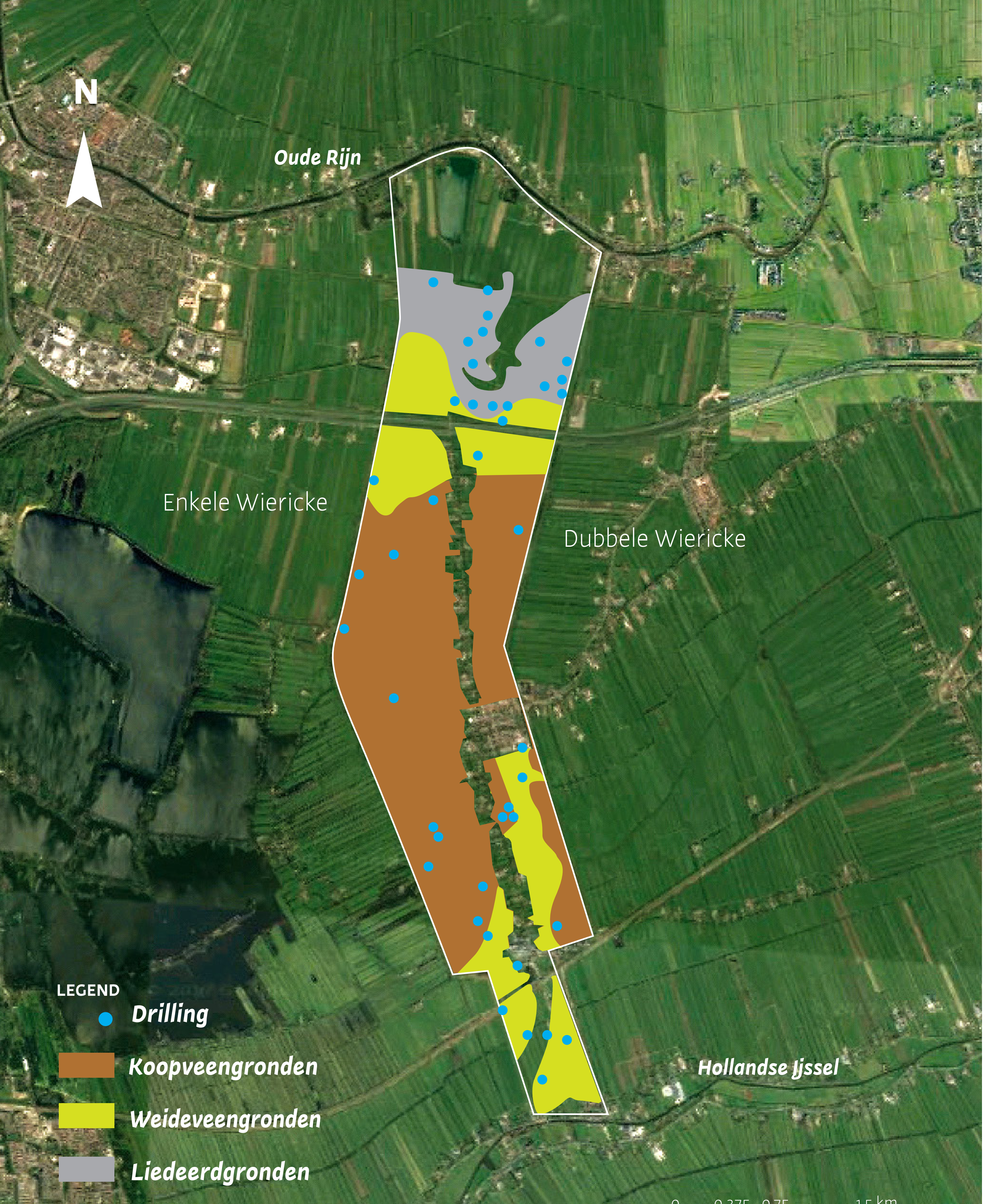



**Figure 4** ▸ The location of random points per soil type

### 3.2.3 *Input variable groundwater (ADG) ▸ choosing the basic map*

According to the formula of van de Akker (2008) the ADG is an important variable. To calculate the absolute ADG for each drainage scenario (from the change in ADG) a basic ADG map is needed. There are two models who provide estimates of the ADG in the Lange Weide. The average ADG is similar for both options however the variability of the ADG is different (see figure 5). The first method is the groundwater model of the water authority 'Hyrdomedah'. The lithology of the model is made with ground drillings of Dinoloket, while the permeability values of Gunnink et al. (2004) are used. The ADG shows a relatively high variability. The deeper (red) zones have an influence on the subsidence rates for these particular zones. The second method is the ADG map developed by Van der Gaast et al. (2010), based on groundwater tubes and soil characteristics such as iron mottling of the soil profile (gley). With IDW and a DEM, called AHN2, a grid map called 'karteerbare kenmerken kaart' is created (Van der Gaast et al. 2010). This raster has a grid size of 25x25 meters and has a relatively low variability.

To determine which method provides the most accurate input data for the ADG, the validity of the deeper spots in the Hydromedah method (red zones) need to be analysed. If it turns out that the deeper spot are invalid, then the second method is deemed more appropriate to use as basic map (and to determine the ADG).

**ADG Hydromedah** **ADG 'Karteerbare kenmerken kaart'**

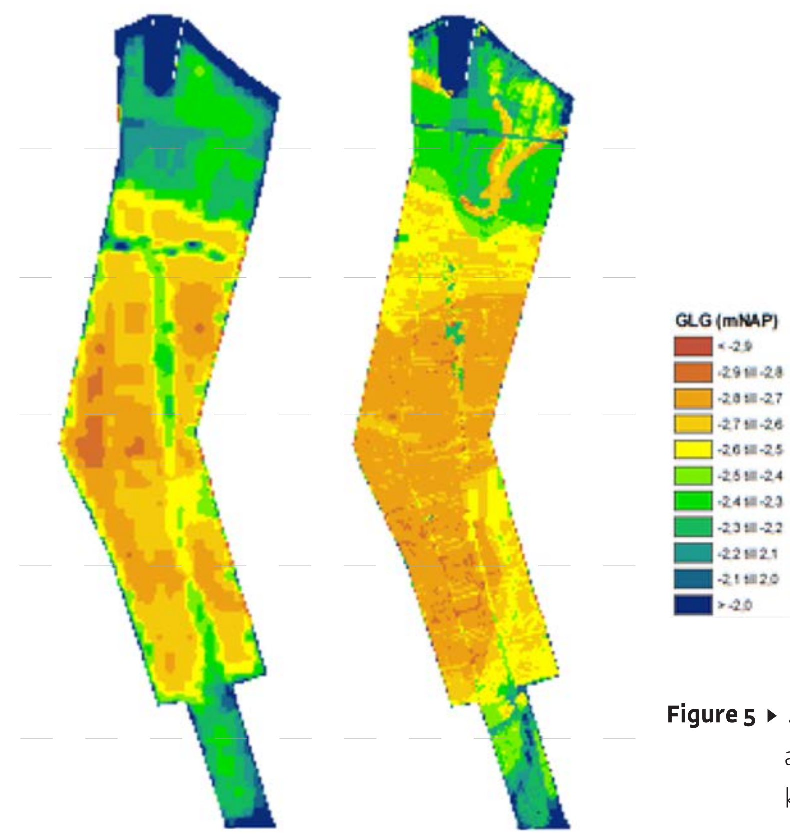



**Figure 5** ▸ ADG according to Hydromedah and the 'Karteerbare kenmerken kaart'




## 4.1 Phoenix model

To make the multi criteria analysis as good as possible, the different input methods for the Phoenix model will be analysed. First the clay thickness methods and secondly the ADG methods.

### *4.1.1 Input variable clay thickness*

In the methods section the different alternatives to estimate the clay thickness are explained. Figure 7 are showing the outcomes of this method.

Striking is the big difference between the soil map method and the interpolation methods. The ground drillings from Dinoloket used as input for the interpolation, are showing a thicker clay layer than the given average values in the soil map polygons. The Thiessen polygon method shows the most extremes. One ground drilling with no clay layer or with a thick clay layer results already in this value on a large part the map, especially if no other drillings are around.. This effect is less with the Kriging and IDW method with the nearest 5 data points. It is even less with the Kriging and IDW method with the nearest 12 data points. The difference between IDW and Kriging are small. The average clay thickness differs only 0,03 cm between IDW and Kriging with the 5 nearest data points. There is also no difference in spatial pattern.

Kriging with external drift is an interpolation method which is not an existing tool in ArcGis. Therefore ,the intention was made to run this interpolation method in the program KT3d.exe. To run this program the semivariogram of the residuals should already been known. To calculate the residuals the surface height and clay thickness are plotted, which gives a coefficient of determination ( ) of 0.23. The found influence is positive, as expected, but the relationship looks more like a cloud than a (linear) relationship. In gamv.exe a semivariogram is made with a lag tolerance of 125 meter. The semivariogram shows not the normal trend. Therefore, no results for Kriging with external drift are shown.

The best interpolation method is determined by independent validation, i.e. by comparing the interpolated values with an additional dataset. To create a new data set 41 ground drillings have been collected at random locations. The results of the different interpolation techniques and the clay thickness according to the soil map are compared with the new data set. This comparison is done with the Root mean square error (RMSE), mean absolute error (MAE) and the mean relative error (MRE). A small value for the RMSE and the MAE means a small deviation.

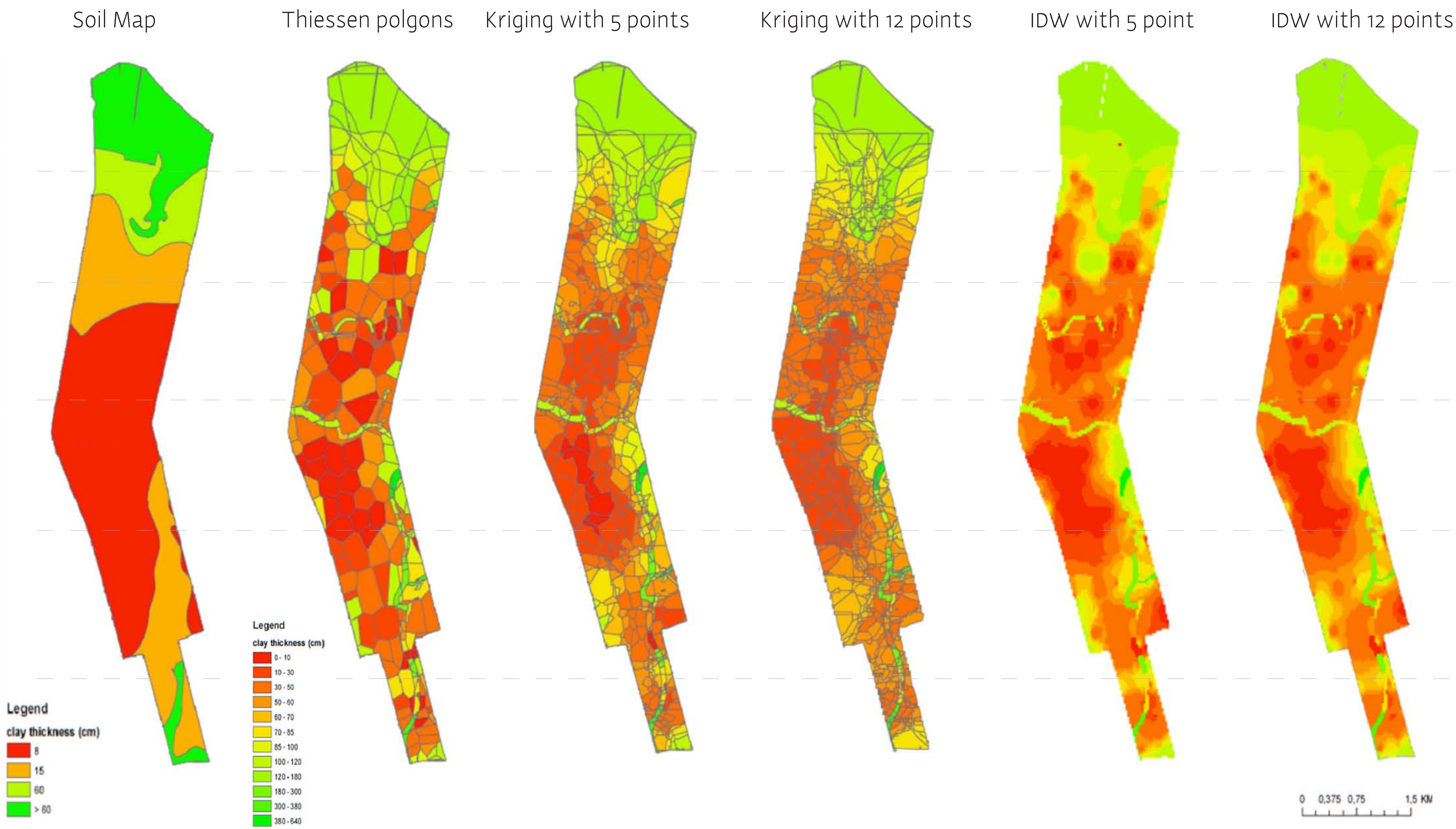



**Figure 6 ▸** Clay thickness according to the different methods

The results are shown in Table 1. The deviation of the soil map method is clearly the largest for every method of comparison and every soil type. This is also not surprising because there is no variation within a soil type. The method of Thiessen polygons gives already a better result than the soil map method but is worse than the Kriging and IDW methods. Kriging with the 5 nearest data points gives overall the smallest deviation. Only on the soil type koopveen kriging with the 12 nearest data points gives a better result.

**Table 1** ▸ Accuracy of the different interpolation methods

| Method | Soil type | RMSE | ME |
|---|---|---|---|
| *Soil Map* | *Koopveen* | *118,19* | *81,14* |
| | *Weideveen* | *120,26* | *83,08* |
| | *Liedeerdgrond* | *85,31* | *60,71* |
| | **total** | **108,81** | **74,78** |
| *Thiessen Polygons* | *Koopveen* | *78,93* | *48,21* |
| | *Weideveen* | *101,76* | *46,54* |
| | *Liedeerdgrond* | *75,02* | *31,43* |
| | **total** | **85,63** | **41,95** |
| *Kriging (5)* | *Koopveen* | *77,46* | *45* |
| | *Weideveen* | *86,34* | *42,23* |
| | *Liedeerdgrond* | *64,97* | *31,64* |
| | **total** | **76,51** | **39,56** |
| *Kriging (12)* | *Koopveen* | *77,19* | *37,21* |
| | *Weideveen* | *94,44* | *44,77* |
| | *Liedeerdgrond* | *65,51* | *35,64* |
| | **total** | **79,55** | **39,07** |
| *IDW (5)* | *Koopveen* | *78,45* | *46,44* |
| | *Weideveen* | *91,03* | *39,90* |
| | *Liedeerdgrond* | *67,33* | *28,17* |
| | **total** | **79,23** | **38,13** |
| *IDW (12)* | *Koopveen* | *77,90* | *43,62* |
| | *Weideveen* | *93,50* | *40,07* |
| | *Liedeerdgrond* | *66,78* | *29,10* |
| | **total** | **79,79** | **37,54** |

## *4.1.2 Input variable ADG (Average Deepest Groundwater table)*

As stated in the Methods sections there are two sources available to determine the reference ADG: a map obtained from the regional groundwater model Hydromedah and a map obtained from the 'Karteerbare Kenmerken Kaart'. In the Hydromedah map there are two deeper spots in the middle of the polder. The difference is most probably caused by a clay layer between 1.5 and 3.5 meters below surface that is present in the Hydromedah hydrogeological schematization, which has peat at the other locations at the same depth.

Figure 7 shows the phreatic groundwater level and the groundwater level in the first aquifer in the period 2013-2015. In summer periods the groundwater level in the 1ste aquifer is at his maximum 0.25 meter higher than the phreatic aquifer. A higher groundwater level in the first aquifer causes seepage. According to the Darcy's law and the permeability of Gunnink et al. (2004), this result in a q of 0,056 mm/day in the deeper spot area and of 0,112 mm/day in the rest of the polder.

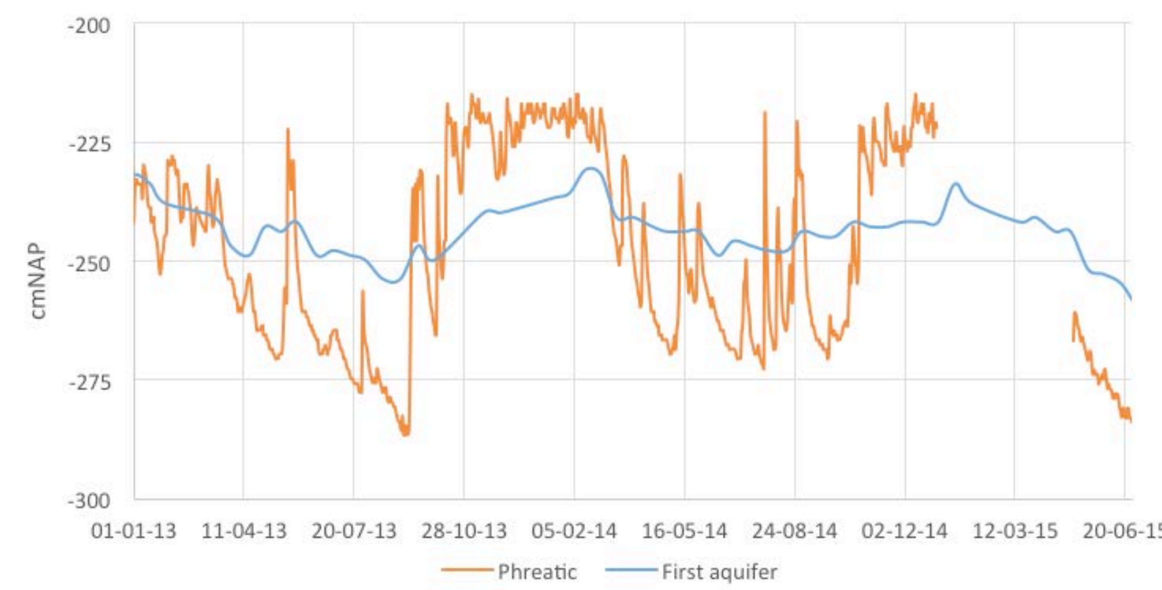



**Figure 7** ▸ Difference between phreatic groundwater level and the groundwater level of the first aquifer in the Lange Weide polder

## *4.1.3. Land subsidence according to the alternatives*

The outcomes of the different alternatives, using the 5-point kriged clay thickness and the ADG from the "karteerbare kenmerken kaart" for reference ADG is shown in figure 8. The middle of the polder has the highest subsidence rate, especially in scenario one. The soil has the thinnest clay layer here. Scenario 3 has the lowest subsidence rate, sometimes the land subsidence is even stopped. The pressure drainage is able to keep the groundwater level in the upper clay layer. According to the formula of van de Akker (2008) there is no subsidence as a result. In the scenarios 4A and 4B the subsidence rate is more fragmentized. In the middle part the lowest plots have pressure drainage while other parts have just invested in submerged drainage. In scenario 4A the submerged drainage is combined with flexible water levels which causes somewhat bigger differences.

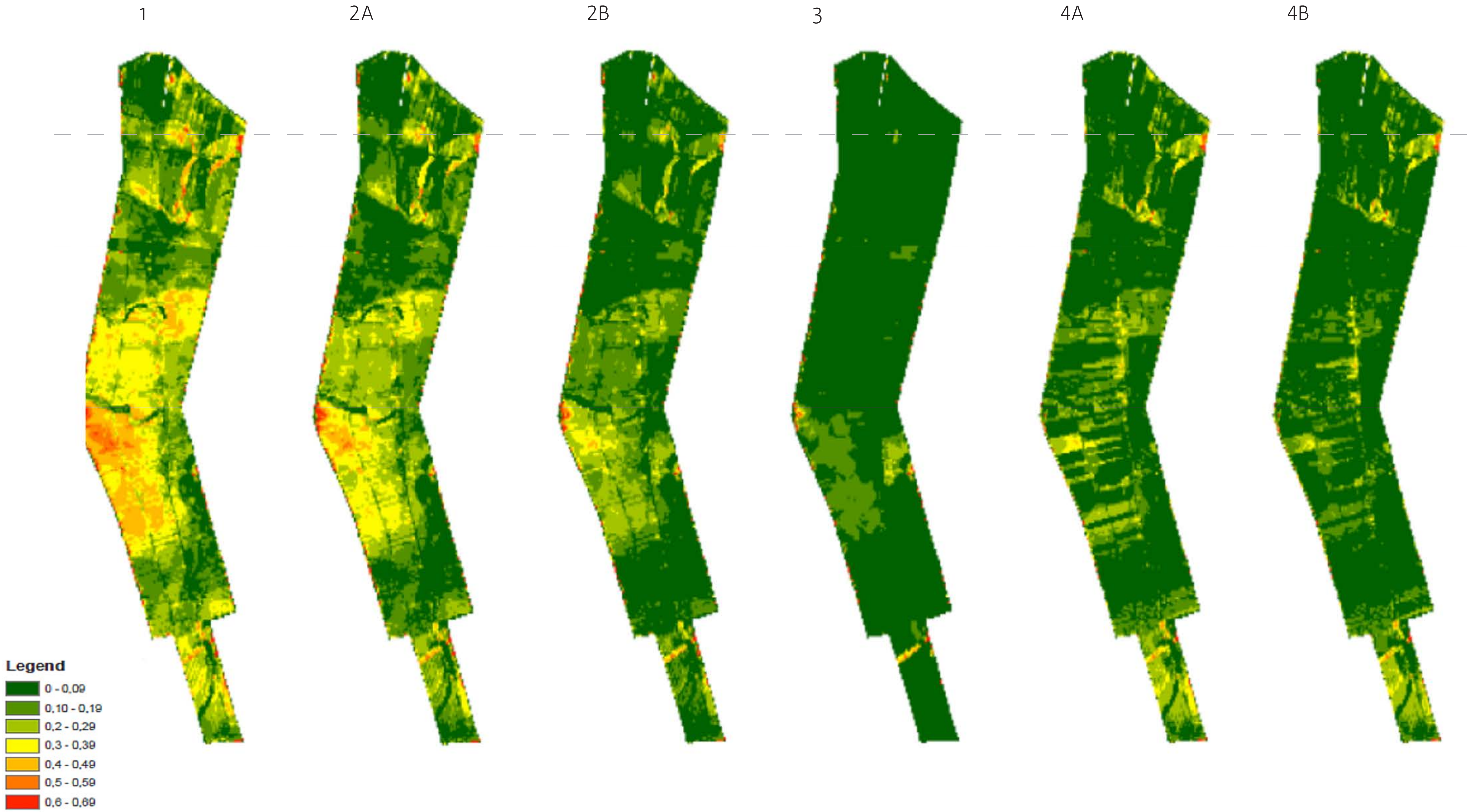



**Figure 8 ▸** Land subsidence in the period between 2010-2050 according to the different scenario's.

# 4.2 Analysing the MCA criteria

## 4.2.1 $CO_2$ emission

The total land subsidence for every scenario is multiplied by the average $CO_2$ and $N_2O$ emission per ha per mm. The result for all scenarios is showed in table 2.

**Table 2 ▸** Greenhouse gas emissions according to the different alternatives

| | 1 | 2A | 2B | 3 | 4A | 4B |
|---|---|---|---|---|---|---|
| $CO_2$ (ton) | 503331 | 349232 | 207776 | 71043 | 168782 | 123766 |
| $N_2O$ (ton) | 18 | 124 | 736 | 25 | 598 | 44 |
| $CO_2$ equivalent (ton) | 558365 | 387417 | 230495 | 78811 | 187236 | 137299 |
| Score | 0,00 | 0,36 | 0,68 | 1,00 | 0,77 | 0,88 |

## 4.2.2 *Storage requirements to prevent flooding*

The water system of water authorities is evaluated with the following rule: during a T = 10 rainfall event, less than 10 percent of the rural area might be flooded. Because of this rule it is handy as the height difference in a water-level area are small. The alternative (1) without submerged drainage has the most height difference in the polder. In the table this is shown as standard deviation of the surface height. The alternative (4B) gives the most equal polder area. The storage of all alternatives is calculated and show in table 3.

**Table 3 ▸** Storage in the different alternatives

| | 1 | 2A | 2B | 3 | 4A | 4B |
|---|---|---|---|---|---|---|
| Water level (mNAP) | -2,7 | -2,63 | -2,55 | -2,47 | -2,51 | -2,48 |
| 10 percent (mNAP) | -2,5 | -2,4 | -2,3 | 2,2 | -2,23 | -2,19 |
| Standard deviation (cm) | 0,21 | 0,197 | 0,177 | 0,157 | 0,151 | 0,139 |
| Storage (cm) | 0,2 | 0,23 | 0,25 | 0,27 | 0,28 | 0,29 |
| Score | 0,00 | 0,33 | 0,56 | 0,78 | 0,89 | 1,00 |

## 4.2.3 *Investment costs*

The investment costs for submerged drainage system are 2300 euro per hectare. The pump and the operating system for the pressure drainage makes this system 3750 euro in total (A. van Schie, personal communication, 2017). The total investment costs for every alternative are shown in table 4.





**Table 4 ▸** Investment costs according to the different alternatives.

| | 1 | 2A | 2B | 3 | 4A | 4B |
|---|---|---|---|---|---|---|
| Investment costs (€1000) | 0 | 1559,4 | 1559,4 | 2542,5 | 1350,9 | 1350,9 |
| Score | 1 | 0,61 | 0,61 | 0 | 0,53 | 0,53 |

## 4.2.4 *Agricultural costs and benefits*

The current agricultural benefits were around 1840 euro/ha/y (Van Hardeveld et al. 2014). In scenario 1 the Average Highest Groundwater table (AHG) is increased in the middle of the polder, because of the low freeboard. However the ADG is decreased because of the warmer temperature and less precipitation. Using the two parameters AHG and ADG the period of a too high groundwater level is calculated. According to the Help-tabellen the agricultural benefits are 1700 euro/ha/y.

Hoving et al. (2015) found out that the grass yields remain stable when submerged drainage is applied. The crop losses through a high or low groundwater table decreases, but on the other hand there are less nutrients available. During the process of peat oxidation nutrients are released. However, the effective grass yields will increase because of a higher bearing capacity, less trampling of grass and a longer graze season. Van de Akker et al. (2013) made the assumption that the graze season becomes 30 days longer and quantified this benefits on 68 euro per hectare.

At the moment the first experiments with pressure drainage in relation towards grass yields are done. However, no serious changes are expected and shown so fare (I. Hoving, personal communication, 2017). The increase in the effective grass yield will probably be higher than with submerged drainage but taken equal for lack of any information.

**Table 5 ▸** Agricultural benefits according to the different alternatives

| | 1 | 2A | 2B | 3 | 4A | 4B |
|---|---|---|---|---|---|---|
| Agricultural benefits (ha) | 1700 | 1908 | 1908 | 1908 | 1908 | 1908 |
| Score | 0,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |

## 4.2.5 *Water consumption*

Submerged drainage and pressure drainage increases the groundwater level in summertime. This increases the evapotranspiration. To sustain the surface water level in the polder area more water should be supplied. However, the used water level strategy determines this increase (Jansen et al. 2009b). Jansen et al. (2009b) made a hydrological model of polder 'Zegveld' and showed that with a flexible water level the water supply is equal to a polder without submerged drainage and a regular water level management. In the alternative with dynamic water level the increase is about 30-40 percent.

At the moment less is known about the water use of pressure drainage. There is just one operating system which used an average flow rate of 0.28 mm/hour in a dry period of June 2017 (K, van Houwelingen, personal communication, 2017). Unfortunately, there is no information for a longer time period. Therefore, the assumption is made that pressure drainage uses just a much water as submerged drainage with dynamic water-level. The alternative with the submerged drainage, flexible water level and pressure drainage will use less water than the alternatives with only pressure drainage.

**Table 6** ▸ Water quantity according to the different alternatives

| | 1 | 2A | 2B | 3 | 4A | 4B |
|---|---|---|---|---|---|---|
| Water consumption | 0 | 0 | -- | -- | - | -- |
| Score | 1 | 1 | 0 | 0 | 0,5 | 1 |

# 4.3 MCA

## 4.3.1 *Total score*

After the weighted summation the alternative with submerged drainage, flexible water level and pressure drainage in plots with a freeboard lower than 40 centimetre (4A) has the heighests score. Followed by the scenario where the flexible water level is replaced by a dynamic water level (4B). The scenario without submerged drainage or pressure drainage has by far the lowest score (1).

**Table 7** ▸ Total score of the different alternatives

| | 1 | 2A | 2B | 3 | 4A | 4B |
|---|---|---|---|---|---|---|
| Score GHG | 0 | 0,36 | 0,68 | 1,00 | 0,77 | 0,88 |
| Score flooding | 0,00 | 0,33 | 0,56 | 0,78 | 0,89 | 1,00 |
| Score investment costs | 1,00 | 0,61 | 0,61 | 0,00 | 0,53 | 0,53 |
| Score agricultural benefits | 0,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |
| Score water quantity | 1,00 | 1,00 | 0,00 | 0,00 | 0,50 | 0,00 |
| Total score | 0,40 | 0,66 | 0,57 | 0,56 | 0,74 | 0,68 |

## 4.3.2 *Sensitivity analysis*

Firstly, the sensitivity analysis is applied to weights, by computing the ranking for all possible values of the weight of a factor at a time. For the weight assigned to $CO_2$ emission holds that alternative 4A has the heights score until a weight of 0.45. Than the alternatives 4B and 3 are higher respectively.

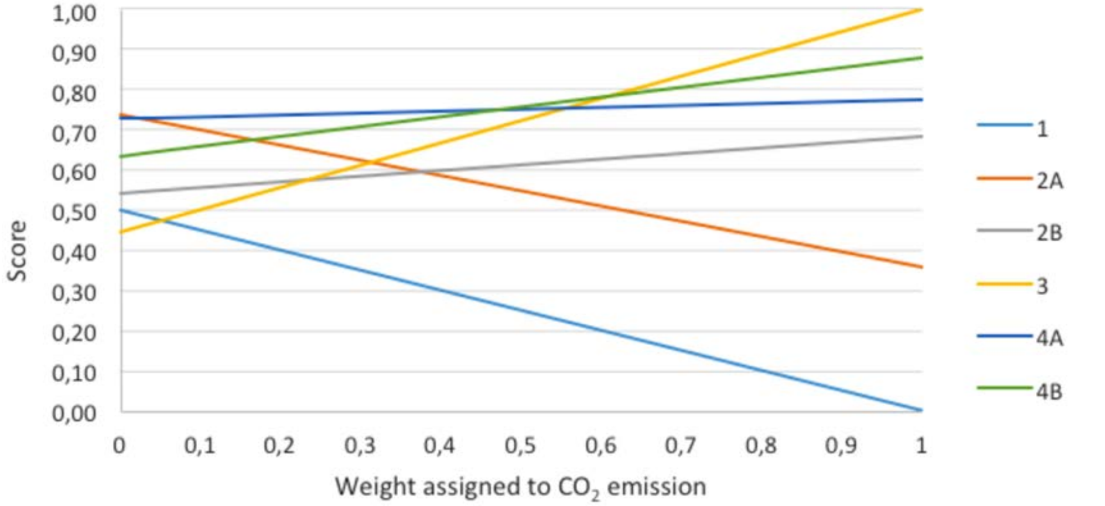



**Figure 9** ▸ Sensitivity of the $CO_2$ emission

For the storage against flooding requirements holds that alternative 2A has the height score when no value is attached towards this requirements. A weight between 0,1 and 0,45 gives the heights score to 4A. An even higher weight gives the prevalence towards 4B.

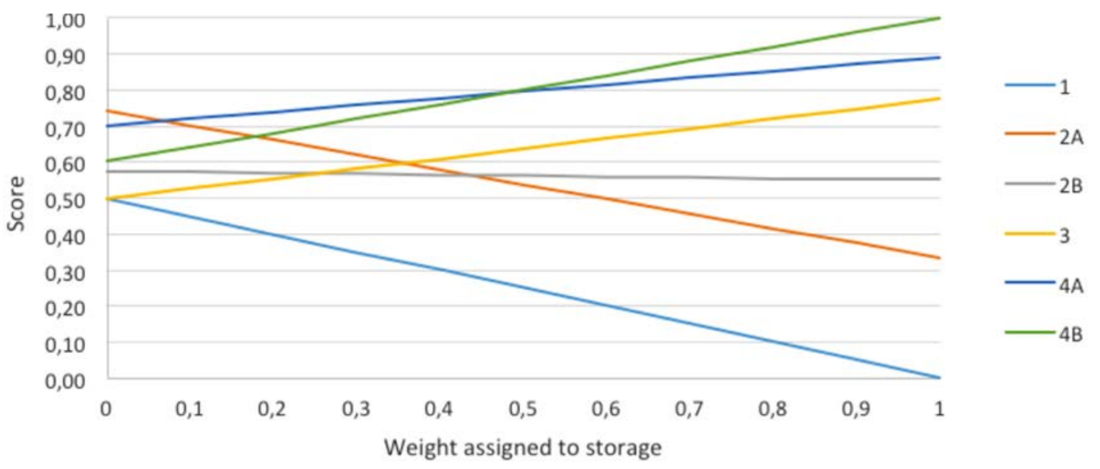



**Figure 10** ▸ Sensitivity of the storage for the storage requirements

When no value is attached towards water consumption, alternative 4B has the heights score. A weight between 0.1 and 0.35 results in scenario 4B and a higher weight than 0.35 gives scenario 2A as output.

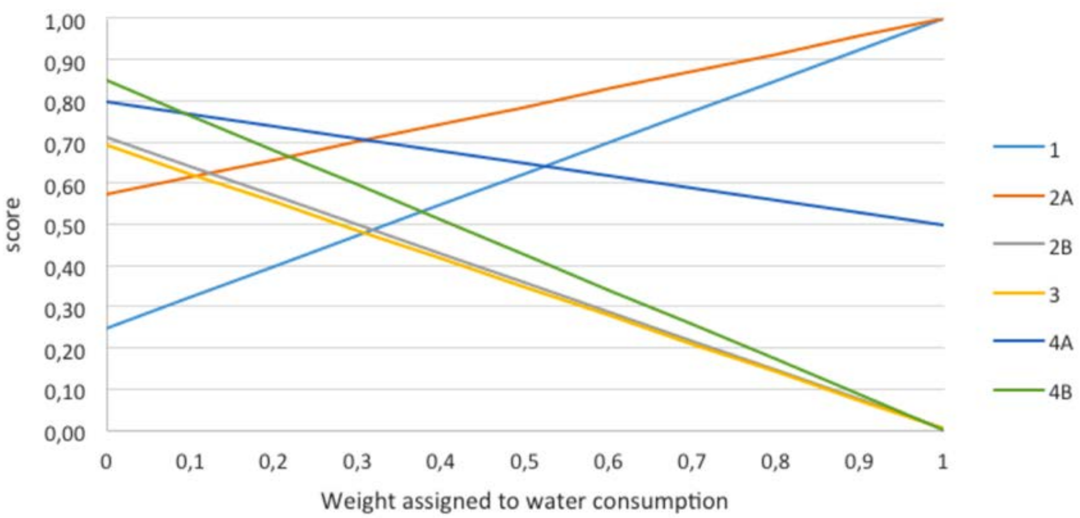



**Figure 11 ▸** Sensitivity of the water consumption criteria

For the agricultural costs and benefits has alternative 4B the highest score regardless the weight. 4B has also the heights score for investment cost until a weight of 0.55. A higher weight result in alternative 1.

To determine the influence of the standardization procedure the scores are also standardized with the maximum standardization method. Striking is the big influence on the alternative without any submerged drainage or pressure drainage (1). In the interval method this alternative had the lowest score while with this method it is the best score together with 4B

**Table 8 ▸** Total score according to the maximum standarazition method

| | **1** | **2A** | **2B** | **3** | **4A** | **4B** |
|---|---|---|---|---|---|---|
| Score $CO_2$ emission | 0 | 0,31 | 0,59 | 0,86 | 0,66 | 0,75 |
| Score storage | 0,69 | 0,79 | 0,86 | 0,93 | 0,97 | 1,00 |
| Score investment costs | 1,00 | 0,39 | 0,39 | 0,00 | 0,47 | 0,47 |
| Score agricultural benefits | 0,89 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |
| Score water consumption | 1,00 | 1,00 | 0,00 | 0,00 | 0,50 | 0,00 |
| Total score | 0,72 | 0,70 | 0,57 | 0,56 | 0,72 | 0,64 |

# 5 ▶ DISCUSSION

In this part, the results are critically analyzed and compared with the results of other research. First the Phoenix model and the input data is discussed. After that the results of the evaluated criteria are discussed and thirdly the results of the MCA.

## 5.1 Phoenix model

### 5.1.1 *Input clay variable*

All interpolation methods had a smaller RMSE and ME than the soil map method. This is however not surprising. For every soil type, there is one average value assumed, so there is no spatial variation left. When a new ground drilling is done there is a bigger chance that the value is more similar to the closest drilling, called spatial correlation, than the average value of the soil type.

In this case interpolation with the five closest data points looks to be an optimum. When only one data point is considered, there is chance of outliers. This influence is shown in the relatively poor score of the Thiessen polygons. Ordinary kriging and IDW with 12 data points however lead to less spatial variation.

The IDW and kriging method with the closest 5 data points have almost similar accuracy. Literature is also inconsistent concerning a potential superiority of one interpolation method over another Hu et al. (2004) showed that ordinary kriging is superior in estimating the soil mercury content. Mabit and Bernard (2007) showed the same for radioactive contamination or pollution. While Spokas et al. (2003) showed that IDW is better in estimating landfill methane fluxes. It appears that the optimal method depends on circumferences and the nature of the targets to be estimated (Gong et al., 2014).

Zimmerman et al. (1999) also found out that the type of sampling, for example random or regular-grid sampling, has influence on the accuracy of the interpolation methods. With the regular-grid method all interpolation methods have a relatively low error. Zhang et al. (2015) found out that IDW is more sensitive for the type of sampling than ordinary kriging. The ground drillings from Dinoloket, however, don't have specific type of sampling. Therefore, it is hard to determine the influence of distribution sampling in this research.

Studies like Attorre et al. (2007) and Van der Gaast et al. (2006) showed that the accuracy of the kriging interpolation increases using an extra variable e.g. kriging with external drift. However, in this study the relationship between clay thickness and the secondary variable (surface elevation) was found to be weak. The relation between surface height and clay thickness might be disturbed by artificial influence. The farmers of the area lower the abandoned riverbeds and raise the lower pieces of their land.

Also, most ground drillings were done in the period that GPS was not widely used. The exact location of the ground drilling was therefore hard to determine. With the AHN the current surface height was determined. Shifting a couple of meters, sometimes gives a different surface height up to 30 cm. That this effect is relevant is showed by the fact that the new ground drillings, located by a GPS had a $R^2$ of 0.41 while the original data set had only a $R^2$ of 0.23. Through these reasons it is not possible to use kriging with external drift.

Making the distinction between humic clay and peat is not always easy. However, the new ground drillings were done by four graduated earth sciences students. The clay thickness of the new data set was on average thicker. However, the clay layer increases over time, because the peat in between oxidizes. Therefore, the new ground drillings can be seen as reliable.

### *5.1.2 . Input variable groundwater*

The 'karteerbare kenmerken kaart' and the Hydromedah output were both options to use as basis ADG input. The Hydromedah output has deeper spots in the middle of the polder. In an ideal scenario those spots were verified with measurements in the field. However, through a lack of time this was not possible. Therefore, the Hydromedah model was further analysed. The deeper spots were not explainable by the different soil types and had a high influence on the subsidence rate. Thus, preference was given to the 'Karteerbare kenmerken kaart'. The analyses behind this decision is weaker than if measurements in the field were used, but still gave a good reason to use the karteerbare kenmerken kaart'.

The 'karteerbare kenmerken kaart' has however also disadvantages. In this method the soil characteristics of every soil type are used for the interpolation. This results in a transitions between the soil types. The soil type borders are also visible in the subsidence map. However, these artefacts are less influential for the estimated subsidence rates than the deeper spots of the Hydromedah model.

### *5.1.3 Subsidence rates*

The equation, which is used to calculated the land subsidence, is based on two formulas of van de Akker (2008). The original formulas were derived from observations of the cumulative soil subsidence caused by the continuous process of periodic indexation. One formula is based on





field observations at plots without clay layer while the other formula is based on observations at plots with a clay layer between 15-45 centimeter. The aim of the formulas was to show the influence of a small clay layer on the subsidence rate.

To have an equation which is useable for every clay thickness, a clay layer of 30 centimeter for the clay formula was assumed. With this assumption it was possible to derive the clay constant of the used equation. After this transformation the equation is linear and therefore the land subsidence could theoretically be calculated for every clay thickness. The question is if the equation gives correct outcomes for the extrapolation part, i.e. a clay layer is larger than 45 centimetres.

Another uncertainty in the used equation is the sharp transition between clay and peat. Intermediate types in the Dutch soil classification like 'Kleiig veen' (peat with a clay component) or 'Venige Klei' (clay with a strong peat component) are not taken into account. This will the percentage of organic material is an import factor to predict the subsidence rate.

Despite the mentioned disadvantages Van Hardeveld et al. (2017) came to the conclusion that the used equation is the best option in this case. The formulas of van de Akker are derived from almost the same circumstances as in the Lange Weide. Other formulas like Hoogland et al. (2012) and Zanello et al. (2011) have also their disadvantages. For example, both formulas work with input data which are not available in all parts of the research area.

When the uncertainties of the used equation are clear, the outcomes of the different alternatives can be analysed. The subsidence rates for the alternative without submerged drainage seems realistic. In the middle of the polder the maximum subsidence is around 55 cm, which is 1.4 cm a year. In the region of HDSR a current subsidence rate of 0.7 cm a year is assumed (HDSR, 2011). The abandoned river beds show a significant lower subsidence rate than the surrounded polder area. These abandoned riverbeds can be recognized by their tortuous shape. A separate interpolation method for these abandoned riverbeds seems to be the right choice.

The alternatives with only submerged drainage (2a & 2b) clearly show the impact of a ADG increase of 10 and 20 cm, respectively. The land subsidence is decreased by 30 to 50 percent, which is also the conclusion of Hendriks et al. (2014) & van de Akker et al. (2013).

When pressure drain infiltration is applied in plots without a clay layer, Hoving (2017) concluded that the decrease in subsidence rate is around 75 percent. However, this percentage is based on the formulas of van de Akker (2008). No direct observations are done. The results of the alternatives in the areas with a small clay layer are in line with the conclusion of Hoving (2017). However, they are also derived from almost the same formula. In an ideal situation, observations of the new subsidence rate confirm these conclusions.

The used equation and the formulas of van de Akker (2008) show that there is no land subsidence if the groundwater level is constantly in the upper clay layer. At a minimum clay layer of 40 centimetre this is technically possible when submerged drainage and, even better, pressure drain infiltration is applied. However slow processes like anaerobic decomposition and consolidation could continue. Because of the lack of observations is it is hard to judge if this theory is true.

Alternative three applies pressure drain infiltration in the whole area. Most plots have a clay layer of 40 cm or thicker and thereby almost no land subsidence is expected. In Alternatives 4A and 4B this is also the case in the areas were pressure drain infiltration is applied. The plots with a current freeboard between the 40 – 60 cm have a higher subsidence rate because submerged drainage is applied here.

In conclusion, the projected subsidence rates for the various alternatives seem realistic and this supports the use of the land subsidence equation applied. Observations on plots with a thicker clay layer should confirm the theory of totally stopping the land subsidence under scenario 3.

### 5.1.4 *Climate scenario's*

In this MCA only the warmest and driest scenario ($W_H$) of The Royal Netherlands Meteorological Institute is used. The influence of this decision on the outcome of the MCA will be discussed here.

The climate scenario has a significant influence on the subsidence rate. When a scenario with a smaller temperature increase was used, the expected subsidence rate was lower. The same land subsidence was not reached in 2050 but for instance in 2070. The lifespan of submerged drainage is mainly determined by the indexation level (Van de Akker et al., 2013). When the water level reaches the level of the drainage they should be removed. Less climate change therefore results in a longer lifespan.

In one lifespan of the submerged drainage or pressure drain infiltration the same amount of greenhouse gasses is emitted. In a scenario with less climate change the greenhouses gasses are emitted over a longer time period. Through the principal of discounting the benefits of the prevented greenhouse gasses are lower.

Van de Akker et al. (2013) and Hoving et al. (2015) mention the agricultural advantages of submerged drainage and pressure drain infiltration. These advantages are however based on the current climate. A longer lifespan as projected under moderate climate change provides a longer period of benefits. However, in the more extreme WH scenario the chance of drought damage is higher than in the other scenarios with would provide a larger benefit per year for this scenario, even if the lifespan is shorter. As conclusion can be made that it is hard to determine the influence of the different climate scenarios. The advantages and disadvantages of a given scanrio might be in balance.

The effect of climate change on the water consumption is more clear. In the WH scenario the change of droughts is higher. The water quantity criteria is therefore in the other scenarios less important. Climate change results in a more unequal land subsidence (Van Hardeveld et al., 2014). Application of submerged drainage and pressure drain infiltration in the lower areas therefore have more advantage than in a more moderate climate change.

The exact influence of the different climate scenarios on the criteria are hard to determine. However, the pros and cons for the criteria seem to be more or less in balance. Therefore, the conclusion can be made that the choice for a certain climate scenario doesn't have a big influence on the outcome of the MCA.

## 5.2 Criteria

### 5.2.1 *Agricultural costs and benefits*

As stated in the Methods section, the yield loss for the alternative without submerged drainage is calculated using the HELP-tabellen. This method calculates for example the oxygen stress, the yield loss through a too high groundwater level. In 2050 the freeboard will be 20-25 centimeters in the middle polder, which in the current climate results in serious oxygen stress.

However, the period of a too high groundwater level is calculated using the AHG and ADG (Van Bakel, 2002). In 2050 the climate change causes a deeper ADG, so according to the formula this reduces the period of a too high groundwater level. Therefore, there might still be suitable conditions for dairy farming. The higher temperatures and more evaporation might allow dairy farming on plots with a low freeboard.

The Help-tabellen could not be used for the alternatives with submerged- and pressure drainage. The submerged drainage changes the groundwater dynamics and therefore disturb the used relation. When submerged drainage is applied less oxygen stress is expected. However, when for example the AHG is decreased by 10 centimeters and the ADG increased by 15 centimeter the oxygen stress is increased according to the HELP-tabellen. Moreover in the Help-tabellen not all agricultural effects of submerged drainage and pressure drain infiltration are included.

Van de Akker et al. (2013) calculated the agricultural benefits of submerged drainage. For this calculation, the assumption of a 30 days longer graze season was made. However, this amount seems unrealistic. Hoving (2017) showed that even with pressure drain infiltration this amount was not achievable in a wet year like 2016. Under wet conditions it is easier to win grazing days. Other mentioned positive effects like a better botanical grass formation and a lower infection risk of liver fluke were not quantified, simply because it was hard to quantify. Through the balance between this positive effects and overestimation of the grazing days the calculated value of van de Akker et al. (2013) is still used.

At the moment, the agricultural effect of pressure drain infiltration is being investigated. No change in grass yields are expected compared to ordinary subsurface drainage (I.Hoving, personal communication, 2017). The effective grass yield could be higher than with submerged drainage through an even better bearing capacity. However, because this is still uncertain, the same value as for submerged drainage is used.

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### 5.2.2 . Storage requirements to prevent flooding

The results show the importance of the height distribution in a water-level area. Through the unequal land subsidence in the alternative without submerged drainage the surface storage is 0.2 cm. The scenario with combined scenario and dynamic water-level, the surface water storage of 0.29 cm. This longterm advantage for flooding is also mentioned by Hendriks et al. (2014).

The method used is of course of limited by the surface water storage. Important parameters like the groundwater table are not used. In wet periods the submerged drainage will lower the groundwater level and therefore there is more storage in the soil. However, in dry periods the groundwater level is higher and less storage is possible (Hendriks et al., 2014). Also, the same average surface water level for the flexible and dynamic water level are used. A high water level just before a rainfall event could eliminates all benefits. The timing of the rainfall event therefore will determine to what degree the submerged drainage and the used water-level strategy will be an advantage.

The duration of the flooding is shorter when submerged drainage or pressure drainage is used (van de Akker er al. 2013). For the landowners this is important. However, the assessment of the storage requirements does not take flood duration into account.

### 5.2.3 Water consumption

Unfortunately is the change in water supply for the submerged drainage alternatives is estimated from a hydrological model of another polder. However the polder areas are hydrological quite similar and therefore the similar effect could be expected. The assumption for pressure drainage is hard to verify. On one hand the period of an increasing surface water level in the dynamic water level strategy consumes a lot of water, however more evapotranspiration could be expected by pressure drainage. These processes might cancel each other out.

Jansen et al. (2009b) showed the increase in water supply for the hole summer, however the peak demand and the moment is for the water system also important. The infiltration of the water is a gradual process and therefore not a big increase in the peak could be expected.

### 5.2.4 Not included criteria

When a criteria is not included in the MCA, there is no different influence of the alternatives. However, some criteria require some explanation.

Subsidence occurs significant damage towards infrastructure and (wooden) foundations (Van den Born et al., 2016). However most infrastructure and buildings are situated in the separate water level of the settlement area, see figure 1 The water level in this water level area will be reduced as little as possible to protect these properties. At the moment the water level and land subsidence in the rural area has no influence on the settlement area.

Hendriks & van de Akker (2012) expect a small increase in water quality through submerged drainage. However this is only modeled and the influence of pressure drainage on water quality is not even investigated. Through the small change and uncertainties the water quality is not taken into account.

The peatland meadows are one of the cultural landscapes of the Netherlands and is characterized by the small plots, high water levels, cows and his open landscape. The sustainer of this landscape is the dairy farming. When this factor changes the cultural value and recreation value changes (Provincie Noord-Holland, 2012). However in all alternatives the dairy farming is still present in 2050.

In the peat land areas the meadow birds get special attention. A change to alternative cultivation makes the landscape unusable for meadow birds and also less open, which is important in their habitat (Van Dijk et al., 2014). However no landscape change is expected. Kruk & Van der Zijden (2013) looked at the influence of submerged drainage on meadow birds, however also no significant influence could be found.

Wageningen Economic research and PBL Netherlands Environmental Assessment Agency both developed techniques to validate nature. Both methods are based on the size, quality and the type of the ecosystem (De Blaeij & Verburg, 2011; Sijtsma et al., 2009). However the quality of the ecosystem in peatland areas are derived from the groundwater characteristics. Submerged drainage however change this normal groundwater dynamics and the soil structure. Therefore this techniques are not usable. However, Hoving et al. (2015) concluded that on the short term no change in the botanical grass formation occurs when submerged drainage is applied. On the longer time there might be an influence.

## 5.3 MCA

To arrive at a quantitative evaluation of the different alternatives, a MCA is performed. A MCA is appropriate because it creates one single score, while criteria in their own dimension can be used (Hermann et al., 2006). A cost benefit analysis (CBA) has not been made, because some of the objectives are hard to express in money, i.e. such as water consumption or the effects of the storage requirements to prevent flooding. The price of water is really determined by the weather conditions and in the current climate there is almost never water stress. In their CBA Van Hardeveld et al. (2014) therefore assumed the price of water to be zero. However, for politicians the future freshwater availability is a topic of concern. In a multi criteria analysis this is easier to include by adjusting the weights.

The sensitivity analysis, however, showed also the weakness of a MCA. The approach of the MCA, for instance the standardization method, has a big influence on the outcome. Raaijmakers (2006) obtained a completely different order of alternatives when using the maximum standardization or the interval standardization. Also, the commissie van de milieueffectenreportage (2002) mentioned the big influence of the standardization methods.

The weighting of the different objectives had less influence on the outcome. The only discussion point is the weighting of the water consumption criterion. When a value is assigned less than 0.1 or more than 0.35, another alternative becomes the highest score. In the other objectives only unrealistic weights could distract alternative 4A from the heights score.

In a lot of MCA the sensitivity analyses were deliberately not conducted to limit discussion on the reliability of the MCA results (Janssen, 2001). However, the role of a MCA should be to make the information transparent and available for all stakeholders. The importance of the MCA results for the final decision is not always clear. In many cases, the political decision is a compromise between the original alternatives (Janssen, 2001).

Following the reasoning of Janssen (2001), the MCA in this study can be seen as successful. It provides a clear description of the uncertainties and a simple method is chosen to arrive at the final outcome: interval standardization and unweighted summation. The best alternatives found in this study, a combination between submerged drainage and pressure drainage (4A & 4B), also resulted as the preferred alternatives from a brainstorm session about the future of polder Teckop (Wageningen University & Research, 2016).

# 6 CONCLUSION





In this research, a MCA is performed to assess the economic and societal advantages and disadvantages of different submerged drainage and pressure drain infiltration alternatives. Used criteria were the agricultural benefits, $CO_2$ emissions, storage requirements to prevent flooding, water consumption and investment costs. The effect on the first three criteria are mainly determined by the subsidence rate. To increase the accuracy of the subsidence model different methods of input data were analyzed. This approach brought us to the following main conclusions:

- The alternatives with a combination of submerged drainage and pressure drainage have the most positive impact across all criteria. The investments are recovered by a lower $CO_2$ emission, increased surface water storage to prevent flooding r and better agricultural conditions.

- All alternatives with submerged drainage and/or pressure drainage had a higher score than the current situation of no technical investments. From this it can be concluded that the use of these technical innovations should be encouraged by the authorities.

- Kriging with the closest 5 data points was the best method to determine the clay thickness. This method gave significantly better results than the standard used soil map method.

- The 'karteerbare kenmerken kaart' method is more appropriate source for estimating estimating the Average Deepest Groundwater table (ADG) than the Hydromedah model.

# 7 POLICY ADVICE AND RECOMMEN-DATIONS

## 7.1 Policy advice

The MCA showed that initiatives for large scale use of submerged drainage and pressure drain infiltration have a positive impact. The investments are recovered by a lower $CO_2$ emission, increased surface water storage and better agricultural conditions. The relevant governmental organizations could support the landowners financially, because the submerged drainage or pressure drain infiltration provide a multiple socio-economic and environmental benefits

The local circumstances of the polder Lange Weide make the use of submerged drainage for the landowners interesting. To export this success to other peatland areas, landowners in these areas should be stimulated to decrease the occurring subsidence rates. At the moment, the landowners have almost no negative financial impact of the land subsidence, because the water level is indexed every so many years. The costs of the land subsidence are thus transferred to the water authorities and its tax payers (Van Hardeveld et al. 2014). When indexation takes place for instance by 70 percent of the subsidence that occurred since the last indexation, the landowners are stimulated to take measures. If these measures are not taken, the landowner are faced with a smaller freeboard in the future. This indexation tool is also used in the new policy of Stichtse Rijnlanden (Holtman, 2016).

The individual landowners should decide for themselves how they will respond to this lower indexation level. They could inves t in submerged drainage, pressure drain infiltration, switch to alternative crops or simply accept a lower freeboard. The governmental organizations could further financially stimulate the development of these measures.

However, there are two weak spots in the policy of a lower indexation level. Firstly, when the freeboard is 30-35 centimeter or lower the investment in submerged drainage could result in a decrease of grazing days during summertime, while the average groundwater table will be less deep than in the original situation. This then results in reduce soil water storage during rainfall events. This shortcoming of subsurface drainage should be communicated beforehand.

Secondly when no measures are taken by the landowners, the storage of the water system is decreased. To compensate this impact, investments in the water system could be required. The question is if these investments are socially desirable. The governmental organizations should therefore start a discussion about the storage requirements and flooding standards in the peatland areas

## 7.2 Recommendations

Hereafter follows a short enumeration of the (technical) recommendations. For more detail see the discussion.

- The lowest 10 percent of the water level area determines how much water can be stored in the water system without juridical consequences. Investments in submerged drainage or pressure drain infiltration could decrease the subsidence rate in the low areas. This will increase the storage in the future. For this research simplified rules for the flooding requirements are used. It will be valuable to investigate the influence of the surface heights in more detail. Probably the investments in submerged drainage are more efficient than an adaptation of the water system itself.

- When the subsidence model is used on a small scale, it is advisable to use the kriging interpolation method for the estimation of the clay thickness. This method has a higher accuracy than the current used soil map method. Landowners and farmers often know where the clay layers are thicker, such as on abandoned riverbeds. When this is not properly represented in the model, it puts the creditability under pressure.

- The application of the formula of van de Akker can be questioned when a relatively thick clay layer is present, as it was developed with clay layer thickness data not exceeding 40 cm. To use the formula for thicker clay layers the formula is in extrapolation mode. In new pilots it is advisable to do field observations to verify the correctness of the formula.

- When the submerged drainage or pressure drain infiltration keeps the groundwater level in the upper clay layer, no subsidence is expected according to the formula. The question is however if this is a realistic assumption. In new pilots surface height measurements should be made to test this assumption.

- According to groundwater dynamics in the Help-tabellen, the circumstances for the dairy farming on plots with a low freeboard will improve under climate change. This is because the higher temperatures in spring time and the associated increased evaporation make for deeper groundwater tables in the beginning of the growing season. This effect might be a chance for the water authorities to decrease the freeboard and prevent the extra land subsidence because of climate change. The storage requirements for the prevention of flooding remain however a point of attention in this case.

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