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The effect of pressuredrain groundwater management on agricultural peatland in the polder Spengen

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Author:	**Arne Hak** **De Stegen 9** **4174 GZ Hellouw** **a.a.hak@students.uu.nl** **0614559994**
University of Utrecht	
Supervisor:	**M.F.P. (Marc) Bierkens** **M.F.P.Bierkens@uu.nl**
Hoogheemraadschap de Stichtse Rijnlanden (water authority)	
Supervisor:	**Peter Hesen** **hesen.plgm@hdsr.nl**
2nd Supervisor:	**Jantine Hoekstra** **Hoekstra.J@hdsr.nl**

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Utrecht University

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Table of Contents

List of Figures:

List of Tables:

List of Appendices:

Summary

Since the medieval the Dutch peatland areas are suffering from land subsidence caused by peat degradation. After the implementation of intensive drainage systems in 1960, the subsidence rates increased to an average of approximately 7 mm/year (Geisler, 2014; Van den Akker et al., 2007). In particular, during dry periods the groundwater level can drop almost 1 meter below land surface, which causes large scale land subsidence. On the other hand, during wet periods the groundwater table can reach higher levels, which negatively influences the bearing capacity (especially in the early spring and late fall). Land subsidence causes significant problems in both rural and urban areas. To deal with these serious subsidence rates, the water authority (HDSR) and the Peatland Innovation Centre (VIC) intends to pioneer a new drainage system, called 'Pressuredrain Groundwater Management' (PGM). This drainage system can manage the groundwater levels in the polder. The major goal of this drainage system is reducing the land subsidence by a minimum of 25 percent (in 2050), through creating a more even groundwater table during a year (50 cm below land surface). The aim of this research is to determine the influence of PGM on the groundwater levels, land subsidence and loss of crop yield for farmers.

This research focuses on polder Spengen (located North East of Utrecht), where the soil is characterised by peat, clay and sand layers. Following varying alternatives of PGM (drain distance and depth in a parcel), groundwater levels are modelled through the program called PMWIN modflow. Here, due to the variation in hydraulic parameters (such as hydrologic conductivity and porosity) the soil structure is very important. Whether PGM should be implemented or not is determined as follows: Firstly, the statistical parameters determining average groundwater level fluctuation, i.e. mean highest water table (GHG) and mean lowest water table (GLG) are calculated from the modelled groundwater levels. Secondly, the standard deviation of the modelled groundwater levels is calculated and compared to a target value of 50 cm below land surface for each variable PGM system. These results are compared with the current situation (no drains). Thirdly, using the calculated GHG and GLG values, for each PGM system analysed, the land subsidence is calculated with a model created by HDSR, called Phoenix. Fourthly, again using GHG and GLG, the loss of crop yield is determined in percentages of crop damages for the farmers caused by the changing groundwater levels (dry or wet conditions).

The most suitable drainage method in polder Spengen is not clear cut and depends on several components, such as costs, environment, soil type and the perceived future of Spengen. Nevertheless, PGM can reduce the land subsidence by a large amount (up to 63 percent) in peatland areas and the system can become beneficial for farmers, focussing on the crop yield. According to this research an advisable PGM system would be to have drains at a distance of 6 meter and creating a hydraulic head at a depth of 35 centimeter below land surface to reduce the land subsidence and enhance the crop yield in times of dry weather conditions as well. With this setup, the land subsidence can be reduced by a percentage of 35.

1. Introduction

For this research a new type of an adjustable pressure drainage system (called 'Pressuredrain Groundwater Management') is evaluated for the Dutch peat areas between Utrecht and Amsterdam in the polder Spengen. The research internship is carried out at the water authority 'Hoogheemraadschap de Stichtse Rijnlanden' (HDSR) located in Houten. This water authority is operating in the surroundings of Utrecht and cooperates with the Peatland Innovation Centre (in Dutch 'Veenweide Innovatie Centrum', or VIC). This study is coherent to a physical experiment for pressuredrains, which is recently started in Zegveld (at VIC).

Almost all stakeholders, such as the water authorities, provinces, municipalities, VIC, agri-and horticultural organizations (in Dutch 'land-en tuinbouw organisaties', abbreviated as 'LTO') and conservation organizations agree on the poor condition and consequently the effects in the future for the Dutch peatlands near Utrecht, because of continuous land subsidence. Therefore, mitigation of peat oxidation is the primary issue to deal with in the near future.

1.1. Background of the problem

Originally the western part of the Netherlands was covered by widespread peaty areas. In this area, the rivers Rhine and Meuse were responsible for delta depositions and high water levels caused by stagnant water. Through the deposition of organic materials (especially plants) in times of high groundwater levels large peaty areas were formed. The history of land subsidence of these peatlands starts approximately thousand years ago, when the Dutch peat areas have been subjected to drainage of soils and peat excavation since the late medieval (Berendsen, 2004). Especially after 1960 the agricultural (dairy) sector carried out large-scale drainage in the Dutch agricultural peatlands (almost 100 percent meadow), to create better agricultural conditions. Due to this intensive drainage of peatlands groundwater tables were lowered (up to 1m below land surface) and the air penetrated deeper into the peat, which caused shrinking and oxidation (soil compaction), this is an ongoing process. Due to the mentioned natural processes, the peatlands are more than ever suffering from land subsidence (Hoving et al., 2008). Land subsidence is not limited to rural areas, due to the rapid growth of the Dutch population, urban areas are suffering of land subsidence as well. This in turn causes less favourable construction conditions for buildings, infrastructure and water management as well (Wolters et al, 2011). Problems for dairy farms are in particular linked to high groundwater levels in the early spring and late fall and too low groundwater levels in the summer. During a year the groundwater tables fluctuate. During the winter groundwater tables increase mainly caused by precipitation, while during the summer period evapotranspiration exceeding precipitation is the main reason for low groundwater levels and the land subsidence associated with these. According to a research of Geisler (2014) and Van den Akker et al. (2007), the average subsidence is approximately 7 mm/year (in the area of HDSR), with maximum subsidence rates reaching 61 mm/year in peat soils around Zegveld (located near polder Spengen). Thus, the current form of water management is becoming a significant problem for the sustained use of peatlands.

The benefits of low groundwater levels for farmers are in conflict with other interests (e.g. ecological values and water quality) in the peatland area. Nevertheless, all stakeholders (including farmers) agree with the common groundwater issues (Joosten, 2015). The natural fluctuations in groundwater levels are causing disadvantages for both the agricultural sector and water authorities. During winter (mainly wet periods) the groundwater levels often reach too high levels, which in early spring and late fall could lead to problems for farmers (water nuisance), e.g. reducing of bearing capacity. For agricultural purposes (especially dairy farms in polder Spengen) costs of land cultivation are becoming more expensive due to the various adverse consequences of high groundwater levels. In dairy farming, high groundwater levels cause damage to vegetation, by cattle or heavy machinery, while the time frame for cultivation of agricultural land is limited by weather conditions. Consequently, these limitations result in a reduction of revenues and yield of grassland. In order to avoid damage and to make land cultivation possible, groundwater levels are lowered by conventional drainage systems before the growing season is started. By doing this, farmers are able to work on their land in spring and in the fall, resulting in a situation that the damages to their grassland are less, which has a cost benefit as well. However, the level of decrease of groundwater levels during spring is generally determined by the lowest surface elevations. As a consequence, groundwater levels at the higher elevations will turn out to be relatively deep when groundwater levels start falling further during summer as a result of a precipitation deficit (see Figure 1). The result is that at these higher elevations capillary rise is limited and soil moisture rapidly decreases, which causes inter alia lower growth of grass and oxidation of peat (Joosten, 2015). Since the groundwater levels are low and the soil temperature is relatively high, especially at the end of the summer, peat degrades rapidly in this period (optimal circumstances for peat degradation).

Peat is a heterogeneous mixture of more or less decomposed plant matter, which oxidizes in contact with air (oxygen) and high temperatures, where oxygenation of peat in term is determined by hydrological factors such evaporation, rainfall, distance between ditches, permeability of the soil and seepage (Van den Akker et al., 2005). Degradation of peat is irreversible and results in land subsidence over several years or decades (Camporese et al., 2006). In the Netherlands, approximately 4.2 million tonnes of peat is oxidized each year and is transformed into greenhouse gas CO_2 (carbon dioxide), 2.6 percent of the total Dutch $C0_2$ emission in 1990. Furthermore, a more powerful greenhouse gas called N_2O (nitrogen oxide) is also produced by the oxidation of peat. Therefore the problem of peat oxidation will have worldwide effects (Van den Akker et al., 2005; Kuikman et al., 2005).

Over the last few years the interest in the future perspectives of peatlands is increasing, mainly due to the effects of peat degradation (Joosten, 2015). The current surface trenches and low groundwater levels are advantageous for the agricultural sector, but the resulting land subsidence causes damage to inter alia infrastructure, sewage systems and buildings, while peat oxidation results in increased greenhouse gas emission and nutrient emission from soil to surface water causing eutrophication. More and more it is realized that the harmful effects provide larger costs for the water management. These problems are aggravated under to climate change with more heavy rainfall and higher temperatures, making the sustainability of the current water management system in peat areas highly questionable (Joosten, 2015).

The aforementioned effects of increasing land subsidence in the Dutch peatland areas are a reason for the water authority (HDSR), together with the Peatland Innovation Centre (VIC) to propose a new drainage management system (explained in chapter 2). This project is called ‘Pressuredrain Groundwater Management’ (PGM) and will be able to stabilize the groundwater level through the year, reducing land subsidence as well. The idea behind PGM (see abbreviations and terminology) is that the system allows dairy farmers to regulate their groundwater levels. By means of a ‘well system’ it generates the over- or underpressure in the drains, which leads to infiltration or drainage of groundwater.

Through PGM it would be possible to regulate the groundwater levels and the moisture content in the upper soil, in relation to weather conditions and land use (Querner et al., 2008; Hendriks et al., 2014). Especially in dry periods (summer) the positive effects of such a drainage system could be higher summer groundwater levels, which will result in reduced peat degradation. A premise behind PGM is that through this new drainage system the farmers themselves obtain the power to control the groundwater levels in their grassland (Jansen, 2015). In this case, mutual agreements would be crucial to create acceptable situations for each aspect for adapting the groundwater levels (e.g. acceptable water quality, reducing land subsidence and maintain the yield of grass). However, the main goal of this drainage system is reducing the current land subsidence rate.

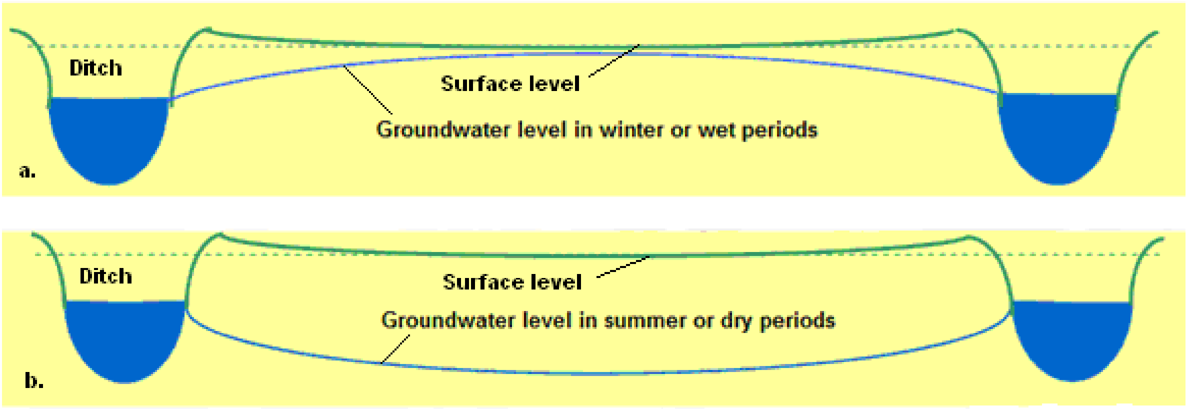

Figure 1. *Representation of common groundwater levels in a parcel without drainage, where a) shows the groundwater level during wet periods and b) shows the groundwater level during dry periods (adapted from VIC, 2015).*

1.2. Research area

For this research a specific peatland area located between Utrecht and Amsterdam (western part of the Netherlands) was investigated for the possibility of PGM (Figure 2). The polder called 'Spengen' is selected for three reasons. Firstly, the farmers are enthusiastic about the principle of PGM. Secondly, a fixed surface water level is managed over the whole polder. Thirdly, variations in soil type (including differences in type of peat and sediments of former rivers) are causing elevation differences as a result of differential oxidation and subsidence rate. As a result a new plan for the surface water level in this area is necessary, which makes PGM an appropriate research focus here.

Generally, the topsoil of the polder consists of a 6 meter thick peat layer. Below this peaty layer a thick sand layer is present. At several locations in this polder thin layers of clay and sand are observed between the peat (DINOloket, 2016). Furthermore, the polder contains sandy and argillaceous river depositions, which causes differences in land elevation. In polder Spengen is also a small pond, a former sandpit. This was used for sand extraction for e.g. infrastructure. Since the composition of the soil influences the groundwater drainage, it is important to know the composition of the soil in detail.

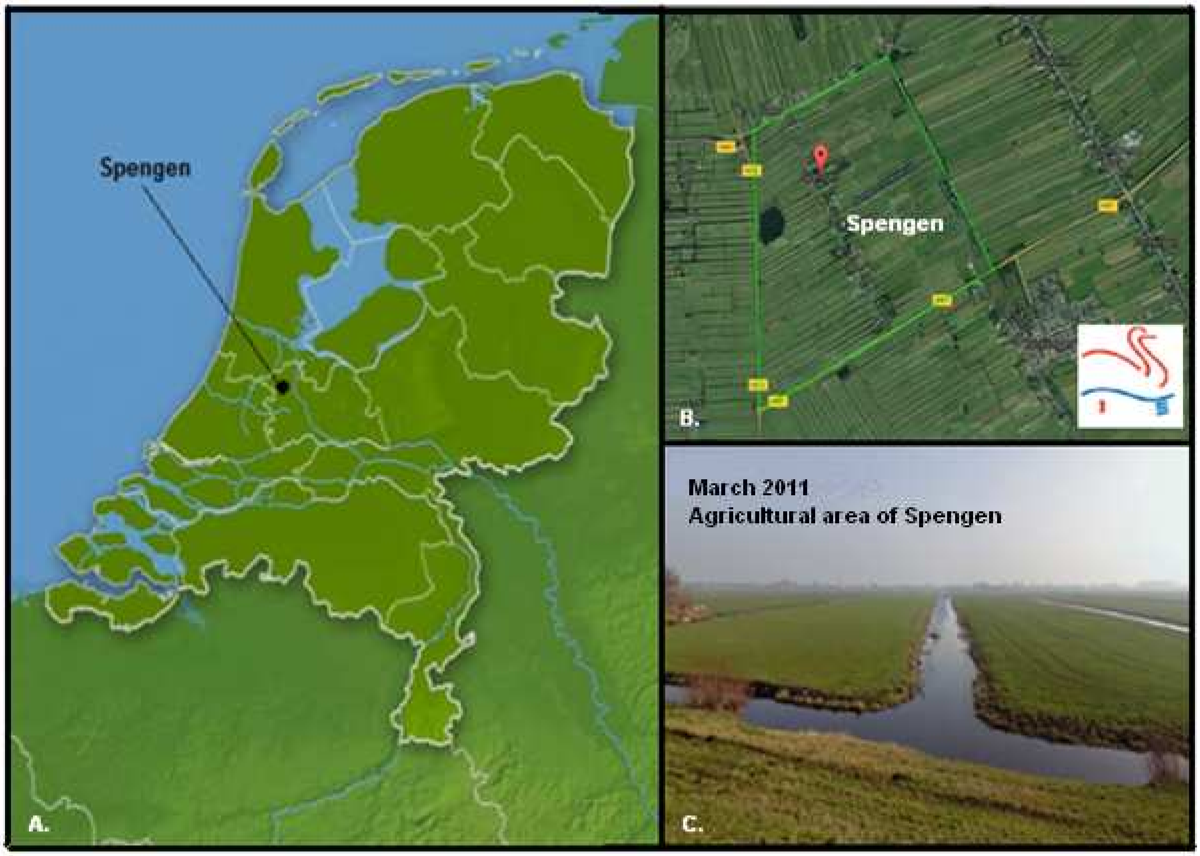

__Figure 2.__ Visualization of the research area. A) Shows the location of Spengen in the Netherlands, B) represents the polder area and C) is a photograph from the polder itself (adapted from Google Maps, 2016).

Hydrogeology in polder Spengen

In general, four different types of formations (see abbreviation and terminology in appendix) are present in the soil (approximately the first 30 meters of the soil are used for this research) in polder Spengen. The peat and clay layers are unconfined and deposited on top of the confined sand layers.

First of all, the Echteld Formation (EC) is often located on top of the peat layer and is originated from fluvial deposits. This formation contains particularly clay (relative low permeability), which is sometimes alternated with the Formation of Naaldwijk (marine clay and sand) and the Formation of Nieuwkoop (Berendsen, 2004).

Two different types of peat soils are linked to the Nieuwkoop Formation. The Nieuwkoop Formation is originated as a result of coastal and fluvial flooding as discussed in the introduction and has normally a large permeability. The upper peat soil is called the “Hollandveen Laagpakket” (NIHO), this peat layer contains an alternating pattern with the Naaldwijk Formation. The relative deep peat soil is called the “Basisveen Laagpakket” (NIBA), this layer contains compacted peat, therefore the permeability is reduced (Berendsen, 2004).

The Naaldwijk Formation is characterized by Holocene deposits, varied from coarse sand to clay. In this research area, the Formation of Naaldwijk is mainly located between the “Hollandveen Laagpakket” and the “Basisveen Laagpakket”. This typical layer is called “Laagpakket van Wormer” (NAWO) and mainly consists of clay and loam with thin sandy layers (Berendsen, 2004).

The deepest soil formations in the model are the Formations of Boxtel and Kreftenheye (BX/KR). These formations are characterized by sandy layers, with a large permeability. In this layer the initial hydraulic head is lower than the above unconfined layers, which causes limited seepage to occur. Both layers are combined as one layer in the models, because these layers are confined and they form the first confined aquifer (Berendsen, 2004).

In addition, the average groundwater level measured at a monitoring well (B31E2623) over approximately a three year period (31-08-2012 until 30-06-2015) is 47 centimeter below land surface, meanwhile the hydraulic head from the confined sand layer is 131 centimeter below land surface on average, see Figure 3 (DINOloket, 2016).

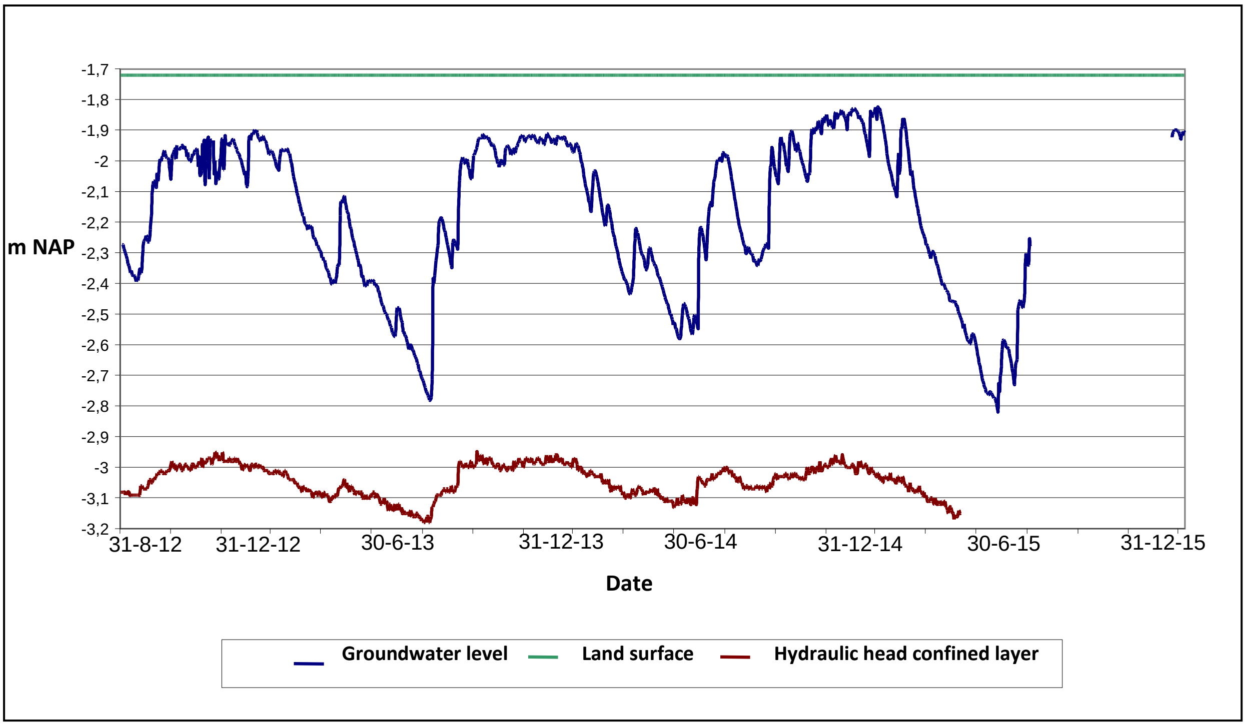

Figure 3. *The groundwater levels, land elevation and hydraulic head in the confined layer (isohypse) measured by a representative monitoring well (B31E2623) in Spengen over a period of approximately 4 years (DINOloket, 2016).*

1.3. Purposes and goal of the research

The main motivation for this research is to mitigate the land subsidence caused by peat degradation and improving the groundwater management in the peatlands, while minimizing damage to agricultural production. This amounts to reducing the temporal variability of groundwater depth over a parcel (Figure 1). Therefore the effects and improvements of a newly designed drainage system will be investigated. The goal of this research is to compare the effects of PGM with the current water management practice. This research will evaluate several effects of the newly designed drainage system on the peatland area. Using a groundwater model (PMWIN) the effects of various design parameters of the drainage system (such as distance and depth of drains) will be researched by their effects on land subsidence (by the Phoenix model) and crop yield (by HELP 200x tables).

1.4. Research questions

Due to the increasing costs caused by peat degradation and land subsidence, the water management sectors are searching for a better drainage system. On the short and medium term, pressuredrain groundwater management could be a solution. Since there is not jet a suitable alternative for mitigation of peat degradation, implementation of such a system is an interesting project. The main question for this research at a specific location is as follows:

“What is the effect of pressuredrain-based groundwater management on groundwater levels and land subsidence in agricultural peatland in polder Spengen?”

For answering the main research question several sub-questions will be analyzed:

1. What is the relation between the water level in the pressurized well and the rate of change in groundwater table (in different soil types)?
2. Have differences in the pressurized drainage methods (distance and depth of drains) an influence on the groundwater levels?
3. What is the effect of pressuredrain groundwater management on land subsidence for different climate scenarios?
4. Is pressuredrain groundwater management beneficial for farmers?

2. Theory

The following paragraphs provide a closer look at comparable drainage systems, Submerged Drainage (SD) and Pressuredrain Groundwater Management (PGM) (see also the figures in Appendix B).

2.1. Submerged Drainage

In general, submerged drainage (SD) is a drainage system that keeps water in the drainage pipes to regulate the groundwater level (see Figure 4), this system was essential for creating PGM. Contrary to submerged drainage, conventional drainage systems are located above the water level in the ditch, therefore water will drain in times with water surplus (in winter). With SD the agricultural fields become less wet and the bearing capacity increases, especially in early spring and late fall (Van Wijk, 1988). Compared to conventional drainage the submerged drainage system has the advantage that it also can infiltrate water during dry periods. By using this drainage system the groundwater levels over a parcel will become more constant over a year. As is shown in Figure 3, without submerged drainage the groundwater level varies over a larger depth in the soil. In addition, submerged drainage gives the dairy farmers the possibility to work on their land earlier in spring and longer in fall and it is a suitable method to mitigate the effects of peat oxidation due to the higher groundwater levels in the summer (Hoving et al., 2008; Joosten, 2015).

The drains are preferably located at a depth between 30 and 60 centimeter below surface level and 20-30 centimeter below the water level in the ditch (Hoving et al. 2008; Heijkers, 2013; STOWA deltafacts, 2016). This relatively shallow depth of the drains is used for prevention of negative effects on the water quality (e.g. less nutrient losses). Furthermore, the distance between the pipes (preferably between 4, 6 or 8 meter), the depth and the length of the drains are site specific. Due to these technical properties of the drainage system it is possible to provide higher groundwater levels over the whole agricultural area during dry periods, which reduces peat oxidation (Hoving et al., 2008).

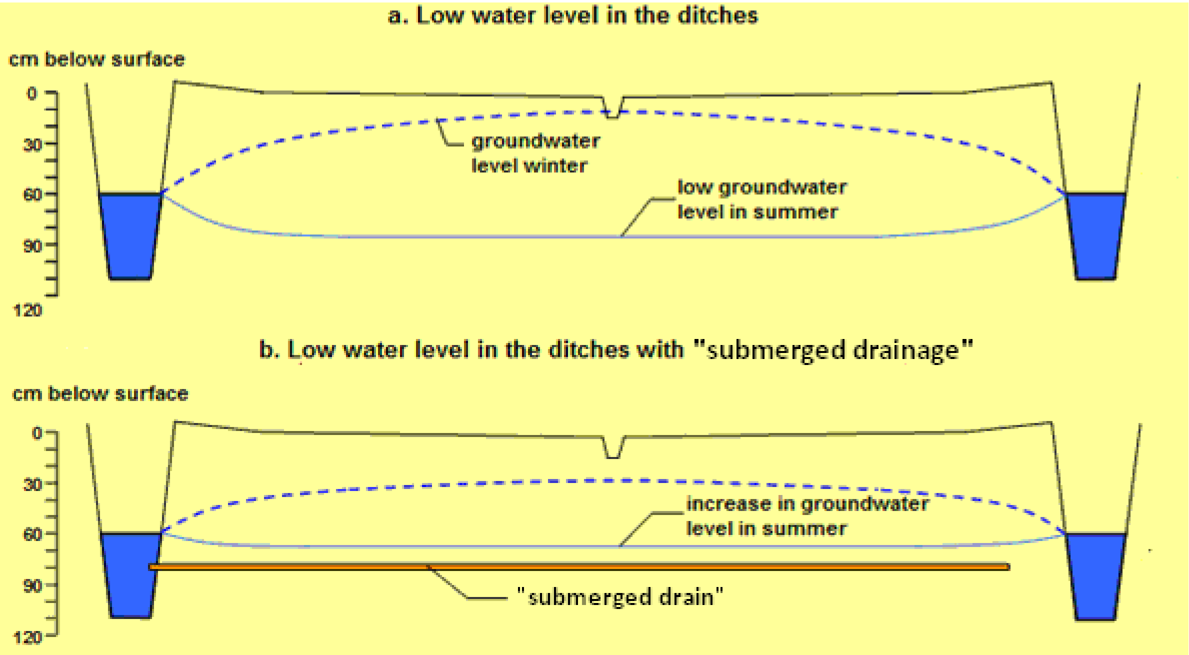

Figure 4. The largest effect of submerged drainage on the groundwater levels in the Dutch peatland areas is observed in the summer. A parcel is enclosed by ditches (adapted from VIC, 2015).

2.2. Pressuredrain Groundwater Management

In general, pressuredrain groundwater management (PGM) is a system to regulate the groundwater levels in relation to land use and expected weather conditions. Therefore this method of water management could vary for different areas. Furthermore, PGM probably enlarges the benefits for submerged drainage (improving agriculture) and rather reduces its detrimental effects such as land subsidence (STOWA, 2016).

PGM is an innovative method for the water management as applied in the Dutch peatland areas (see Figure 5). With the aid of submerged drainage systems (section 2.1), the groundwater level could easily be managed for a certain parcel. The PGM system exists of drainage pipes which are connected to a well or reservoir, whereby the well creates pressure for rising or lowering the groundwater level faster than conventional drainage systems. In fact this ‘well’ is a pressure reservoir, which generates the pressure in the drains. These technical aspects in combination with soil type and efficiency of the drainage system are linked to the effects on peat degradation, land subsidence and agricultural costs. Various technical proportions of the well and drainage system could be used to achieve a more favourable system. For instance, the shape and length of the drainage system could vary. Several patterns could be used for PGM systems, which depends on soil type, parcel size and land use. For example, a fan type pattern (all pipes directly connected to the reservoir) or a collective drain system (where one collection drain is connected to the reservoir or well) could be used. The most suitable pattern or length of the drainage system is site specific (Hoving et al., 2008).

The water level in the well regulates groundwater level, whereby the groundwater level could vary within strict boundary conditions in the well. According to STOWA (deltafact, 2015) the preferred drainage depth for PGM is between 45 and 75 cm below land surface.

Due to several disadvantages of using a whole ditch (like what is done at SD) for creating pressure in the drain, PGM will use wells. For instance, such a pressurized well could create more pressure in the drains than a whole ditch, therefore the groundwater level rises faster. Also, embanking of ditches impedes the water passage through the whole polder system. PGM will mainly be used in smaller areas compared to the conventional drainage systems to enhance the influence of a pressurized well (Joosten, 2015; Hoving et al., 2008).

PGM is a method that aims to create an optimal drainage system catering to varying requirements in time and space. Moreover this management system increases the sustainability (less peat oxidation) and creates benefits for all stakeholders as well (see chapter 2.3.). With specific and direct groundwater management in the parcels a wide variety of goals could be achieved. The key is to ensure that all stakeholders agree with the measures that are taken to avoid peat oxidation are part of a water management system that serves all stakeholders. To achieve this, PGM gives farmers the responsibility over the groundwater level. Applying PGM will require larger water demand in these areas. Strict regulation for the farmers, i.e. ‘governance (in cooperation with water authorities and provinces), are necessary to develop a suitable water management system for all functions in the peaty areas, including reduction of peat oxidation (Joosten, 2015).

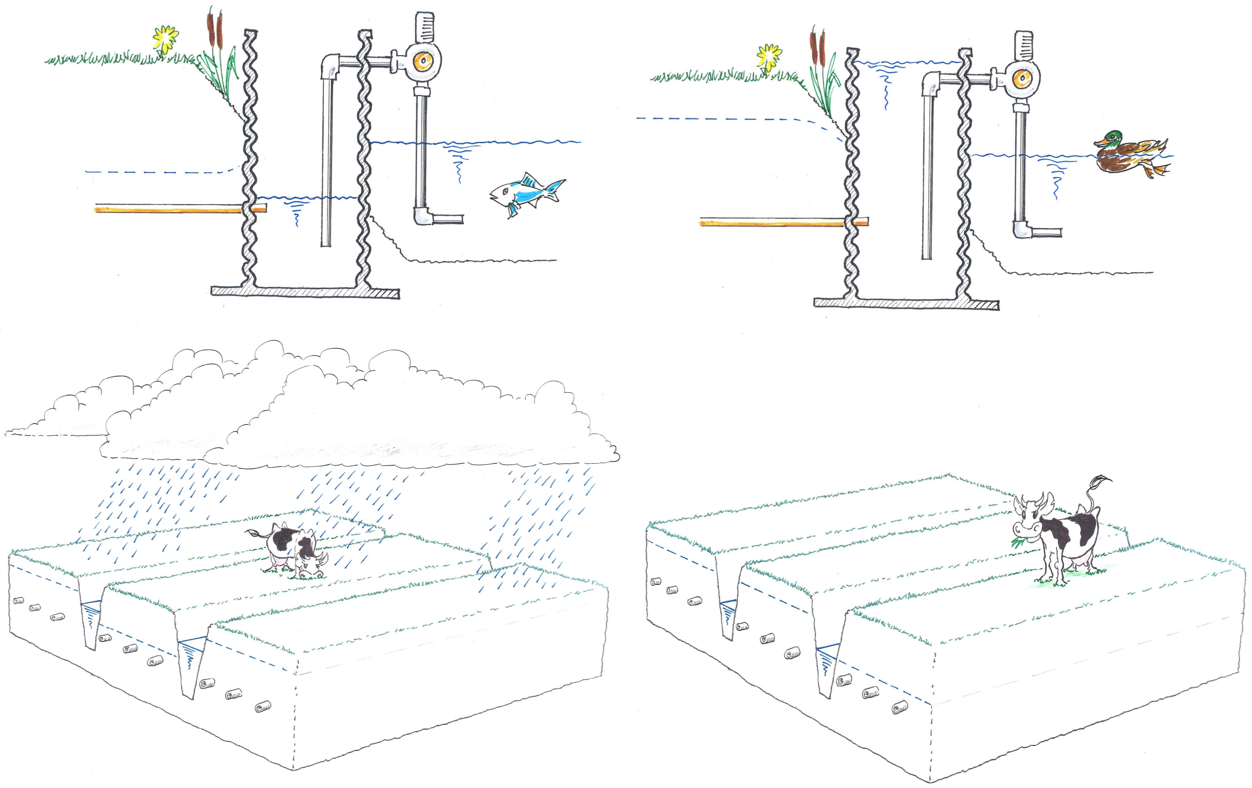

Figure 5. *The principle of PGM. By using a pump (see figures above) the water level in the well is regulated, the water level influences the groundwater levels of a agricultural field (see figures below) in anticipation to weather conditions and land use (figures by Anten, 2016).*

2.3. General effects and financial aspects of pressuredrain groundwater management

Whether it is a good idea to apply PGM depends on several factors. Firstly, the future development of PGM depends on the costs and benefits for the agricultural sector. Secondly, the (positive and negative) effects of this system related to the functions of the soil are essential for introducing it in the peatlands.

The cost and benefits for the agricultural sector will be a crucial factor for implementing this management system. Therefore the most ideal situation is when farmers are willing to invest in this system. In this case the potential benefits for the agricultural sector are clear. Below several benefits for PGM are described (Joosten, 2015):

- An increase in bearing capacity results in an improved functionality of the soil.
- Improved rooting of grasses (both winter and summer) results in an increase of the quality of grasses.
- In course of time the costs of land subsidence will increase, reduction of land subsidence results in less maintenance costs for the drainage systems.
- The protein content in grass will increase due to the reduction of peat oxidation and nitrogen mineralisation. This will result in an improved quality of cattle feed (leads to increasing revenues) as well as less nitrogen emissions and losses (Holshof & Van Houwelingen, 2008).
- Less damage by drought and an increase of nutrient usage out of the soil probably result in a larger harvest of grass.
- CO2 and N2O emissions reduce due to the mitigation of peat oxidation.
- Due to PGM the groundwater level is managed per parcel, therefore the groundwater table in the neighbouring areas (for example nature) is less affected.

Conversely, costs for a PGM system consists of the purchase of different components for this system (inter alia: pumps, the well and drains) and the maintenance of the system itself (Joosten, 2015). When the benefits of PGM at least cover the costs (break even) it would be interesting for the agricultural sector to participate. On average, the costs (including investment and construction) of a SD system are approximately 1600 euro per hectare. Over a period of 25 years the costs are 165 euro per year (including maintenance costs). These costs are twice as high as the conventional drainage systems. These costs may vary due to the differences in parcel size, number of pumps and wells. The costs for a PGM system are around 2600 euro per hectare, including construction. Over a period of 25 years the maintenance costs are comparable to SD. These costs are estimated without taking into account the costs for damages of the system (Joosten, 2015; Smorenburg et al., 2016).

As aforementioned, albeit a lot of positive effects for all stakeholders can be the result of PGM, there are uncertainties about several aspects. These uncertainties could cause negative effects to the environment and could negatively influence the decisions of farmers (Jansen, 2015). Below some negative effects of this system are described (Heijkers, 2013):

- Rapid fluctuations in groundwater levels are not preferable. The roots of vegetation can not adapt quickly to a new situation, which results in degradation of the grass quality (Stuyt et al., 2012).
- Differences in land subsidence and water drainage between agricultural fields, because PGM will probably not be applied to all parcels.
- Fragmentation of water systems due to dams and sluices causes e.g. a reduction in fish migrations.
- Shorter breeding season for birds due to the earlier cultivations.
- Managing of groundwater will influence the ecology by reduction of zoning.
- Increase in water demand during dry periods by 10 to 15 percent
- Low water capacity of the Dutch polders. During dry periods there is probably not enough freshwater available for all parcels.
- Changing water levels in the ditch through PGM could cause problems for other farmers, who aren't using PGM.

Several of these negative effects could be managed and mitigated by varying the construction of the drainage system (e.g. distance between the drains) as well as varying the operating rules. In general, the negative effects, including costs, of PGM are expected to be less than the positive effects.

2.4. Hypothesis

Pressuredrain systems will improve groundwater management in agricultural peatland and will reduce land subsidence. They will result in higher average groundwater levels during summer and lower groundwater levels in early spring and late fall. Decrease in land subsidence will be significant, approximately 50%.

3. Methodology

In this section the research methodology will be explained. The proposed materials, methods and the extent of the research are relevant to obtain valuable data for answering the main research question. In order to obtain answers on the sub-questions the effect of PGM on the groundwater levels, land subsidence and loss of crop yield in Spengen can be determined. This research is carried out in several steps, whereby each step corresponds with a sub-question. In short, 1) and 2) PMWIN models the groundwater levels, to determine the effects of PGM on soil type and drainage alternatives (chapter 3.1.1.). 3) The Phoenix model calculates the rates of land subsidence for each drainage method with respect to the situation without PGM (chapter 3.5.). And 4) the HELP 200x table determines the loss of crop yield, which could become lower than the current situation (no drains) due to PGM (chapter 3.6.). All these sub-questions will give an answer, which gives information to determine the most suitable drainage system per location.

The set-up of this research consists of a literature part, followed by a modelling and analysis part, discussion, conclusions and recommendations. The literature study obtains information from calculations, measurements, experiences and several reported tests and modelling of pressuredrain groundwater management. Additionally, (parameter) data for soil types is obtained from literature, interviews, core data and calibration.

3.1. Modelling methods

Modelling the fluctuation in groundwater level is the most important part of this research. The modelling part is carried out with the numerical groundwater flow model PMWIN Modflow (Chiang et al., 1998) to create a fluctuating groundwater model. A land subsidence model called Phoenix calculates the subsidence rates (Van Hardeveld, 2014) and the HELP 200 x table calculates the percentage of optimal crop yield (Brouwer & Huinink, 1987). Once the modelling part is accomplished, an analysis of the modelling results in combination with literature and practical information from interviews is carried out. The analysis mainly focuses on the differences and associated effects groundwater levels between the situation with and without PGM in Spengen. Therefore modelling gives insight into the influences of PGM on the groundwater fluctuations, land subsidence and loss of crop yield in polder Spengen.

3.1.1. PMWIN Modflow 5.3.3.

PMWIN Modflow is a suitable (environmental) groundwater modelling program to create a conceptual model for a groundwater system (see Figure 6). This program is using the basic laws of physics for groundwater flow, for instance Darcy’s law (Chiang et al., 1998). Considering physical boundaries of the groundwater system, several groundwater models for different parcels in Spengen will be created. The considered physical boundaries are inter alia: recharge, groundwater interaction with ditches and pumping. To determine the effects of technical differences in the drainage system, the physical boundaries (hydrological parameters) will be varied during the research (Weerts, 1996). The groundwater flow model shows the behaviour of the groundwater system over time.

Based on soil type, the polder is divided into six areas with a different soil type (chapter 3.2). One groundwater model is built for each type of soil (in total 6 groundwater models are used for modelling including a calibration groundwater model). A model includes only one parcel, which is representative for that area. Each grid cell in the groundwater model has a resolution of 1 x 1 m, this small grid resolution is chosen because of the expected small-scale spatial variation in groundwater levels due to drainage tubes. A model is representing a parcel from the polder and has a resolution of approximately 50 x 100 m in reality (see Figure 1). Due to computational restrictions of PMWIN it is impossible to build a groundwater level for the entire polder. In this research we are mainly interested in the phreatic groundwater level. In polder Spengen a parcel is practically hydrologically isolated because of the complete surrounding by ditches (surface water), the ditches are the outer boundaries of the model. Therefore it is suitable to make a groundwater model of only one parcel.

A groundwater model will be created to analyse the effects of PGM on the groundwater levels for specific parcels representative of a specific soil type. A conventional drainage (without a pressurized well) system is easily created with PMWIN using the drain package. However, water can only be drained using this package, while PGM also infiltrates. Therefore the river package is used. Through this method the groundwater system has a water in- and output by 'drains' (Chiang et al., 1998). For using the river package, the ditch and drain conductance is required. The calculation of the conductance values is explained in chapter 3.1.2..

The specific parameter values for peat which will be used for the conceptual PMWIN model are obtained by literature review and calibration, which will be explained further in the following sections. Some parameters vary within a large range, therefore average and conventional values are taken in combination with a sensitivity analysis. Through a sensitivity analysis the minimum and maximum values will be compared, to determine the effect of this parameter on the groundwater levels.

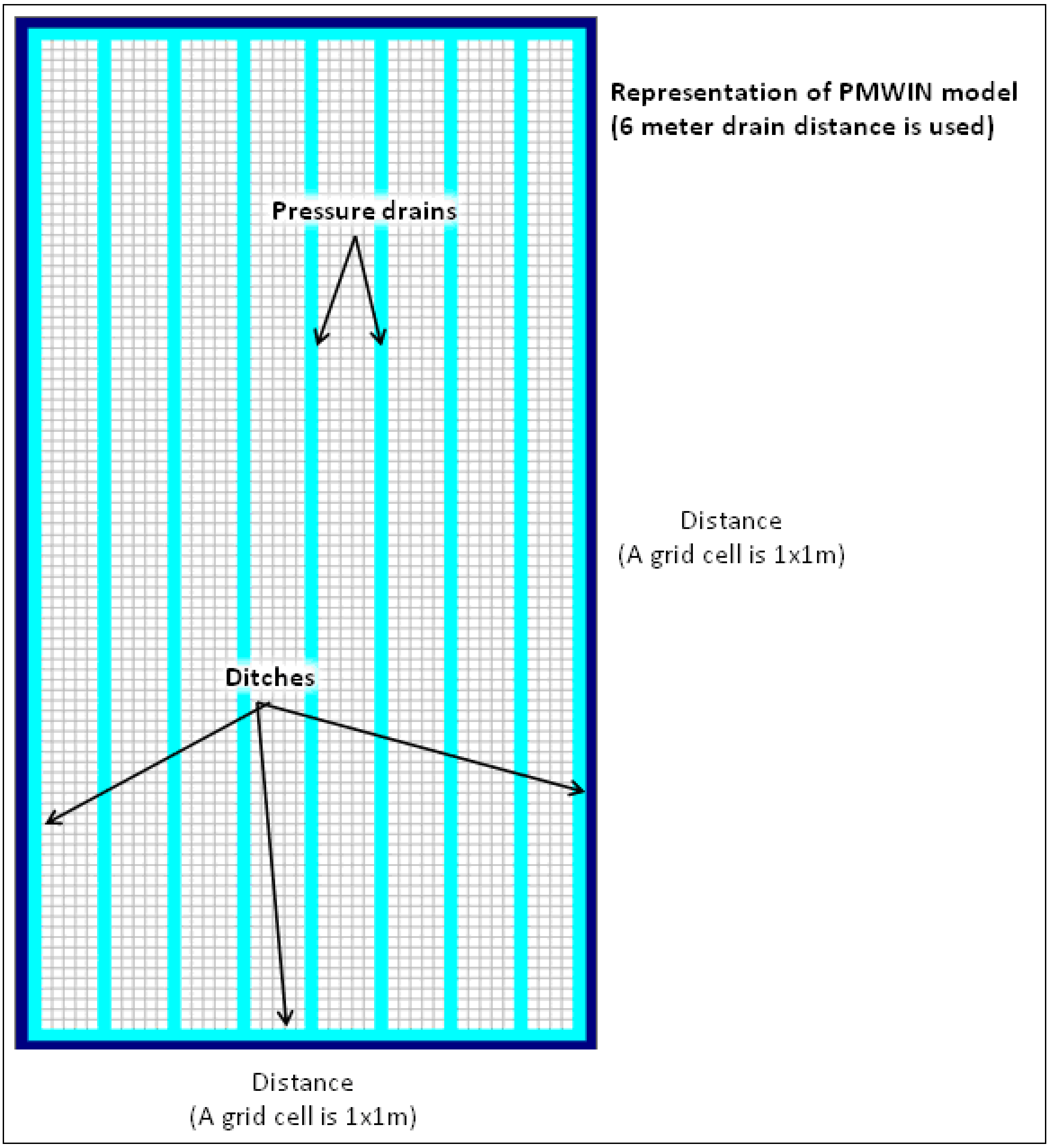

Figure 6. *A representation of the top view of the conceptual model (PMWIN).*

3.1.2. Ditch and drain conductance

Conductance is the reciprocal of resistance, the unit is m^2/day. There are two different conductance values needed for the river package in the models. Firstly, the conductance in the ditch is determined from information of Wilco Klutman (Arcadis Nederland B.V., 2016). A common used resistance in a ditch is 5 days (muddy bottom layer of 5 cm thick and a permeability of 10 cm/day). For the groundwater model the gridsize is 1 m x 1 m, therefore the area 1 m^2. The area divided by the resistance of the mud layer will be 0.20 m^2/day. The wetted perimeter of the real waterway is approximately 2 m (width bottom plus talus) times the length of a gridcel is 2 m^2. Finally the wet perimeter will be divided by the gridsize (2/1=2) and is multiplied by the conductance 0.20 m^2/day, which results in a conductance of 0.40 m^2/day in the ditches.

Secondly, the conductance in the drain is determined by the same method as is described above. For a drain the resistance is 1 day and the wetted perimeter is equal to the circumference, π times diameter of the drains, 6 cm (Jansen, 2015). Therefore the conductance in the drains will be 0.19 m^2/day, which is lower than the conductance in the ditch mainly caused by the wetted perimeter.

3.1.3. Simulating groundwater levels with PMWIN modflow

During this research six different conceptual parcels in polder Spengen will be modelled. The difference between the parcels is merely based on the soil profile, by which the porosity and permeability play a major role. The soils consist of peat, clay and sand layers. Differences in soil structure, will influence the hydrological parameters which will for a large part result in differences in groundwater levels. The (hydrological) parameters used in PMWIN are: time, initial hydraulic head, horizontal and vertical hydraulic conductivity, specific storage, effective porosity and the specific yield. Furthermore, the transmissivity and vertical leakance are calculated by PMWIN itself. With PMWIN it is possible to show results for two different simulation flow types: steady state and transient. A steady state flow is constant over time throughout the whole domain, this means that the direction and magnitude of the flow (hydraulic head) are constant and the amount of water doesn't change. During a transient flow the magnitude and direction of the flow changes with time (Chiang et al., 1998). Therefore the hydraulic head changes during the time are calculated. The hydrological parameters related to (specific) storage and specific yield are only necessary for transient flow situations. In this research a transient flow situation is used, to create a suitable simulation with realistic weather conditions. To simulate the groundwater fluctuations a historical period of two years is used for the specific weather conditions (evaporation and rainfall). For this period a transient flow type is used where each day is simulated, so in total a time period of 730 days. Historical weather data measured at the Bilt (KNMI, 2016), located near polder Spengen, from both years 2014 and 2015 are put into the PMWIN models.

For winter and summer months a different water level in the ditch is used (Hemel et al., 2007). The water level in the ditches (displayed as boundary rivers in PMWIN models) is 50 centimeter below LS in the winter period (a 50 cm depth relative to the monitoring well B31E2623). In the summer period the water level in the ditches is 43 centimeter below LS. In PMWIN these seasonal conditions are set by the following time periods 1 until 91 is winter (01-01-2014 until 01-04-2014), 91-274 summer (01-04-2014 until 01-10-2014), 274-457 winter (01-10-2014 until 01-04-2015), 457-639 summer (01-04-2015 until 01-10-2015) and 639-730 winter (01-10-2015 until 31-12-2015) (Hemel et al., 2007).

For argillaceous and sandy soils the hydrological parameters are relatively easily available from the literature. Conversely, the parameters for peat are much more difficult to determine and could vary a lot in the research area. Peat soils consist of a wide variety of organic matter, therefore the transportation of water through the pores is difficult to determine. Furthermore, peat, argillaceous and sandy soils could vary in structures and layering, which are classified in different formations (Berendsen et al., 2004). For this reason the conceptual model is calibrated, to determine realistic values for hydrological parameters specific for polder Spengen. See Table 1 for different parameter values obtained from literature research (before calibration). The initial hydraulic head is obtained from the monitoring well in polder Spengen and the hydrological parameters are related to several formations and a soil mixtures present in the polder.

Soil formations	Initial Hydraulic Head (cm -LS)	Horizontal Hydraulic Conductivity	Vertical Hydraulic Conductivity	Specific Storage*	Effective Porosity	Specific Yield**
Echteld Formation	-1.93	0.017	0.009	0.01	0.15	0.15
Nieuwkoop Formation (Hollandveen)	-1.93	0.18	0.18	0.001	0.44	0.44
Nieuwkoop Formation (Basisveen)	-1.93	0.025	0.019	0.001	0.22	0.22
Naaldwijk Formation	-1.93	0.005	0.005	0.01	0.02	0.02
Kreftenheye Formation (confined layer)	-2.98	17.6	16	0.0001	0.32	0.26

Table 1. *Hydrological parameters from literature research before the calibration (DINOloket, 2016; Gunnink et al., 2009).*
** Specific Storage is equal to the effective porosity in an unconfined aquifer*
*** Specific Yield should be equal or lower than Effective Porosity*

In the research, variations in drain depth and distance will be simulated and are called PGM alternatives. During this research the drain distance will vary from 3, 6 and 12 meter between the drains. The drainage depth will vary from 0.45 and 0.75 meter below land surface, these are suitable values to test the range of limited drainage depths set by VIC (2016) and STOWA, deltafacts (2016). The hydraulic head in the drain is 0.10 meter higher than the depth of the drain (because the drain diameter is approximately 0.10 meter). Therefore, the hydraulic head is 0.35 and 0.65 meter below land surface, both are located 0.15 meter away from the target value of 0.50 meter below LS (Bot, 2011). According to the groundwater HELP tables the most suitable groundwater depth for grasslands in peat areas (both summer and winter) is 0.50 meter below land surface. This groundwater level is in particular based on the effects on crop yield (Bot, 2011). According to the ideal groundwater depth of 0.50 meter, the difference (standard deviation) between the modelled and ideal data will be calculated and evaluated, as a criteria for determine the best PGM alternative (see chapter 3.4.).

Eventually, the results will be showed in graphs and groundwater elevations. Due to the function Boreholes and Observations in PMWIN and a matlab HeadsTool, MCR 2012a (Calje, 2016), it is possible to create graphs from the groundwater fluctuation over time and transport the data to Excel. By using Excel graphical results the calculated groundwater levels can be compared and used for calculating the GHG and GLG (see chapter 3.1.4.). Two observation boreholes are put into the model, both are located in the middle of a parcel. One above a drain and another between the drains (in the middle), the coordinates in the grid are: X=20, Y=50 and X=26, Y=50, for 12 m drain distance, X=23, Y=50 and X=26, Y=50, for 6 m drain distance and X=25, Y=50 and X=26, Y=50 for 3 m drain distance. These are the most important locations for evaluating the effects of PGM on a the groundwater levels in a parcel.

3.1.4. Calculating GHG and GLG

For calculating the GHG and GLG in the Netherlands it is customary to measure the groundwater levels over a minimum of 8 hydrological years. A hydrological year starts at April 1th until March 31th the next year. From these calculations an average value of the highest and lowest 3 values at the 14th and 28th of each month are used to determine the GHG and GLG (Van der Gaast et al., 2010). In other words, the GHG is an average of the maximum groundwater level and the GLG is an average of the minimum groundwater level over a period of 8 years. For this research the groundwater levels for hydrological year 2014 are used to determine the GHG and GLG, whereas this method deviates from the customized method of calculating the GHG and GLG. But, the time period of running the PMWIN model is limited, so just one hydrological year can be used for calculating the GHG and GLG.

Moreover, for each different PGM alternative the groundwater levels are calculated in the middle of a parcel, were the largest effect of a drainage systems occurs. As mentioned before, two observation wells are located in a model. The effect of PGM is the most important between the drains, there a concave (summer) and convex (winter) groundwater table occurs and causes larger fluctuations groundwater levels. Therefore, the GHG and GLG are calculated for the location between the drains in the middle of a parcel. To determine the effect of PGM the GHG and GLG values for a PGM system will be compared with the current situation (no drains).

In addition, the combination of GHG and GLG are divided in different categories. These categories are based on the difference between GHG and GLG and are called the groundwater dynamics (GT), which will be used for calculating the loss of crop yield (see chapter 3.6. and Figure 9).

3.2. Soil profiles

As mentioned before, there are six models (see appendix for the coordinates) created by PMWIN to simulate the groundwater levels, which are influenced by PGM. Each model represents a different soil type present in polder Spengen. Below the models are described in more detail (including structures in Figure 7 and 8), data is obtained from DINOloket (2016), Stouthamer et al. (2008), GeoTOP (2016), the surface elevation by AHN3 (2015):

- Calibration model: the surface elevation of this model is 1.72 meter below NAP (see abbreviations and terminology), the soil profile consists of a thin clay layer with a thickness of 0.85 meter (Echteld Formation) on top of a peat deposition (Nieuwkoop Formation, Hollandveen). This peat layer is observed until a depth of 6 meter and followed by compacted peat layer of 0.70 meter (Basisveen). At a depth of 6.32 meter the confined sand layer (Kreftenheye Formation) is located.
- Model 1: this model is located in the South Eastern part of the polder. A two layered model is created. The surface elevation is 1.60 meter below NAP, where the first layer reaches a depth of 6.5 m, containing peat from the NIHO Formation. Below this layer of peat a sandy confining layer from the Kreftenheye Formation is present.
- Model 2: the surface elevation of this model is 1.75 meter below NAP. The first 1 meter soil contains clay from the Echteld Formation (alternating with peaty layers). Between 1 and 4 meter peat is observed from the Nieuwkoop Formation, followed by approximately 1.5 meter thick clay layer (Naaldwijk Formation, Laagpakket van Wormer). Below this clay layer a 1 meter thick compacted peat layer from the Nieuwkoop Formation is observed (NIBA). At a depth of 8.25 below surface the confining layer is present.
- Model 3: the surface elevation is 1.60 meter below NAP, where the first 4 meter of the soil profile contains peat (NIHO). The peat layer is alternating with clay layers. Below the peat layer a 0.5 meter thick layer of clay is present (NAWO), followed by a 1.5 meter thick layer of peat (NIBA). At a depth of 7.60 meter the confining layer is present (BX/KR).
- Model 4: is located at a surface elevation of 1.70 meter below NAP, the first 5 meter contains clay (EC). This parcel is situated near a former stream channel (in the floodplains). Below the clay a 1 meter thick peat layer from the Nieuwkoop Formation is present. The first 0.5 meter is Hollandveen Laagpakket and the other 0.5 meter is originated from Basisveen Laagpakket. This thin peat layer is located on top of the confining sand layer.
- Model 5: this model is based on a former stream channel. The surface elevation of this parcel is 1.50 below NAP. Firstly, a 3.5 meter thick peaty layer from the NIHO formation is observed. Secondly, at a depth of -5 meter below NAP a 2.5 meter thick clay/sand layer from the NAWO formation is present. Thirdly a 0.5 meter thick compacted peat layer is the boundary between the NAWO Formation and the confined sand layer (BX/KR).

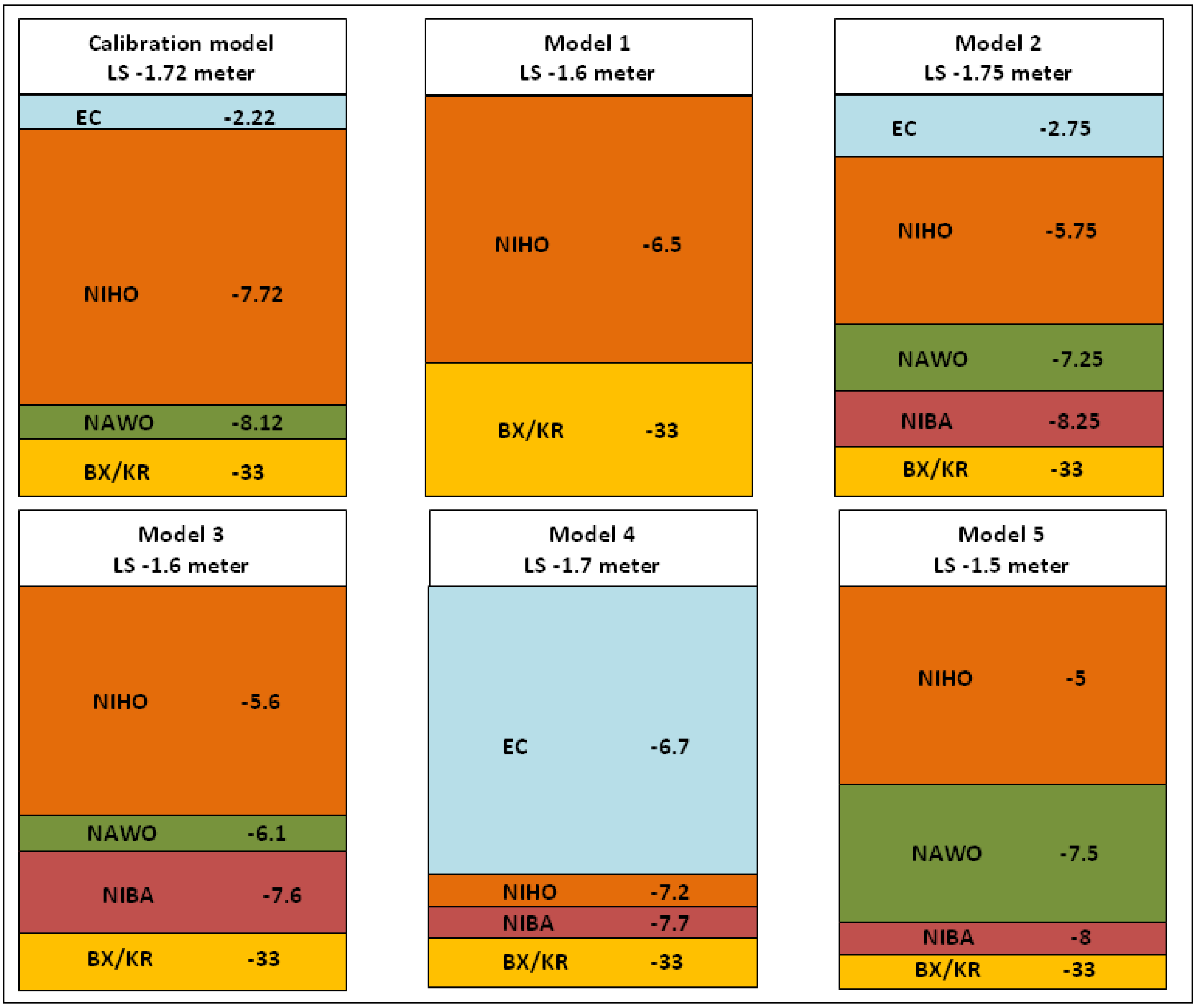

Figure 7. *This figure shows the soil profiles for each conceptual model, which are used in the groundwater model. The depth of the layer (in meter) is displayed next to the formation code. The proportions of the layer thickness are equal to the used thicknesses in the groundwater model. The definitions of the codes of the formations are as follows: NIHO is a peat layer from the Formation of Nieuwkoop, Hollandveen Laagpakket. The EC is a clay layer from the Formation of Echteld. NAWO is more permeable clay layer from the Formation of Naaldwijk, Wormer Laagpakket. The NIBA is a compacted peat layer from the formation of Nieuwkoop, Basisveen Laagpakket. Finally, the sandy BX/KR layer is from the Boxtel/Kreftenheye Formation.*

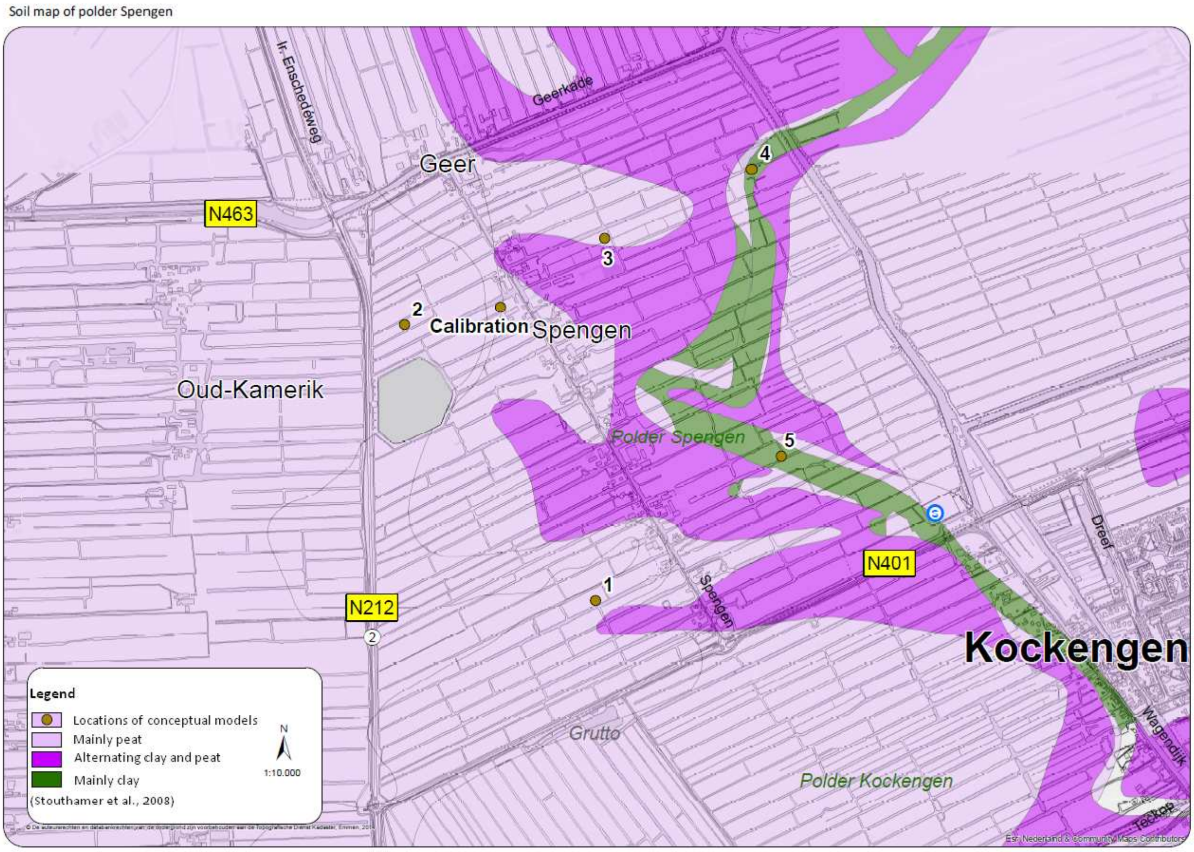

Figure 8. The locations of the models in the polder. The map show also soil profiles from Stouthamer et al. (2016). The core data is obtained from DINOloket (2016).

3.3. Calibration and validation of groundwater model

The first step of modelling PGM in polder Spengen is calibrating the obtained groundwater data from a monitoring well, see Figure 3 (DINOloket, 2016). The purpose of such a calibration model is to determine realistic hydraulic parameter values by correlating these parameters with literature and discussion with other researchers. Comparing data from the monitoring well (B31E2623, see the location of this calibration model in Figure 8, which is near the location of model 2) with the model for that specific parcel (modelled by PMWIN) provides more accurate information about the hydraulic parameters. Through the comparison between modelled and monitoring data it becomes clear whether or not the hydraulic parameters for the conceptual model should be adjusted.

The model uses daily recharge and evaporation data from KNMI in the Bilt (2016). Due to the incomplete groundwater data of the monitoring well, almost a two year period (1-1-2014 until 17-11-2015) is modelled by PMWIN. The first layer is 70 cm in depth, therefore the groundwater level will become lower than the depth of the first layer in this PMWIM model, which causes an error. In order to avoid such an error the label of the first layer is changed to “confined” (Klutman, 2016), in this case the value for the specific yield is used for the storage coefficient. Therefore PMWIN identifies the first layer with water (zero head). Furthermore, the groundwater level in the monitoring well is flattened on top of the graph. This is probably caused by surface drainage (shallow trenches) to drain excess water. Therefore the model includes also a drainage system at 10 cm depth.

The validation of this model will be provided by comparing the modelled GHG and GLG, with the groundwater tables (GT, “grondwatertrappen” in Dutch) measured by the monitoring well (Bot, 2011; Van der Gaast et al., 2010). So, the simulated map of the GHG and GLG values (for the modelling time of two years) at this (calibration) location will be compared with the GT map with that of well B31E2623.

3.4. Deviation from target value

A criterion to determine whether PGM is suitable for using at a specific parcel, is calculating the deviation from a target value (standard deviation). As mentioned before, an average freeboard of 50 cm during a year is selected as a target value (Hooghart, 1986). Because a freeboard of 50 cm is very suitable for agricultural grassland (Bot, 2011).

For calculating the deviation value between the graphs and a 50 cm target value a quadratic formula is used. This equation gives a certain value for the standard deviation to obtain information about the groundwater graphs relative to the target value. The groundwater graphs resulted from an observation well between the drains is used for calculating the standard deviations, because this is the most important location for examining the effect of a drainage system. The standard deviation is expressed in the same unit as the target value, so the results are in meters. Based on the quadratic formula a graph with a low standard deviation varies little from the target value.

See below the equation for calculating the standard deviation. A standard deviation is calculated from the datasets of the groundwater levels which are obtained by PMWIN. In this case the average variable is 0,5 m minus land surface (Wiskunde.net, 2016).

$$S_N = \frac{\sqrt{\sum_{i=1}^{N}(Z_i - 0.5)^2}}{N}$$

For calculating the standard deviation several steps have been taken:

1. Calculate the difference between the variables: $Z_i - 0.5$, where the number of variables is 730.
2. Take the square of the results calculated in step 1.
3. Calculate the average of the results from step 2 (so dividing the by N).
4. Summation of the quadratic results: called the variance.
5. Square root of the variance gives the standard deviation of a dataset.

Determining the most suitable drainage system is to compare the standard deviation for each PGM alternative with the current situation.

3.5. Effect on land subsidence (Phoenix model)

Due to the increase in damage, costs and safety risk in both rural and urban areas caused by land subsidence, HDSR together with the province of Utrecht have designed a land subsidence model named Phoenix (Van Hardeveld, 2014). To reduce the negative effects of land subsidence it is useful to have a model which could estimate the land subsidence rates. The Phoenix model is an instrument to calculated the land subsidence for various future scenarios (under future KNMI climate scenario for 2050 (IPCC, 2013) Gl, Gh, Wl and Wh) as a result of the differences in subsoil and water management (in this research the drainage properties). For the climate scenarios the G means a moderate temperature increase and W is large temperature increase. In addition, the small character stands for the airstream, which could be low or high (IPCC, 2013), see abbreviation and terminology for more detailed information of these scenarios. Admittedly, climate change will change rainfall and evaporations as well, which were not taken into account in the Phoenix model. So the Phoenix model will calculate the minimum subsidence rates for different climate scenarios without the change in rainfall an evaporation.

The Phoenix model is based on several mathematical relations between the soil profile, groundwater and the land subsidence. The following formula is used to calculate the rate of land subsidence (Van der Schans & Houhuessen, 2011):

$$dV / dt = a \times GLG + b \times K + c$$

Where dV/dt is the rate of subsidence calculated in mm/year, a is certain rate depending on the temperature increase caused by climate change, calculated by the Phoenix model (Table 2), this will influence the microbial activities in the soil, which alternates the oxidation in the soil. GLG calculated by PMWIN. Only the GLG is used in the formula, because the land subsidence is especially caused by lowering of the GLG. b is a constant factor for the thickness of the upper clay layer (0.01263), K is the thickness of the upper clay layer (see chapter 3.2.) and c is a constant factor for the soil type (0.00668) (Van der Schans & Houhuessen, 2011).

Moreover, absolute values of land subsidence calculated by this research could deviate from literature due to several reasons, like location differences and modelling methods. Consequently, it is more appropriate to use the fraction of land subsidence, to determine the effect of PGM on the land subsidence. This means that the difference between the current land subsidence with the PGM alternatives is calculated and displayed in percentages.

Climate scenario 2050	Temperature increase (in C)	a-factor
Gl	1	-0.0247
Gh	1.4	-0.02527
Wl	1.7	-0.02543
Wh	2.3	-0.02615

Table 2. *Several climate scenarios related to an a-factor (IPCC, 2013).*

3.6. Effect on crop yield (HELP 200x table)

To create recommendations for managing PGM, the loss of crop yield is essential to take into account, whether PGM is beneficial for farmers. The effects of PGM on the groundwater levels will influence the crop yield. With the use of HELP 200x tables (dependent on the GHG and GLG) it is possible to determine the loss of crop yield for wet and dry periods. This loss of crop yield for a PGM system will be compared with the current situation (no drains) to determine the effect of PGM.

Help 200x tables

Interventions of the water systems in agricultural areas will alter the crop yield. Consequently, changing groundwater levels influences the growth of vegetation and the bearing capacity of an agricultural field, which determines the loss of crop yield. Therefore so-called HELP tables have been created to represent the relation between groundwater dynamics (GT) and long term agricultural damage (caused by wet or dry conditions). In this research the loss of crop yield caused by the hydrological effects of PGM will be calculated for the grasslands (Van Bakel et al., 2005).

The HELP 200X table application gives the loss of crop yield caused by too wet and too dry conditions (also called crop damage). This loss is defined as the difference between the potential physical crop yield minus the actual physical crop yield. In addition, the difference can be multiplied by the actual value of the crop yield and deduct the value with the additional costs related to the crop yield, like storage and auction fees.

By selecting the soil type (in codes), crop type and GHG and GLG values, the application is able to estimate the loss of crop yield in percentages per hectare agricultural land (Brouwer & Huinink, 1987). In order to deal with the yearly GHG and GLG values, instead of the usual 8-year observation period, the weather conditions of that specific hydrological year is observed. To determine whether it was a wet or dry year, so the GHG and GLG can slightly be adjusted to fit in the used GT tables (Figure 9), wherefore the crop damages can be calculated. For the hydrological year 2014 (14-04-2014 until 31-03-2015) the overall precipitation was lower than normal, but where the research area is located (polder Spengen) the precipitation was larger than usual. Therefore the groundwater levels could be higher than calculated. By knowing this, the values for GHG and GLG could be increased for a minimal amount to fit in a specific GT range (KNMI, 2016; provincie Utrecht 2016; Brouwer & Huinink, 1987; Stouthamer et al., 2008).

The different soil units which are present in Spengen are meadow peat ('weideveengrond' in Dutch), 'koopveengrond' and drechtvaaggrond both in Dutch. The corresponding codes are: pVb, hVb and Rv01c. Furthermore, by discussing with the farmers it became clear that the type of vegetation is grass without reseeding costs, every now and then bald spots will be reseeded (but this can be neglected).

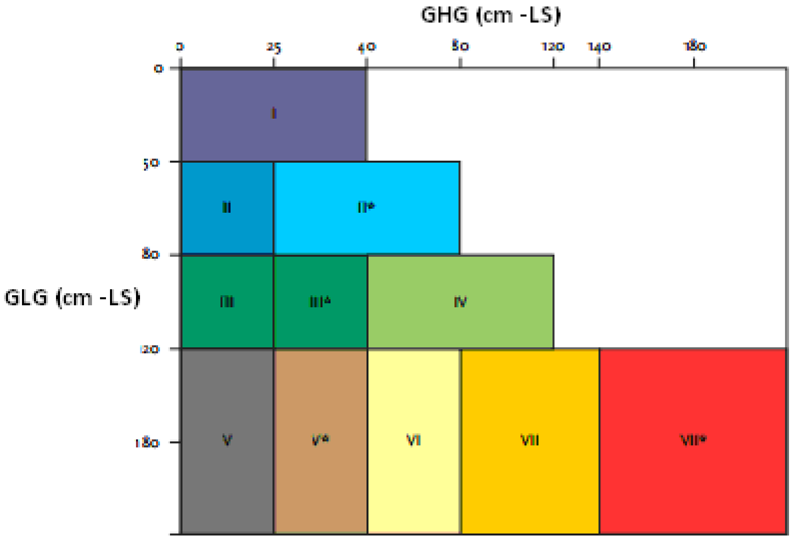

Figure 9. *GT map which shows the variations in groundwater level relative to land surface (Van der Gaast et al., 2006).*

According to the HELP 200x tables the results are being displayed in percentages. These percentages can be converted into costs, which are different for each dairy farm (see example below for the relation between costs and percentage of the loss of crop yield). In other words, the loss of crop yield is expressed in a percentage of the maximum achievable yield. For each type of vegetation this percentage of damage is different, by multiplying the yield in euro's per hectare the total loss in euro's is calculated (Van Bakel et al., 2007). In the agricultural sector the preference is a general approximation of the crop damage (percentages), because the crop yield for diary farms is in many cases dissimilar.

Example: Suppose, a farmer has 40 hectare of grassland. The total percentage of crop damages for a certain drainage method is increased by 17 percent relative to the former situation (no drains). Also, the crop yield is reduced by 2000 euro. This means that the total crop yield is reduced by 50 euro per hectare (2000/40). As a result the additional costs for this farmer are 3 euro (17/50=3) per 1 percent crop damage per hectare. Although the costs are different per farmer due to the amount of agricultural land and total crop yield. But, in this case the crop damage gives an suitable indication of the shift in crop damage after changing the drainage system (Van Bakel et al., 2007).

4. Results

In this section the results for simulating with PGM systems in polder Spengen will be evaluated according to the sub-questions (mentioned in chapter 1.4). In total, there are six different simulations for PGM systems performed by PMWIN modflow distributed over the polder. To determine which drain distance and hydraulic head are most suitable for a specific situation the standard deviations are calculated exactly in the middle between the drains (related to a 50 cm boundary value instead an average groundwater level). Figures of PMWIN are shown in appendix B and all graphs are located in appendix C. Furthermore, the obtained groundwater data is used to determine the land subsidence with the Phoenix model (Hardeveld et al., 2014) and for creating an overview of crop damages by the HELP-2005 tables of Alterra (Van Bakel et al., 2005). The goal of this chapter is to compare the differences between the situation in a parcel without pressure drains (current situation) and with pressure drains by different alternatives proposed.

4.1. Effects groundwater level

Initially this chapter will show the results of calibration and validation. It becomes clear which hydraulic parameters are used for this research. Moreover, by analyzing groundwater hydrographs and standard deviations the effects of PGM will be evaluated.

Furthermore, in the beginning of this research a question from the water authority was: is it possible to determine the height of the water level inside the pressure well to create a specific hydraulic head inside the parcel? Without restrictions of the groundwater flow the height of the water column inside the well would create the same height of the hydraulic head inside the parcel. However, due to resistance of the drains and a large variation of hydraulic parameters (porosity and permeability) in peaty soils it is very difficult to calculate actual values for the associated water level inside the pressure well. Therefore, the associated water level in the pressure well should be determined from recent field experiments with PGM as is done at VIC.

4.1.1. Calibration and groundwater modelling

As can be observed in the figure below (Figure 10), the groundwater level calculated with the calibrated groundwater model within PMWIN deviates a little from the measured data from well B31E2623 (DINOloket, 2016). Generally, the results after calibration are good. The calibrated PMWIN model shows somewhat larger groundwater fluctuations. These observed differences could be caused by e.g. missing or underestimating rainfall events by using the rainfall data from de Bilt instead of local meteorological data or differences in soil structures.

In Table 3 the calibrated parameter values are displayed. These parameters vary with respect to the parameters derived by literature (see Table 1). In general, the parameter values are increased after calibration, especially the combination of marine clay and sand (from the Naaldwijk Formation) has a slightly larger permeability than peat layers. Moreover, compacted peat form the Nieuwkoop Formation ("Basisveenlaag") has the lowest hydraulic conductivity.

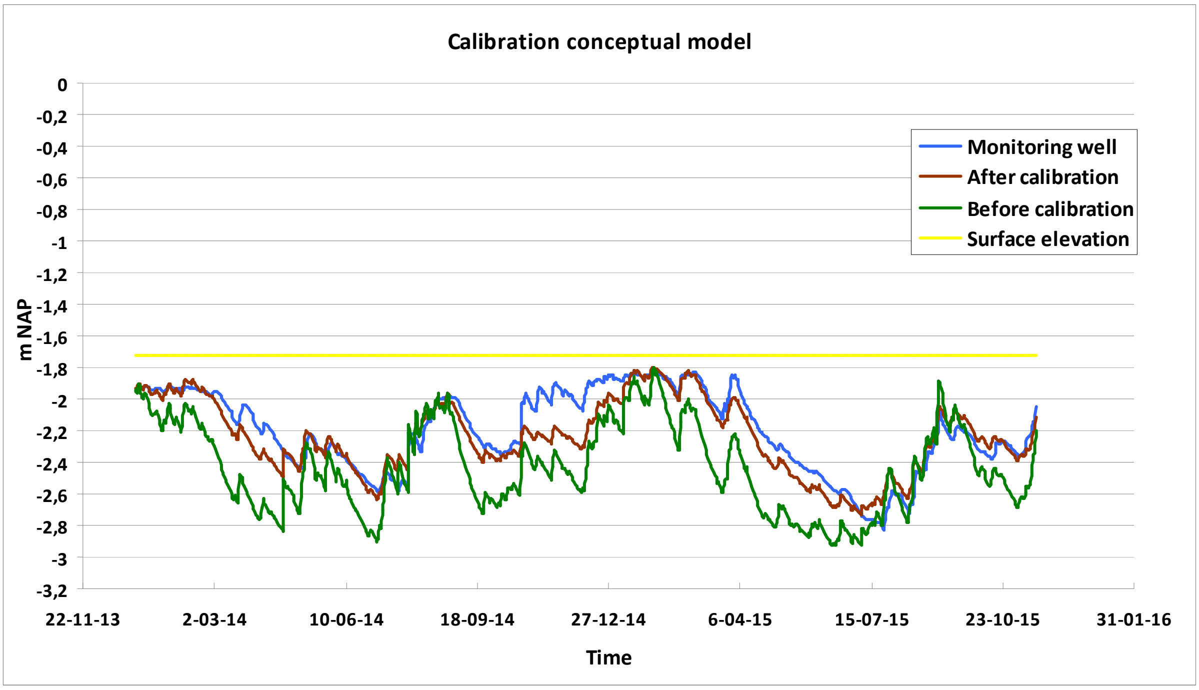

Figure 10. *Groundwater levels for the monitoring well (B31E2623), before and after calibration of the model created by PMWIN together with the surface elevation at the monitoring well in polder Spengen.*

Soil formations	Initial Hydraulic Head (cm -LS)	Horizontal Hydraulic Conductivity	Vertical Hydraulic Conductivity	Specific Storage*	Effective Porosity	Specific Yield**
Echteld Formation	-1.93	0.02	0.015	0.01	0.15	0.15
Nieuwkoop Formation (Hollandveen)	-1.93	0.021	0.021	0.001	0.25	0.25
Nieuwkoop Formation (Basisveen)	-1.93	0.0055	0.0055	0.001	0.1	0.1
Naaldwijk Formation	-1.93	0.03	0.025	0.01	0.26	0.26
Kreftenheye Formation (confined)	-2.98	17.6	16	0.0001	0.32	0.26

Table 3. *Hydrological parameters after the calibration, these parameters are used in the conceptual models by PMWIN modflow (DINOloket, 2016; TNO, 2009).*

** Specific Storage is equal to the effective porosity in an unconfined aquifer*

*** Specific Yield should be equal or lower than Effective Porosity and used for all layers the phreatic groundwater level is traversing through (so also when the upper layer is confined).*

In Table 4 the calculated GHG and GLG values (after calibration) at the calibration location are shown. These values are comparable with GT II as can be observed in Figure 7, which is of frequent occurrence in the Dutch peatland areas (Provincie Utrecht, 2016).

Model	GW	No drains (cm -LS)	GT
Calibration (LS: 172 cm -NAP)	GHG	12	II
	GLG	74	

Table 4. *GHG and GLG values after calibration, no drains in this situation.*

Table 5 shows the results of GHG and GLG for the current situation. GLG is the most important value in relation to peat oxidation. Notice the high groundwater level for the models 2 and 4, which particularly consist of clay. In clay soils the difference in GHG and GLG (called groundwater dynamic) is large caused by a high GHG value, which could ascend above land surface. This high groundwater table occurs mainly during wet periods (winter), when the recharge is restricted by the low permeability of clay. This causes a large groundwater dynamic in clay soils. For peat soils (especially model 1 and 5) the calculated GHG and GLG for the current situation are low compared to clay soils.

Model	GW	No drains (cm -LS)	GT
Model 1 (LS: 160 cm -NAP)	GHG	88	IV
	GLG	119	
Model 2 (LS: 175 cm -NAP)	GHG	-18	I
	GLG	46	
Model 3 (LS: 160 cm -NAP)	GHG	20	I
	GLG	57	
Model 4 (LS: 170 cm -NAP)	GHG	7	II
	GLG	74	
Model 5 (LS: 150 cm -NAP)	GHG	77	IV
	GLG	109	

Table 5. *Calculated GHG and GLG values (in centimeters below LS) for each location without drains.*

Some remarks about the groundwater graphs displayed in the following sections. The figures, which includes PGM contains two graphs, the blue graph shows the calculated groundwater levels near the drains and the green graph shows the results between the drains, both groundwater levels are measured in the middle of a parcel. The difference between the graphs is to show the effect of convex (winter) or concave (summer) water tables between the drains. Furthermore, in all models the first days of the modelling period the groundwater results are incorrect. Because the initial values are determined by the calibrating data, the influence of this data disappears within a few days. Therefore this data is not included by calculating the GHG and GLG values.

4.1.2. Groundwater model 1

As is mentioned in section 3.2., this simulation model located at area 1 (Figure 8) mainly consists of a thick peat layer on top of the sandy confining layer, this peat layer has a large hydraulic conductivity. In general for location 1, PGM provides an increase in groundwater levels for both drainage depths, see Table 6 (where distance and depth of hydraulic head are displayed in the tables below as e.g. 3 m, 35 cm). In the current situation the difference between GHG and GLG is low and will become smaller for a shorter drain distance. For the optimal PGM system (so drains at 3 m distance and creating a hydraulic head of 35 cm below LS) the GHG can become 40 cm higher and the GLG could be increased by 57 cm compared to the current situation, because the drains (with a higher hydraulic head of 35 cm below LS) are increasing the overall hydraulic head. The GHG and GLG become lower when the drains distance and depth increases. But, the difference between GHG and GLG increases for larger drains distance, because there are fewer drains present in the soil (for 12 m drain distance) for creating a fixed groundwater table. So the effect of PGM reduces as well. The effect of PGM on the GHG is less than on the GLG, especially for a larger drain depth. Because the difference between GHG and drain depth is less than the difference between GLG and the drain depth. Therefore the GHG changes less than the GLG by applying PGM.

Notice that the influence of drain distance becomes more significant when the drains are located at a shallower depth. Furthermore, the effect of PGM on GLG is larger than on GHG. This is a positive result for using PGM in this area, because a higher groundwater level can be realized during dry periods and a little increase of groundwater level occurs in wet periods, which has a minor effect on the bearing capacity in early spring and late fall.

Model	**GW**	**No drains (cm –LS)**		**3 m; -35 cm (cm –LS)**	**6 m; -35 cm (cm –LS)**	**12 m; -35 cm (cm –LS)**		**3 m; -65 cm (cm –LS)**	**6 m; -65 cm (cm –LS)**	**12 m; -65 cm (cm –LS)**
Model 1 (LS: 160 cm -NAP)	GHG	88		48	60	78		73	76	82
	GLG	119		62	88	108		86	97	111

Table 6. *Calculated GHG and GLG values (in centimeters below LS) for different PGM alternatives at location 1.*

As is observed in Figure 11 the groundwater level drops more than 1 meter relative to LS (-1.6 m) in the current situation (Table 6). In the current situation the difference between GHG and GLG is about 31 cm, however by PGM these differences reduce. A hydraulic head (in the drains) of 35 cm below LS provides in this situation a large groundwater level increase with respect to the current situation. A drainage depth of 65 cm (as is showed in Figure 12) provides an increase in groundwater level, but not reaching the preferred 50 cm below LS. So, in this case a hydraulic head of 35 cm will be the most suitable depth to reach a 50 cm groundwater table.

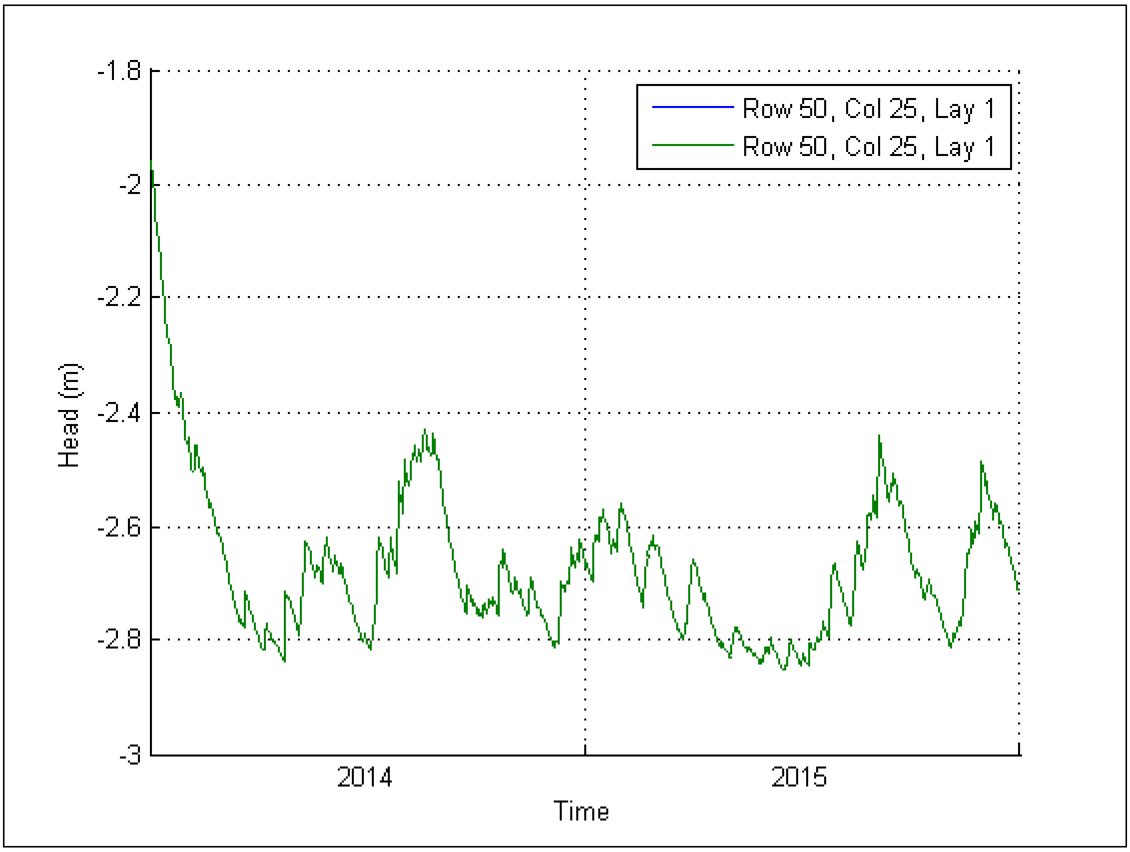

Figure 11. *Modelled groundwater level over the period 2014-2015 for the situation without drains at location 1.*

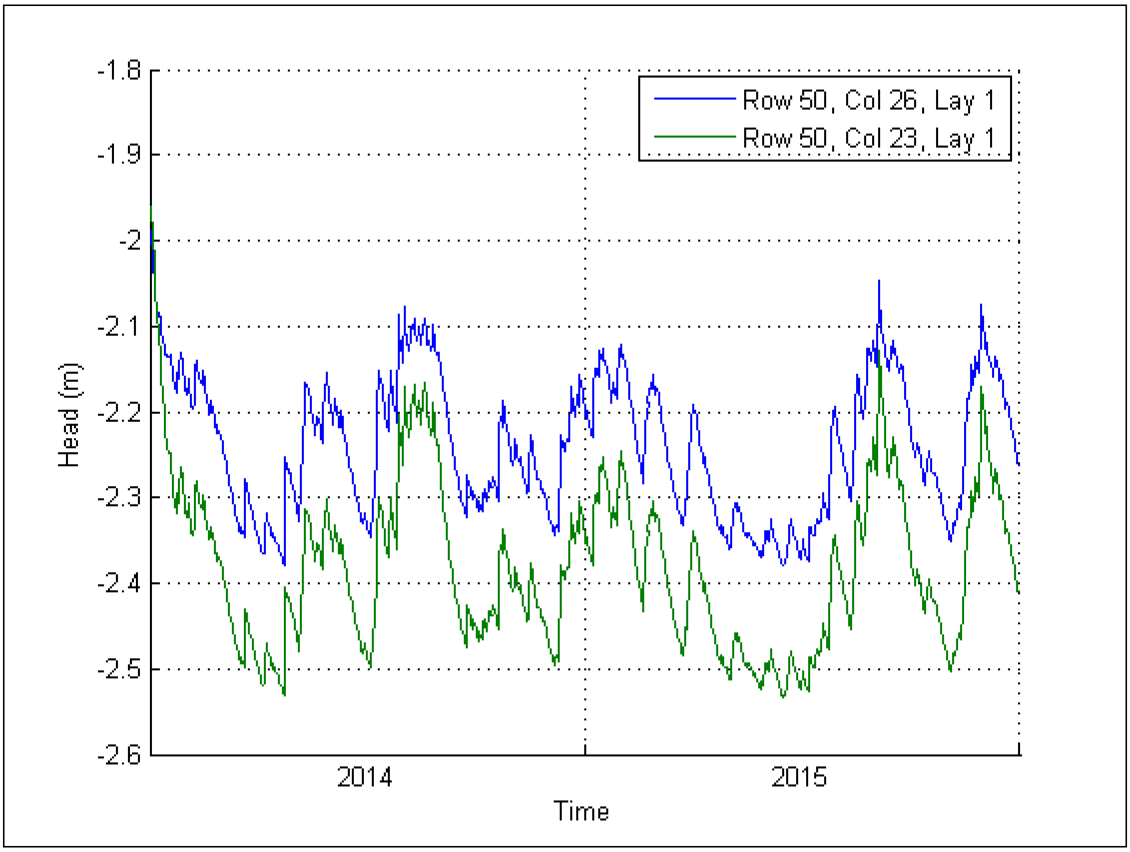

Figure 12. *Modelled groundwater level over the period 2014-2015 for a drain distance of 6 m and a hydraulic head in the drains of 35 cm below LS at location 1.*

Standard deviation

In Table 7 the calculated standard deviations are shown for the different PGM alternatives. Note that, for the situation without a drainage system the standard deviation has the highest value, which corresponds with the expectations. The groundwater levels in the situation without drains differ significantly with target value and the various situations with a certain drainage system. Therefore, PGM is suitable to influence the groundwater levels at this location.

Both drain distance and depth have a large influence on the standard deviation for this soil type. At a drainage depth of 35 cm the changes in drain distance are highly influencing the groundwater levels for this location, because the standard deviation differs a lot from the current situation. Also, the effect of PGM is larger when a shallower drainage depth is set. Conversely, for a deeper drainage system the effect of drain distance becomes less. This is a good reason for applying a shallower drainage depth for PGM.

Model 1	Deviation (m)
No drains	0.586
3m; 0.35 m	0.082
6m; 0.35 m	0.296
12m; 0.35 m	0.487
3m; 0.65 m	0.317
6m; 0.65 m	0.405
12m; 0.65 m	0.515

Table 7. *The calculated standard deviation between the drains (relative to the target value) for the groundwater levels at location 1 for different PGM alternatives.*

4.1.3. Groundwater model 2

The groundwater levels located in area 2 (Figure 8) are mainly influenced by the argillaceous top layer (see section 3.2.). Clay soils have a lower permeability than peat soils, which means the flow of water through clay soils is restricted. This causes a higher groundwater table during rainfall events and increasing groundwater dynamics. According to the results in Table 8, it can be noticed that the groundwater doesn't reach very low levels (relative to LS) and the difference between GHG and GLG increases for larger drains distance. The draining of groundwater decreases for fewer drains (e.g. 12 m drain distance). At this location the effect of PGM on GHG is larger than on the GLG. The effect of PGM on the GHG is larger than on the GLG, because the difference between GHG and drain depth is larger than the difference between GLG and the drain depth. Therefore the GHG changes more than the GLG. The high GHG is also caused by the low permeability of clay. Therefore, in clay soils draining of surplus groundwater will be larger than the infiltration, this is advantageous for the bearing capacity in early spring and late fall.

Model	GW	No drains (cm –LS)		3 m; -35 cm (cm –LS)	6 m; -35 cm (cm –LS)	12 m; -35 cm (cm –LS)		3 m; -65 cm (cm –LS)	6 m; -65 cm (cm –LS)	12 m; -65 cm (cm –LS)
Model 2 (LS: 175 cm -NAP)	GHG	-18		21	2	-11		39	14	-5
	GLG	46		52	52	49		74	65	54

Table 8. *Calculated GHG and GLG values (in centimeters below LS) for different PGM alternatives at location 2.*

In the Figures 13 and 14 below, the calculated groundwater levels for model 2 are showing a high groundwater level (hydraulic head in the drains is 35 cm below LS), this is mainly caused by the soil structure (less permeable clay layer). This clay layer causes a rapid increase in groundwater level during rainfall events. Remarkable for this model is the large difference between groundwater levels between the drains. Drains with a 12 m distance between each other experience extremely large groundwater fluctuations between the drains. In this case, little effects of PGM are observed. Also, a hydraulic head of 65 cm provides too low groundwater levels over this period. Therefore, a drain distance of 3 m and a head of 35 cm below LS are useful to diminish especially the convex shapes (in the winter) of the groundwater table.

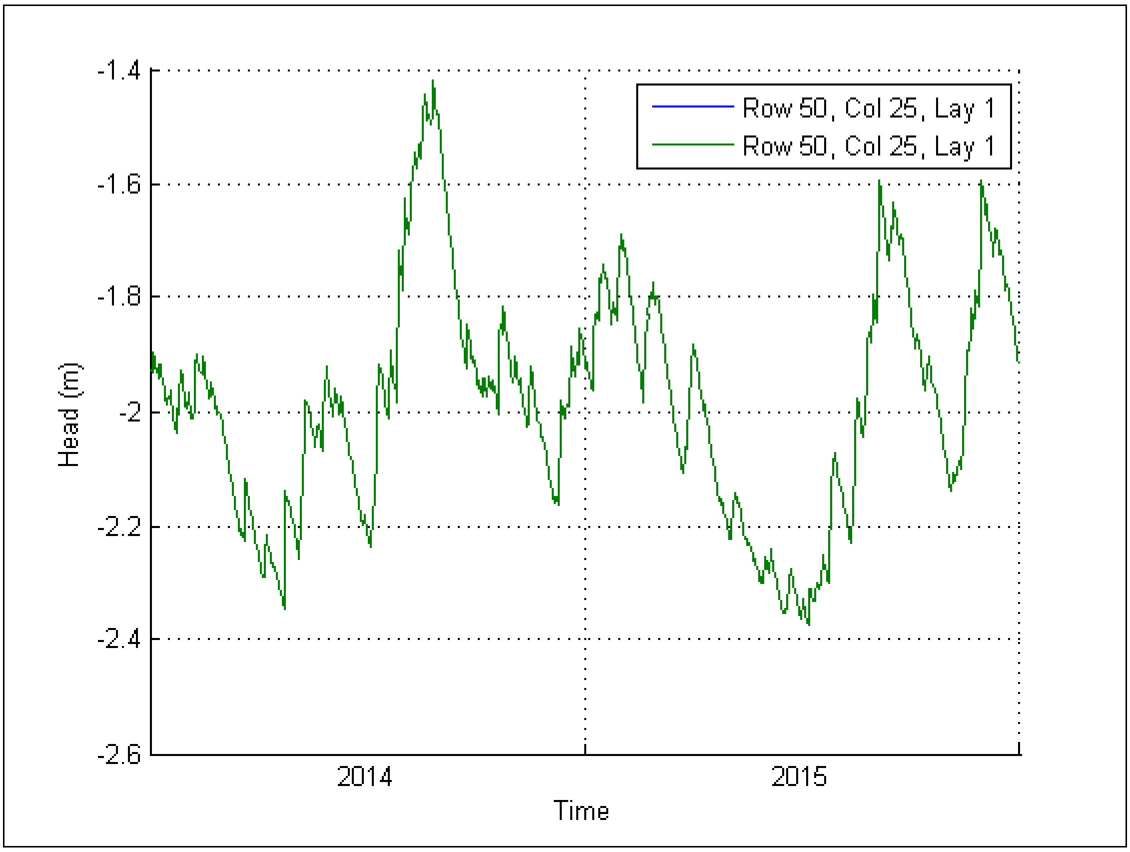

Figure 13. *Modelled groundwater level over the period 2014-2015 for the situation without drains at location 2.*

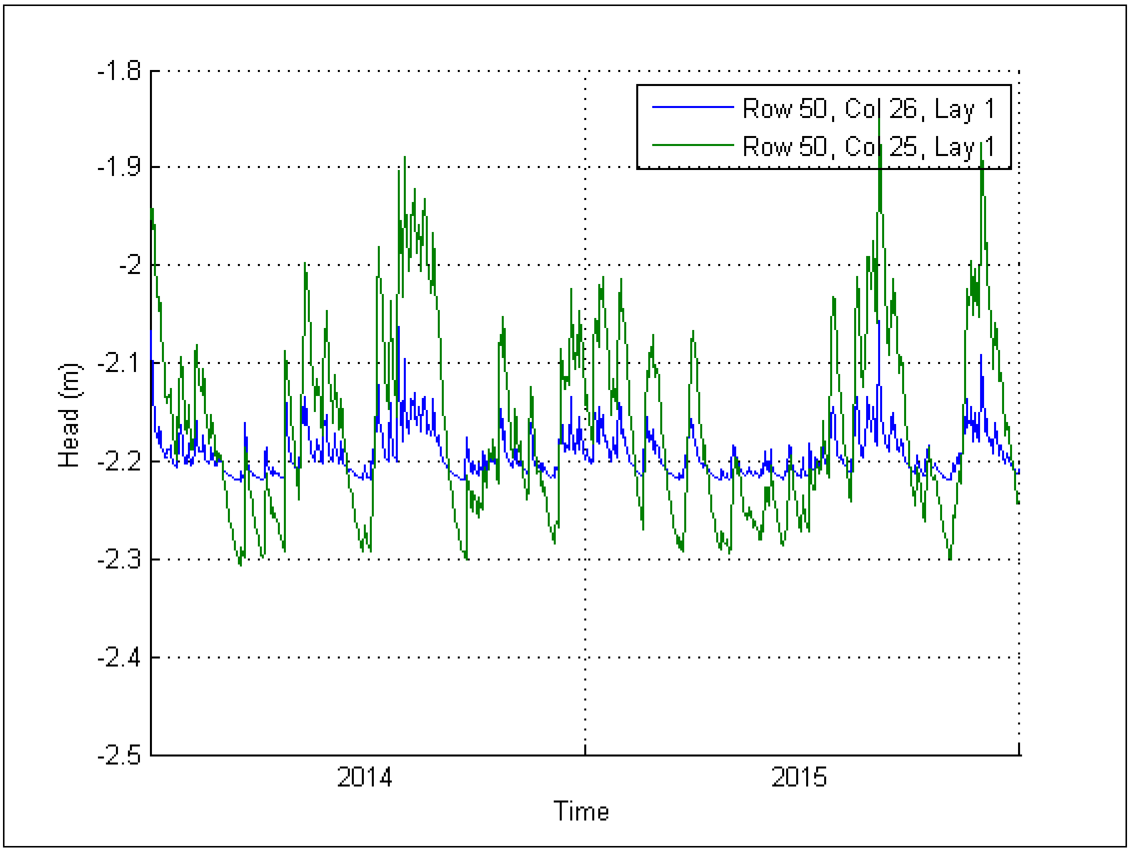

Figure 14. *Modelled groundwater level over the period 2014-2015 for a drain distance of 3 m and a hydraulic head in the drains of 35 cm below LS at location 2.*

Standard deviation

The influence of a clay top layer is noticeable by the standard deviation (Table 9). The values become lower compared to soils containing thicker peat layers, which probably means that these more argillaceous soils are less susceptible for changes in groundwater level (caused by PGM) than the peat soils.

Furthermore, variations in drainage depth don't show many differences in the standard deviations. In this case the drain distance is influencing the groundwater levels more than the depth of draining. However, it is not distinct which drainage depth is more suitable to apply at this location. The difference in standard deviation between the various drainage alternatives is small.

Model 2	**Deviation (m)**
No drains	0.335
3 m; 0.35 m	0.129
6 m; 0.35 m	0.211
12 m; 0.35 m	0.279
3 m; 0.65 m	0.167
6 m; 0.65 m	0.164
12 m; 0.65 m	0.238

Table 9. *The calculated standard deviation between the drains (relative to the target value) for the groundwater levels at location 2 for different PGM alternatives.*

4.1.4. Groundwater model 3

As is showed in section 3.2., there is a lot of peat present in model 3. Nevertheless, a thick compacted peat layer (NIBA) on top of the sandy confining layer influences the permeability (which becomes lower) and results in an increase of the groundwater level. The modelling results (Table 10) show a slightly larger effect of PGM on the GHG, when the drain distance increases. The effect of PGM increases with shorter drain distances. The difference between GHG and GLG becomes larger when the drain distance increases (a larger groundwater dynamic), because fewer drains are present in the soil to create a fixed groundwater table. Besides, what strikes is that the GLG show minor effects of PGM. So the draining effect of groundwater caused by PGM is larger at this location than the infiltration of water to increase the GLG in dry periods.

Model	**GW**	**No drains (cm –LS)**		**3 m; -35 cm (cm –LS)**	**6 m; -35 cm (cm –LS)**	**12 m; -35 cm (cm –LS)**		**3 m; -65 cm (cm –LS)**	**6 m; -65 cm (cm –LS)**	**12 m; -65 cm (cm –LS)**
Model 3 (LS: 160 cm -NAP)	GHG	20		35	27	19		63	51	35
	GLG	57		50	54	56		78	78	73

Table 10. *Calculated GHG and GLG values (in centimeters below LS) for different PGM alternatives at location 3.*

Some results of this groundwater model are displayed in Figures 15, 16 and 17. Large differences between the drains, probably due to the restricted groundwater flow caused by low permeable soil layer (compacted peat). So differences in drain distance do have a significant effect on the groundwater levels in this parcel. Furthermore, the effects related to the different soil profiles are clearly visible. The groundwater is reaching a high level during wet periods and drops not as low as in peaty soils in dry periods.

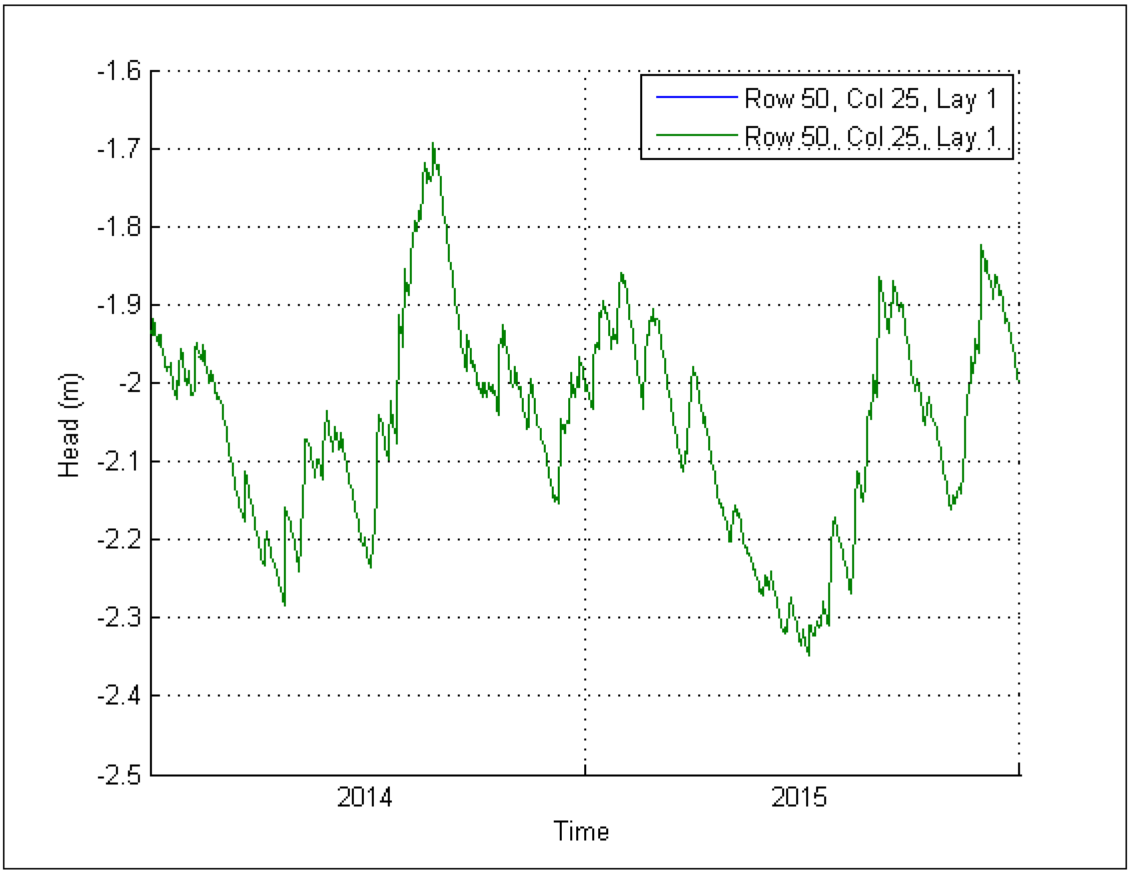

Figure 15. *Modelled groundwater level over the period 2014-2015 for the situation without drains at location 3.*

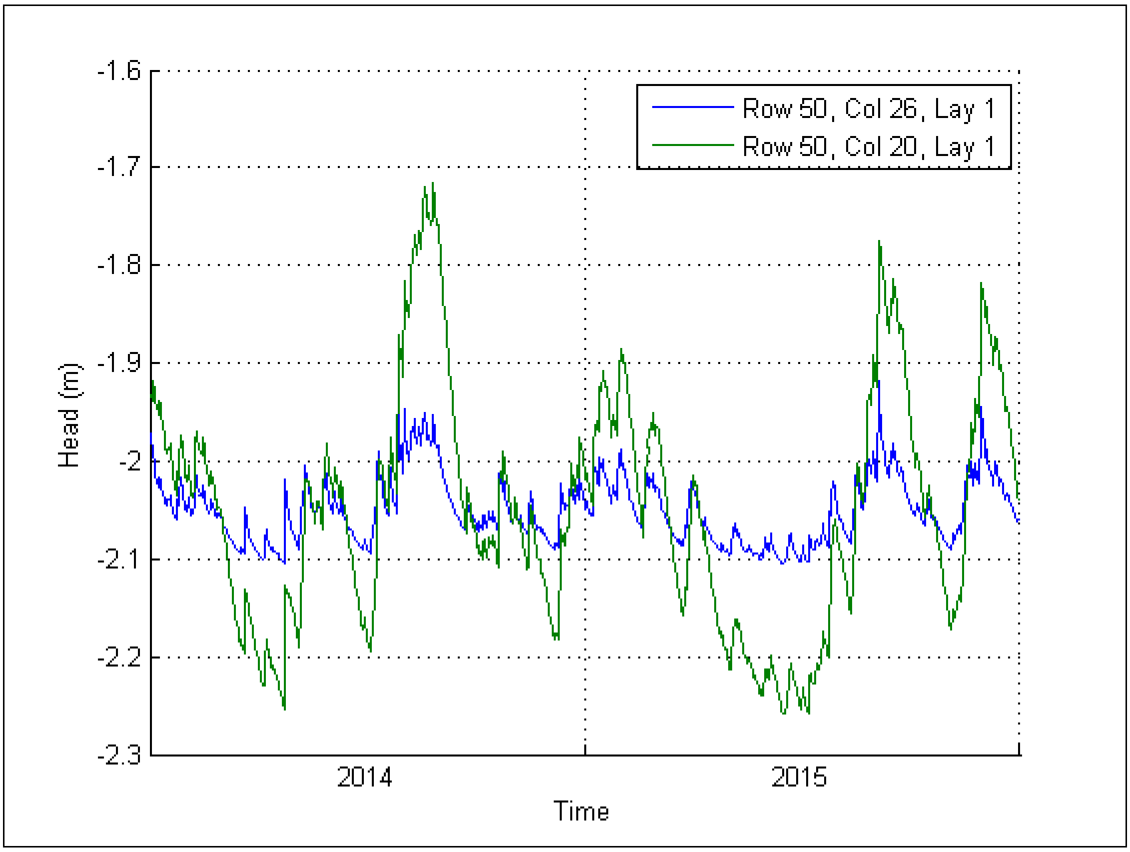

Figure 16 *Modelled groundwater level over the period 2014-2015 for a drain distance of 12 m and a hydraulic head in the drains of 35 cm below LS at location 3.*

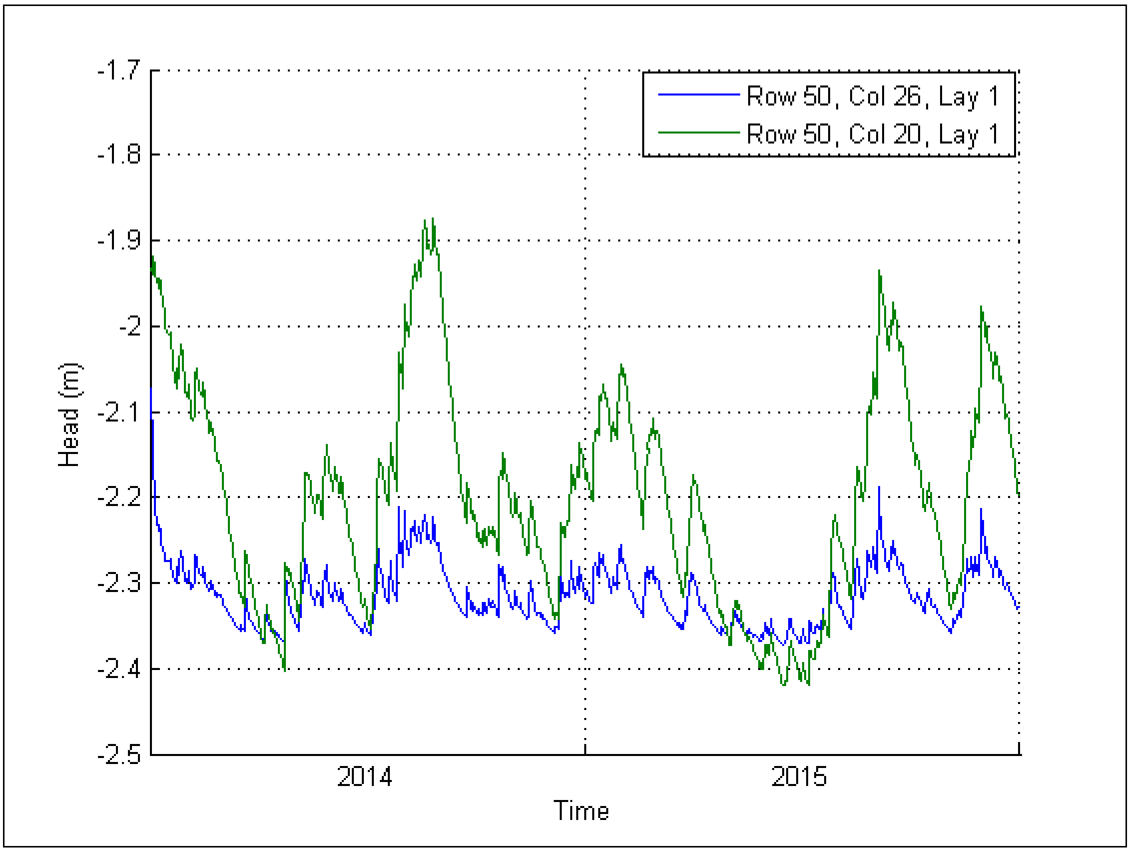

Figure 17. *Modelled groundwater level over the period 2014-2015 for a drain distance of 12 m and a hydraulic head in the drains of 65 cm below LS at location 3.*

Standard deviation

This model is particularly influenced by the compacted peat layer. This compacted layer has a low permeability, which causes little variations in the groundwater levels as is observed at the standard deviations (Table 11).

In a situation where the drains are creating a hydraulic head of 65 cm below LS, the standard deviation reduces when the distance between the drains increases. Furthermore, the effect of drain distance doesn't show any large differences when the drainage depth is changed. A shallower drainage depth shows smaller deviations and would be more appropriate to create a optimal groundwater level.

Model 3	Deviation (m)
No drains	0.144
3 m; 0.35 m	0.067
6 m; 0.35 m	0.096
12 m; 0.35 m	0.130
3 m; 0.65 m	0.231
6 m; 0.65 m	0.204
12 m; 0.65 m	0.160

Table 11. *The calculated standard deviation between the drains (relative to the target value) for the groundwater levels at location 3 for different PGM alternatives.*

4.1.5. Groundwater model 4

This groundwater model located at point 4 (Figure 5) consist (for a large part) of clay. Therefore the permeability is somewhat lower than is observed in the peat layer. This model is comparable with model 2 (chapter 4.1.3.), which is also located in a argillaceous area. For the current situation, the difference between GHG and GLG is large. Probably caused by the restricted groundwater flow in the low permeable clay layer, especially during rainfall events an increasing groundwater table occurs. Moreover, the difference between the GHG and GLG becomes smaller when a shorter drain distance is applied. The GHG is more heavily influenced by PGM than the GLG, due to the larger difference between GHG and hydraulic head in the drains. So the draining of surplus groundwater is larger than infiltration during dry periods.

Model	GW	No drains (cm –LS)		3 m; -35 cm (cm –LS)	6 m; -35 cm (cm –LS)	12 m; -35 cm (cm –LS)		3 m; -65 cm (cm –LS)	6 m; -65 cm (cm –LS)	12 m; -65 cm (cm –LS)
Model 4 (LS: 170 cm -NAP)	GHG	7		32	24	14		58	47	28
	GLG	74		52	62	72		80	85	86

Table 12. *Calculated GHG and GLG values (in centimeters below LS) for different PGM alternatives at location 4.*

According to Figures 18 and 19 it can be clearly observed that the calculated groundwater levels are fluctuating very fast over a short time period, mainly as a result of the lower permeabilities and porosities of clay soils mentioned before. Also, the groundwater level between the drains heavily fluctuates, large convex and concave shapes of the groundwater table.

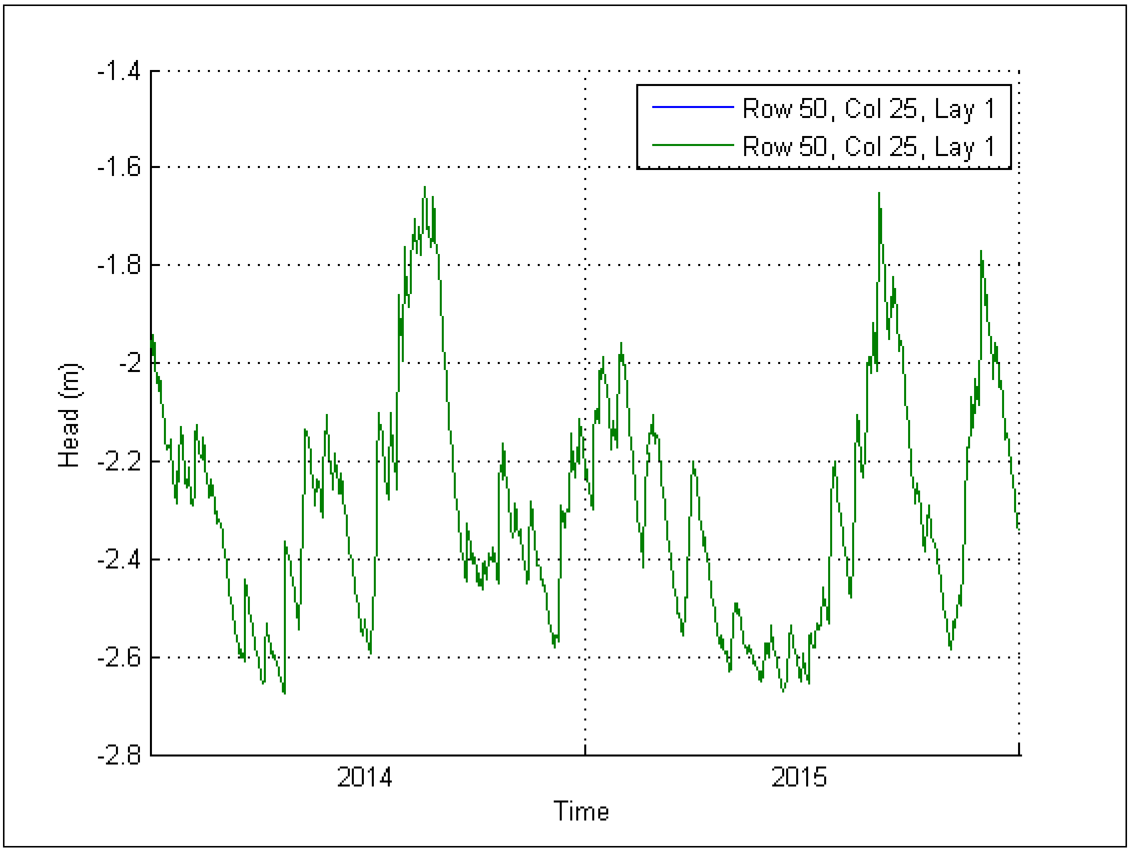

Figure 18. *Modelled groundwater level over the period 2014-2015 for the situation without drains at location 4.*

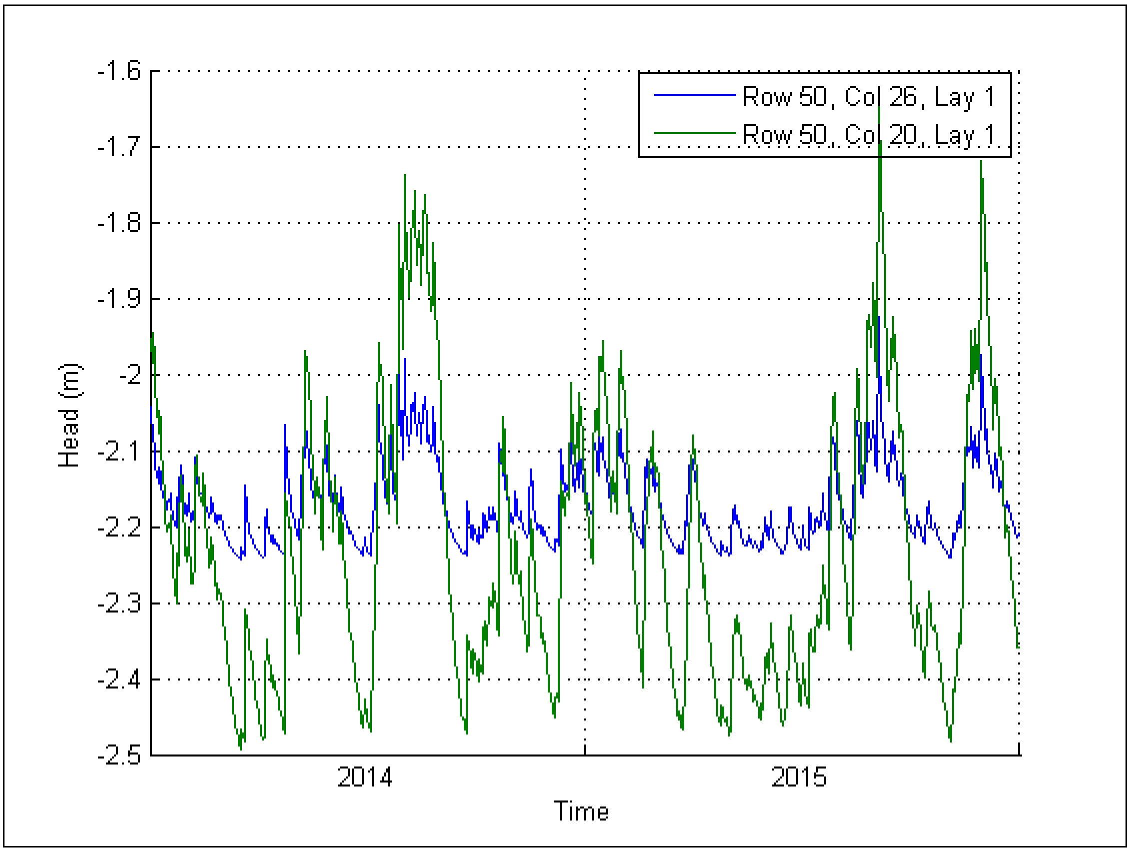

Figure 19. *Modelled groundwater level over the period 2014-2015 for a drain distance of 12m and a hydraulic head in the drains of 35 cm below LS at location 4.*

Standard deviation

The thick clay layer in this model produces less differences in the standard deviation between alternatives, mostly caused by the low permeability, which is comparable to model 2 (see Table 13). Therefore, PGM provides a less convex and concave shaped groundwater table compared to a more permeable soils. Notice that the standard deviation at the drains and between the drains is almost equal, but the standard deviation is larger at a deeper drainage system (a hydraulic head of 65 cm below LS).

Model 4	Deviation (m)
No drains	0.253
3 m; 0.35 m	0.068
6 m; 0.35 m	0.110
12 m; 0.35 m	0.180
3 m; 0.65 m	0.244
6 m; 0.65 m	0.242
12 m; 0.65 m	0.247

Table 13. *The calculated standard deviation between the drains (relative to the target value) for the groundwater levels at location 4 for different PGM alternatives.*

4.1.6. Groundwater model 5

As can be observed in section 3.2., the main part of this groundwater model contains high permeable layers caused by the NIHV and NAWO Formations. Therefore the effects of PGM on the GLG are large, which is observed in the results showed in Table 14. For drains at 3 m distance and 35 cm depth, the GLG could be increased by 51 cm. The difference between GHG and GLG is relatively low in the current situation. This difference becomes smaller for a shorter drain distance. In addition, the influence of drain distance reduces when the depth of the drains becomes larger. As mentioned before, the effect of PGM on the GHG is less than on the GLG, because the difference between GHG and drain depth is less than the difference between GLG and the drain depth. Therefore the GHG changes less than the GLG.

Model	GW	No drains (cm –LS)		3 m; -35 cm (cm –LS)	6 m; -35 cm (cm –LS)	12 m; -35 cm (cm –LS)		3 m; -65 cm (cm –LS)	6 m; -65 cm (cm –LS)	12 m; -65 cm (cm –LS)
Model 5 (LS: 150 cm -NAP)	GHG	77		43	48	62		69	67	70
	GLG	109		58	74	96		84	94	105

Table 14. *Calculated GHG and GLG values (in centimeters below LS) for different PGM alternatives at location 5.*

This model shows comparable results with model 1 (see Figure 20 and 21), as like model 1 the soil has a large hydraulic conductivity. This indicates that the soil type plays a major role in the groundwater levels. Primarily in peaty soils, like this model, it is observed that the groundwater table reaches a much lower level than is observed in clay soils. As can be observed in the figures below, a shallower drainage depth would have a larger effect on creating a fixed groundwater level in peat soils.

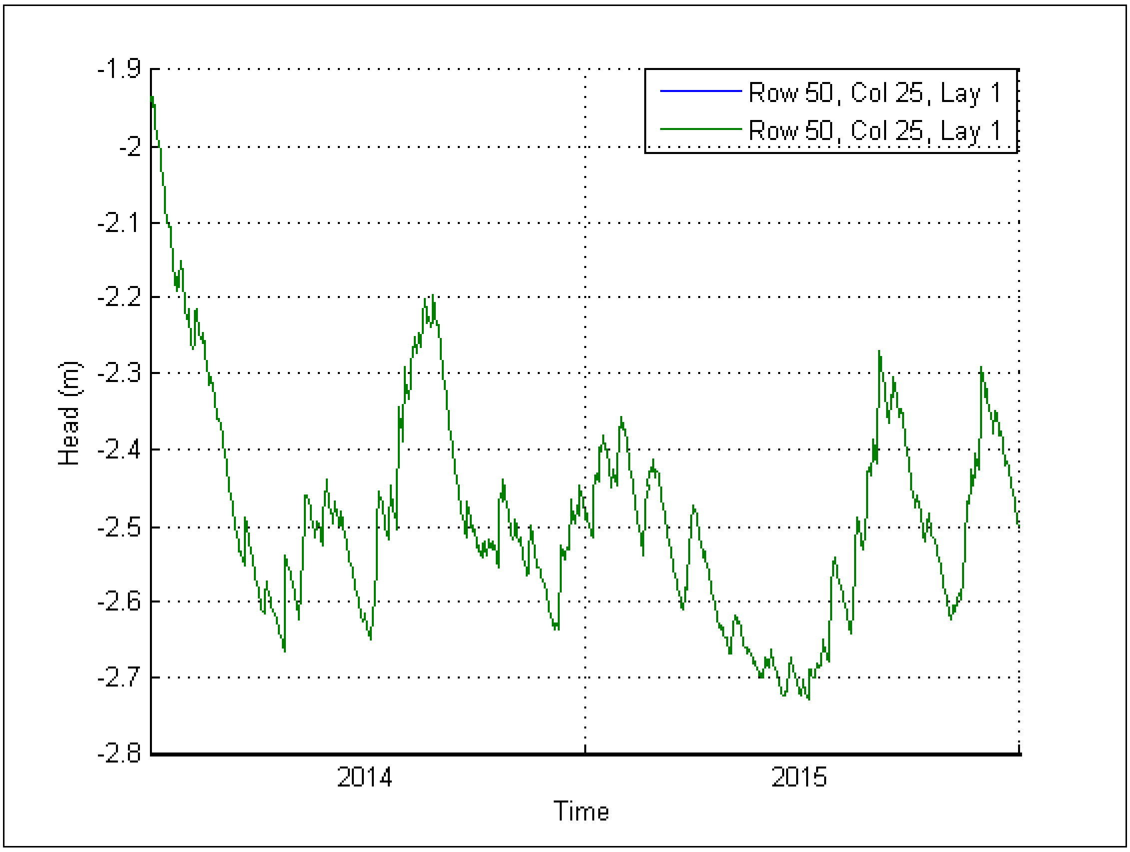

Figure 20. *Modelled groundwater level over the period 2014-2015 for the situation without drains at location 5.*

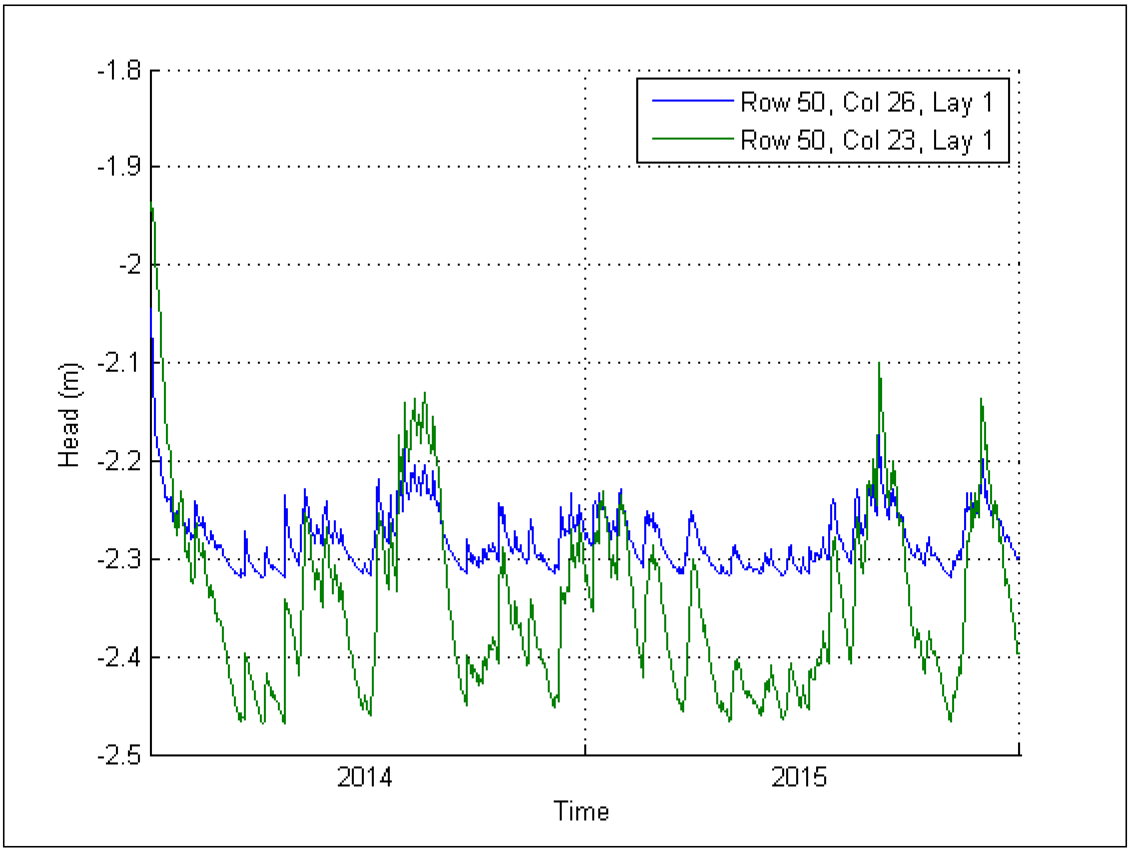

Figure 21. *Modelled groundwater level over the period 2014-2015 for a drain distance of 6m and a hydraulic head in the drains of 65 cm below LS at location 5.*

Standard deviation

Comparable with the model located at area 1, the differences in standard deviation between the alternatives is also large (Table 15). For this reason, a peaty soil is suitable to manage the groundwater levels. At a drainage depth with a hydraulic head at 35 cm below LS, the PGM system has the largest influence on the groundwater table. But at this depth the difference with the standard deviation between the drains is larger, resulting in larger convex and concave shapes of the groundwater table.

Model 5	Deviation (m)
No drains	0.504
3 m; 0.35 m	0.054
6 m; 0.35 m	0.175
12 m; 0.35 m	0.364
3 m; 0.65 m	0.291
6 m; 0.65 m	0.355
12 m; 0.65 m	0.441

Table 15. *The calculated standard deviation between the drains (relative to the target value) for the groundwater levels at location 5 for different PGM alternatives.*

4.1.7. Comparison GLG and GHG for all groundwater models

In general, PGM provides large differences between clay and peat soils, by applying PGM the groundwater dynamics increases (Table 16). These differences are probably caused by the difference in permeability. In clay soils (especially model 2 and 4) the difference between GHG and GLG is large (large groundwater dynamics), mainly caused by a high GHG value, which could ascend above land surface. As mentioned before, the reason for this is that the water flow through clay layers is restricted compared to peat soils, which is causing an larger increase of the groundwater table in these layers during rainfall events.

In particular, the GHG and GLG values show a larger effect of PGM in primarily peat soils (especially model 1 and 5). In addition, for these soils the effect of drain distance is more significant than the effect of the depth of drainage, which is contrary to the clay soils, model 2 and 4 (Table 16). Furthermore, in peat soils the GHG and GLG drops when the drains have a larger distance between each other. This result is questionable for the GHG. Usually the GHG will increase when the drain distance decreases. The reason for an lowering in GHG could be that the permeability of peat is high, therefore the GHG drops faster. Also, in a no drain situation the GHG is lower than it would be expected, which probably is caused by a high permeability of for example peat. Therefore, the GHG drops also when the drain distances increased. But, the difference between GHG and GLG increases for a larger drain distance for all models.

Model	GW	No drains (cm -LS)		3 m; -35 cm (cm -LS)	6 m; -35 cm (cm -LS)	12 m; -35 cm (cm -LS)		3 m; -65 cm (cm -LS)	6 m; -65 cm (cm -LS)	12 m; -65 cm (cm -LS)
Calibration (LS: 172 cm -NAP)	GHG	12		-	-	-		-	-	-
	GLG	74		-	-	-		-	-	-
Model 1 (LS: 160 cm -NAP)	GHG	88		48	60	78		73	76	82
	GLG	119		62	88	108		86	97	111
Model 2 (LS: 175 cm -NAP)	GHG	-18		21	2	-11		39	14	-5
	GLG	46		52	52	49		74	65	54
Model 3 (LS: 160 cm -NAP)	GHG	20		35	27	19		63	51	35
	GLG	57		50	54	56		78	78	73
Model 4 (LS: 170 cm -NAP)	GHG	7		32	24	14		58	47	28
	GLG	74		52	62	72		80	85	86
Model 5 (LS: 150 cm -NAP)	GHG	77		43	48	62		69	67	70
	GLG	109		58	74	96		84	94	105

Table 16. *Calculated GHG and GLG values (in centimeters below LS) for different PGM alternatives for all models.*

Table 17 shows the corresponding GT codes for the calculated GHG and GLG in polder Spengen. The GT codes for the different PGM alternatives deviates from the GT codes of the current situation. This is caused by the influence of PGM on the groundwater table. Furthermore, these GT codes are essential for calculating the loss of crop yield with the HELP 200x application.

Model	No drains (GT)		3 m; -35 cm (GT)	6 m; -35 cm (GT)	12 m; -35 cm (GT)		3 m; -65 cm (GT)	6 m; -65 cm (GT)	12 m; -65 cm (GT)
Model 1 (LS: -160 cm -NAP)	IV		II*	IV	IV		IV	IV	IV
Model 2 (LS: -175 cm -NAP)	I		II	II	I		II*	II	II
Model 3 (LS: -160 cm -NAP)	I		I	II*	II		II*	II*	II*
Model 4 (LS: -170 cm -NAP)	II		II*	II	II		II*	IV	III*
Model 5 (LS: -150 cm -NAP)	IV		II*	II*	IV		IV	IV	IV

Table 17. *Corresponding GT codes from all GHG and GLG values.*

4.2. Effect on land subsidence

According to four different climate scenarios (IPPC, 2013), described in the terminology (Appendix A), the land subsidence in the Dutch peatlands is calculated under the various drainage systems proposed. In the figure below the absolute land subsidence for the extreme climate scenario Wh is given in centimeters per year for different models, drainage system and soil profile. The figures for land subsidence of each climate scenario are located in Appendix D. Both model 2 and 4 (clay soils) didn't show subsidence at all, therefore these models haven't been included into Figure 22. For the current situation, the land subsidence is more than 2 cm/year for peat soils (model 1 and 5), which have a larger hydraulic conductivity. Especially in these peat soils the calculated subsidence rates are larger than the average values of 0.77 cm/year (with maximum rates up to 6 cm/year), this difference could be caused by the relatively low GLG values calculated for peat soils or different locations of modelling. Therefore the subsidence rates could be larger than the averaged rates, according to Geisler (2014) and Van den Akker et al. (2007). The fraction of reduce subsidence rates is much more significant for this research than the absolute values. This fraction is calculated from the difference between the current subsidence rate and for the PGM alternatives, see Table 18. Table 19 shows the calculated reduced subsidence rates in percentages. In this table the effects of PGM on land subsidence can clearly be observed.

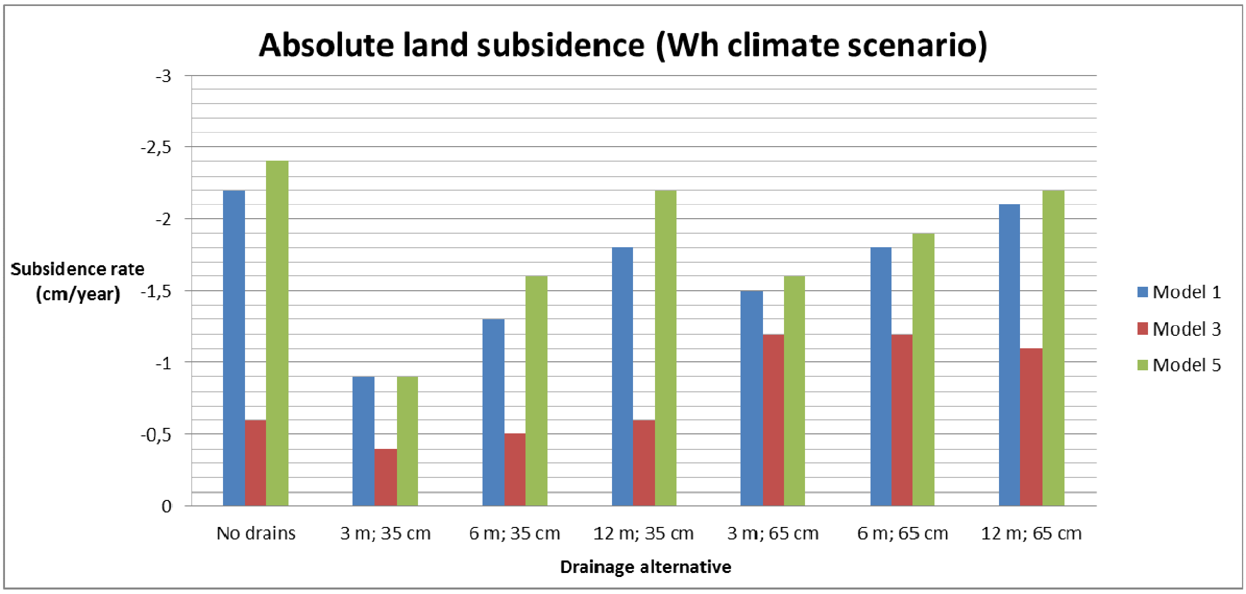

Figure 22. *Absolute land subsidence rates in cm/year calculated by the Phoenix model for the extreme Wh climate scenario.*

In general, the effects of the different climate scenarios show a minor increase in subsidence rates. A maximum difference in subsidence rate (between the climate scenarios) can become 0.2 cm per year. This is actually the minimum change in the rate of subsidence, because rainfall and evaporation are not taken into account for the climate scenarios in the Phoenix model.

Only the parcels with peat soils show significant land subsidence (models 1, 3 and 5). In Table 18 the land subsidence for the various drainage alternatives is compared with the current situation. The effort for HDSR is to reduce the land subsidence with a minimum of 25 percent until year 2050. On the basis of this goal a given drainage system can be elected. In general, a PGM system with a 3 m drain distance and a hydraulic head of 35 cm below land surface is reducing the land subsidence for peat soils significantly, up to a maximum of 1.5 cm/year, which is 0,45 meter in 30 years. This means that the subsidence will be reduced by approximately 63 percent. (Maximum reduction of 1.5 cm/year divided by maximum subsidence of 2.4 cm/year times 100 percent gives a maximum reduction of 63 percent). This is a significantly larger percentage than is required. The optimal drainage alternative will vary for different soil profiles, but for agricultural peatlands the optimal distance between the drains is around 6 meter and a depth of 35 centimeters. Consequently, the subsidence is reduced less than 0.8 cm/year. Compared to current subsidence rates between 2.0 and 2.3 cm/year, the reduction is approximately 35 percent. Note that the land subsidence will increase for model 3 when a hydraulic head of 65 cm below LS is used. Because the GLG becomes lower, when a hydraulic head of 65 cm below LS is applied in the drains,. This is probably causing an increase in land subsidence for this model.

Overall PGM is a suitable method to reduce the land subsidence in peat soils, for example over a period of 30 years. However, it is still the decision of the farmers and the water authority for what percentage the land subsidence should be reduced and which preferences of drainages system will be used.

KNMI ‘14 Scenario	Model	No drains (cm/year)	3 m; -35 cm (cm/year)	6 m; -35 cm (cm/year)	12 m; -35 cm (cm/year)	3 m; -65 cm (cm/year)	6 m; -65 cm (cm/year)	12 m; -65 cm (cm/year)
Scenario Gl	**Model 1**	0	-1.2	-0.9	-0.3	-0.6	-0.4	-0.1
	Model 3	0	-0.2	-0.1	0.0	0.6	0.6	0.4
	Model 5	0	-1.4	-0.8	-0.3	-0.8	-0.5	-0.2
Scenario Gh	**Model 1**	0	-1.3	-0.9	-0.3	-0.6	-0.4	-0.1
	Model 3	0	-0.2	-0.1	0.0	0.5	0.5	0.4
	Model 5	0	-1.4	-0.8	-0.3	-0.8	-0.5	-0.2
Scenario Wl	**Model 1**	0	-1.3	-0.9	-0.3	-0.6	-0.4	-0.1
	Model 3	0	-0.2	-0.1	0.0	0.5	0.5	0.4
	Model 5	0	-1.4	-0.8	-0.3	-0.8	-0.5	-0.2
Scenario Wh	**Model 1**	0	-1.3	-0.9	-0.3	-0.6	-0.4	-0.1
	Model 3	0	-0.2	-0.1	0.0	0.6	0.6	0.4
	Model 5	0	-1.5	-0.8	-0.3	-0.8	-0.0	-0.2

Table 18. *Reduction of subsidence according to the measurements for the research locations where subsidence occurs. Difference between the calculated land subsidence in cm/year and the no drains situation.*

KNMI '14 Scenario	Model	3 m; -35 cm (%)	6 m; -35 cm (%)	12 m; -35 cm (%)	3 m; -65 cm (%)	6 m; -65 cm (%)	12 m; -65 cm (%)
Scenario Gl	Model 1	60	40	15	30	20	5
	Model 3	20	0	0	0	0	0
	Model 5	61	35	13	35	26	9
Scenario Gh	Model 1	62	43	14	29	19	5
	Model 3	33	17	0	0	0	0
	Model 5	61	35	9	35	22	9
Scenario Wl	Model 1	62	43	14	29	19	5
	Model 3	33	17	0	0	0	0
	Model 5	58	33	13	33	21	8
Scenario Wh	Model 1	59	41	14	27	18	5
	Model 3	33	17	0	0	0	0
	Model 5	63	33	13	33	25	8

Table 19. *Reduction of Land subsidence (for the research location where land subsidence occurs) compared to the current situation displayed in percentages for four different climate scenarios.*

4.3. Effect on crop yield

According to the HELP 200x tables, the loss of crop yield on agricultural land can be determined. Hence, the percentages of crop damage are calculated by the HELP 200x application, see Table 20 (Brouwer & Huinink, 1987). In general, Larger percentages means larger costs (for farmers) caused by the loss of crop yield. These percentages are determined for each drainage system per hectare and compared with the present situation, see Table 21 for the negative (in red) and positive (in green) effects on the crop yield. When the percentage of crop damages is less than the current situation (Table 20) there will be an increase in crop yield, which is beneficial for farmers. In Table 21 a majority of green values can be observed, which means that PGM is in many cases beneficial for farmers.

Loss of crop yield per hectare		**No drains (%)**	**3 m; -35 cm (%)**	**6 m; -35 cm (%)**	**12 m; -35 cm (%)**	**3 m; -65 cm (%)**	**6 m; -65 cm (%)**	**12 m; -65 cm (%)**
Model 1	**wet**	**1**	16	2	1	2	1	1
	dry	**15**	3	5	10	5	7	12
	combination	**16**	19	7	11	7	8	13
Model 2	**wet**	**65**	32	54	60	5	23	54
	dry	**1**	1	1	1	3	2	1
	combination	**66**	33	55	61	8	25	55
Model 3	**wet**	**27**	26	28	29	3	4	7
	dry	**2**	2	2	2	3	3	3
	combination	**29**	28	30	31	6	7	10
Model 4	**wet**	**22**	29	19	18	3	3	7
	dry	**1**	1	1	1	1	1	1
	combination	**23**	30	20	19	4	4	8
Model 5	**wet**	**1**	21	5	1	2	1	1
	dry	**11**	3	4	7	5	6	9
	combination	**12**	24	9	8	7	7	10

***Table 20**. Loss of crop yield per hectare in percentage of total production costs (Brouwer & Huinink, 1987).*

It appears from this study that the crop damages vary a lot through differences in soil profile (permeability), drain distance and depth. In general, the results show that for the drainage setup with the maximum reduction of subsidence for peat soils (3 m drain distance and a 35 cm depth), the total damage somewhat increases on the wet side, while for the optimum setup given the target of 25% reduction, the total damage remains similar or even reduces due to reduced damage on the dry side.

For the current situation, clay soils will experience a larger loss of crop yield caused by wet conditions than peat soils, but PGM can reduce this loss. In contrary, peat soils are suffering more loss due to dry conditions in the current situation. By infiltration of water the loss of crop yield caused by wet conditions can increase, instead the crop damage by dry conditions decreases. Probably, in peat soils a little increase in crop damage caused by wet conditions is acceptable, if the crop damage by dry condition can be reduced even as the subsidence rates. Because drought has much more negative effects, like land subsidence and the emission of greenhouse gases. Therefore, for peat soils the loss of crop yield caused by dry conditions can significantly be reduced by shorter drain distances and shallower drainage depth. This means that the influence of infiltrating water due to PGM is large during dry periods. Conversely, for clay soils the loss of crop yield is mainly caused by wet conditions. In this case the influence of draining water is larger than infiltration. But, the main reason for applying PGM is to reduce the land subsidence in peat soils caused by dry weather conditions. Therefore, reducing the crop damage by dry conditions is the most important and a low or probably no increase in crop damage by wet conditions would prefer. The best way to determine the effect on the crop yield for peat soils is to observe the combination damage. A PGM system with 6 m drain distance and a 35 cm depth show beneficial effects on the crop yield and the land subsidence can be reduced to a sufficient amount as well (Table 19 and 21).

Loss and profit of crop yield per hectare		**No drains (%)**	**3 m; -35 cm (%)**	**6 m; -35 cm (%)**	**12 m; -35 cm (%)**	**3 m; -65 cm (%)**	**6 m; -65 cm (%)**	**12 m; -65 cm (%)**
Model 1	**wet**	**1**	-15	-1	**0**	-1	**0**	**0**
	dry	**15**	+12	+10	+5	+10	+8	+3
	combination	**16**	-3	+8	+4	+9	+8	+3
Model 2	**wet**	**65**	+33	+11	+5	+60	+42	+11
	dry	**1**	**0**	**0**	**0**	-2	-1	**0**
	combination	**66**	+33	+11	+5	+58	+41	+11
Model 3	**wet**	**27**	+1	-1	-2	+24	+23	+20
	dry	**2**	**0**	**0**	**0**	-1	-1	-1
	combination	**29**	+1	-1	-2	+23	+22	+19
Model 4	**wet**	**22**	-7	+3	+4	+19	+19	+15
	dry	**1**	**0**	**0**	**0**	**0**	**0**	**0**
	combination	**23**	-7	+3	+4	+19	+19	+7
Model 5	**wet**	**1**	-20	-4	**0**	-1	**0**	**0**
	dry	**11**	+8	+7	+4	+6	+5	+2
	combination	**12**	-12	+3	+4	+5	+5	+2

***Table 21**. Loss (in red) and profit (in green) of crop yield per hectare in percentage of total production costs compared to the current situation (Brouwer & Huinink, 1987).*

5. Discussion

This study was aimed to investigate the influence of PGM on the groundwater levels in Spengen. In order to create a suitable PGM system in polder Spengen, several design limits had to be taken into account (deltafacts, 2015). Among other things the drains should have a minimum depth of 45 cm and a maximum of 75 cm below LS (hydraulic head of 35 cm and 65 cm). Hence, the modelled PGM alternatives in this research are based on these depths. Furthermore, the perfect drain distance is probably around 6 meter (deltafacts, 2015), however it appears from this research that the optimal distance can be different for each parcel depending on its soil profile (see chapter 4). Since June 2016 HDSR started quarterly measurements of the phreatic groundwater at eight different locations in polder Spengen. These measurements show significant fluctuations in the groundwater levels for the clay soils compared to the peat soils. Such an effect for clay soils was noticed by modelling with PMWIN as well. The modelling effort show that the effects of PGM are more important for peat soils than for clay soils to increase the GLG and reduce land subsidence, but the observed fluctuations in groundwater levels in clay soils could be mitigated by PGM as well. Therefore, PGM is a tool to lower the GHG in clay soils, but probably the systems is too expensive for using it for this purpose alone in polder Spengen.

Overall, the effects of PGM on the groundwater for soils with a low permeability (clay soil) are different with the soils with a higher permeability (peat soils). This research uses formations to distinguish the difference in soil profile. Because the soil profiles can be conveniently described in terms of these formations. It was observed that the effects of PGM on the groundwater levels are advantageous for both peat soils and clay soils, but in a different way. Due to an increase in GLG during dry periods in peat soils and a decrease in GHG in clay soils. In fact, PGM isn't probably the perfect tool for clay soils (i.e. less permeable soils) due to the large GHG, because this will negatively affect the bearing capacity, also mentioned by Van Wijk (1988) and Joosten (2015). Therefore, a conventional drainage system (only draining of groundwater) would be more appropriate in clay soils to decrease the GHG and increase the bearing capacity as well. In addition, such a system is cheaper (both construction and maintenance costs) and the regulations of creating good groundwater levels would be less, which means less work (Stuyt et al., 2012).

PGM is a suitable method to reduce the land subsidence for peatlands, for instance over a period of 30 years the subsidence can be reduced by 45 cm as maximum. However, it is still the decision of farmers and the water authority in what amount the land subsidence should be reduced and which preferences of drainages system they have. Therefore the results of the HELP 200x tables are useful to calculate the extra costs of PGM caused by the loss of crop yield. From this, effects of PGM on the groundwater levels are more advantageous for peat soils than for clay soils. Because a higher groundwater level in peat soils during a dry (summer) period is significant to mitigate the land subsidence and can easily be realized with PGM (Van den Akker et al., 2011).

Furthermore, to meet with the attempts of 50 cm target value, a reduction of land subsidence of 25% (Van Schie, 2016) and a minor loss of crop yield, the optimal alternative proposed for PGM in peatlands would be a distance between the drains of 6m and a hydraulic head of 35 cm below LS (with a hydraulic head of 35 cm below LS), compared with Heijkers (2013). This result is in line with the targets determined by STOWA, delta facts (2015). Consequently, the subsidence is reduced with approximately 0.8 cm/year. Compared to current subsidence rates between 2.0 and 2.3 cm/year, the reduction is approximately 35 percent. The land subsidence can be reduced by a maximum of 63%. The decrease of land subsidence rate exceeds the rate of 50% (hypothesis). So the PGM system can reduce the land subsidence more than was expected. The reduction of land subsidence given in percentage will give the best indication for the effects of PGM, because the calculated absolute values of subsidence rates are somewhat different from other research.

In addition, various remarks can be made about the reliability of the results of this research. The uncertainty of computer modelling with PMWIN, the Phoenix model and the HELP tables was considerable and these tools could certainly be improved. Below, short reflections on each of these tools are given as well as suggested improvements following from of this research.

5.1. Groundwater model

In general, modelling with PMWIN 5.3.3. is useful for getting indications of groundwater flows, but it has some uncertainties as well, which can cause errors in the results. During the research it became clear that the hydrological parameters for the different soil types in this area are difficult to determine. These hydrological parameters differ per parcel (also noticed by farmers), because the composition of the soil, with specific types of peat and the mixture with argillaceous soils, varies quite strongly. Therefore it became difficult to determine confident values for these parameters. Literature and knowledge about this area (additionally through a recent study on the hydraulic conductivity by Van Houwelingen et al., 2016) in combination with model calibration (there was only one monitoring well available for calibration), the parameters were defined as accurately as possible. Furthermore, data on soil profiles in this area is uncertain as well. Farmers noticed large variations in soil profiles between parcels in the polder, whereas the soil data from DINOloket doesn't show large variations in the soil structure. Data from DINOloket sometimes miss detailed information about the soil profile, because the maps are made in terms of geological formations and without detailed lithology information. For instance, DINOloket doesn't show variations in types of peat, which is significant for this research. However, differences in type of peat are difficult to determine. Also, soil data from DINOloket also occasionally differ from the data derived from the soil map of Stouthamer et al. (2008). Data from DINOloket could be older and therefore the topsoil may be affected by field operation or peat oxidation. This difference in soil information has been taken into account by creating the models.

About the calibration and validation several remarks can be made as well. The upper soil layer can't become "dry", therefore the upper layer in the calibrated model is set as a confining layer (conventional method for modelling), which is not comparable to the real situation (unconfined top layer). Therefore the calibration model varies a little from the other groundwater models, whereby the parameter values are influenced. The hydrological parameters are slightly adapted for the "new" situation.

Several other minor issues remain. For instance, the used modelling period (two year, 2014-2015) is too short for modelling accurately the GHG and GLG. Also, using two hydrological years would have been preferable for calculating the GHG and GLG instead of using two normal years as is done here. The GHG and GLG should be calculated over 8 years, but this isn't possible for PMWIN 5.3.3.. In addition, several constraints managing the real PGM system, for instance including a pressurized well, isn't possible to simulate with PMWIN as well. An advantageous of an updated modelling program (like PMWIN 8) is that the groundwater flow could be observed in cross sections, however this (free) version is limited by 5000 cells and three layers, which is not appropriate for this research. Besides, cross-sections of groundwater flows give additional information about the groundwater fluctuations and could be useful to determine the effects of PGM in the study area. That means, for obtaining more accurate results for further research, it would be appropriate to use more updated modelling programs. Moreover, the MRC2012a headstool is a useful program to show the results more easily than PMWIN. But a disadvantageous of this program is that it can only show one model from PMWIN, so a line of the land surface or a graph of the situation without drains can not be included to the graphs showing the different alternatives for a PGM system.

5.2. Phoenix model and HELP table

The above mentioned limitations of PMWIN have effect on the results from the Phoenix model and HELP tables. The Phoenix model does include different climate scenarios, these scenarios are based on temperature increase, without any information of changing rainfall and evaporation. The change of rainfall and evaporation will have effect on the land subsidence as well. Therefore, further research with the Phoenix model, the effect of climate change could be improved by including the change in rainfall and evaporation together with an increasing temperature. Moreover, the calculated land subsidence in peat soils (around 22 mm/year) is larger than the average subsidence rates gained from literature (around 7 mm/year), according to Van den Akker et al. (2007) and

Geisler (2014). But, land subsidence can have maximum values up to 60 mm/year (Geisler, 2014), so the calculated subsidence rates are in the same order of magnitude compared to literature. The calculated difference could be caused by location difference (different soil profiles), a different time period of modelling, different climate change effects and a low calculated GLG value.

Usually, the GHG and GLG values are measured over 8 hydrological years. Unfortunately a single hydrological year is used to determine the GLG, which influences the accuracy of the Phoenix model. Due to the restrictions of PMWIN it is impossible to simulate the groundwater levels over such period. This is an inaccurate method, but inevitable to determine the GHG and GLG in this situation. Hence, the groundwater levels are tested over a hydrological year to make a decision whether this year was a wet or dry one (Table 20).

Average yearly in 2015 (mm/year)	De Bilt in 2014 (mm/year)	De Bilt in 2015 (mm/year)	De Bilt hydrological year 2014 (mm/year)
880	951.6	904.1	1023.6

Table 22. *Average precipitations measured at de Bilt for different time periods (KNMI, 2016).*

By knowing the hydrological year of 2014 is wet, the GHG and GLG values could be fitted to the weather conditions over that specific hydrological year. The reason for doing this is to create realistic GHG and GLG values that fit in the GT maps. Accurate GHG and GLG values are useful to give more realistic results from the HELP 200x tables and the Phoenix land subsidence model. Certainly, some calculated GHG and GLG don't fit in the GT maps, which is understandable because these groundwater levels in the study area have been derived from PGM and will for that reason differ from the usual groundwater levels in a polder. For instance, the current groundwater level in Spengen fits in a certain GT range. But PGM will adapt these groundwater levels, as a result the groundwater levels aren't comparable to the GT values before and should be adapted to a certain realistic GT for calculating the loss of crop yield.

The HELP tables are based on the soil properties, vegetation type and the groundwater levels in a certain area. Several remarks about these criteria could be made. Firstly, the soil structure often varies over a specific parcel, therefore the crop damage (in percentage related to yield costs) a farmer will experience is site specific and difficult to determine specifically. Especially in this case, the peat soils vary within parcels and will cause differences in the crop damages. Secondly, the vegetation type is primarily grassland without reseeding. However, once in a while the farmers are forced to intervene when reseeding is necessary, but these reseeding costs are deemed negligible (van Schie, 2016).

Applying PGM results in artificial groundwater levels, while the HELP tables are based on occurring "natural" groundwater levels. Therefore these tables could be less appropriate to use for calculating the loss of crop yield. In addition, to improve these HELP tables the kind of livestock that is grazing on the land (which could induce the length of vegetation) and information about the bearing capacity (e.g. in the early spring and late fall) could be useful to add to the application. Consequently, the length of vegetation could also have an influence on the crop damage of agricultural land. Also, directly converting the crop damage in percentage to costs would give a better indication of the total extra costs. Therefore, more options could be added to the HELP application, like total costs and parcel size (Brouwer & Huinink, 1987). These are some minor remarks on the HELP application that would create more accurate results for the extra costs caused by crop damages and has to be taken into account for all stakeholders by making decisions about PGM.

5.3. PGM system

During the period of this research internship more information became available about PGM. Not all of this recently gained information could be used for modelling the principle of PGM in this research. Besides, managing the groundwater level in a pressurized well on heavy rainfall events is almost impossible to simulate with PMWIN Modflow. Therefore this research has been modelling a slightly different method of PGM.

In general, the PGM system can cause a lot of discussion with all stakeholders. In my opinion, scientists disagree about the suitable drainage alternatives (drain distance and depth). During the research, it became clear that the drainage alternatives have to be discussed in more detail (useful for new research), to create the most suitable drainage circumstances in the peatlands.

In the group of stakeholders lots of different interests are present. For instance, the environmental instances plea for less plastic drains in the submerged and to the conservation of birds in the Dutch peatlands. On the other hand farmers have a preference to reduce the land subsidence and increasing the bearing capacity (during early spring and late fall). To achieve this, PGM is probably a suitable system. But, the main question about the Dutch peatland areas still remains: “what is the future for peatland areas?” For example, paludiculture (agriculture based on high groundwater levels, Van de Riet et al., 2014) or a large natural reserve in the peatland areas could be good alternatives for dairy farms to deal with the significant land subsidence. Particularly through the question, whether there is enough fresh water available or not (particularly during dry periods), PGM systems could be vulnerable. The use of fresh water during dry periods could cause large disagreements among the stakeholders. Therefore, in my opinion strict agreements should be taking into account to mitigate the problems of fresh water shortages. Furthermore, by introducing PGM in the polder, farmers become responsible for their own groundwater level. This may have both positive as negative consequences. The farmers can adapt the groundwater tables to their own preference, probably limited by strict regulations from the water authority. For the water authority it is positive to reduce the amount of labour which is normally used to determine the suitable groundwater tables. However, when the groundwater levels are managed by the farmers, the water authority loses a certain amount of control over this area. However, direct and good communication with the farmers should reduce this problem.

Furthermore, the range of drainage alternative is determined according the STOWA, deltafacts (2014). Drain placements between 45-75 cm drainage depth and between 3-12 m distance are preferred for SD, but is this also suitable for PGM? Optimal settings may be different for PGM and different per parcel and specific goal. A deeper drainage system will have some advantages with respect to a shallower system. In particular, a deeper PGM system is less susceptible for land subsidence, the system keeps a certain depth during tenths of years with land subsidence. Moreover, it is easier to lower the groundwater levels when the drains are located lower in the parcel. Heightening the groundwater level is possible at both drainage depths. When a certain drainage pipe is broken, the groundwater bulge increases automatically. Therefore a lower drainage depth is preferred (Van Houwelingen, 2016). But, Large fluctuations of groundwater levels will probably have adverse effects on the environment, especially focussed on natural vegetation and crops. Deeper groundwater levels during early spring provide the roots of grasses to grow better and reach a deeper groundwater level during the summer. Consequently, the quality of grass increases and probably the growth increases as well (VIC, 2016). This is probably also a reason why managing a groundwater level (hydraulic head) of 35 cm all year long is too high.

For further research, the capillarity in the top soil would improve the knowledge of hydrology in this study area and is beneficial for PGM. Admittedly, the unsaturated zone (phreatic water) in peatlands is difficult to calculate and would probably be a whole research by its own. The unsaturated zone is related to the water level inside the pressure well. The height of the water column inside this well provides a certain height of phreatic water in a parcel. Both quantities are difficult to estimate due to the spatial variation in resistance (e.g. inside the drains) and permeability in especially peat soils. In addition, the most optimal position (e.g. in the middle of the ditch or at one of the corners) for this pressure reservoir is still uncertain. Therefore, further research could give indicative values about these uncertainties.

Finally, to put PGM into practice it is necessary that the farmers should agree with the costs and properties of the proposed drainage system. Without any agreement from the farmers in a specific polder, the PGM system can not be used. Therefore, research, like this study, could be useful to convince the farmers about the positive effects of using PGM.

6. Conclusion

This research provides an answer to the following research question:

> "What is the effect of pressuredrain-based groundwater management on groundwater levels and land subsidence in agricultural peatland in polder Spengen?"

The goal of this research was to determine the effects of PGM on the groundwater levels, land subsidence and loss of crop yield in polder Spengen. Below, the results of the sub-questions are mentioned:

1) The effect of PGM in peat soils is mainly observed in an increasing GLG, the infiltration of water is larger than draining. Conversely, the effect of PGM in clay soils is mainly observed in a decreasing GHG, draining of groundwater is larger than infiltration.
2) The effects on drain distance and depth on the GHG and GLG is large, so PGM can influence the groundwater table more smoothly. In general, the effect of drain distance is larger when a shallower depth is used.
3) In peat soils, PGM can reduce the land subsidence by a significant amount each year, with an optimal drainage setup the subsidence rates can be reduced by 63% (3 m drain distance and a 35 cm head below land surface).
4) The drainage setup with the maximum reduction of subsidence for peat soils, the total loss of crop yield somewhat increases on the wet side, while for the optimum setup given the target of 25% reduction, the total loss remains similar or even reduces due to reduced damage on the dry side.

In general, PGM is mainly aimed at reducing land subsidence in the Dutch peatland areas, by creating a more constant groundwater level over a year. It can be concluded that the influence of PGM is specific per area depending on soil type and drainage alternative. PGM can be suitable to manage the groundwater levels in peat soils and reduce the land subsidence as well.

According to this research, PGM is less suitable to use in argillaceous soils (i.e. less permeable soils). The large GHG values in the wet periods will be lowered by PGM, but this could also be achieved by conventional drainage systems. By contrast, peat soils experience positive effects on the GLG by using PGM. This can especially be observed by looking at the standard deviations of groundwater levels, the differences with the target level (see chapter 4). Large differences occur between standard deviations of different PGM configurations in peat soils, which mean that PGM has large influence on the groundwater table in peatlands. Furthermore, the distance between the drains experiences a larger effect on land subsidence than drainage depth. Difference in drainage depth has a larger effect on the costs compared to differences in drain distance, this is important information for constructing the kind of PGM system. In general, drains at 3 m distance and at a depth of 35 cm, results in the largest increase in GLG. The maximum subsidence rates can be reduced by 1.5 cm/year, in case the entire top soil consists of peat (or another layer with a high hydraulic conductivity). As a result, the land subsidence can be reduced by approximately 63 percent (which is more than the 50% that was expected). However, the water authority (HDSR) wants to reduce land subsidence by a minimum of 25 percent, the negative impacts on the crop yield and environment are taken into account (Brouwer & Huinink, 1987; Van Houwelingen, 2016). Therefore, a drain depth of 35 cm and a drain distance of 6 meter can also be sufficient.

It can be concluded, that for each specific location the interests from all stakeholders should be taking into account when deciding about the installation and setup of a PGM system. The most suitable drainage method in polder Spengen is not clear cut and depends on several characteristics, such as soil type, costs, environment and the future. A major conclusion, PGM is suitable as a tool for combating land subsidence for peat soils and not preferred for argillaceous soils.

6.1. Recommendations

According to the results of this research it is recommended to use a PGM system for peatlands with the drains placed at a distance of 6 meter and a hydraulic head at a depth of 35 centimeter below land surface and the latter based on the following criteria:

- Results are comparable with the recently measured groundwater tables in Spengen (HDSR, 2016).
- The land subsidence can be reduced by more than 25 percent, which is the most important issue for the Dutch peatlands.
- Positive results for creating a fixed groundwater level by using this drainage method.
- In peat soils PGM is suitable to manage the groundwater table.
- The losses of crop yield by too dry and too wet conditions are relatively low compared to other drainage methods.
- It should be kept in mind that the investments and construction costs for a drainage system with more drains is more expensive than a system with fewer drains.

These recommendations are also related to the PGM experiment performed at VIC in Zegveld. For all possible scenarios analysed in chapter 4, I suggest the stakeholders should select not only the economically feasible method for their agricultural land, but also taken into account the environmental and future perspectives of this area.

The following major improvements are recommended for further research:

- The time period of modelling has to be extended to a minimum of 8 years. Although, the obtained results gives an suitable indication of the effects of PGM in polder Spengen and there will always be some question remarks about the accuracy.
- When estimating land subsidence under KNMI climate scenarios, the effects of climate change on the groundwater level variation itself (through changes in precipitation and evaporation) should be taken into account.
- The hydraulic parameters, such as hydrologic conductivities are a fundamental piece of knowledge to understand and model the groundwater flows. Currently these values are obtained from literature and calibration, but could vary per location (especially in the peaty soils of Spengen). It is evident that fieldwork in the beginning of any research might increase the knowledge of hydraulic parameters in any area (e.g. see Van Houweling et al., 2016).
- Knowledge about the capillarity of the soil provides more information about e.g. the roots of crops, which influences the quality of grasses. More research about the capillarity effects of groundwater in this area will enhance the knowledge and is advantageous for e.g. farmers.
- The water level inside the pressurized well (which provides pressure in drains) for creating a certain groundwater table in a parcel is difficult to estimate. This is due to the resistance of the drains and a large variation of hydraulic parameters (e.g. porosity and permeability) in peat soils. However, experimenting with these wells is the most suitable method to gain more knowledge about the height of the water column inside the well.

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9. Appendix

This appendix is divided into four major parts (A, B, C and D). The first part contains the abbreviation and terminology of this research (A). Followed by the schematization of the PMWIN model (B) and all groundwater graphs modelling by PMWIN (C). Finally, additional tables and figures from modelling and calculations are showed (D).

A: Abbreviations and Terminology

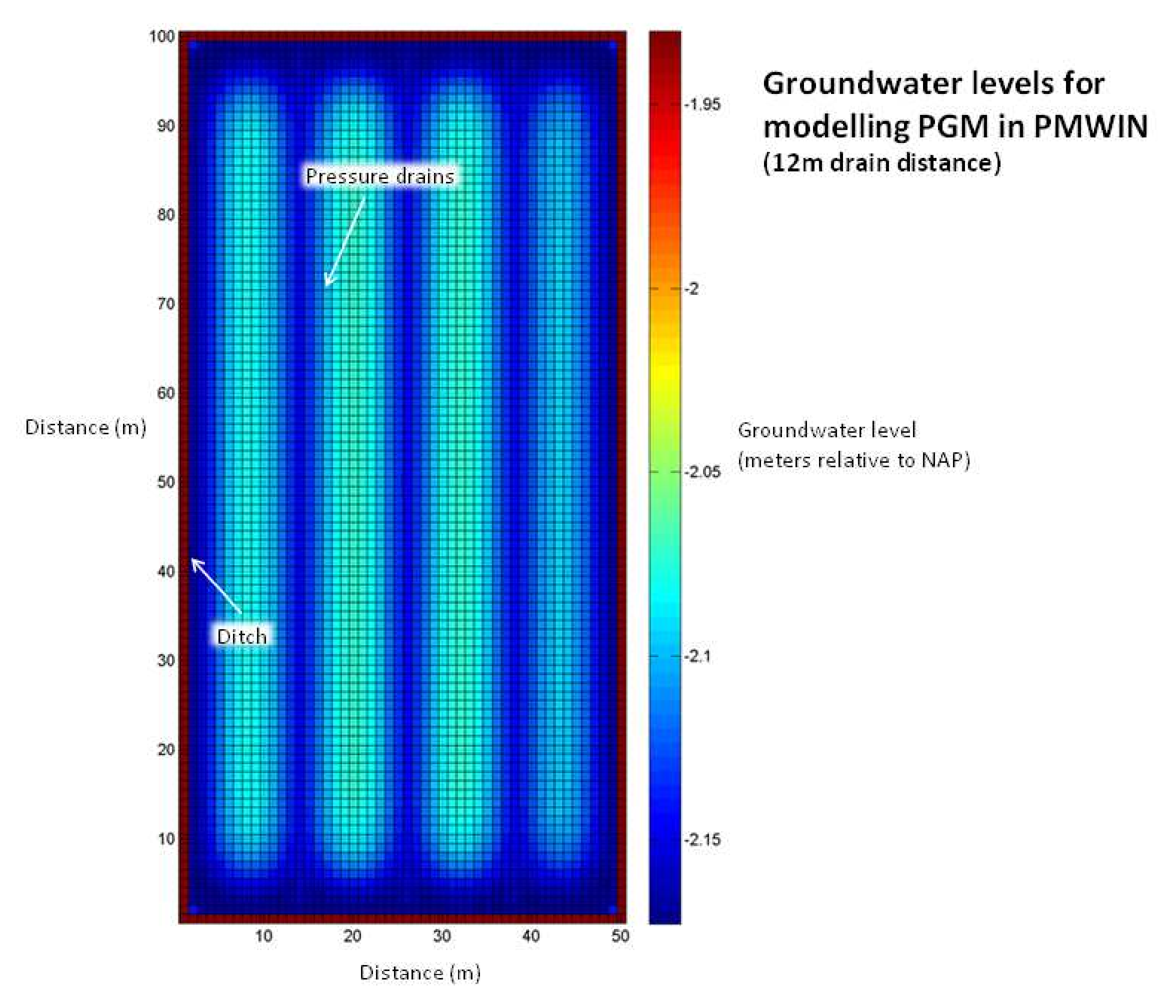
Freeboard: Difference between land surface and water level in the ditch, *drooglegging* in Dutch.
HDSR: Hoogheemraadschap De Stichtse Rijnlanden (Water authority)
GW: Groundwater
GHG: Average highest groundwater level, *Gemiddeld hoogste grondwaterstand* in Dutch. This value is obtained by measuring the three highest groundwater levels per year from each 14th and 28th per month during a minimum of 8 years.
GLG: Average lowest groundwater level, *Gemiddeld Laagste Grondwaterstand* in Dutch. This value is obtained by measuring the three lowest groundwater levels per year from each 14th and 28th per month during a minimum of 8 years.
Groundwater dynamics: Difference between GHG and GLG, g*rondwater dynamiek* in Dutch.
GT: Groundwater dynamics, *Grondwatertrappen* in Dutch. This code gives an indication on the groundwater dynamic.
LS: Land Surface, *Maaiveld* in Dutch.
NAP: Dutch ordnance datum, *Nieuw Amsterdams (Algemeen) Peil* in Dutch.
PGM: Pressurized Groundwater Management, *Sturen met Grondwater* in Dutch.

Hydrological parameters:
Kh: Horizontal Hydraulic Conductivity
Kv: Vertical Hydraulic Conductivity
sS: Specific Storage
Ne: Effective Porosity
Y: Specific Yield

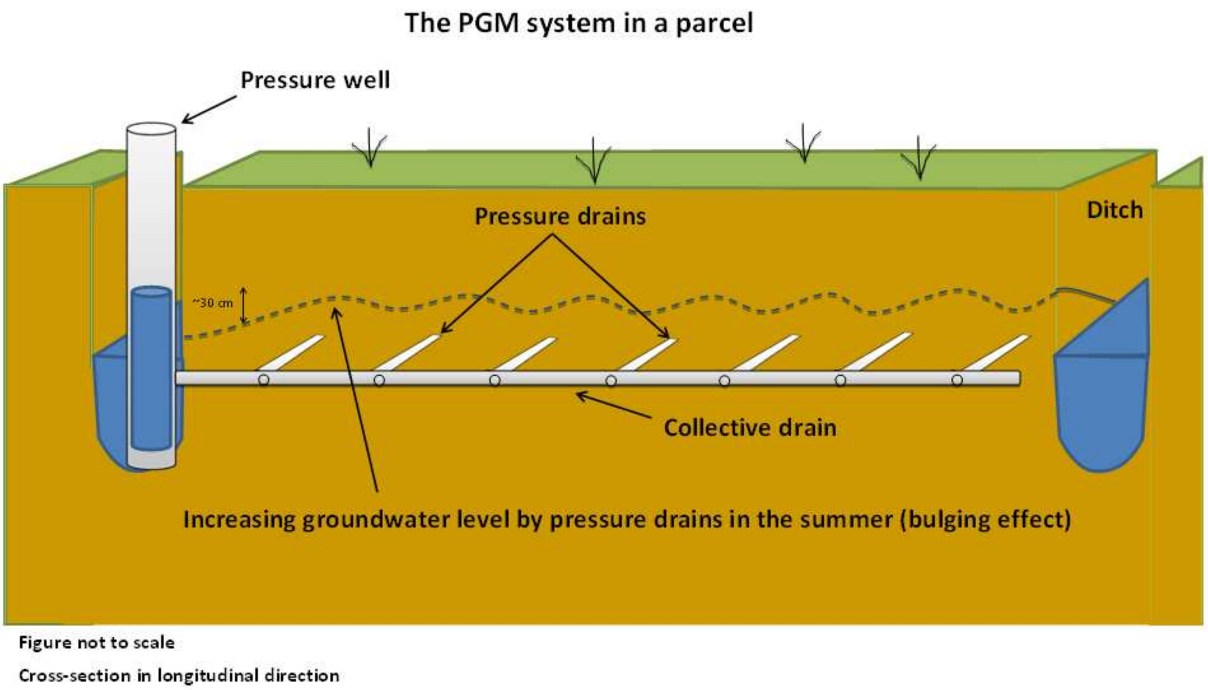
Soil formations:
EC: Echteld Formation
NIHO: Nieuwkoop Formation, Hollandveen Laagpakket
NIBA: Nieuwkoop Formation, Basisveen Laagpakket
NAWO: Naaldwijk Formation, Laagpakket van Wormer
BX/KR: Boxtel and Kreftenheye Formation

Climate scenarios (KNMI, 2014):
Gl: Moderate temperature increase and possible changes in airstream are low. *Gematigd laag* in Dutch.
Gh: Moderate temperature increase and possible changes in airstream are high. *Gematigd hoog* in Dutch.
Wl: Large temperature increase and possible changes in airstream are low. *Warm laag* in Dutch.
Wh: Large temperature increase and possible changes in airstream are high. *Warm hoog* in Dutch.

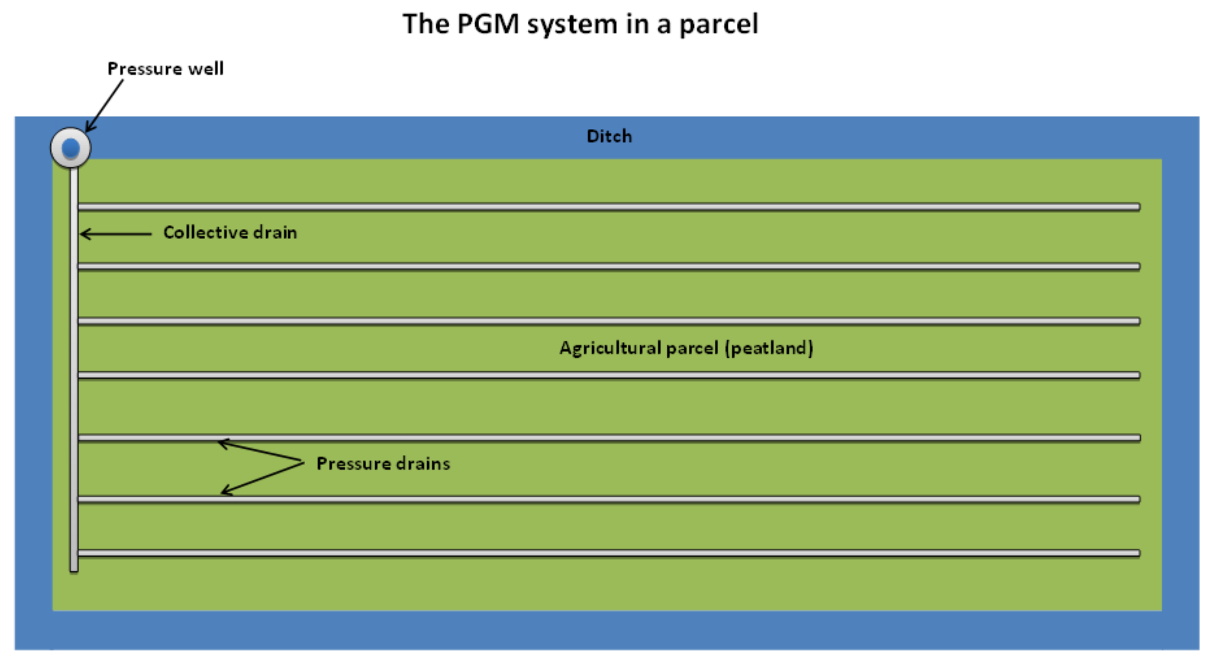
B: Schematization of the PMWIN model and PGM



B1. *A representation of the top view of the conceptual model (PMWIN), including the groundwater levels for modelling with PGM.*



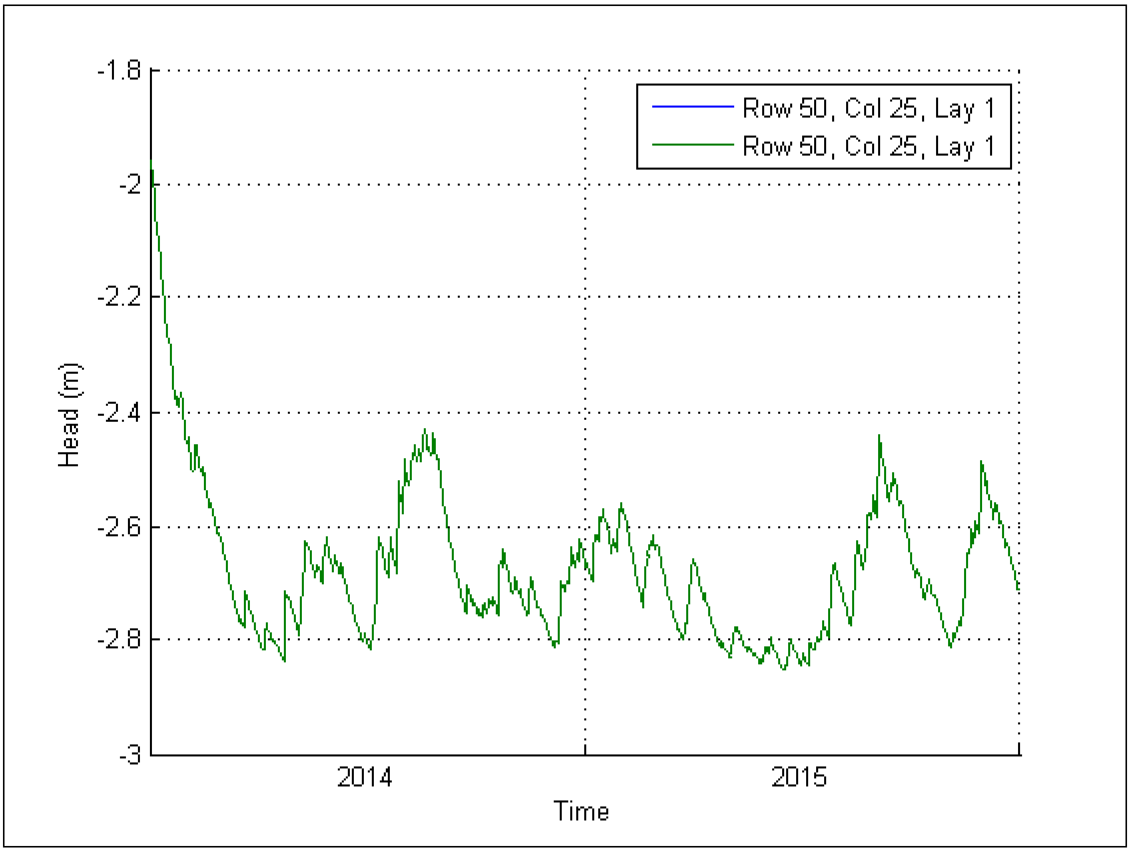
B2. *A cross-section of the principle of PGM in an agricultural parcel.*



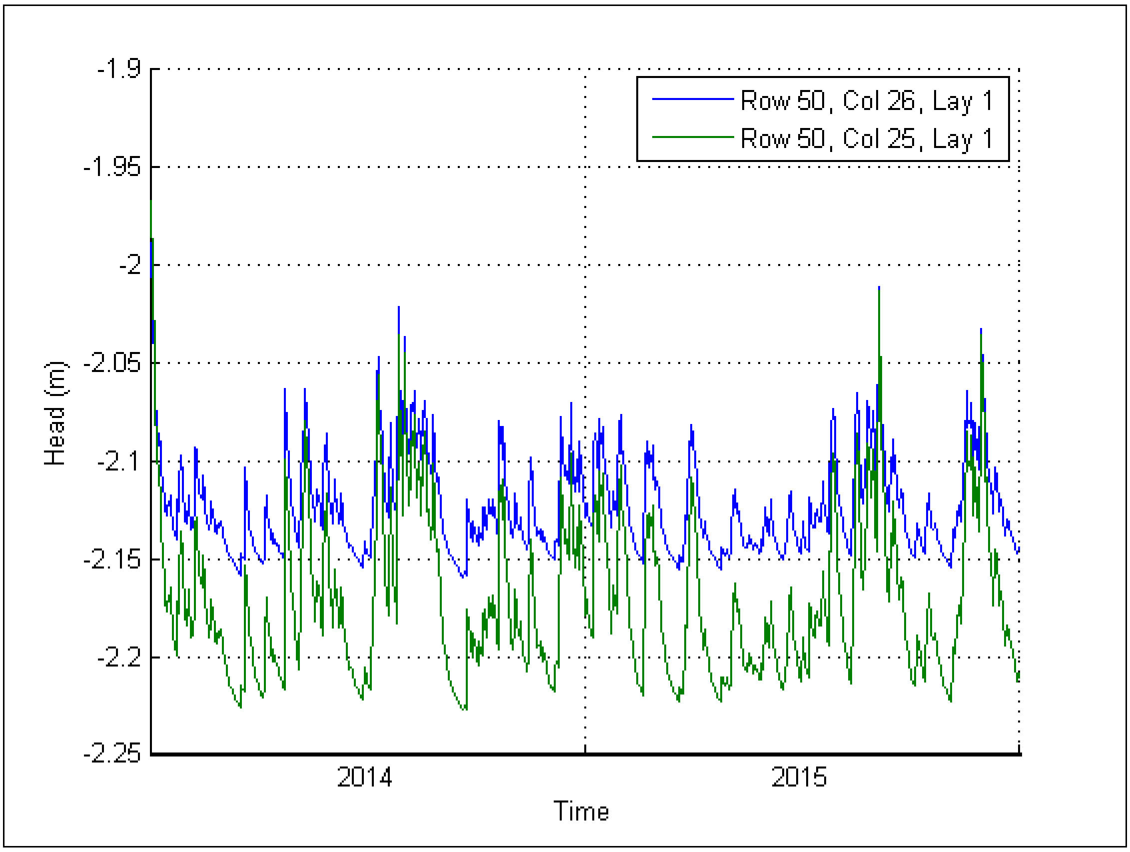
B3. *A top view of the principle of PGM in an agricultural parcel.*

C: Groundwater graphs

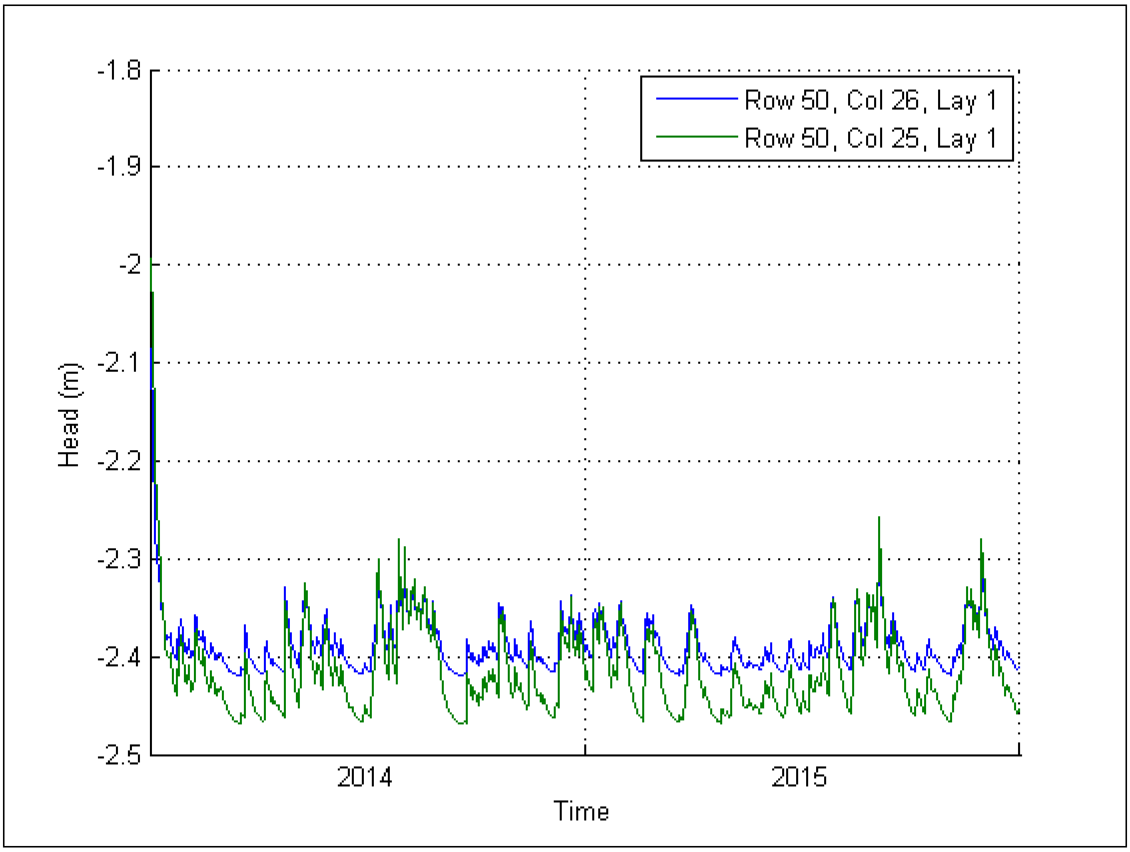
C1. Model 1



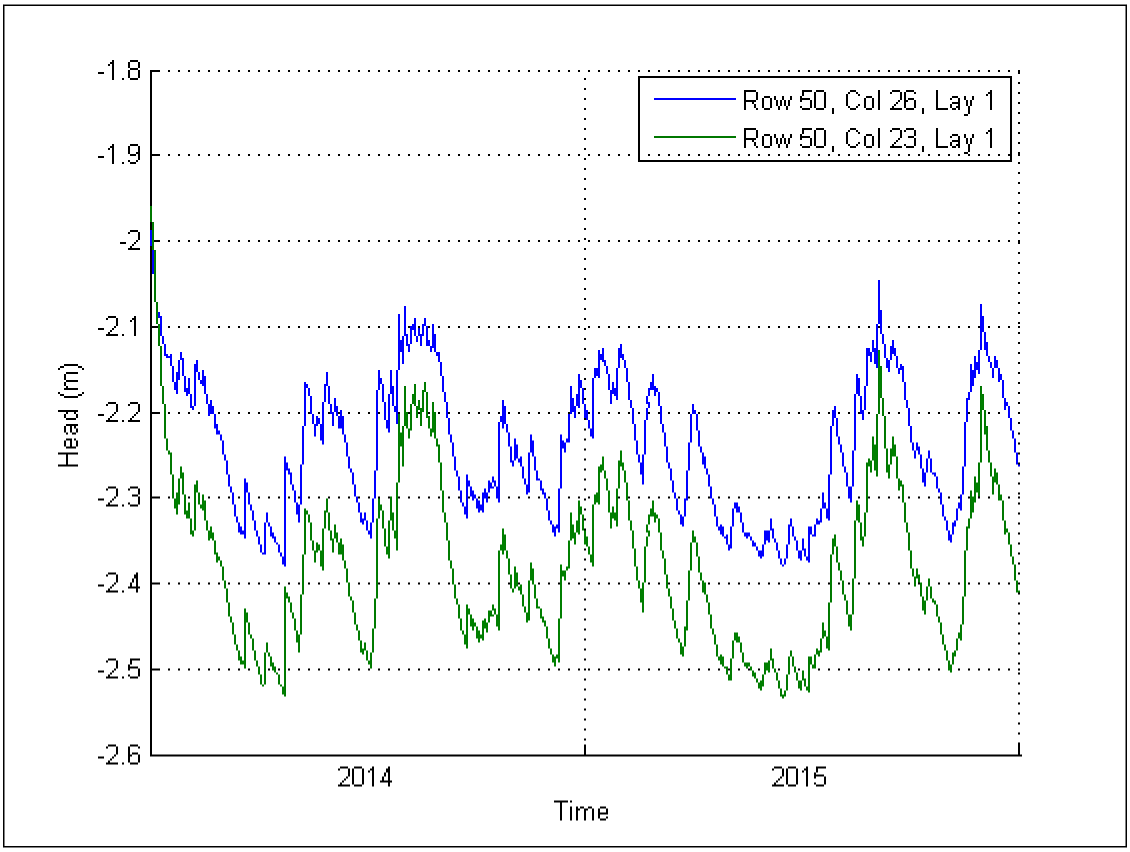
C1.1. *Modelled groundwater level over the period 2014-2015 for the situations without drains at location 1.*



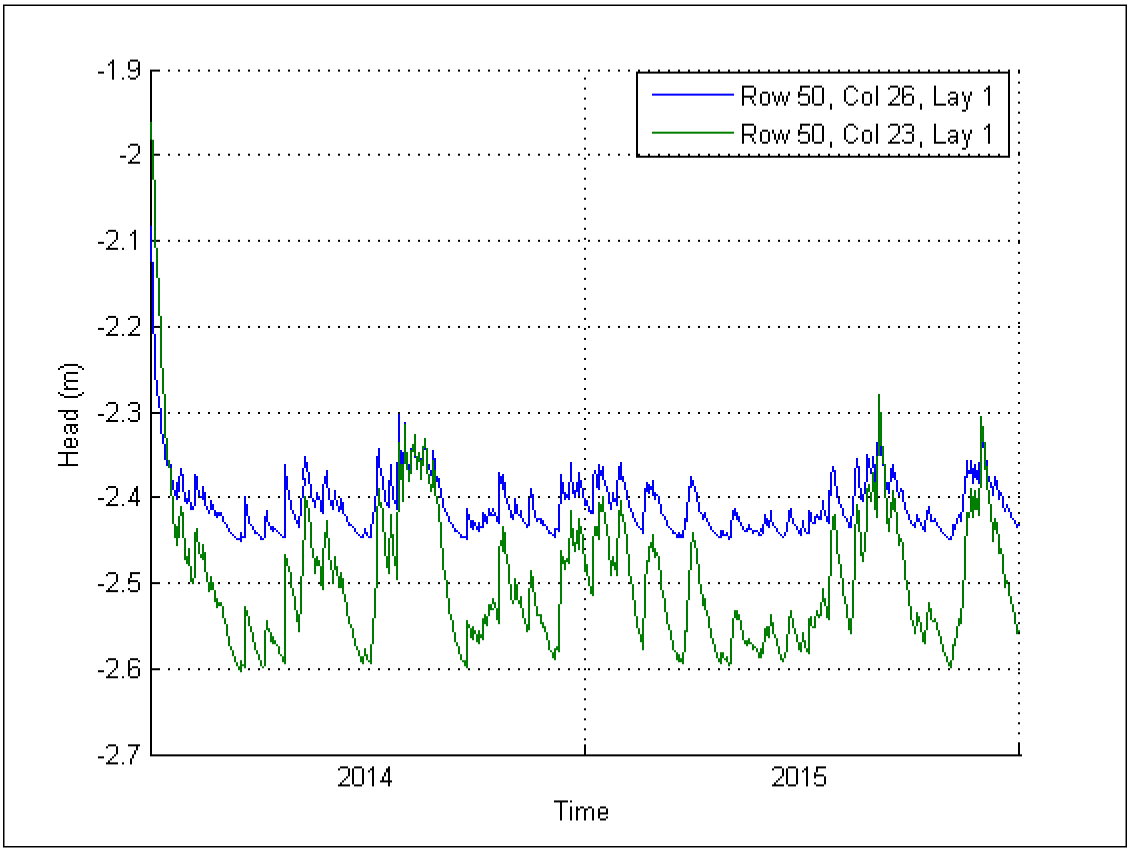
C1.2. *Modelled groundwater level over the period 2014-2015 for the drain distance of 3 m and a hydraulic head in the drains of 35 cm below LS at location 1.*



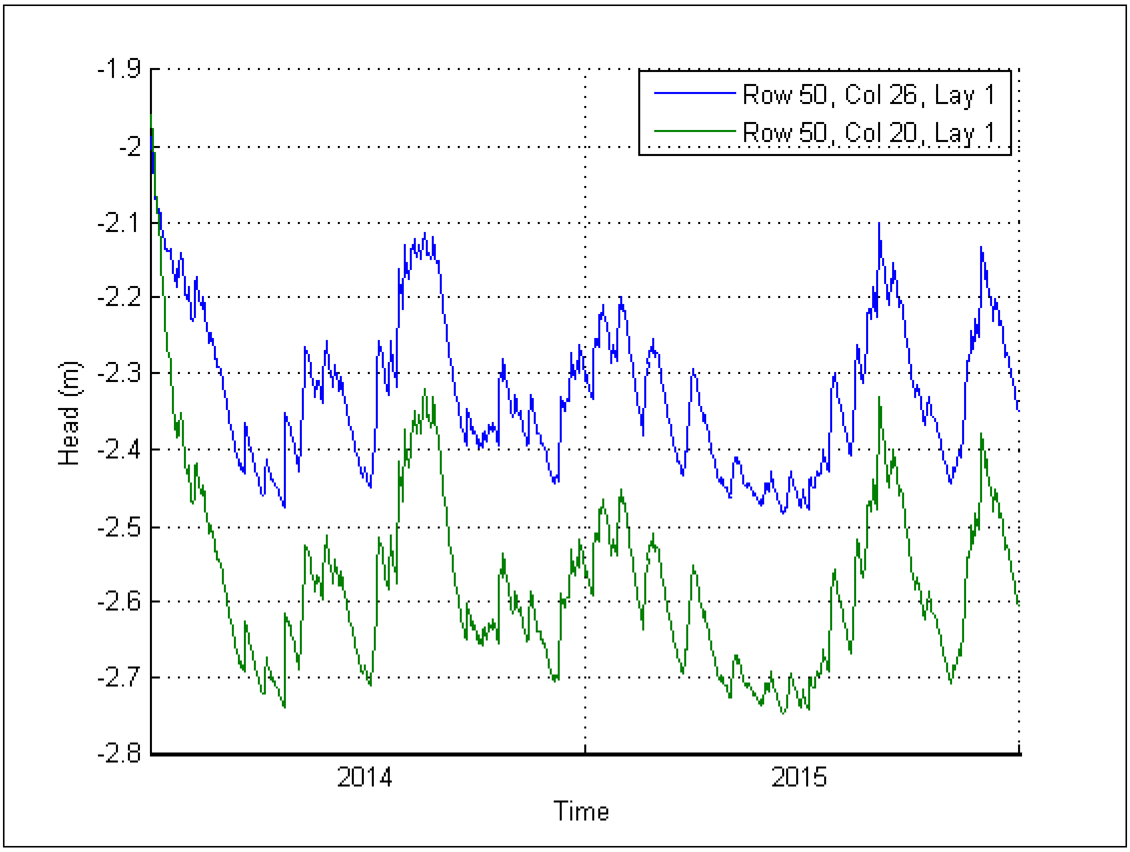
C1.3. *Modelled groundwater level over the period 2014-2015 for the drain distance of 3 m and a hydraulic head in the drains of 65 cm below LS at location 1.*



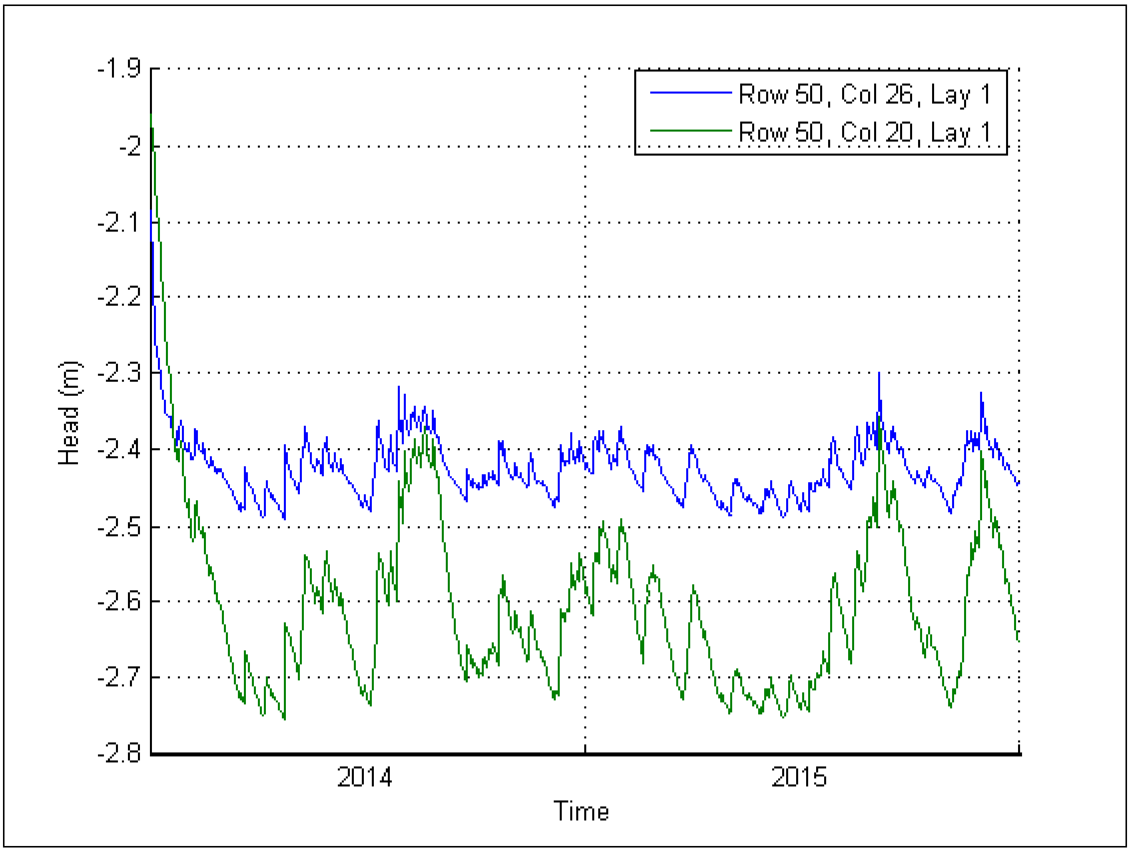
C1.4. *Modelled groundwater level over the period 2014-2015 for the drain distance of 6 m and a hydraulic head in the drains of 35 cm below LS at location 1.*



C1.5. *Modelled groundwater level over the period 2014-2015 for the drain distance of 6 m and a hydraulic head in the drains of 65 cm below LS at location 1.*

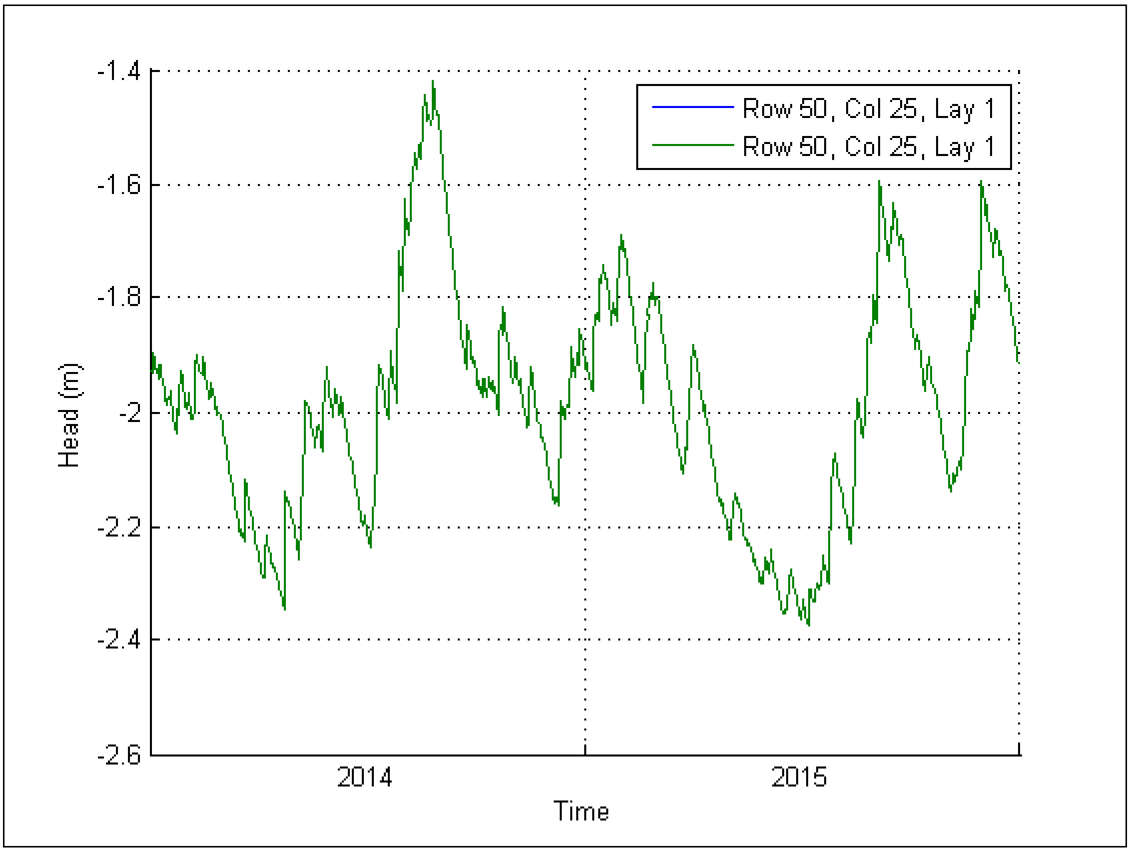


C1.6. *Modelled groundwater level over the period 2014-2015 for the drain distance of 12 m and a hydraulic head in the drains of 35 cm below LS at location 1.*

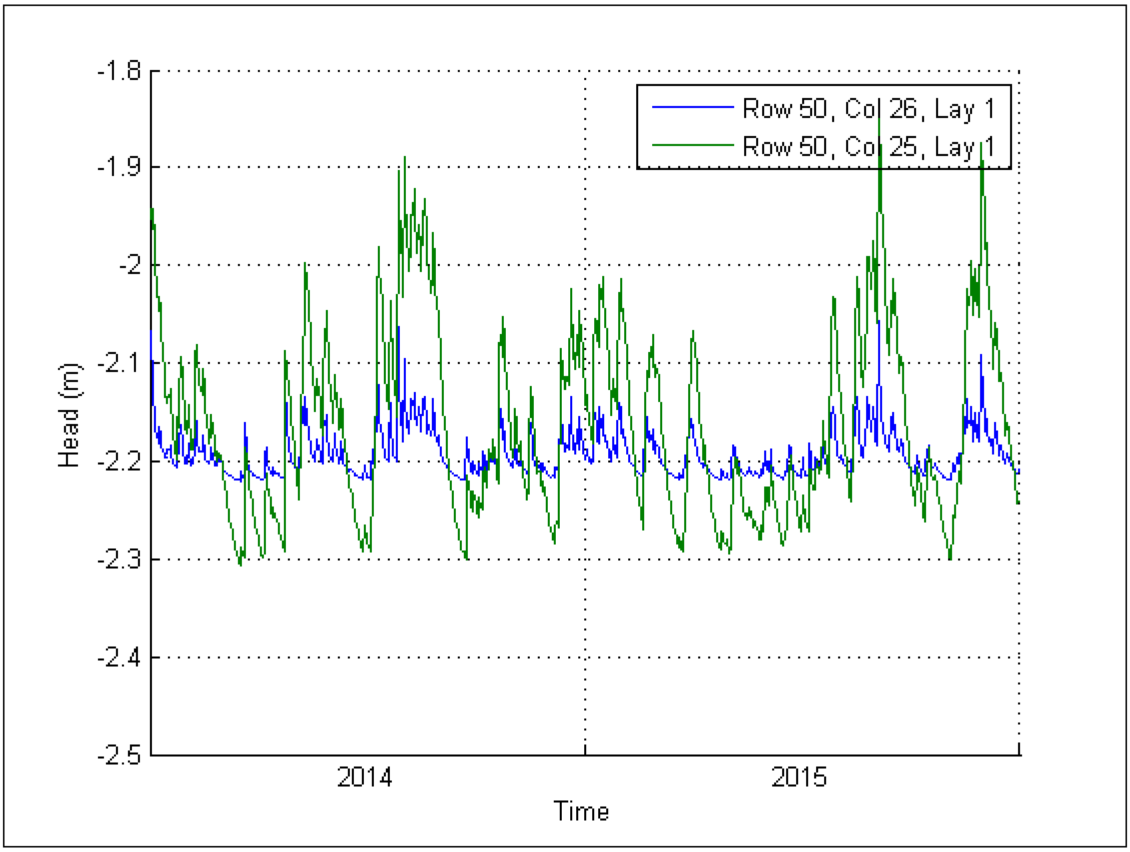


C1.7. *Modelled groundwater level over the period 2014-2015 for the drain distance of 12m and a hydraulic head in the drains of 65 cm below LS at location 1.*

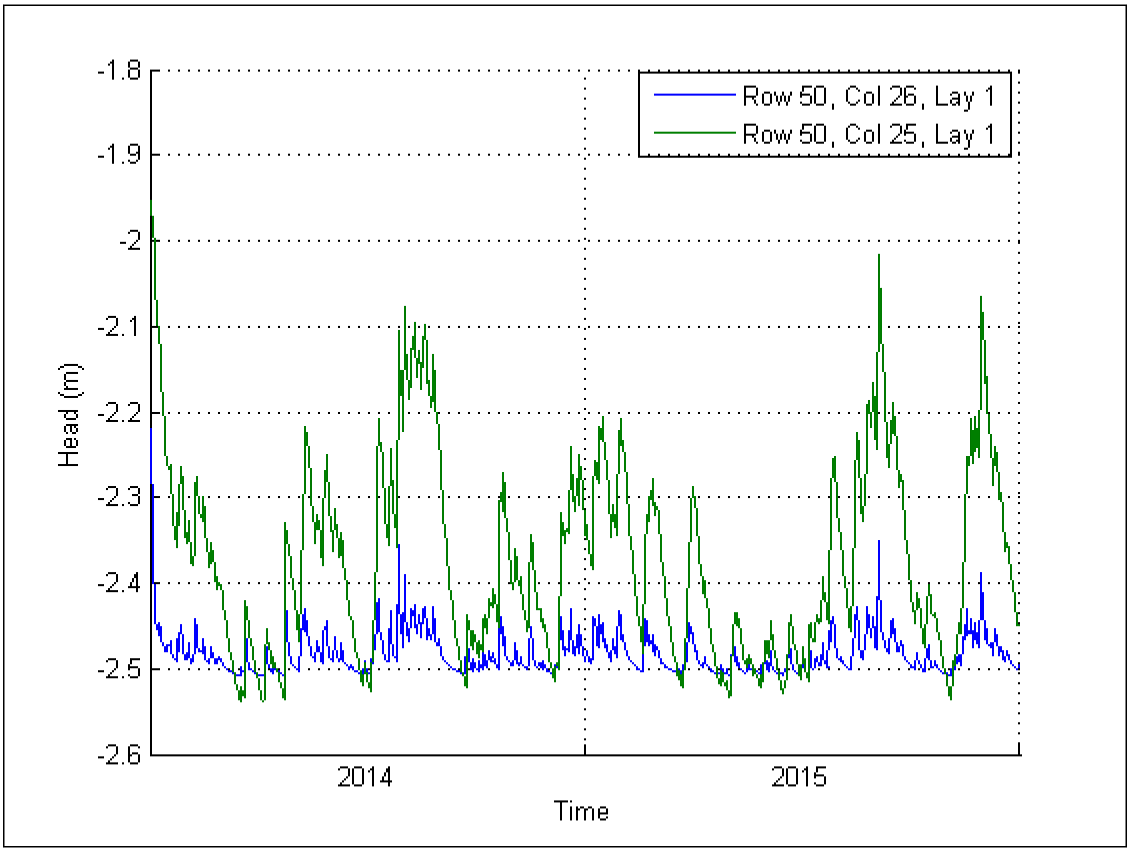
C2: Model 2



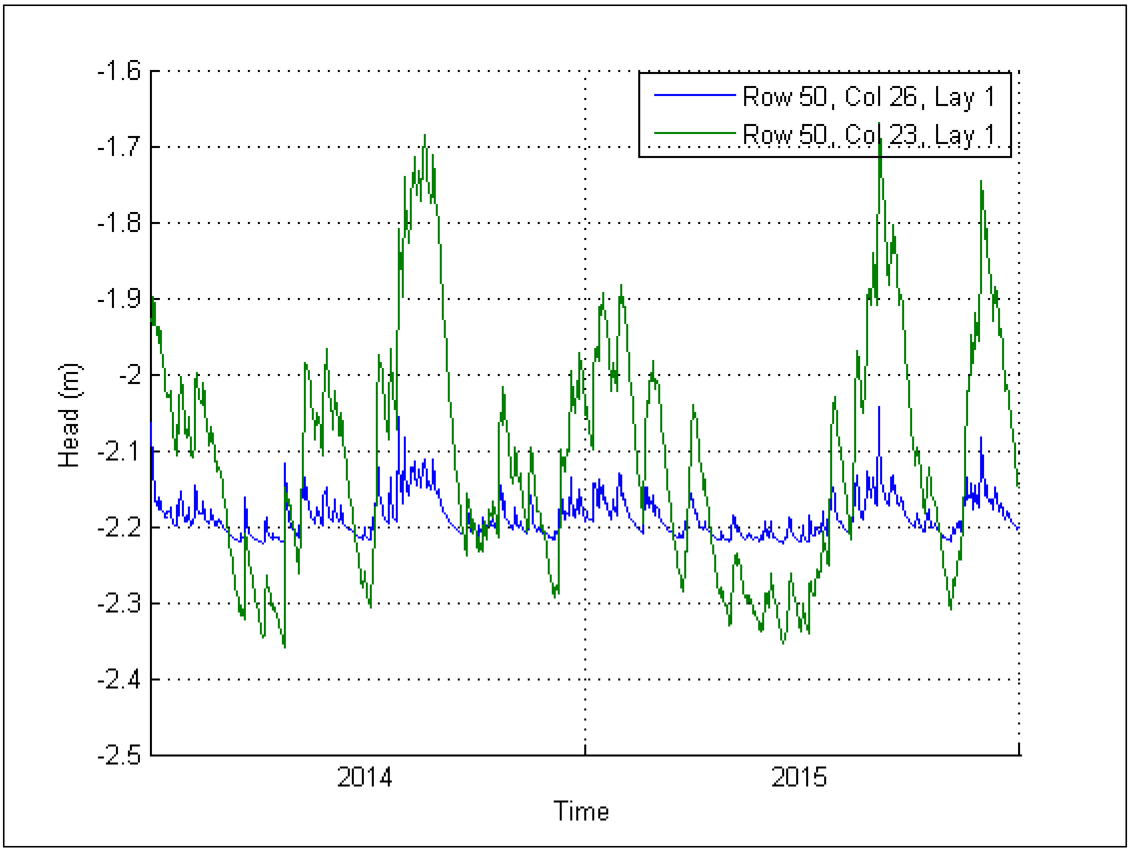
C2.1. *Modelled groundwater level over the period 2014-2015 for the situation without drains at location 2.*



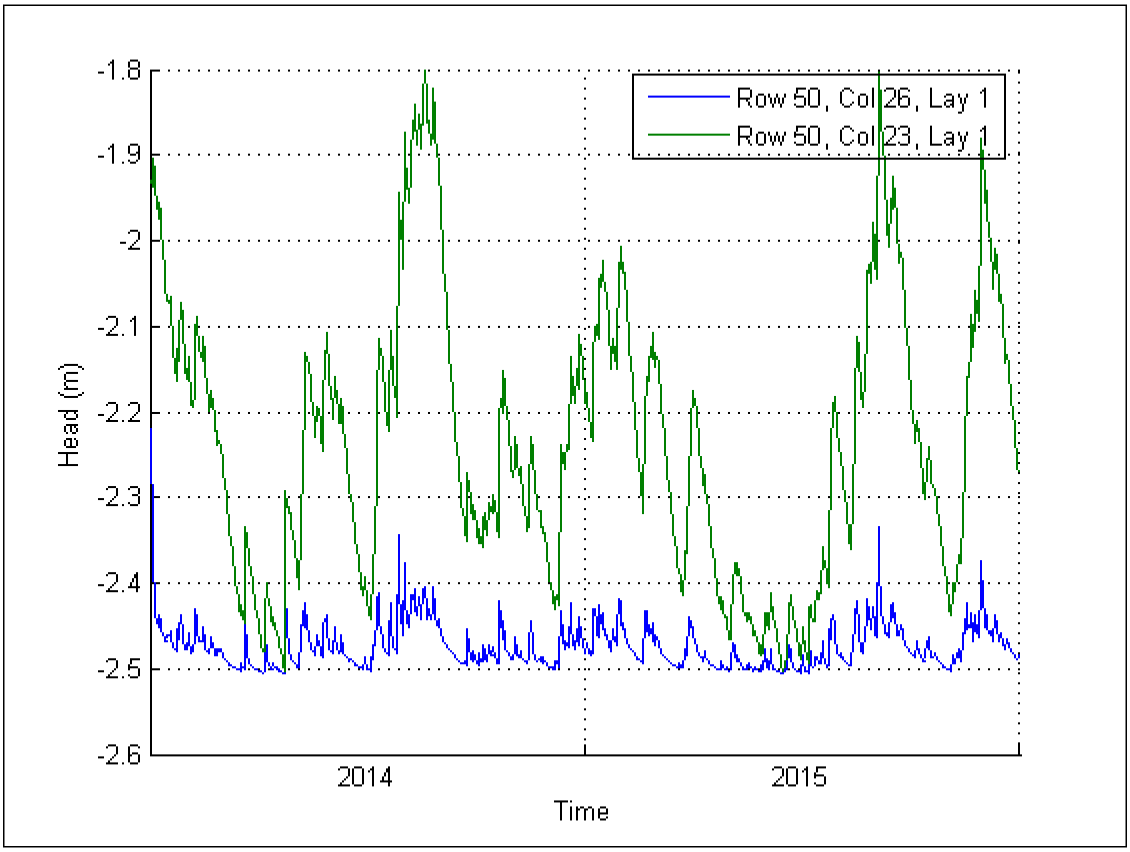
C2.2. *Modelled groundwater level over the period 2014-2015 for the drain distance of 3m and a hydraulic head in the drains of 35 cm below LS at location 2.*



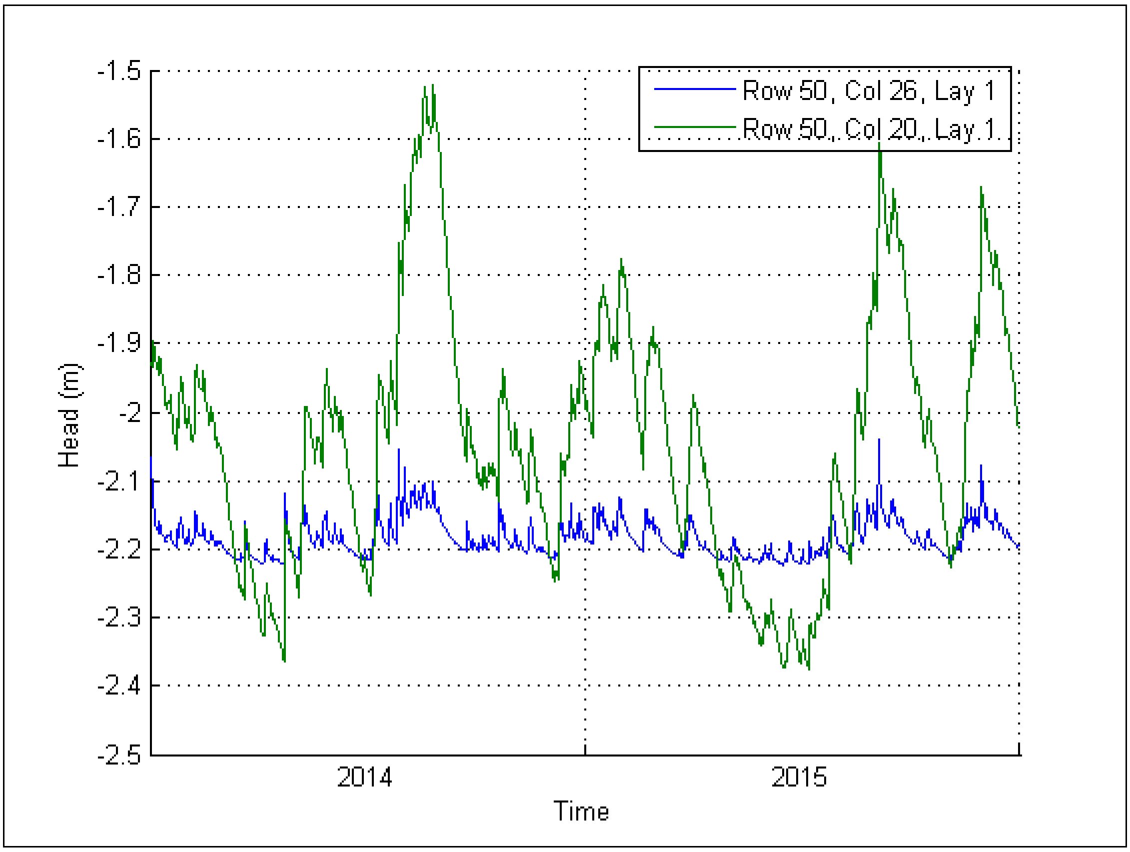
C2.3. *Modelled groundwater level over the period 2014-2015 for the drain distance of 3m and a hydraulic head in the drains of 65 cm below LS at location 2.*



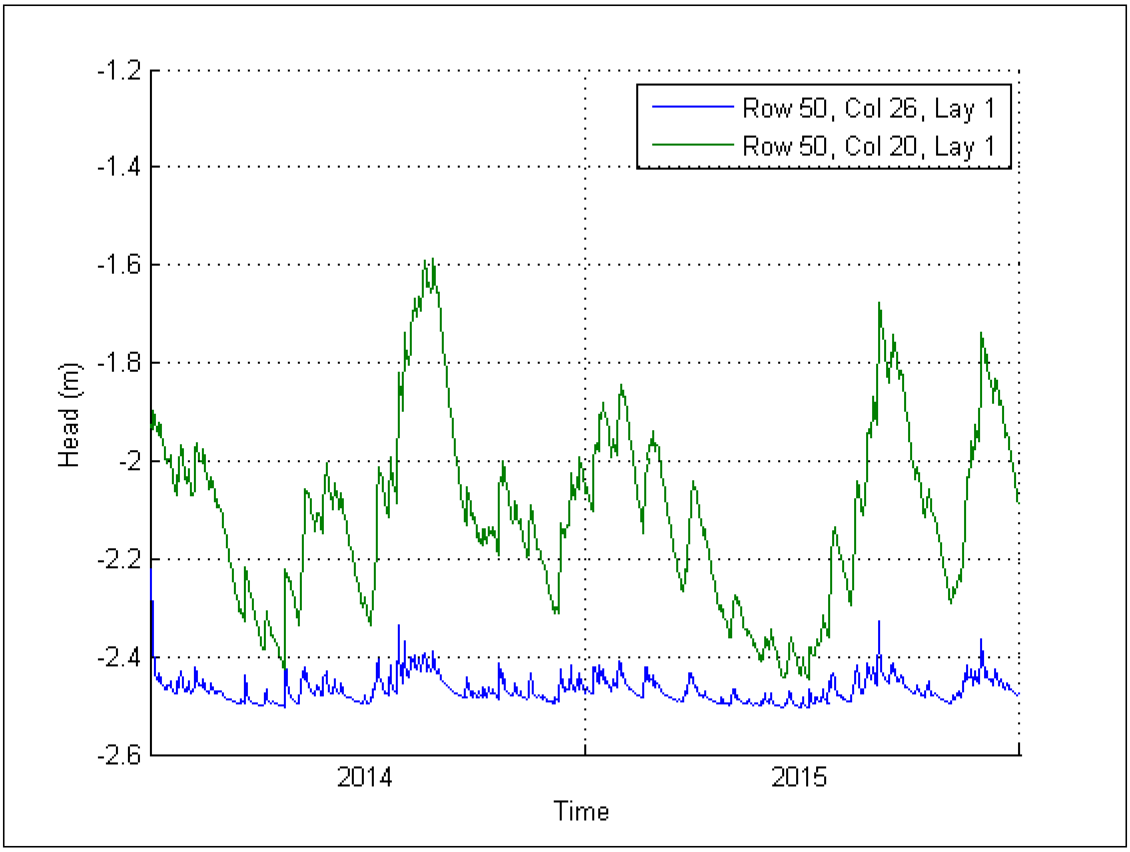
C2.4. *Modelled groundwater level over the period 2014-2015 for the drain distance of 6m and a hydraulic head in the drains of 35 cm below LS at location 2.*



C2.5. *Modelled groundwater level over the period 2014-2015 for the drain distance of 6m and a hydraulic head in the drains of 65 cm below LS at location 2.*

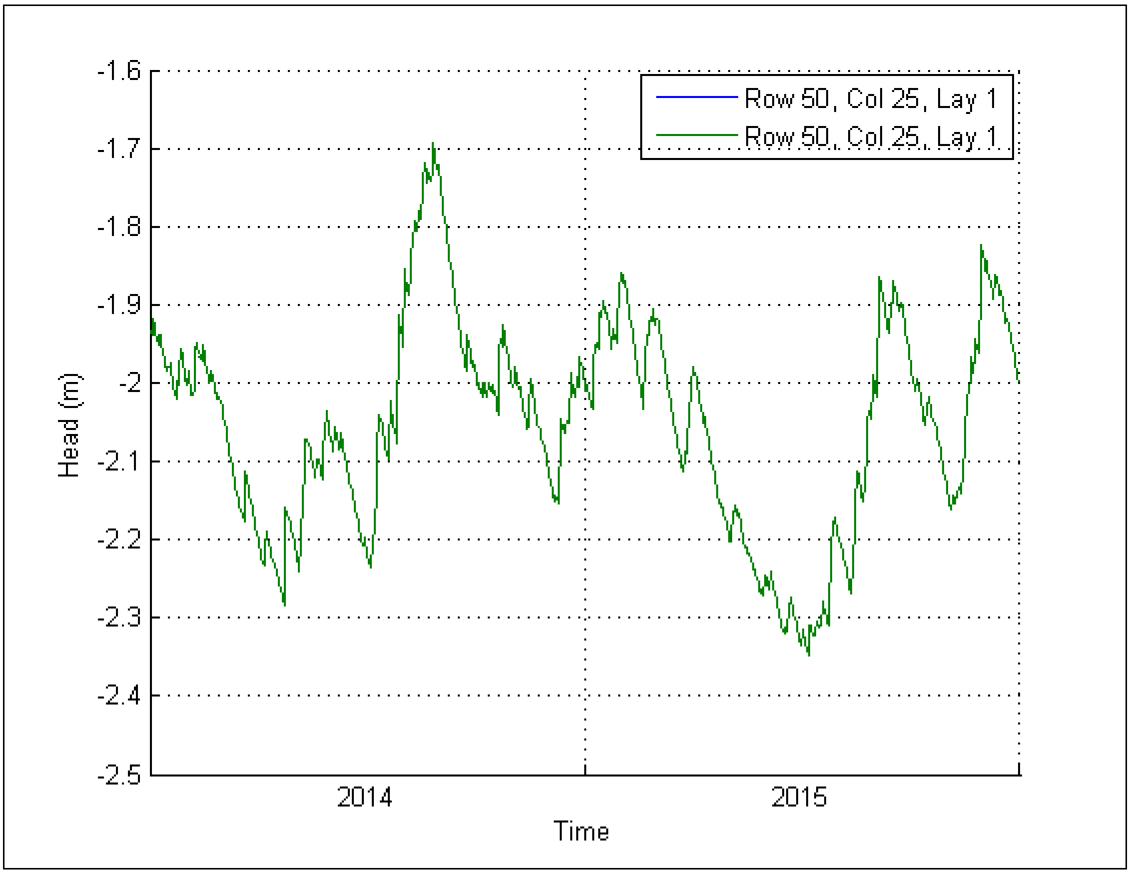


C2.6. *Modelled groundwater level over the period 2014-2015 for the drain distance of 12m and a hydraulic head in the drains of 35 cm below LS at location 2.*

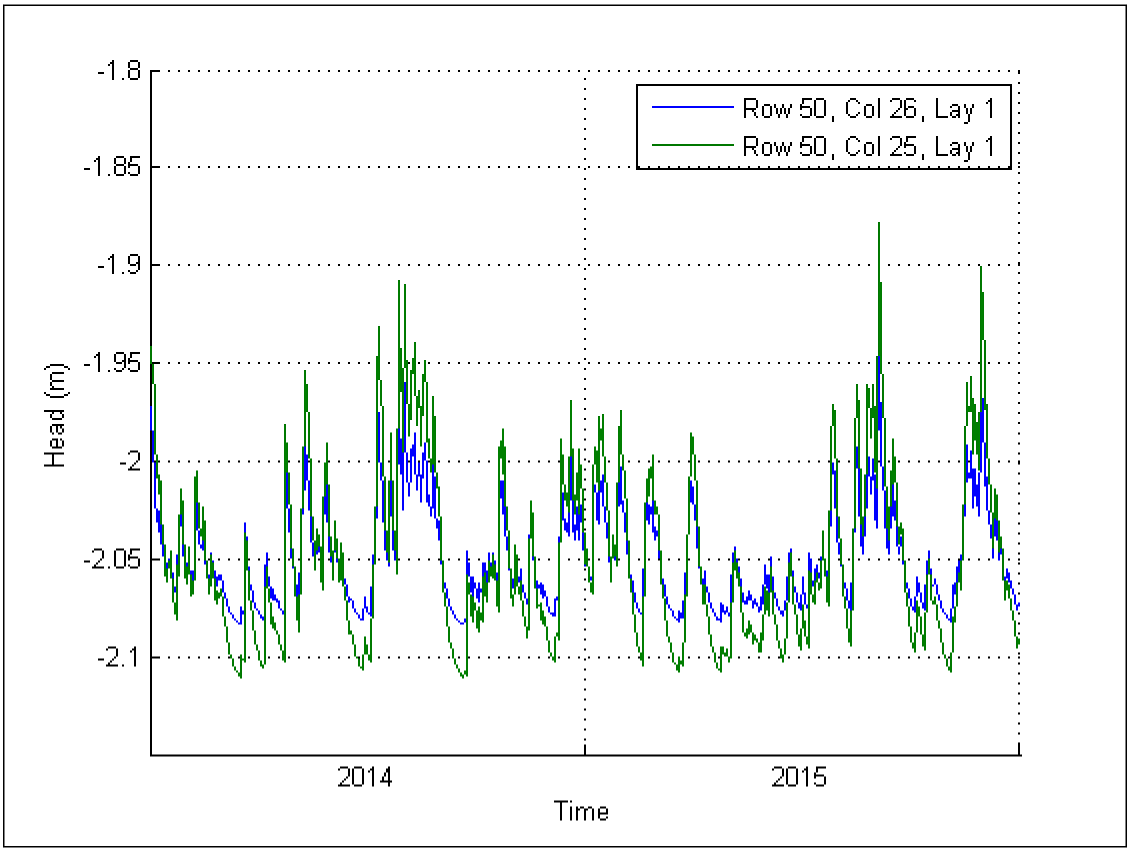


C2.7. *Modelled groundwater level over the period 2014-2015 for the drain distance of 12m and a hydraulic head in the drains of 65 cm below LS at location 2.*

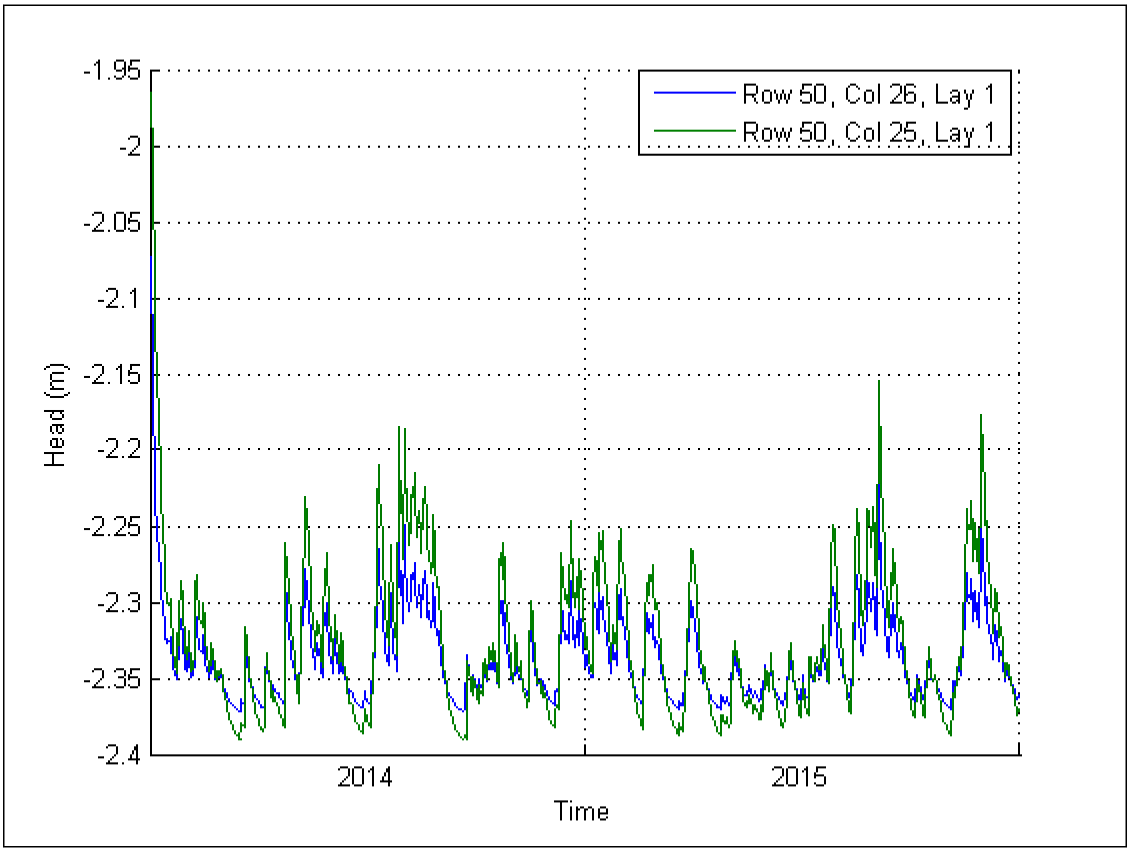
C3: Model 3



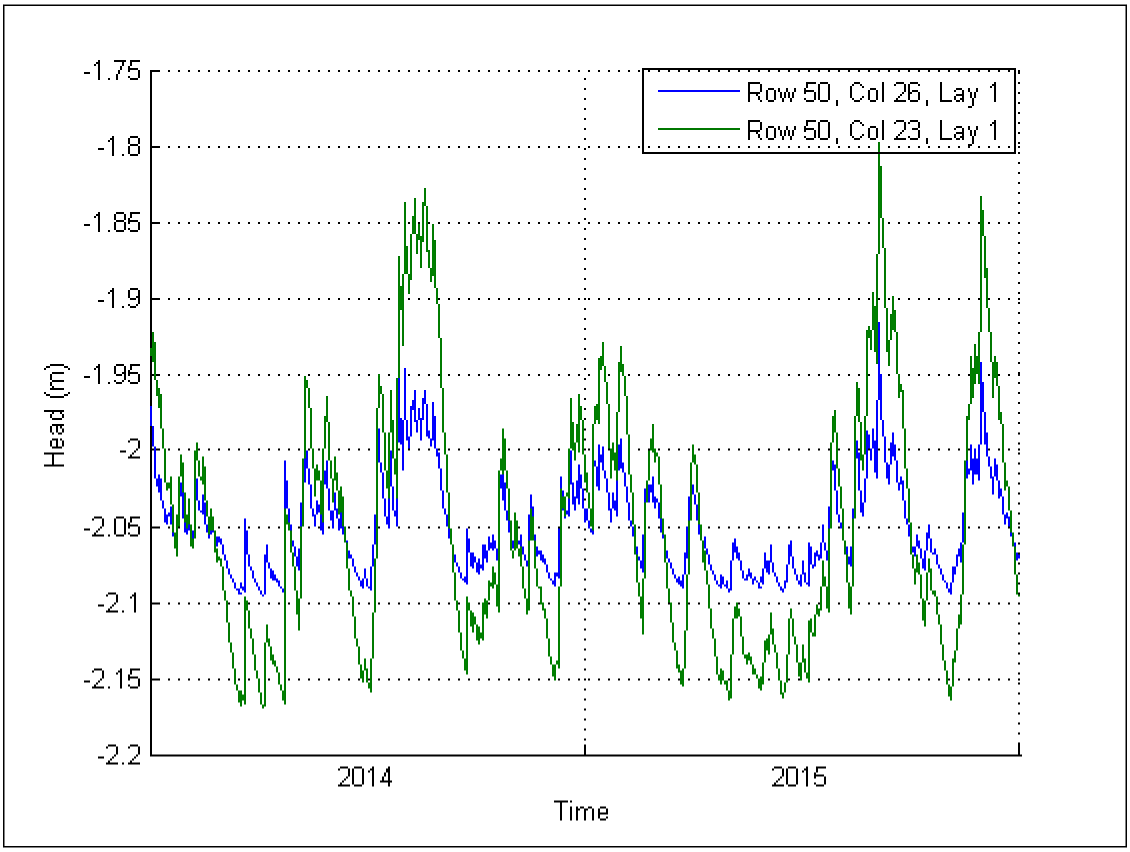
C3.1. *Modelled groundwater level over the period 2014-2015 for the situations without drains at location 3.*



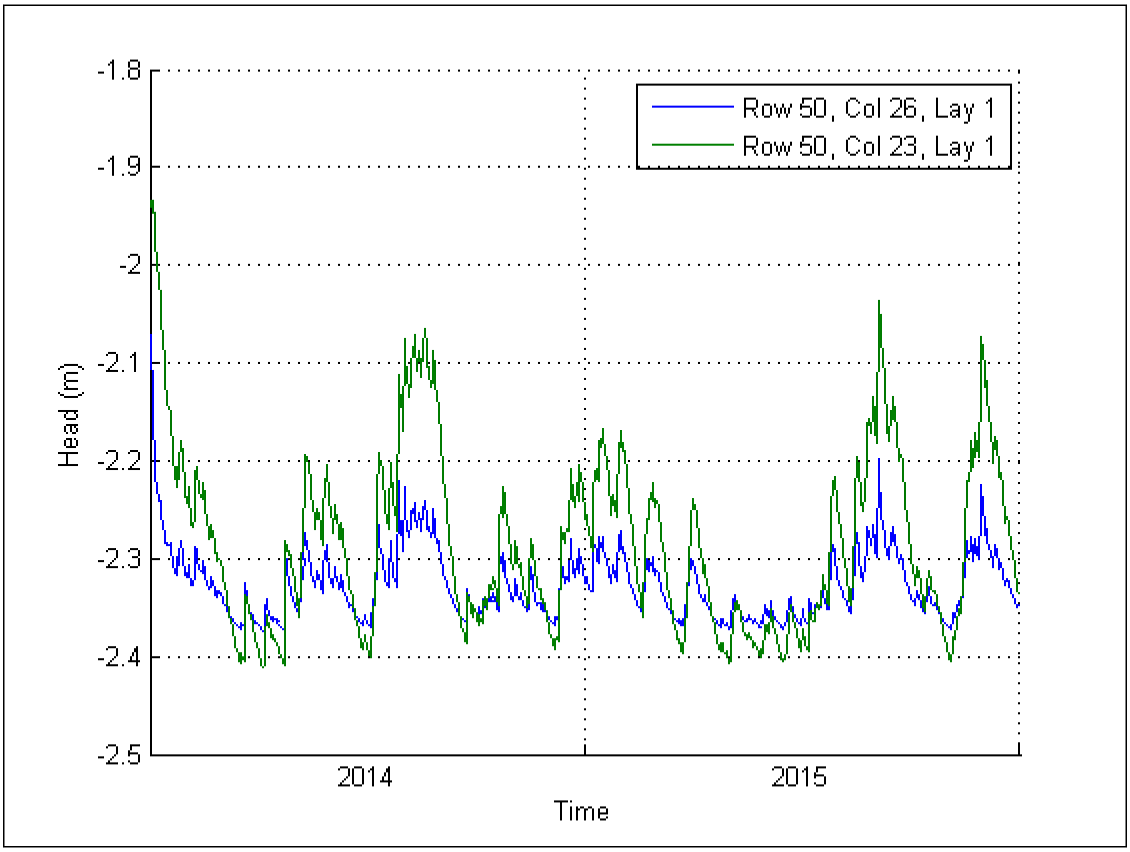
C3.2. *Modelled groundwater level over the period 2014-2015 for the drain distance of 3m and a hydraulic head in the drains of 35 cm below LS at location 3.*



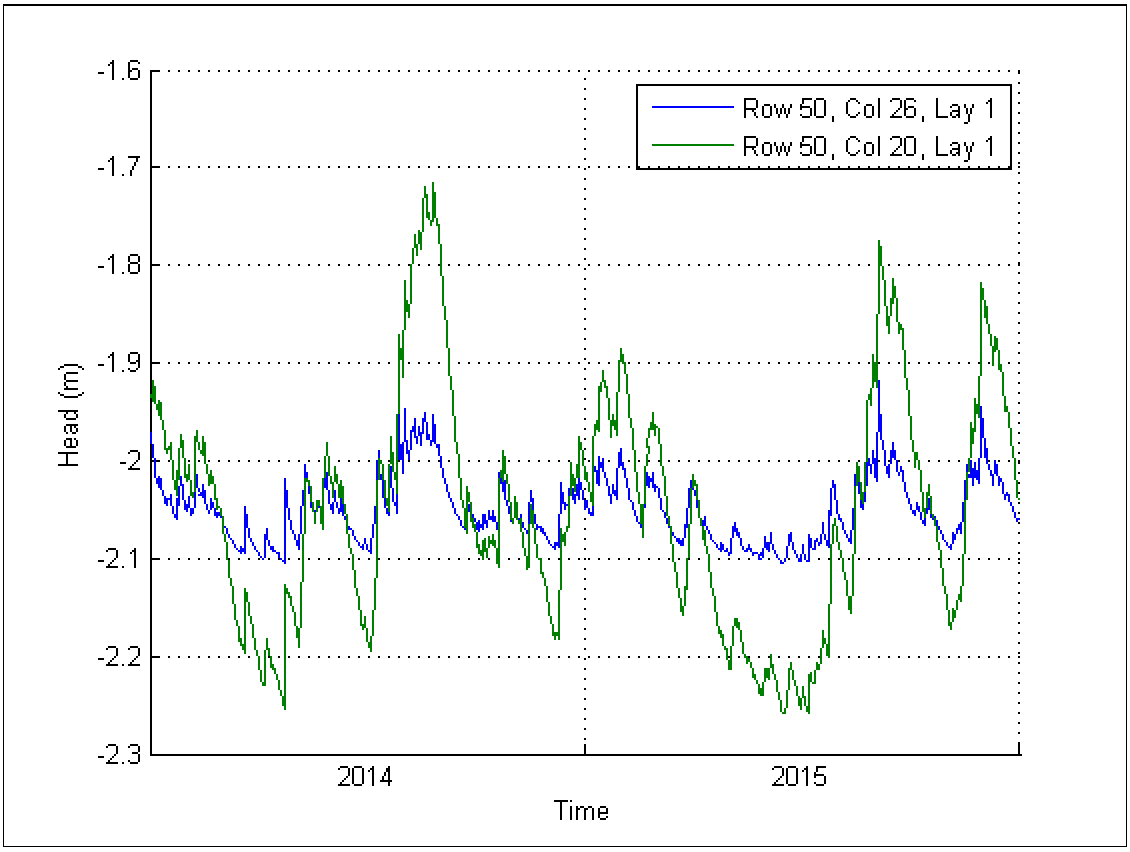
C3.3. *Modelled groundwater level over the period 2014-2015 for the drain distance of 3m and a hydraulic head in the drains of 65 cm below LS at location 3.*



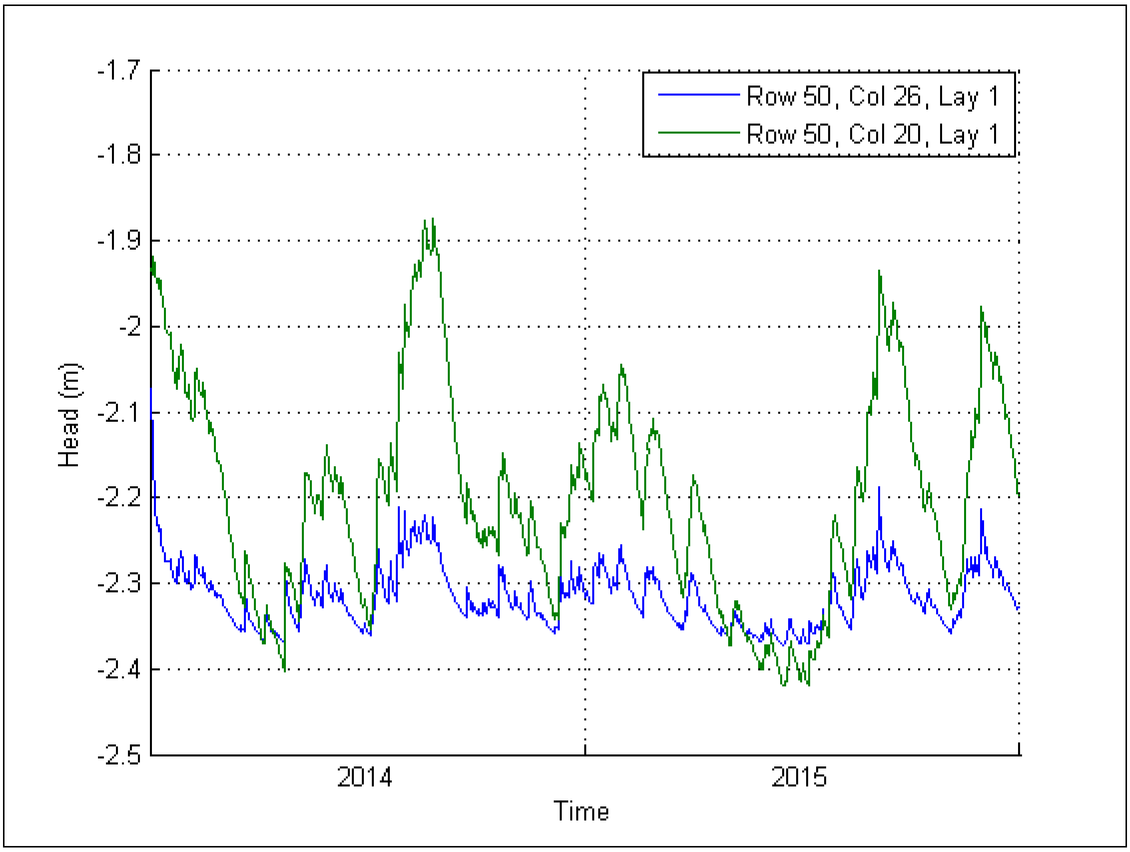
C3.4. *Modelled groundwater level over the period 2014-2015 for the drain distance of 6m and a hydraulic head in the drains of 35 cm below LS at location 3.*



C3.5. *Modelled groundwater level over the period 2014-2015 for the drain distance of 6m and a hydraulic head in the drains of 65 cm below LS at location 3.*

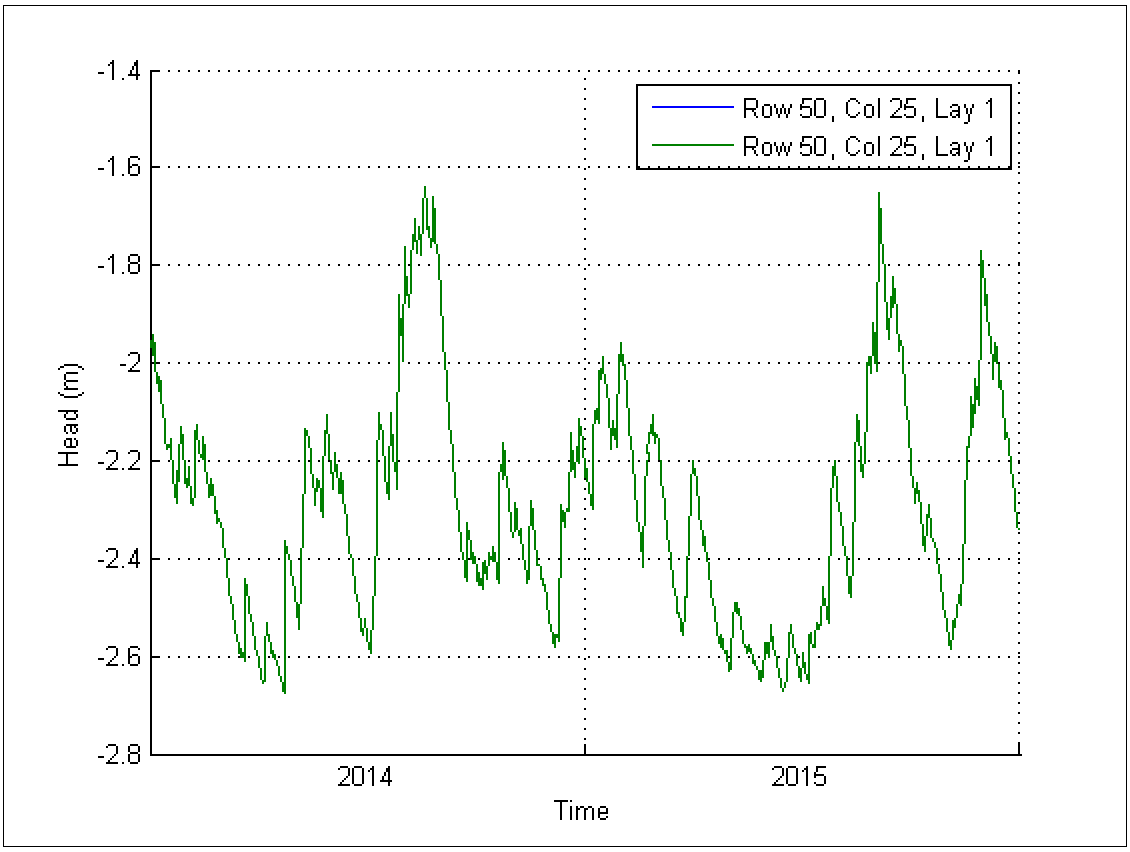


C3.6. *Modelled groundwater level over the period 2014-2015 for the drain distance of 12m and a hydraulic head in the drains of 35 cm below LS at location 3.*

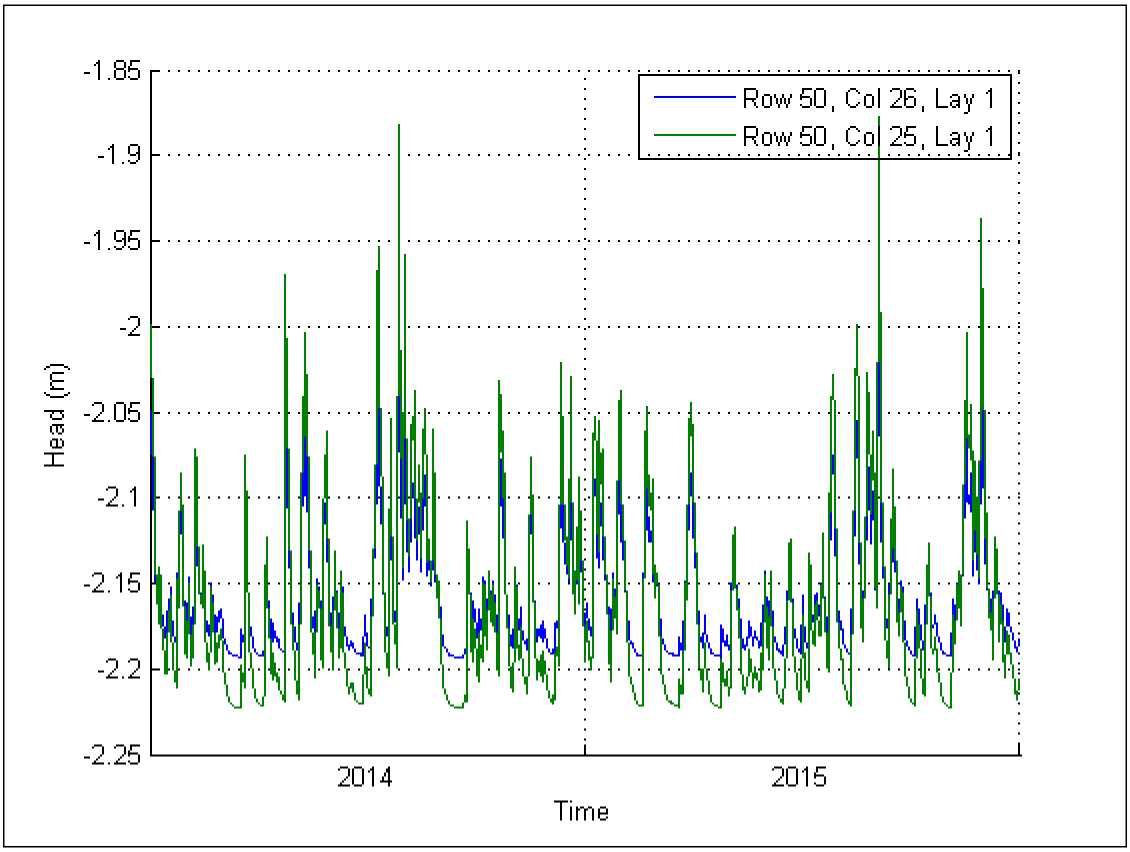


C3.7. *Modelled groundwater level over the period 2014-2015 for the drain distance of 12m and a hydraulic head in the drains of 65 cm below LS at location 3.*

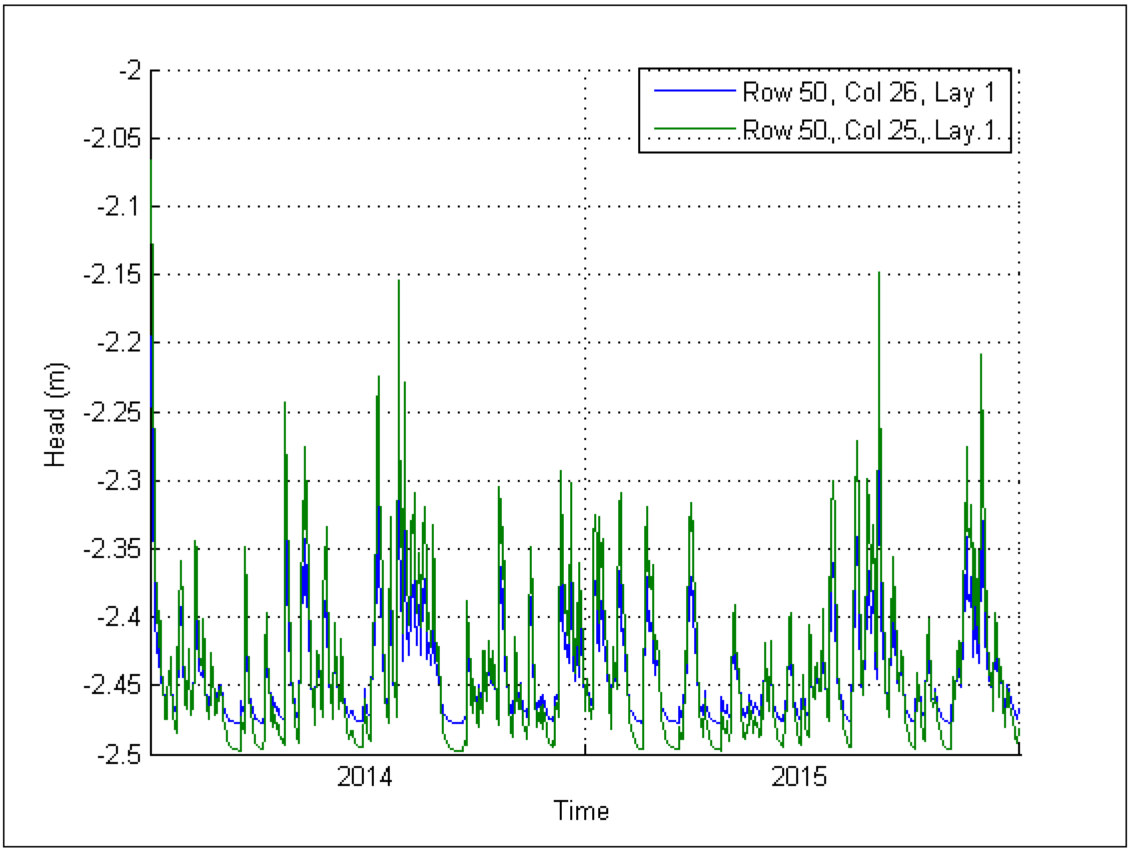
C4. Model 4



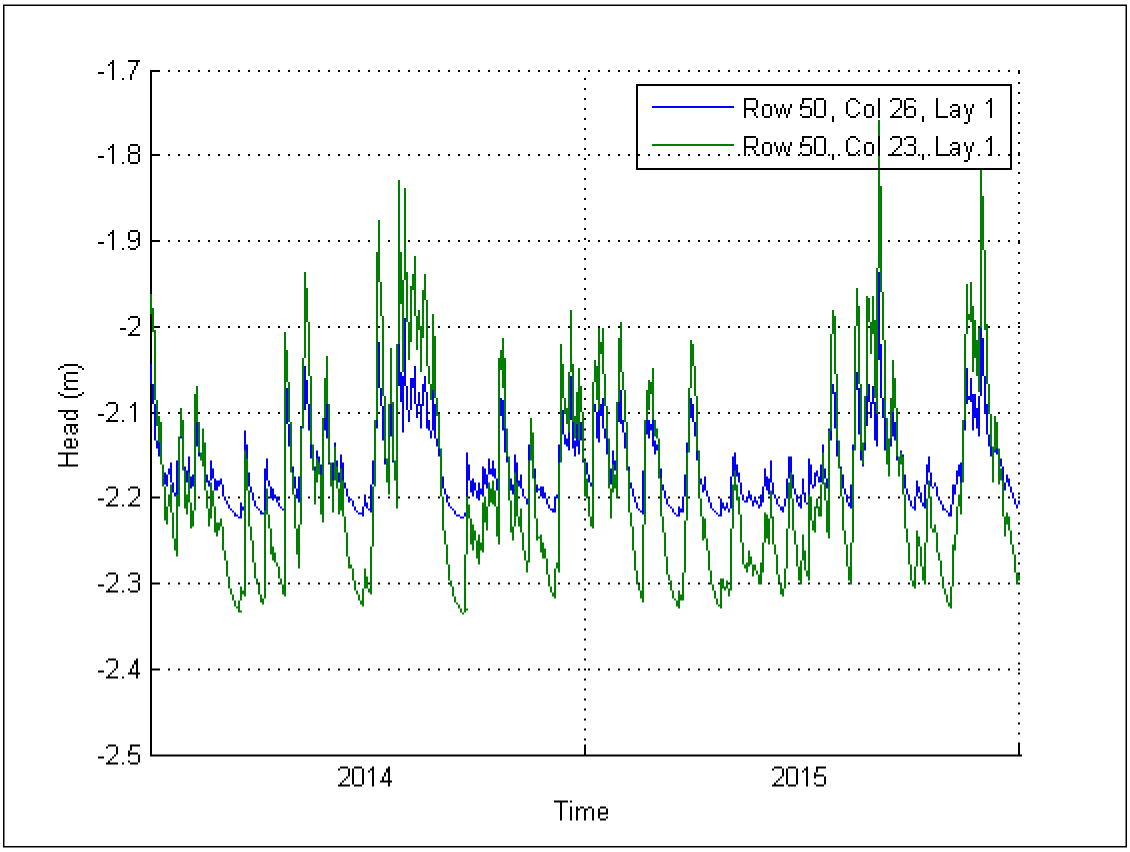
C4.1. *Modelled groundwater level over the period 2014-2015 for the situations without drains at location 4.*



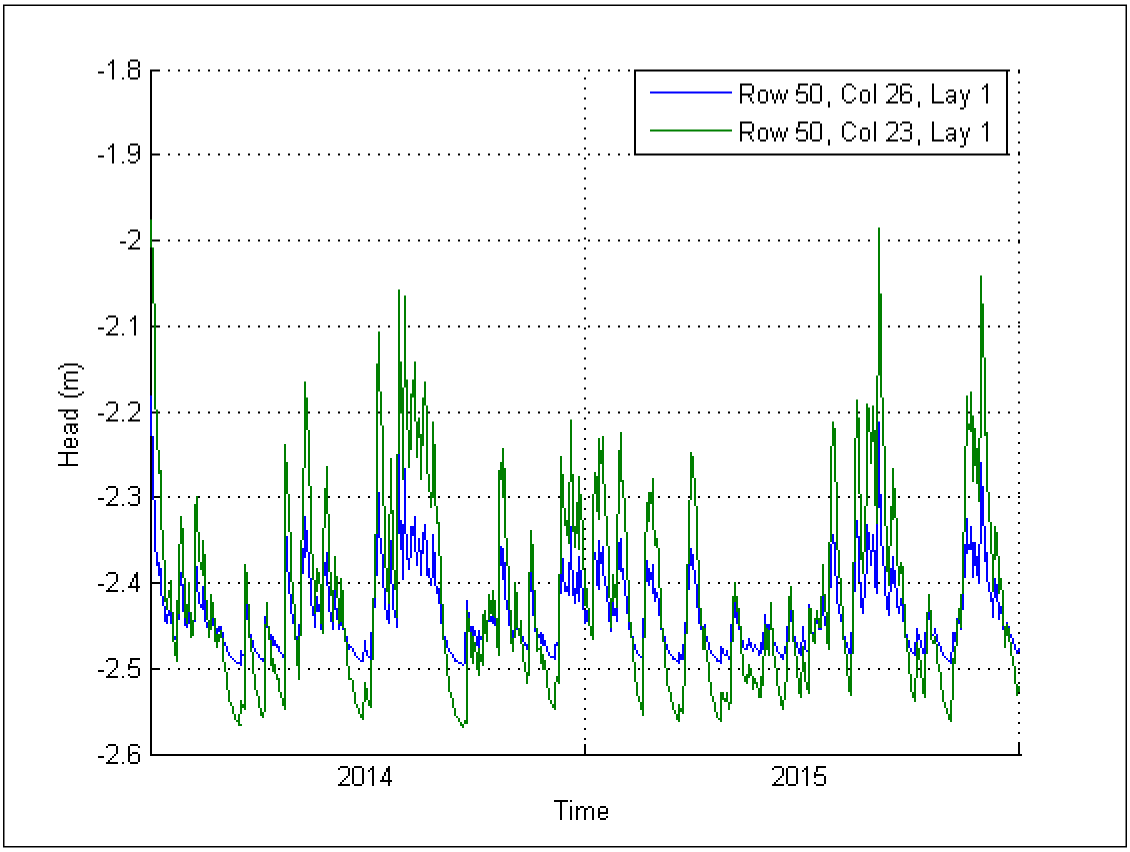
C4.2. *Modelled groundwater level over the period 2014-2015 for the drain distance of 3m and a hydraulic head in the drains of 35 cm below LS at location 4.*



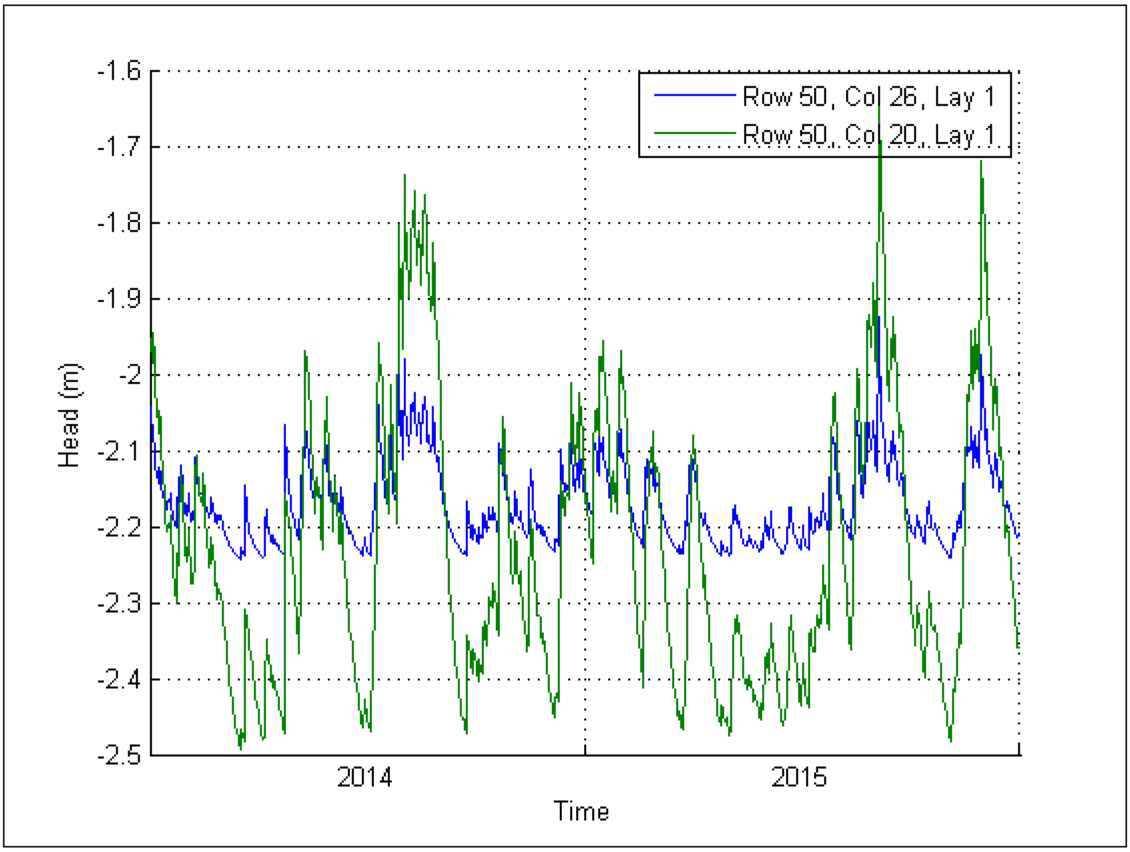
C4.3. *Modelled groundwater level over the period 2014-2015 for the drain distance of 3m and a hydraulic head in the drains of 65 cm below LS at location 4.*



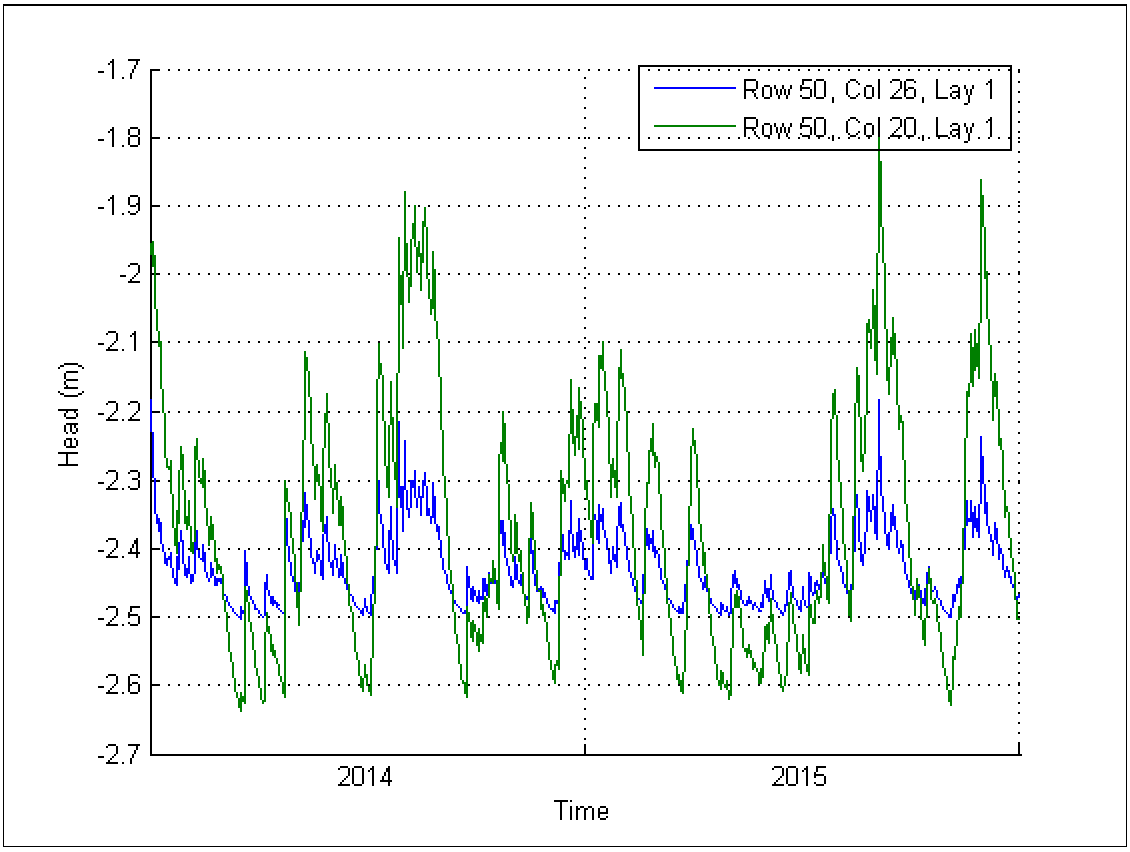
***C4.4.** Modelled groundwater level over the period 2014-2015 for the drain distance of 6m and a hydraulic head in the drains of 35 cm below LS at location 4.*



***C4.5.** Modelled groundwater level over the period 2014-2015 for the drain distance of 6m and a hydraulic head in the drains of 65 cm below LS at location 4.*

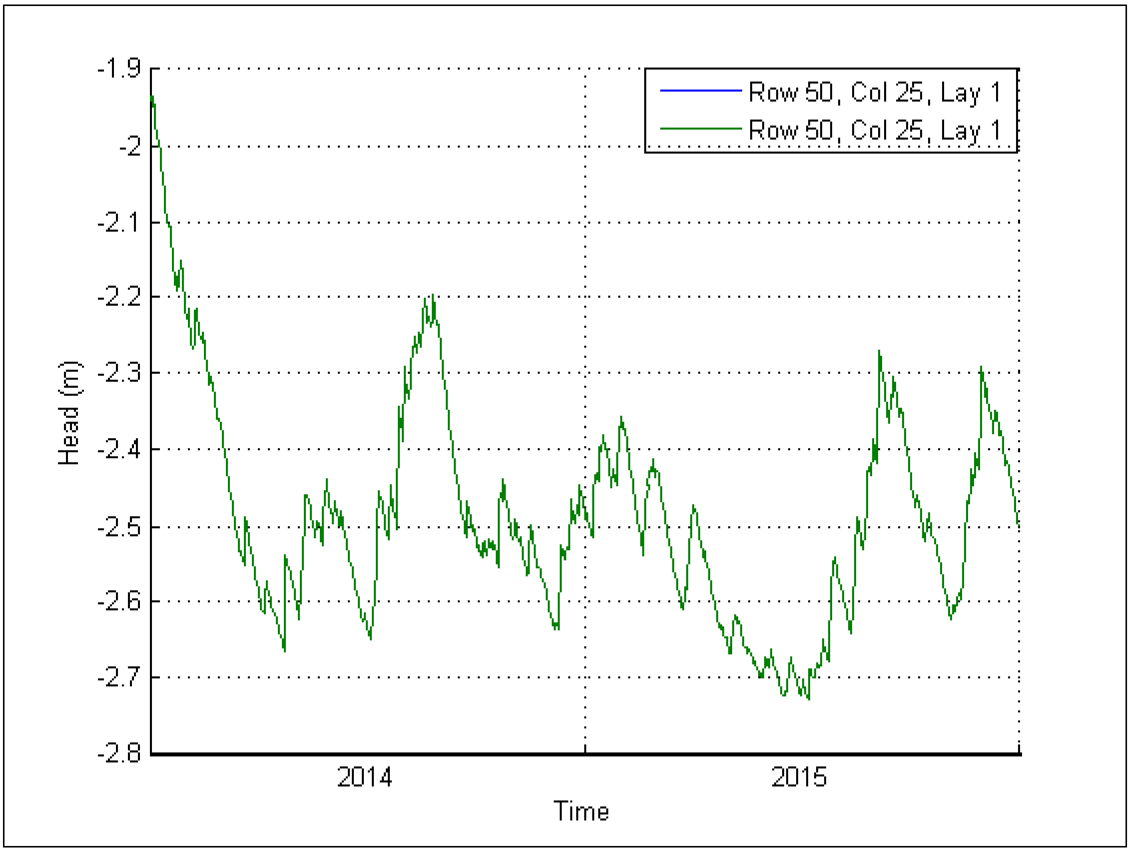


C4.6. *Modelled groundwater level over the period 2014-2015 for the drain distance of 12m and a hydraulic head in the drains of 35 cm below LS at location 4.*

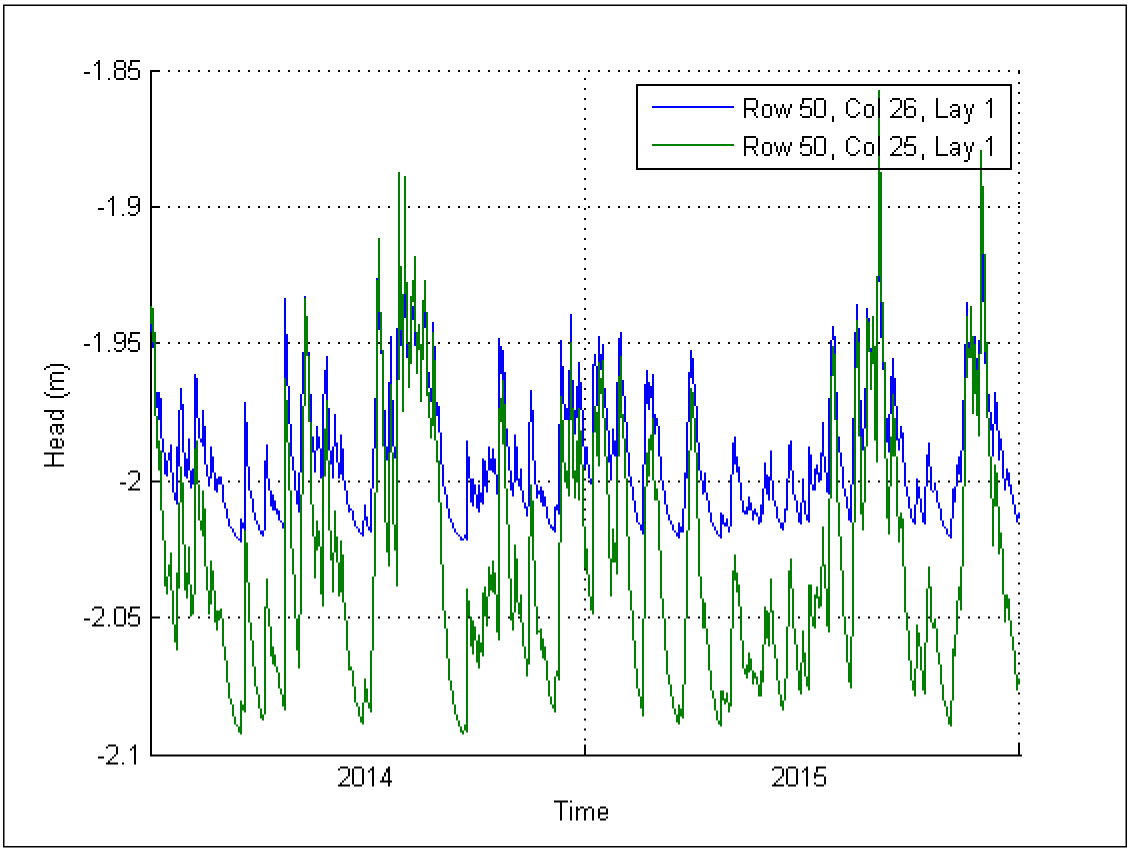


C4.7. *Modelled groundwater level over the period 2014-2015 for the drain distance of 12m and a hydraulic head in the drains of 65 cm below LS at location 4.*

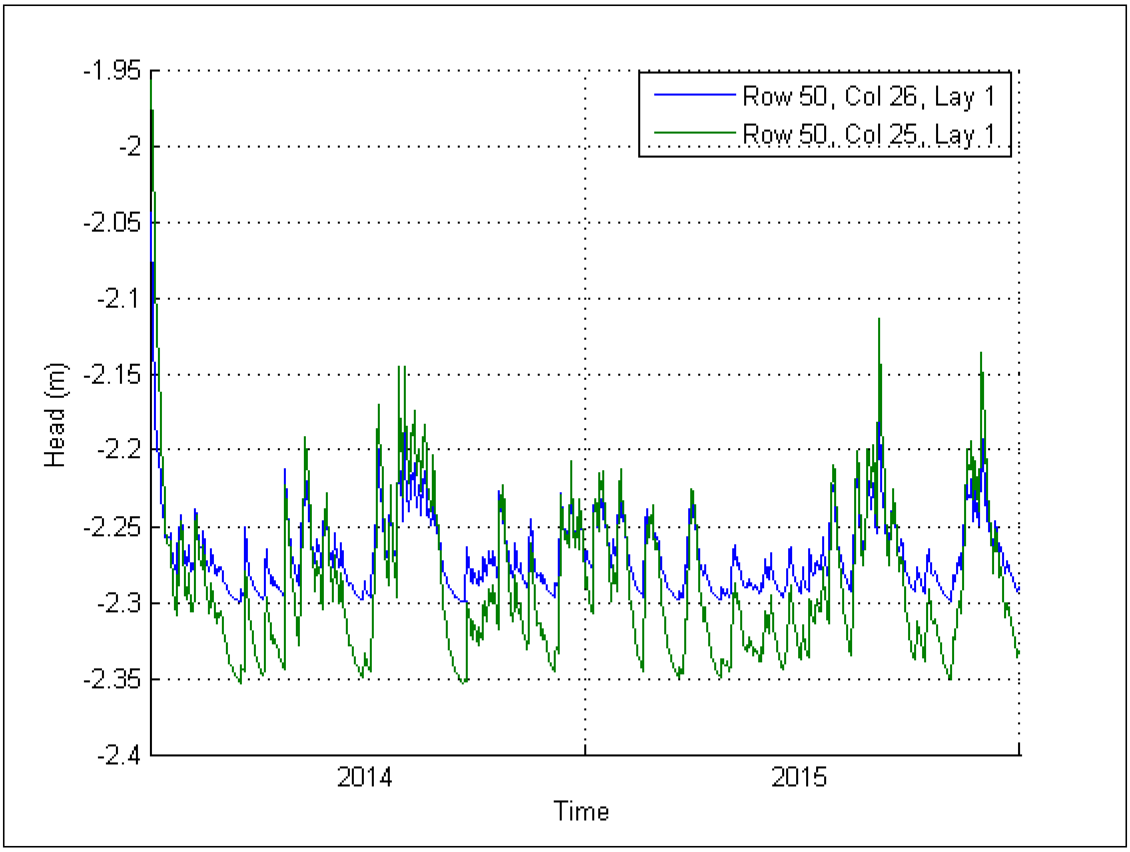
C5. Model 5



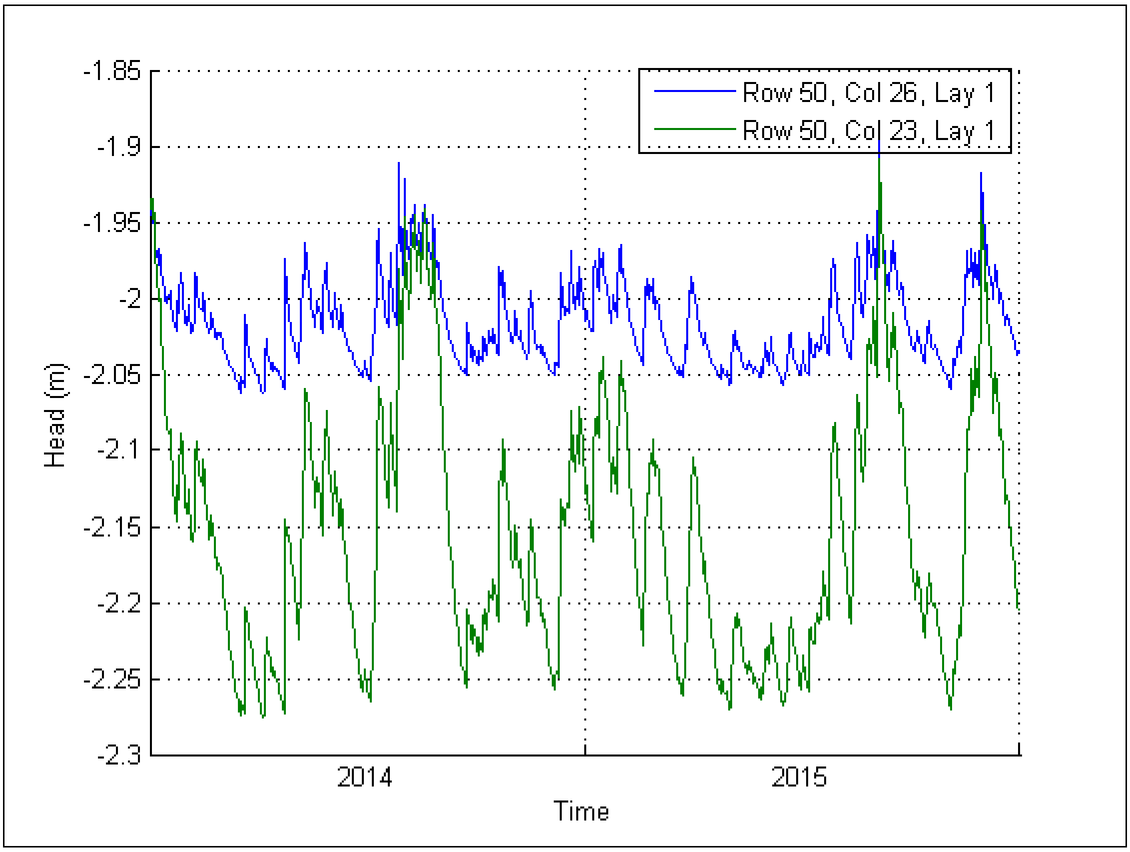
C5.1. *Modelled groundwater level over the period 2014-2015 for the situations without drains at location 5.*



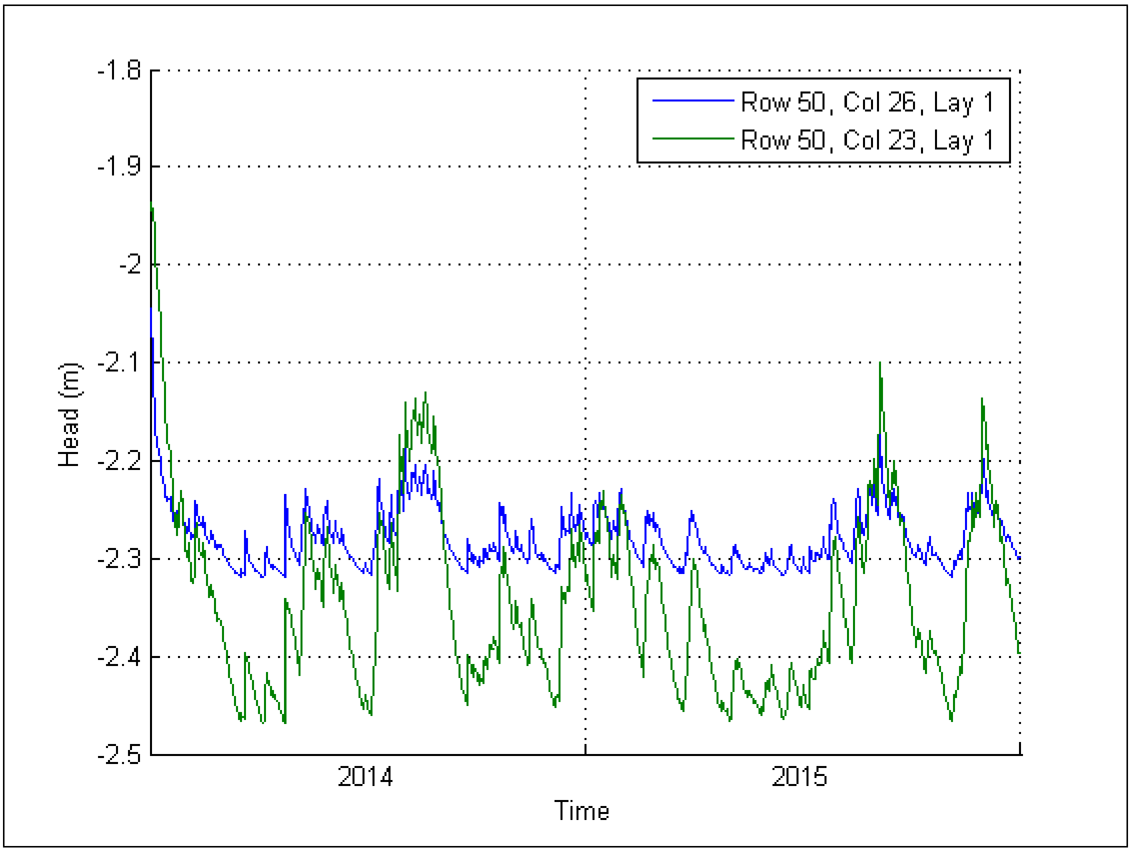
C5.2. *Modelled groundwater level over the period 2014-2015 for the drain distance of 3m and a hydraulic head in the drains of 35 cm below LS at location 5.*



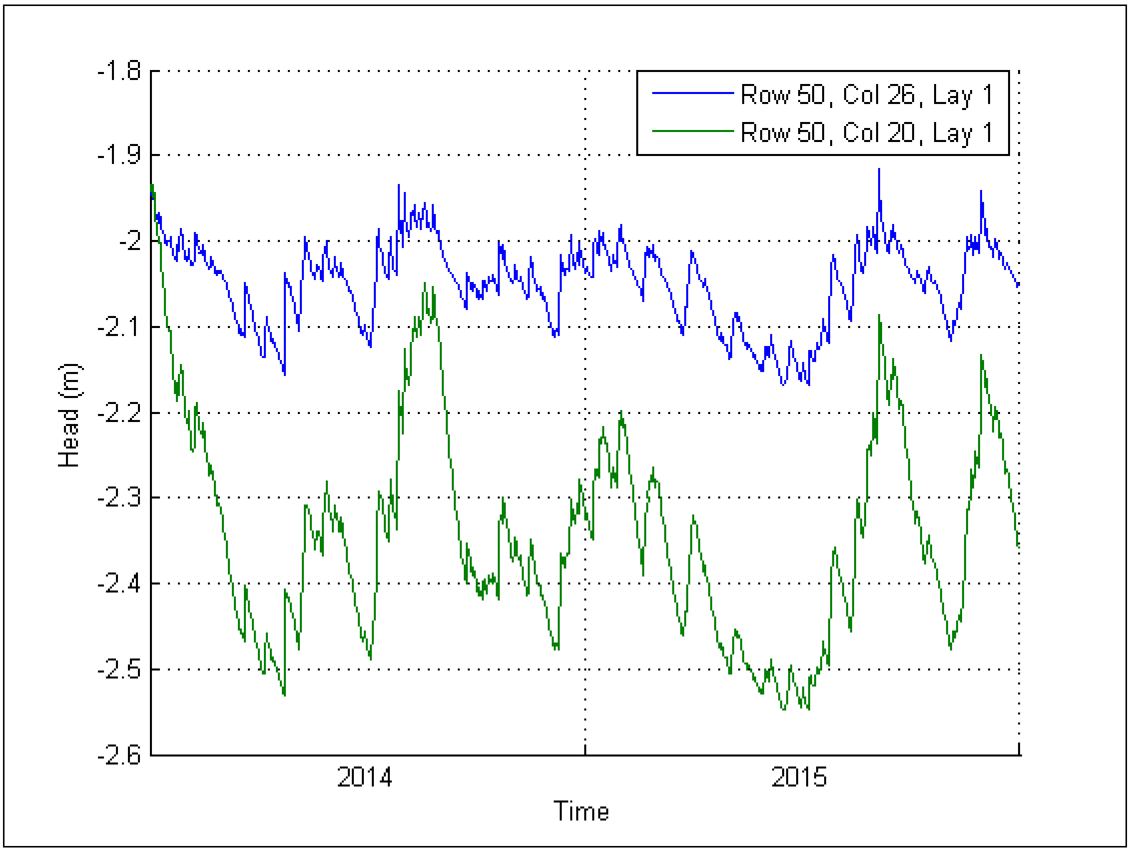
C5.3. *Modelled groundwater level over the period 2014-2015 for the drain distance of 3m and a hydraulic head in the drains of 65 cm below LS at location 5.*



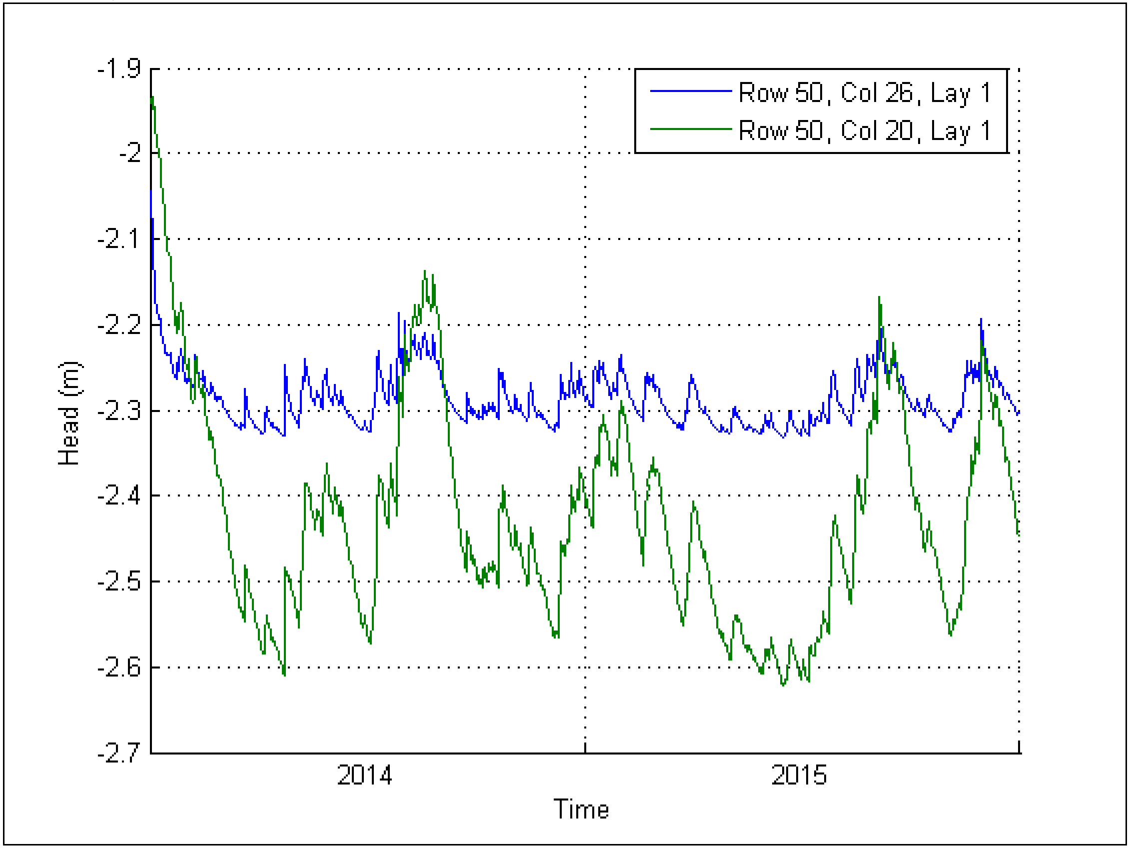
C5.4. *Modelled groundwater level over the period 2014-2015 for the drain distance of 6m and a hydraulic head in the drains of 35 cm below LS at location 5.*



C5.5. *Modelled groundwater level over the period 2014-2015 for the drain distance of 6m and a hydraulic head in the drains of 65 cm below LS at location 5.*



C5.6. *Modelled groundwater level over the period 2014-2015 for the drain distance of 12m and a hydraulic head in the drains of 35 cm below LS at location 5.*



C5.7. *Modelled groundwater level over the period 2014-2015 for the drain distance of 12m and a hydraulic head in the drains of 65 cm below LS at location 5.*

D: Additional tables and figures from research results

PGM alternative	Model 1	Model 2	Model 3	Model 4	Model 5
	Deviation (m)	Deviation (m)	Deviation (m)	Deviation (m)	Deviation (m)
No drains	0,586	0,335	0,144	0,253	0,504
3 m; 0.35 m; col. 26	0,034	0,063	0,056	0,055	0,026
3 m; 0.35 m; col. 25	0,082	0,129	0,067	0,068	0,054
6 m; 0.35 m; col. 26	0,160	0,068	0,060	0,059	0,033
6 m; 0.35 m; col. 23	0,296	0,211	0,096	0,110	0,175
12 m; 0.35 m; col. 26	0,243	0,072	0,061	0,061	0,069
12 m; 0.35 m; col. 20	0,487	0,279	0,130	0,180	0,364
3 m; 0.65 m; col. 26	0,289	0,234	0,239	0,245	0,269
3 m; 0.65 m; col. 25	0,317	0,167	0,231	0,244	0,291
6 m; 0.65 m; col. 26	0,309	0,225	0,229	0,240	0,280
6 m; 0.65 m; col. 23	0,405	0,164	0,204	0,242	0,355
12 m; 0.65 m; col. 26	0,325	0,218	0,218	0,235	0,287
12 m; 0.65 m; col. 20	0,515	0,238	0,160	0,247	0,441

D1. *The calculated standard deviation (relative to the target value) for the groundwater levels for all locations for different PGM alternatives.*

Coordinates	X	Y	Number of drilling
Calibration	122861	463544	B31E2623
1	123182	462545	B31E1354
2	122540	463483	“Appelboor”
3	123213	463777	B31E0458
4	123707	464013	B31E0579
5	123806	463034	B31E0455

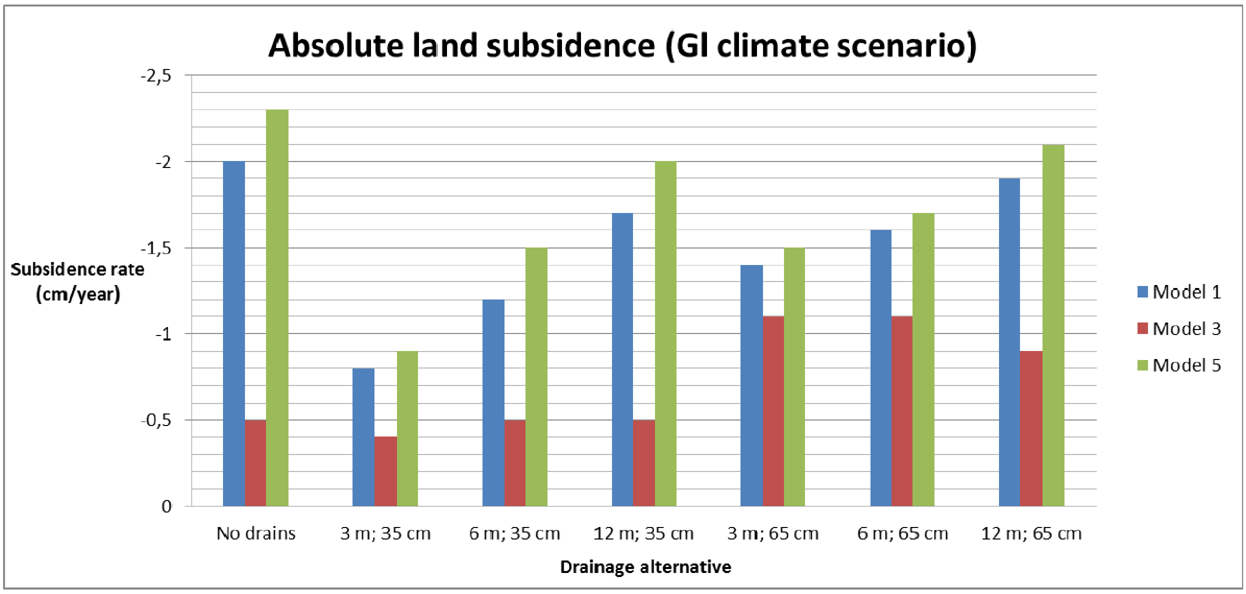
D2. *Coordinates of used core data.*

		No drains (m –NAP)	3 m; -0.35 m (m –NAP)	6 m; -0.35 m (m –NAP)	12 m; -0.35 m (m –NAP)	3 m; -0.65 m (m –NAP)	6 m; -0.65 m (m –NAP)	12 m; -0.65 m (m –NAP)
Calibration	GLG	2.46	-	-	-	-	-	-
(LS: 172 cm -NAP)	GHG	1.84	-	-	-	-	-	-
Model 1	GLG	2.79	2.22	2.48	2.68	2.46	2.57	2.71
(LS: 160 cm -NAP)	GHG	2.48	2.08	2.20	2.38	2.33	2.36	2.42
Model 2	GLG	2.21	2.27	2.27	2.24	2.49	2.40	2.29
(LS: 175 cm -NAP)	GHG	1.57	1.96	1.77	1.64	2.14	1.89	1.70
Model 3	GLG	2.17	2.10	2.14	2.16	2.38	2.38	2.33
(LS: 160 cm -NAP)	GHG	1.80	1.95	1.87	1.79	2.23	2.11	1.95
Model 4	GLG	2.54	2.22	2.32	2.42	2.50	2.55	2.56
(LS: 170 cm -NAP)	GHG	1.77	2.02	1.94	1.84	2.28	2.17	1.98
Model 5	GLG	2.59	2.08	2.24	2.46	2.34	2.44	2.55
(LS: 150 cm -NAP)	GHG	2.27	1.93	1.98	2.12	2.19	2.17	2.20

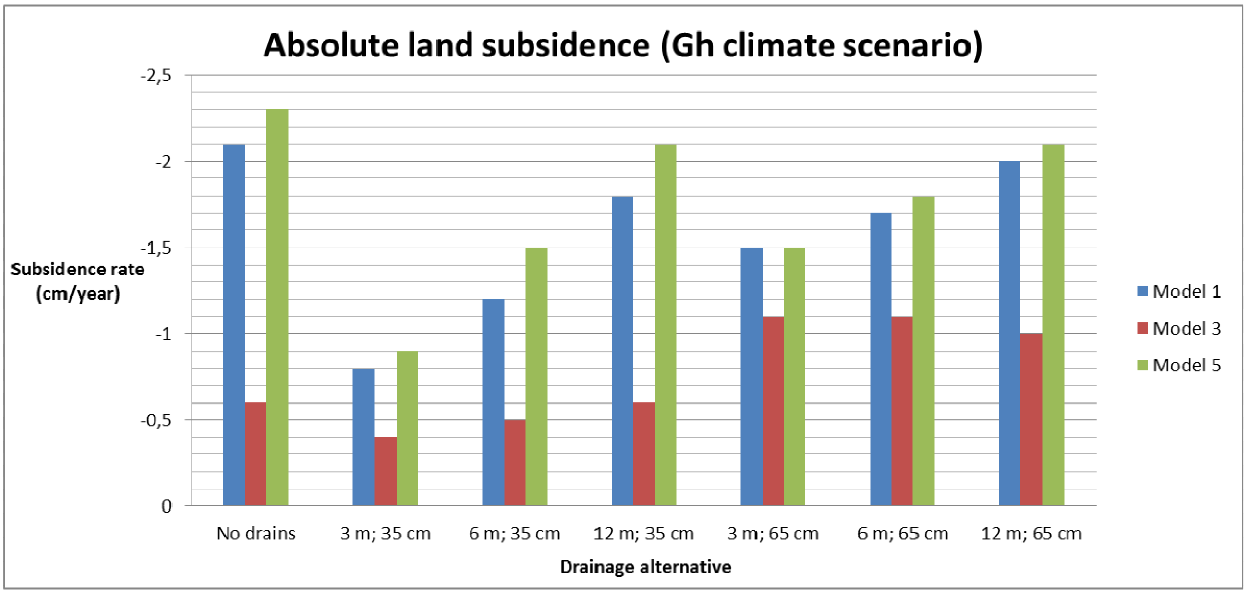
D3. *The calculated GHG and GLG value displayed in meter below NAP for all models and different PGM alternatives.*

KNMI '14 Scenario	Model	No drains (cm/year)	3 m; -35 cm (cm/year)	6 m; -35 cm (cm/year)	12 m; -35 cm (cm/year)	3 m; -65 cm (cm/year)	6 m; -65 cm (cm/year)	12 m; -65 cm (cm/year)
Scenario Gl	**Model 1**	-2.0	-0.8	-1.2	-1.7	-1.4	-1.6	-1.9
	Model 2	0	0	0	0	0	0	0
	Model 3	-0.5	-0.4	-0.5	-0.5	-1.1	-1.1	-0.9
	Model 4	0	0	0	0	0	0	0
	Model 5	-2.3	-0.9	-1.5	-2.0	-1.5	-1.7	-2.1
Scenario Gh	**Model 1**	-2.1	-0.8	-1.2	-1.8	-1.5	-1.7	-2.0
	Model 2	0	0	0	0	0	0	0
	Model 3	-0.6	-0.4	-0.5	-0.6	-1.1	-1.1	-1.0
	Model 4	0	0	0	0	0	0	0
	Model 5	-2.3	-0.9	-1.5	-2.1	-1.5	-1.8	-2.1
Scenario Wl	**Model 1**	-2.1	-0.8	-1.2	-1.8	-1.5	-1.7	-2.0
	Model 2	0	0	0	0	0	0	0
	Model 3	-0.6	-0.4	-0.5	-0.6	-1.1	-1.1	-1.0
	Model 4	0	0	0	0	0	0	0
	Model 5	-2.4	-0.9	-1.6	-2.1	-1.5	-1.8	-2.2
Scenario Wh	**Model 1**	-2.2	-0.9	-1.3	-1.8	-1.5	-1.8	-2.1
	Model 2	0	0	0	0	0	0	0
	Model 3	-0.6	-0.4	-0.5	-0.6	-1.2	-1.2	-1.0
	Model 4	0	0	0	0	0	0	0
	Model 5	-2.4	-0.9	-1.6	-2.2	-1.6	-1.9	-2.2

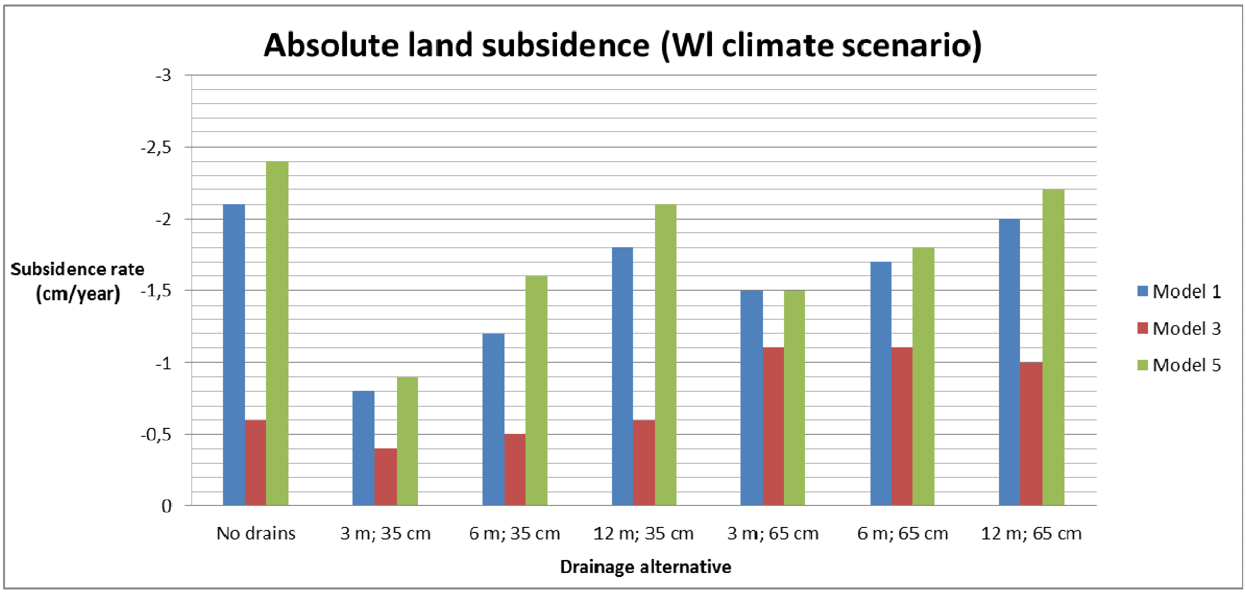
D4. *Absolute values of the Land subsidence in cm/year calculated at all research locations for four different climate scenarios.*



D5. *Absolute values of the Land subsidence in cm/year calculated for Gl climate scenarios.*



***D6.** Absolute values of the Land subsidence in cm/year calculated for Gh climate scenarios.*



***D7.** Absolute values of the Land subsidence in cm/year calculated for Wl climate scenarios.*