Effects of land subsidence on regional groundwater flow in De Stichtse Rijnlanden (The Netherlands)

MSc. Research Thesis (30 ECTS)

Student	Emma Lönsjö
	emma.lonsjo.949@gmail.com
Program	MSc. Earth Surface and Water, track Hydrology
University Supervisor	prof. dr. Ruud Schotting
Organization	Hoogheemraadschap de Stichtse Rijnlanden (HDSR)
Organisation Supervisor	Jantine Hoekstra MSc.
	drs. Henk van Hardeveld
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Abstract/ Summary

It has long been recognized that the changing climate will influence groundwater resources, but there is no extensive research within the area (IPCC 2001; Holman 2006). The main objective of this MSc Research thesis is to increase the knowledge of how land subsidence influences the regional groundwater flow due to an alteration of the vertical flow resistance of the Holocene top layer. The vertical flow resistance is expected to decrease, which mainly is caused peat oxidation, shrinkage and loss of bouyancy (van der Schans & Houtuessen 2012; Geisler 2014). The research that will be based on computer simulation can help to improve our understanding of how climate change and current water management affects soil subsidence and what the impact is on the regional groundwater flow. Two five year intervals, during 2050 and 2100 are simulated and one worst-case scenario where all the peat in the Holocene top layer is gone. The location of the research is the management area of Hoogheemraadschap de Stichtse Rijnlanden (HDSR). To determine what the effect of peat subsidence will have on the regional groundwater a combination of two computer models and one computer program was used (KNMI 2014). The two models that will be utilized is Phoenix, which is a subsurface model that calculates the new ground surface (van der Schans & Houhuessen 2012) and the regional groundwater model Hydromedah (Borren et al. 2009).

The results indicate a strong correlation between land subsidence and lowering of surface water levels. When peat subsides, it generates a lowering of the ground surface. The freeboard is no longer as desired; therefore, the surface water level must be lowered. This is accomplished by pumping surface water out of the system, resulting in a replenishment of groundwater to the river systems (Brunke & Gonser 1997; Sophocleous 2002). By lowering the surface water levels, more peat will be present above the saturated zone and further subsidence will be taking place (Geisler 2014; Price 2003). The negative developing trend of the peat areas will lead to a lowering of the hydraulic head in the regional aquifer, decrease in the vertical flow resistance and an increase in the upward flow. The upward flux from the first aquifer is increasing as peat continues to subside (Schot & Van der Wal 1992). As the global warming continues the rate of peat subsidence is expected to double until 2100 (RECARE 2017). National collaboration is strongly suggested for the purpose of developing drainage systems to reduce the land subsidence.

Keywords

Peat subsidence, regional groundwater flow, vertical flow resistance, hydraulic head

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Emma Lönsjö

Content

1. Introduction

1.1 Peat subsidence

Peat covers nearly 3 % of the land surface on Earth which represents 4.2 million km^2 (Clymo 1987). In the Netherlands, around 10 % of the total land surface is covered with peat which represents approximately 2.98 km^2. In the Netherlands 77 % of the land-use in the peat areas is agriculture (mainly grassland) (Langeveld et al. 1997; RECARE 2017; van den Akker et al. 2007). Organic soils, such as peat have an organic element of more than 50 % and up to 90 %. The high organic content is causing land subsidence foremost in drained areas that are mainly used for agriculture. Two primary processes are responsible for land subsidence. Firstly, from densification which includes compaction, reduction and a decrease of buoyancy. Secondly, the actual loss of mass due to erosion and biological oxidation (Gambolati et al. 2006; Stephens et al. 1984). Biological oxidation generates a release of greenhouse gasses carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) back into the atmosphere (Langeveld et al. 1997; RECARE 2017). The amount of CO_2 that is released back into the atmosphere is predominantly controlled by the water content, peat type and the temperature in the soil. The greenhouse emissions from peat soils, in the Netherlands, represent 2.5 % of the total emissions which equals the use of 1.7 million cars (RECARE 2017) . In the past, the loss of peat in the Netherlands was mainly a result of human actions such as drainage, mining and burning the peat for fuel (Querner et al. 2008; Witte et al. 2012; de Vries 2007).

The adaptability of peat is high, which allows changes in the volume of peat in connection with variating water tables (Price 2003). It is also possible to see a deviation of the permeability of water transported through peat throughout a daily scale as a result of a loss in moisture content in the upper layers (Raddatz et al. 2009). During the summer months when the groundwater levels are lower, the mechanical strength increases as well as the bulk density which can lead to a collapse of the peat pores. During the winter months, the process reverses, and the peat can swell in volume. Areas exposed to processes such as decomposition and consolidation generate a long-term change in the hydraulic and physical properties of the peat (Price 2003). Due to the oxidation/ disappearance of the peat, the vertical resistance of the top Holocene layer decreases. Therefore, vertical seepage (both in downward and upward direction) from the top Holocene layer towards the first aquifer is influenced. The alteration in vertical resistance and hydraulic head may result in a change of the regional groundwater flow and areas for upward flux. Nowadays the effect of land subsidence also has a significant impact on the society as well as the cost for water management and infrastructure (Gambolati et al. 2006; Stephens et al. 1984; van Hardeveld et al. 2014).

1.2 Research area

The Netherlands is divided in twenty-two regional water authorities (Dutch water authorities 2014). The research area for this MSc. Research thesis is the management area of the water authority Hoogheemraadschap de Stichtse Rijnlanden (HDSR) situated in the middle of the Netherlands (Fig. 1). The research area is mainly situated in the province of Utrecht and covers an area of approximately 820km^2 (HDSR 2011). The weather is characterized by a temperate climate with an average of 700-900 mm precipitation per year distributed throughout the year (KNMI 2017). In the current situation, the peat has a thickness of approximately 7 m in the Western part of the research area (Fig. 2) (de Vries 2007; TNO et al. 2016).

One of the responsibilities HDSR has, is to keep a suitable freeboard for different kind of land uses. The freeboard is the vertical height between the surface water level and the ground level surface. In the peat area, the primary land use is grassland, a suitable freeboard for this type of land use is 0.5 m (HDSR 2011; RECARE 2017). Because of the ongoing soil subsidence, over time the freeboard cannot be maintained. The surface water levels and thus the groundwater table must be lowered again. The continuous lowering of the water level allows for land subsidence to carry on. The subsidence is, in turn, resulting in that the water level in the ditches is lowered even further to maintain the required freeboard (Caro Cuenca et al. 2007; RECARE 2017).

Fig. 1 A) The location of Hoogeheemraadschap de Stichtse Rijnlanden at the national level. **B)** A close-up of Hoogeheemraadschap de Stichtse Rijnlanden, the green ridge in the east represent the ice-push ridge and in the Western part of the domain is peat present. The line that extends from east to west (1b) represent where the cross-section is made in figure 3 (TNO et al. 2016; van der Wateren 1985; de Vries 2007).

1.3 Problem description

The Netherlands is situated in a low-lying delta where nearly one third of the country is located below the mean sea level (Oude Essink et al. 2010). The population in the Netherlands is expected to keep increasing, together with an expected intensification of agriculture which creates a higher demand of fresh water resources. At the same time the land subsides, which represents 10 % of the Netherlands where peat is present (Langeveld et al. 1997; van den Akker et al. 2007).

It has long been recognized that the changing climate will influence groundwater resources, but there is no extensive research within the area (IPCC 2001; Holman 2006). Previous studies have focused on what the direct effect will be on groundwater due to changes in temperature and precipitation patterns. A common assumption when modeling is to maintain parameters with the same value except for a change in precipitation and temperature (Arnell 1998; Holman 2006; Loaiciga et al. 2000; Yusoff et al. 2002). There have been some previous studies that have gone further and take into account indirect effects e.g. soil, land cover and water demand. By conducting research in this way, it take a step away from impact studies where climate change is considered as an environmental compartment (Feddema & Freire 2001; Holman 2006; Loukas et al. 2002). The Earth would change even without the climate change, e.g. socio-economic such as increased in urbanization which indirect affect the land use. This parameter is difficult to quantify and is for that reason remained the same throughout the modeling (Holman 2006).

The continued lowering of the ground surface will result in an increase in the complexity of water management. As the soil subsides an alteration in the groundwater system can be expected as well major effects on the infrastructure and safety of society (Gambolati et al. 2006; Stephens et al. 1984). It is difficult to determine what the effects will be at different times and it requires sequential use of multiple models for proper estimations. Until now this has not been done (van Hardeveld et al. 2014). Research is important to get an indication of how the soil subsidence is going to affect the surface water and groundwater system and to get an idea of which areas might be in risk of large alterations.

To determine the effect of soil subsidence on groundwater systems two models have been combined; Phoenix and Hydromedah. The Phoenix model can calculate land subsidence for different climate scenarios by combining water management parameters such as predetermined freeboard height, groundwater levels and soil characteristics. In addition to the two models the computer program ArcGIS has been used. Hydromedah is a groundwater model that can use the results from Phoenix to simulate how land subsidence affects the regional groundwater flow. The results can be used to determine the effect of soil subsidence on other parameters such as the vertical flow resistance and hydraulic head.

1.4 Objectives and aim

The main objective of this MSc Research thesis will be to increase the knowledge of how land subsidence influences the regional groundwater flow in the first aquifer of the research area due to an alteration of the vertical resistance of the Holocene top layer. This change of the vertical resistance is mainly caused by peat oxidation, shrinkage and loss of bouyancy. The research can help to improve our understanding of how current water management affects soil subsidence and what the impact is on the regional groundwater flow for different time periods. To obtain an insight of how the conditions will change within the research area three-time intervals were chosen, in the year 2050, the year 2100 and when all the peat is subsiding The MSc Research thesis will focus on the following research questions;

(1) If the water management is continued in the same manner as it presently is, how will this influence the regional groundwater flow in the first aquifer at 2050, 2100 and when all peat is removed?

(1a) How will the vertical resistance in the Holocene layer change for the different scenarios?

(1b) How will the hydraulic head change as land subsidence continues?

(1c) How will the upward flux (seepage) change as land subsidence continues?

The hypothesis of the MSc research thesis is that the land subsidence will continue as the peat soil continues to subside. The groundwater flow is expected to be altered as the soil subsides with a decrease of the hydraulic head in the Western part of the research area where peat is present. The decrease in hydraulic head is not expected to create a significant change in the regional groundwater flow in the first aquifer, as the changes occur in the Holocene top layer and the parameter in the first aquifer remain the same. Presently, the groundwater flows from southeast to northwest. The land subsidence is expected to affect the vertical flow resistance as the level of the ground surface keep decreasing and the residence time will be reduced. As the land subsidence, continuous the flux between the Holocene layer and the first aquifer is anticipated to change. More upward flux (seepage) is anticipated when the thickness of the Holocene layer is decreasing. Throughout the chosen time interval, the effect of soil subsidence is going to be increasingly severe on the hydraulic head, vertical flow resistance and areas where upward flux occurs.

2 Area Description and soil subsidence

2.1 Geology

Geology refers to materials of Earth and processes acting upon them as well as the structure of those materials. A significant part of geology is the research of how structures, processes and Earth´s material have altered over time. Research in the field of geology can identify and reconstruct changes physical processes of the Earth, from a microscopic up to palaeotectonic scale (Davis & Reynolds 1996). The geology section is divided into two parts; Western part of the research area including fluvial deposits and the peat areas (Fig. 2), the second part include the Eastern part of the research area where an ice-push ridge is located (Fig. 2).

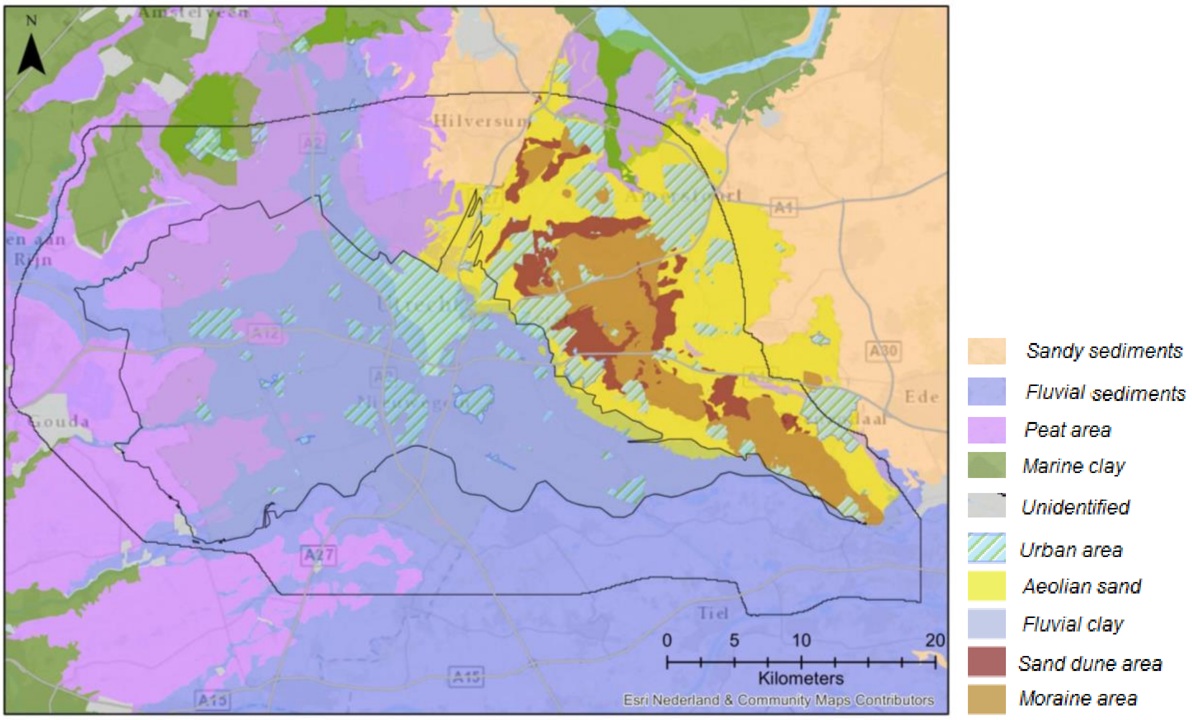


Fig. 2 Show the physical geographic regions to get a better visualization of the research area. The inside line represents the research area and the outside line the extension of the model area, see further explanation in the method section. The province of Utrecht provides a higher detailed map for the province which is combined with a more regional schematization (NGR 2013; Province of Utrecht 2017).

2.1.1 Western part of the research area

A Large part of the sediments in Netherlands is deposited from meandering rivers such as Scheldt, Meuse, and The Rhine (Querner et al. 2008; Witte et al. 2012; de Vries 2007; Oude Essink et al. 2010). In conjunction with a rapid sea level rise during the inter-glaciations, the drainage of surface water was prevented which resulted in a stagnation of freshwater and a steady increase in groundwater levels, which caused extensive peat formation in the area West of Utrecht (Fig. 2; 3) (de Vries 2007; Berendsen & Stouthamer 2001). In early Holocene, about 10 000 yr ago, the temperature was slowly rising in Europe and the Netherlands, and more vegetation started to appear in the landscape. This change led to more humid conditions and an increase in discharge for the rivers in the Netherlands. There was a general decrease of coarser sediments and an increase in fine sediments which resulted in an alteration of the river patterns, from braided rivers to meandering rivers (Berendsen 1995; Berendsen & Stouthamer 2001). Meandering rivers are characteristic by relatively small flood basins and wide channel belts (1-2 km). The river is distinguished by one single channel that shifts laterally as a result of deposition and erosion (Brice 1984; Leopold & Wolman 1957).

In early Atlantic, about 8 000 yr ago, a rapid sea level rise took place which influenced the gradient lines in the rivers present in the Netherlands. When the North Sea got in contact with the river areas around the country, it gave rise to narrow and low-energy anastomosing river systems as the fresh water was prevented from draining into the North Sea; these characterized the landscape between 7 500-4 000 yr ago (Berendsen & Stouthamer 2001). The lateral migration for rivers was restricted by thick layers of peat and clay; these had a tendency to stabilize the river shape. The river was forced to reworked its sediment within the channel belt. There was no advantage for the river to use the gradient in different directions as the permeability was low in the surrounding peat and clay (Berendsen & Stouthamer 2001).

2.1.2 Eastern part of the research area

In the Eastern part of the research area the landscape is reflected by an ice-pushed ridge. An ice-pushed ridge is an elongated hill that can reach from 40 km long up to 20 km wide. The ridge has an average width of 2.5 km, with a plateau located at 45 and 60 m+ NAP, the highest point is at 70 m+ NAP (Fig. 3) (van der Wateren 1985*)*. The ridge is present in the deeper substrate and consists of glaciotectonic deformed sediment from a non-glacial source where it was transported and deformed by the glacier that was formed during the glacial period Saalian, 200 000 to 130 000 years ago during Middle Pleistocene (Berendsen & Stouthamer 2001; Van Kolfschoten 1985). The majority of the sediment in the ice-pushed ridge is coarse sand (van der Wateren 1985; de Vries 2007*)*. The oldest sediment found in the research area are incorporated in the ice-push ridge and consist mainly of fluvial gravel and sand (Berendsen & Stouthamer 2001).

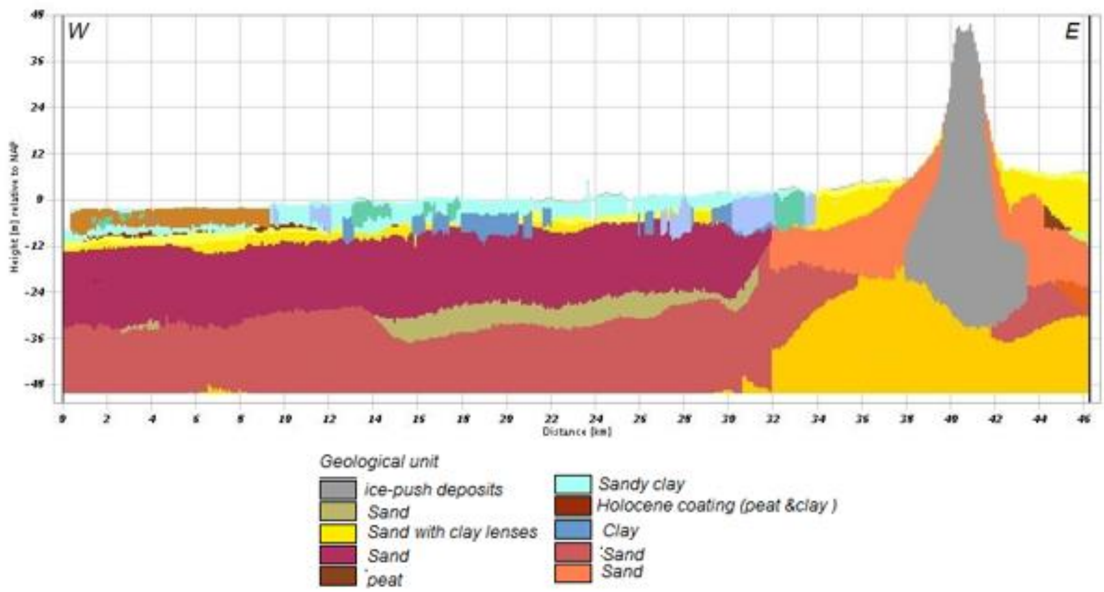


Fig. 3 Represent a cross-section of the research area, from 40m+ NAP to 50m- NAP. The location of the ice-push ridge is partly located within the research area (TNO et al. 2016).

2.2 Hydrology

Hydrology includes all type of water, from atmospheric water to subsurface water and surface water near the Earths surface. The flow of water to and from the subsurface water are directly linked to the surface and atmospheric water. The subsurface water is water flowing beneath the ground surface and is another word for groundwater (Fitts 2002). Prior to settlements in the Netherlands the hydrology had a dynamic equilibrium, the water management, e.g. lowering of surface water and ground water extraction, offset the balance (Brunke & Gonser 1997; Sophocleous 2002). The current patchwork of polders originates back from 1800 B.C, from drainage peat soil (Fig. 4). The purpose behind the drainage was to make the land suitable for agricultural use. During recent decades has the peat been drained deeper which has resulted in that the polders are now located below 1-2 m- NAP (Fig. 4). The historical water management in this area aimed to keep the groundwater levels more natural, with 0.4 m in the summer months and 0.2 m in the winter months below the ground surface. Agriculture could still be conducted, but less intensively. In the Netherlands is the peat areas managed "contrary to nature" with higher water levels in summer, 0.4 m below ground surface, and lower water levels in winter, 0.7 m below ground surface. One of the main ideas behind this is to conduct extensive agriculture in the peat areas. The relative low water level will result in drainage related processes such as oxidation, shrinkage and loss of buoyancy and the peat will subside (Caro Cuenca et al. 2007). The continues lowering of the surface water levels generates a loss of storage in the aquifer and more peat exposed to drainage related processes, as the system strives to reach a new state of equilibrium. By lowering the surface water levels to maintain a desirable freeboard and pumping surface water out of the system, it includes a groundwater flow to these surface water systems (Fig. 4). There is also an induced recharge from the first aquifer to the river systems (Brunke & Gonser 1997; Sophocleous 2002). The close connection between the different parameters in the hydrological cycle and their pursuit to reach a new state of equilibrium drives the lowering of the hydraulic head in the first aquifer at the same rate as peat subside. The hydrology section is divided into four parts; atmospheric water, surface water including rivers and polders. The third part include groundwater and the forth part how the hydrology might change in the future.

2.2.1 Atmospheric water (climate)

At present in the Netherlands, the climate is characterized by a maritime climate with an average of 700-900 mm precipitation per year. The discharge in the Netherlands is reflected by precipitation patterns. In the winter discharge is higher and more constant compared to the summer. Throughout the year rain storms occur which generate peak flow in rivers (Verdonschot 2001). The Dutch streams and rivers are mainly fed by rainwater or springs. A spring is where groundwater flows up to the ground surface which was formed during the Holocene period. It is common to find springs at the base of a slope or where there is an intersection between a slope and an aquifer (Fitts 2002).

2.2.2 Surface water

In the Netherlands 36 major canals; one of these, the Amsterdam-Rhine canal, flows through the research area (Stichting Deltawerken 2004; Provincie Utrecht 2017). The canals are major waterways that are human-made for water transportation or transportation of ships (Fig. 4). The Amsterdam-Rhine canal connects the river Rhine and Amsterdam and has a length of 72 km. Four sluices are present in the canal, whereof sluice "Prinses Irenesluizen" is in the research area (Stichting Deltawerken 2004; Provincie Utrecht 2017). Near Nieuwegein the Lekkanaal connects the Lek and the Amsterdam-Rhine canal as well through the Prinse Beatrixsluizen. One river is flowing through the research area; the Lek. The location of the river is the southern border of HDSR management area (Fig. 4). The total length of the river in the HDSR area is 60 km. (HDSR 2017).

The peat areas in the research area consist of a patchwork of polders. Each polder has its artificially controlled water levels which resulted in a complex system with different surface and groundwater levels (Fig. 4) (de Vries 2007). The waterlevels are controlled by weirs, sluices and pumpings stations (Fig. 4). The waterlevels have to be maintained to keep a constant water level throughout the year to maintain the needed freeboard (Barendregt et al. 1995). The water from the polder is pumped at the canals (Dutch Boezem) which eventually flow in to the sea (Fig. 4). For periods with water deficit fresh water from rivers can led into the channels and the channels led it into the polders. In the western part of HDSR there are 3 major channels (Dutch Boezems); Gekanaliseerde Hollandse Ijssel, Leidsche Rijn and Oude Rijn (HDSR 2017).

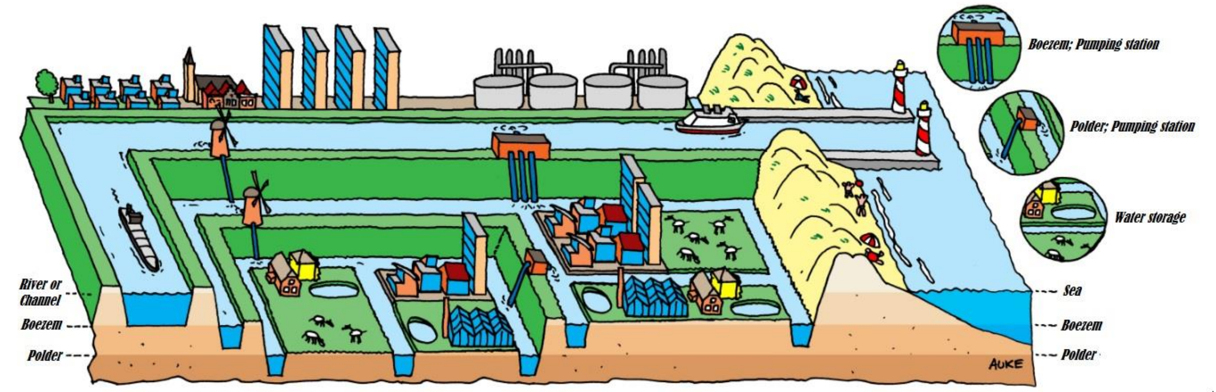


Fig. 4 Schematization of the Dutch water systems (Hoogeheemraadschap van Delfland 2017)

2.2.3 Groundwater

Depending on where a cross-section is made in the research area does the image variate significant, but in general, is the groundwater in the research area is reflected by three aquifers and two aquitards. However, the focus of this project is on the peaty top layer (deklaag) and the first aquifer (Fig. 5).

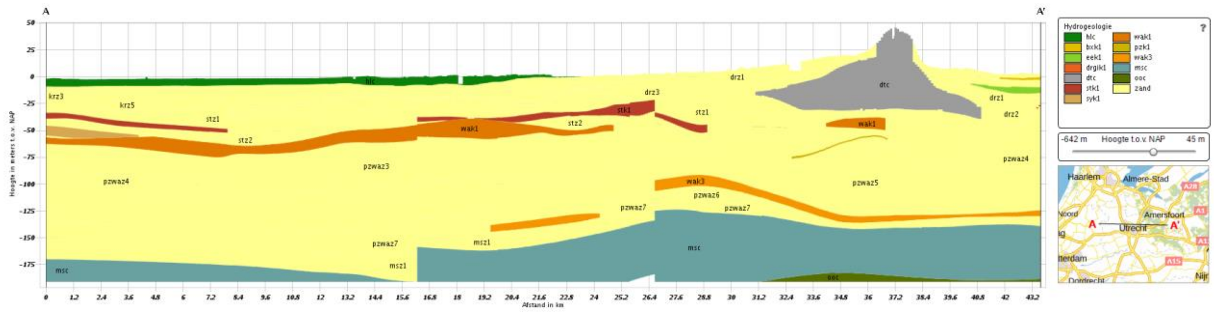


Fig. 5 Show a vertical transect from REGIS ll v2.1 of the research area to a depth of 200 m- NAP (available to a depth of 500 m- NAP). Yellow represent aquifers, coloured parts; aquitards, green; Holocene top layer (TNO et al. 2016)

The stratigraphy of the area is following; the first layer represents the top layer, in the Western part of the research area Holocene deposits are present such as peat (green layer in transect) and in the Eastern part of the research area the fluvial deposits and the ice-push ridge are present (Fig. 3; 5; 6). The first aquifer (yellow layer in transect) is present below the Holocene layer and starts at approximately 4.8 m- NAP with a thickness of 7 m in the East up to 30 m in the West and extends to a depth of approximately 35 m- NAP (Fig. 5) (Borren et al. 2009; Oude Essnik et al. 2010). The first aquifer is partly unconfined; the sediment is fluvial deposits and is classified to be part of the van Sterksel, van Urk, and van Kreftenheye Formation. The formations are composed of sand and gravel with layers of clay. Below the first aquifer is an aquitard present (Fig. 5). The groundwater model divides the first aquifer in two layers with an aquitard in between, see method section for further explanation (Borren et al. 2009).

The aquitard that is present in the Eastern part of the research area (brown layer in transect) consists of peat with local areas of clay and sand and is part of the Woudenberg formation (Fig. 5). The thickness of the aquitard varies significantly, wherein the research area the aquitard has a thickness of approximately 5 m in the Eastern part to not be present in the Western part of the research area. The absence of the aquitard allows for the first aquifer to extend to the second aquitard located at 35 m- NAP (Gunnink et al. 2004; de Vries 2007; TNO et al. 2016).

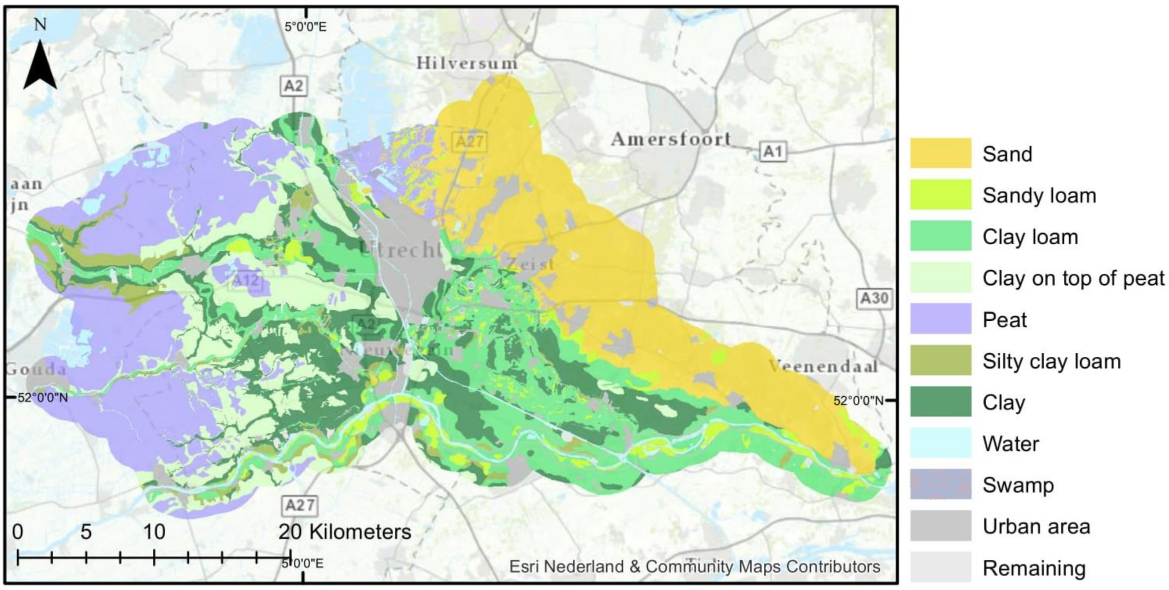


Fig. 6 Represent the soil map for the research area.

The general groundwater flow in the first aquifer at present day is southeast to northwest (Fig. 7) (Oude Essink et al. 2010). A deviation from the large-scale groundwater flow is the flow towards the Prinses Irene sluices as the direction of the groundwater flow is perpendicular to the contour lines. The hydraulic head is a measurement of the surface elevation of the groundwater where a combination of multiply points can be used to determine the gradient. The driving force of groundwater flow is due to an irregular distribution of energy in the water. The irregularities result in that the water flow from regions with high energy towards areas with lower energy. For this reason, it is possible to know that the water is always flowing from areas with a high hydraulic head towards regions with the low hydraulic head (Fitts 2002). The hydraulic head is higher in the Eastern part of the research area where the ice-push ridge is located. Moving towards the western parts the hydraulic head decreases as the land surface is lower in this area. Throughout the year the phreatic groundwater level fluctuates due to variations in precipitation and evaporation, a rise in groundwater level can be expected during winter and a lowering of the groundwater level during the summer months (de Vries 2007). Peat soils are vulnerable to drainage and are important for the hydrology in an area (Bragg 2002; Cannell et al. 2002). This fluctuation in groundwater level is a major problem for areas that are dominated by peat because when the peat is exposed to oxygen, the process of biological oxidation starts. In the past, before the water levels were controlled only during in winter, the rate of subsidence was 1.7 mm per year and after 6-7mm per year. The rate also depends on the drainage depth; for shallow drainage (< 0,5 below land surface) a rate of 2 mm per year is typical and for deep drainage (> 0,5 m below land surface) 6 mm per year is expected. For further explanation, see the section with physical processes of land subsidence (Schothorst 1977). Between 1950 to 2012 the temperature has increased with 1.4 °C due to a decrease in atmospheric aerosols and increase in western winds. The peat subsidence has increased to 10 mm per year (RECARE 2017).

Human activities on fresh water systems can be observed in first aquifer at present day. At a few locations, a cone of depression is a result of groundwater extraction, e.g. Soestduinen and Woerden (Fig. 7). Just North of Utrecht the Bethune polder is located where large amount of upward flux occurs and the fresh water is pumped away and used for drinking water (Fig. 7; 8). Another action that can be seen is the location of sluice Prinses Irenesluizen where the water level in the Amsterdam-Rhine canal is regulated with the sluice (Fig. 7) (Province Utrecht 2017).

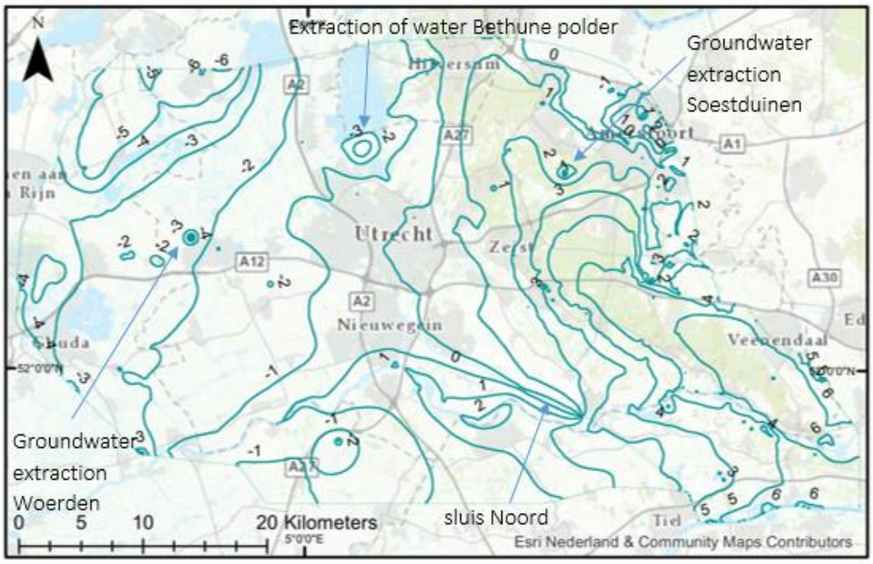


Fig. 7 The hydraulic head in the first aquifer at current day, including some of the human activities that affect the first aquifer at present day (Province Utrecht 2017).

The vertical resistance of the top Holocene layer is the primary controlling factor of the flux between the Holocene layer and the first aquifer, for more information about the resistance see the folowing chapter with physical processes (de Vries 2007). In present day the upward- and downward flux map does show large-scale patterns of downward flux at the ice-push ridge and upward flux in the western part of the research area (Fig. 8). The area just West of the ridge has an upward flux, the reason for this is that the groundwater levels are higher in the ice-push ridge compared to the lower lying area next to the ridge which creates a groundwater flow from the ridge towards this area which results in upward flux (Fig. 8) (Barendregt et al. 1995). The different surface water and groundwater levels affect surrounding polders. For a higher elevated polder compared to lower surrounding polders which have a lower surface and groundwater levels is a groundwater flow generated from the higher elevated polder to the lower lying polders. For the higher raised polder does a downward flow occur and in the lower-laying polders does upward flux occur (Fig. 8) (Barendregt et al. 1995). For some areas, does more upward flow from the first aquifer occur e.g. *De Nieuwkoope Plassen* where the water levels are kept high as well as in some deep lying polders. During the present day, the majority of the peat area has downward flux except for a zone North and South of the river *De Lek* which has a low rate of upward flux (Fig. 8).

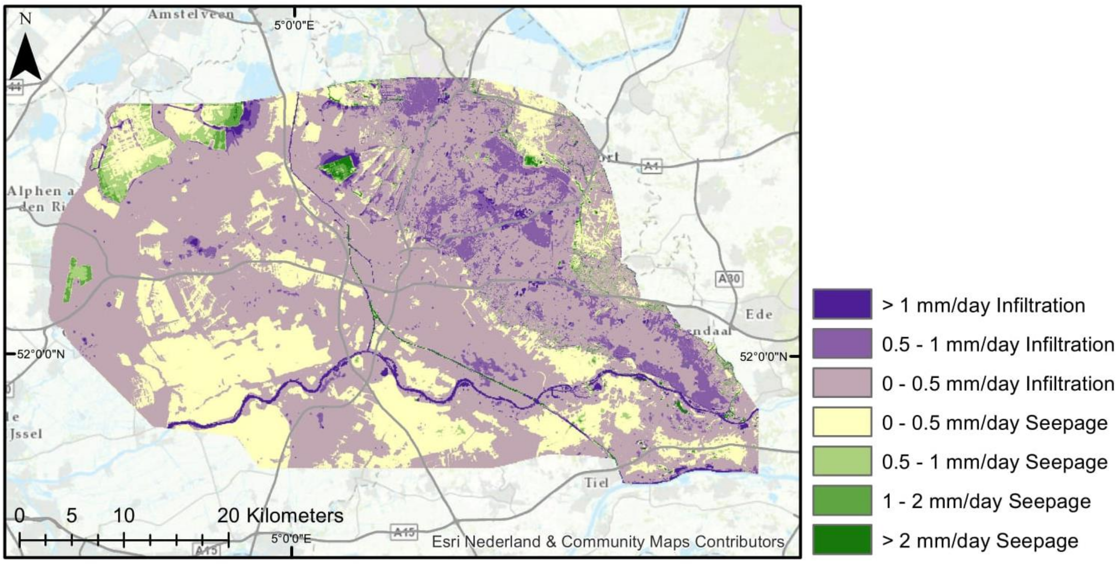


Fig. 8 Areas for upward- and downward flux at present day, as a result of the first run of groundwater model, which represent the water exchange between the Holocene top layer and the first aquifer.

2.2.4 Future Hydrology

The rapid increase in greenhouse emissions worldwide are resulting in a global change (Goldewijk 2001). Climate change will affect the hydrology in the Netherlands. There will be an increase in the probability for flooding during winter due to higher groundwater levels and more precipitation and low water levels during summer as a result of more evaporation and less precipitation which is affecting the groundwater and surface water levels. Low surface water levels may influence the water availability for industry and agriculture (Middelkoop et al. 2001). Models that are used to predict changes in precipitation and evaporation all show the same trend, higher discharge during winter and decrease in discharge in summer. The increase in discharge will be a result of an intensification of snow-melt as well as an increase in rainfall during the winter months. The decrease in summer release will be a consequence of more evapotranspiration and less storage of winter snow (Middelkoop et al. 2001). In the future is a warmer climate to be expected which is going to permit for a longer growing season. Where the soil start drying earlier in the spring and it reach field capacity later in the autumn. The changes in the soil is going to affect the time where groundwater recharge can occur. The overall effect is that the groundwater recharge will decrease even if annual precipitation increase (Holman 2006).

The Dutch landscape is undergoing large-scale changes when it comes to land-use, climate change, urbanization which alters the hydrology in streams. The environment within a stream is dynamic and has a complexity between parameters such as a substrate, flow, and habitat; there are difficulties how to predict how this will be affected as the climate is changing (Verdonschot 2001).

To get a better understanding of how the climate is going to change has four different scenarios been developed. Each scenario builds on Representative Concentration Pathways RCP which represents an estimation of greenhouse gas emissions (KNMI 2015). The climate scenarios that will be used in this thesis is KNMI´06 w+/ KNMI´14 W_H. Which is the climate scenario that was available as input data, see more in the method section. Due to time limitations and long calculation times focus will be on one climate scenarios, scenario W_H/w+ and the two time periods. The reasoning behind the choice is to create an understanding of how the research area might change in the future.

2.3 Physical processes of land subsidence

For areas dominated by peat and organic soils a broad range of processes are going on simultaneous (Fig. 9). For urban-, and rural areas the dominating processes for subsidence are slightly different. In urban areas consolidation is an important process. In rural areas peat oxidation, loss of buoyancy and shrinkage have the largest influence on land subsidence. In the research area both urban and rural areas are present.

2.3.1 Loss of buoyancy

There is a hydrostatic pressure that is active between the grains within the soil. When the sediment is below the groundwater table is the hydrostatic pressure in equilibrium between the forces of the water and the soil particles. In connection of a lowering of the groundwater levels, natural of human induced the pressure on the grains does decrease which can generate a loss of buoyancy. In the unsaturated zone where the pores are filled with air and water are the hydrostatic pressure lower and the weight of the overlying sediment result in that the soil is compacted. The properties of the sediment such as hydraulic conductivity and thickness of the unit play a significant role in determining when the soil reach equilibrium in the hydrostatic pressure (van den Akker et al. 2012).

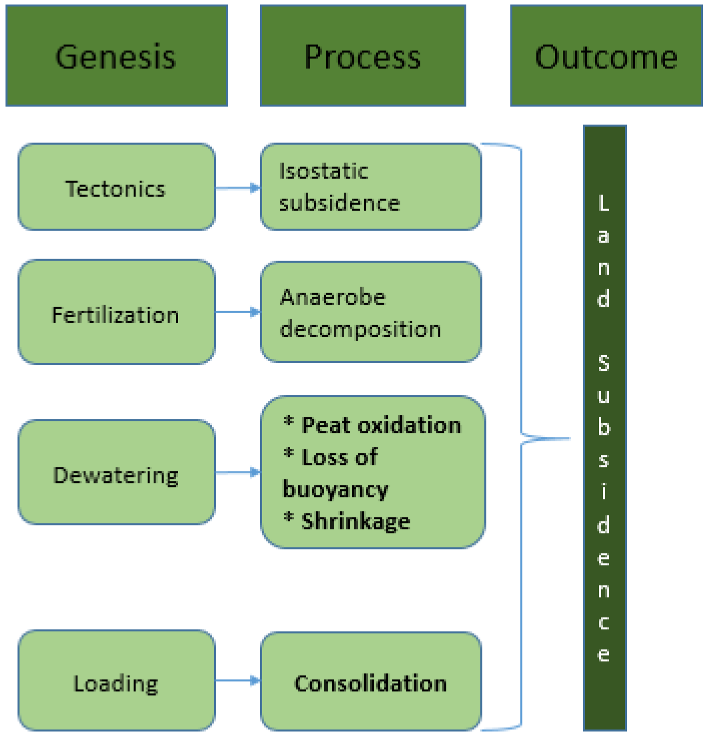


Fig. 9 An overview of processes and their origin of land subsidence. The text in bold represent processes that will be described below (van der Schans & Houhuessen 2012; Geisler 2014).

2.3.2 Shrinkage

The adaptability of peat is high, which allows changes in the volume of peat in connection with variating water tables (Price 2003). It is also possible to see a deviation of the permeability of water transported through peat throughout a daily scale as a result of a loss in moisture content in the upper layers (Raddatz et al. 2009). During the summer months when the groundwater levels are lower, the mechanical strength increases as well as the bulk density in peat which can lead to a collapse of the peat pores. During the winter months, the process reverses, and the peat can swell in volume. Areas exposed to processes such as decomposition and consolidation generate a long-term change in the hydraulic and physical properties of the peat (Price 2003).

2.3.3 Oxidation

In the western peat area the majority of the land subsidence is a result of peat oxidation, the actual loss of mass due to erosion and biological oxidation (Fig. 9; 10) (Gambolati et al. 2006; Stephens et al. 1984). The process is irreversible where biological oxidation generates a release of greenhouse gasses carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) back into the atmosphere (Langeveld et al. 1997; van der Schans & Houhuessen 2011). The amount of CO_2 that is released back into the atmosphere is predominantly controlled by the water content, peat type and the temperature in the soil. The main driving force of oxidation is the transformation of organic matter to repertory functions and building materials by microorganisms (van den Akker et al. 2012).

To maintain a suitable Freeboard, the surface water is continuously lowered, which result in an unsaturated zone where aerobe oxidation can occur. During the summer months when the temperature is higher and on average groundwater levels lower, the rate of oxidation increases. For areas where clay is present on top of the peat the rate of oxidation reduces as less oxygen is available for the oxidation of the peat (van den Akker et al. 2008; Geisler 2014).

2.3.4 Consolidation

The process of consolidation is typical to urban areas as external pressure take place. The external pressure can be a result of the settlement of buildings and roads. The loading of external weight can lead to that water in the pores are forced out as the space between the grains are decreased due to the pressure. The compaction of grains often generates that the bulk density increase and a reduction of the sediment volume and permeability in close connection of external weight. Consolidation results in that the ground surface subsides (Berry & Poshitt 1972; Dhowian & Edil 1980).

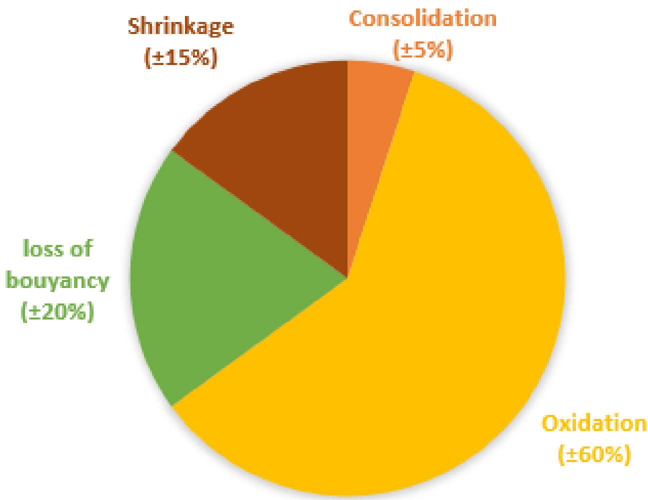


Fig. 10 The distribution between four factors causing land subsidence in peat areas (Stouthamer et al. 2008; van der Schans & Houhuessen 2011).

2.3.5 Vertical flow resistance holocene top layer

The vertical flow resistance represents the ratio between vertical hydraulic conductivity and the thickness of the Holocene layer (Fig. 11). As peat subsides, due to drainage related processes, the vertical flow resistance decreases, therefore it takes less time for the water to pass through the top Holocene layer. Within the research area the vertical flow resistance does variate between <100 days up to >5000 days. Hereinafter, is soil subsidence all processes related to drainage that cause peat subsidence, including loss of buoyancy (including shrinkage and compaction) excluding compaction and consolidation due to loading (Borren et al. 2009; HDSR 2011).

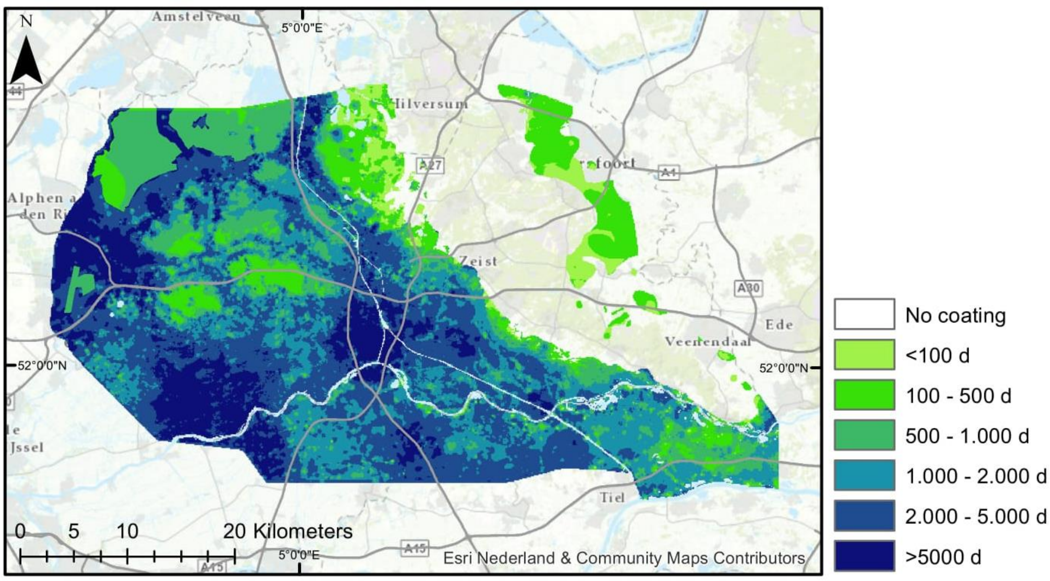


Fig. 11 Represent the vertical flow resistance in the top Holocene layer at present day based on the digital geological model Regis II (Borren et al. 2009).

3. Methodology

Computer modeling will be used during this project to answer the research questions. During the project, two computer models will be used to provide simulations. The first model that will be utilized is Phoenix, which is a subsurface model that provides the new ground surface for chosen time periods and climate scenarios, for more information about the different steps taken see below. To determine the new vertical flow resistance and new surface water levels the computer program ArcGIS was used. To simulate the regional groundwater flow because of land subsidence the groundwater model Hydromedah was used.

The method is divided in four major steps; these are described in figure 12. In the first step is the new ground surface calculated, for the peat area (Fig. 13). The lack of available input data restricts the possibility to apply Phoenix for the buffer zone and an average land subsidence is calculated in step 2 (Fig. 12). The main purpose with step one and two is to calculate the new ground surface and the difference in ground surface for the time interval 2050 and 2100 (Fig. 12). In step 3 is the vertical flow resistance calculated in the computer program ArcGIS. In the last step, step 4, the groundwater model Hydromedah is used (Fig. 12). The worst-case scenario is calculated in a slightly different way and is described in figure 14.

The extension of the model includes the research area as well as a surrounding buffer zone (Fig. 12). The buffer zone prevents that the boundary conditions are affecting the model results (Vermeulen et al. 2016). The function of the buffer zone depends on the geohydrological subsoil, model-, and scenario configuration. In this case the primary purpose of the buffer zone is to reduce the influence of the research area on the calculations (Borren et al. 2009; Vermeulen et al. 2016).

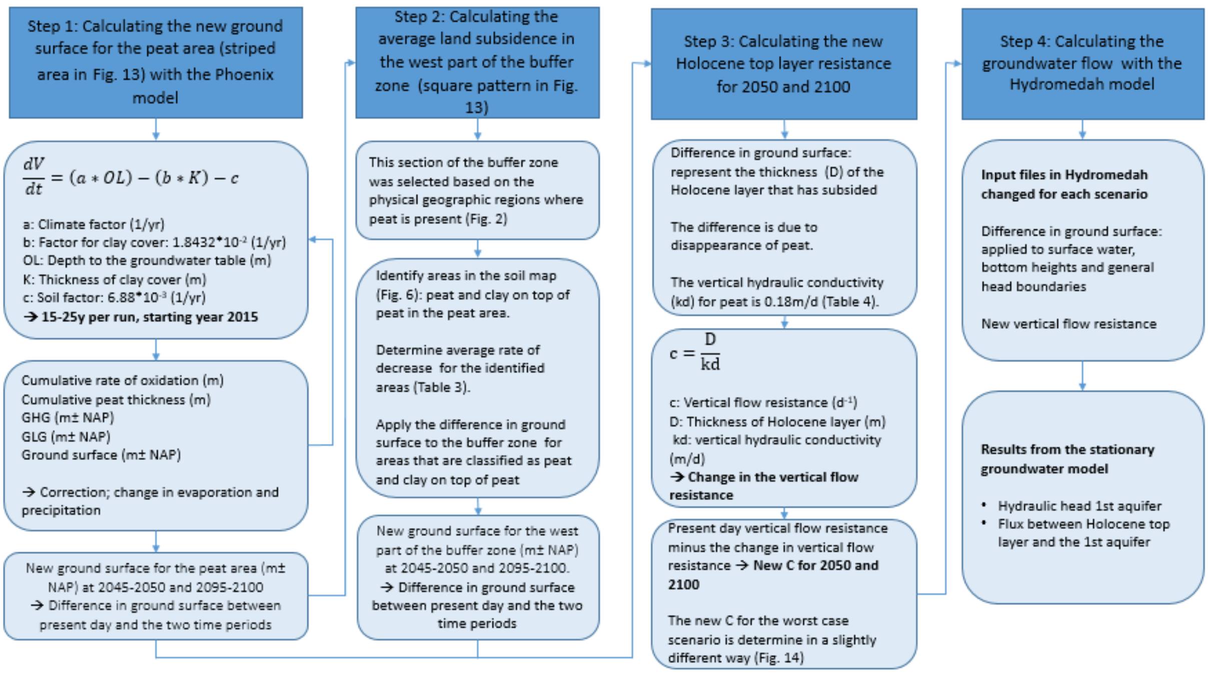


Fig. 12 Represent a flowchart of the different steps that have been take in the methodology.

3.1 Step 1: Calculating the new ground level with the Phoenix model

3.1.1 Model theory

The subsurface model Phoenix will provide this research with information about land subsidence in the peat area for a chosen climate scenario and period (striped area in Fig. 13). Phoenix works within ArcGIS where the model takes into account which effect an expected increase in temperature has on land subsidence for different time periods. The model considering mathematical relationships between the soil structure, water and land subsidence. The original equation variated depending on if peat had clay on top or not and is based on a previous study in Zegveld ("Effects of water strategies in the peatland area," Van Akker et al., Alterra 2007). The formula was rewritten to equation one to apply for the entire area, regardless the clay thickness.

$$[1] \qquad \frac{dV}{dt} = (a * OL) - (b * K) - c$$

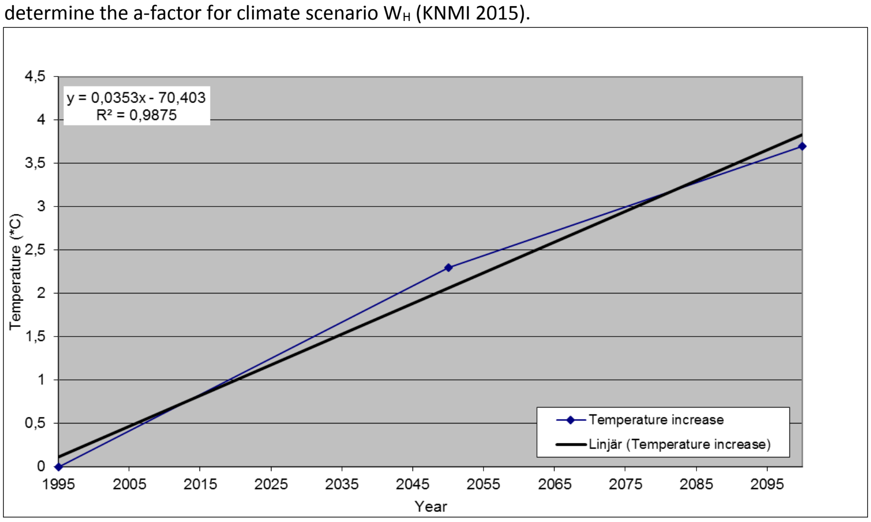
a: Climate factor (1/yr)
b: Factor for clay cover: $1.8432*10^{-2}$ (1/yr)
OL: Depth to the groundwater table (m)
K: Thickness of clay cover (m)
c: Soil factor: $6.88*10^{-3}$ (1/yr)
dV/dt: Land subsidence over time.
Based on the land subsidence over time does Phoenix generate output data every fifth year (Fig. 12);

- Cumulative rate of oxidation (m)
- Cumulative peat thickness (m)
- GHG (m± NAP)
- GLG (m± NAP)
- Ground surface (m± NAP)

The calculated land subsidence considers a temperature change. Before Phoenix can run again does the change in evaporation and precipitation must be correlated for to generate a new input file to use in the model, see Appendix A for further explanation of the correlation.

The climate factor is calculated in Excel based on the temperature change (equation, 2-3). The increase in temperature is not linear and therefore it is of importance to determine the a-factor for shorter time periods (15-25 yr) (Table 1). The expected temperature increase for time step 1995, 2050 and 2100 for the climate scenario (KNMI 2015) is plotted versus the year, where Excel generates a function based on the plotted data. The values of the function were inserted in equation 2-3 to create a new a-factor to use in Phoenix (Table 1) (van den Akker et al. 2007; van der Schans & Houhuessen 2012; Geisler 2014).

Table 1 Represent the expected temperature increase from the year 2100 that were used to determine the a-factor for climate scenario W_H (KNMI 2015).



[2] $\emptyset = A * yr + z$

[3] $$new\ a-factor = \left(\frac{\left[\left[\left[\left[3^{\left(\frac{\emptyset}{10}\right)}\right] - 1\right] * \omega\right] + 1\right]}{h} \right) * old\ a\text{-}factor$$

$\emptyset$; *Summer temperature on a yearly scale*

ω; 0.6 *oxidation fraction*

h; *time period* $(15 - 25yrs)$

Table 2 Represent the a-factor, which is the climate factor for an expected temperature change for scenario W_H/w+

a-factor	
Time-period	**W_H/w+**
2015-2030	0.02552
2030-2050	0.02685
2050-2075	0.02873
2075-2100	0.03104

3.1.2 Data used

When calculating the land subsidence four files are required, as well as calculation points and the area for the calculation. To get more information about the data that were used see below.

- Climate predictions, for expected temperature, evaporation and precipitation change. For two time periods: 2036-2065 and 2071-2100 for the Netherlands, developed by KNMI based on the data published by IPCC (2013). The climate scenario that was available with correction data for a change in precipitation and evaporation; KNMI´06 w+ and predictions of temperature change; KNMI´14 W_H. The W scenario builds on the Representative Concentration Pathways 8.5 which represents an estimation of greenhouse gas emissions (KNMI 2015).
- Zones with water level that containing information about current water management as well as corrections for precipitation and evaporation. The file is constructed as a shape file with different zones of how the water levels will change (internal database HDSR).
- GLG for the w+ scenario is the available data which is an output from iMOD. It is a raster file based on the climate scenario from 2006 with correction for a change in precipitation and evaporation. The data is available for the research area including the buffer zone with a cell size of 25 *25 meter (KNMI 2014; internal database HDSR).
    - Due to limitations in the non-stationary model in iMDO there is a restriction on a maximum amount of cells, set to 260 000 cells, that can be used in the model. To not exceed the limitation of cells would be acquired a cell size of 200*200 meter. The results of a run like this would be a rough estimation of what could be expected and not detailed enough. During discussions with supervisors and expert of the model, it was suggested that a possible option was to divide the research area into subareas to be able to use the desired cell size of 25 meters. However, this was not an alternative due to the problem with model boundaries, overlapping areas as well as computing time. For this reason, the decision to use use available data for glg based on the 2006

climate scenario was taken. The predictions of temperature, wind pattern, evaporation and precipitation are different between climate scenarios from 2006 and 2014. However, the two predictions follow the same trend, with an increase in temperature, an alteration in precipitation patterns and more extreme weathers (KNMI 2015). Since this is a MSc Research Thesis is to keep a high scientific level and use the most recent data and therefore were the temperature predictions from 2014 chosen, even if the data over GLG are based on climate scenarios from 2006.

- Calculation points for the peat area are used, they contain information about the sediments and each point consists of a grid cell of 25 *25 meter. The information they contain are: a coordinate system, elevation, soil characteristics and peat- and clay thickness. The points also contain information about summer and winter surface water levels as well as GLG and GHG. The lithology is based on data from GeoTop and a soil map, where correction for constructions, e.g. roads and houses has been made. The water levels in the point file represent current water levels from HDSR (van der Schans & Houhuessen 2012).

3.1.3 Implementation of Phoenix

The land subsidence model Phoenix will provide the MSc Research with predictions of the new ground surface at 2050 and 2100 for the peat area (striped area in Fig. 13). The computer model is running for a 15-25 years' period and generates output files after every five years (Fig. 12). Based on the climate scenarios from IPCC and KNMI with predictions regarding temperature, precipitation, and evaporation has the new ground surface been calculated for time slice 2045-2050 and 2095-2100. Technically, the new ground surface is within a five-year period but will hereafter be denoted as 2050 and 2100. The output data from Phoenix will be used as input data in ArcGIS to determine the new vertical resistance in the Holocene layer (Fig. 12) (van der Schans & Houhuessen 2011).

The output data from previous run in Phoenix were used together with water level areas, and GLG for the w+ scenario to correct for a change in precipitation and evaporation in a model builder. This step is to generate a corrected point file to use to calculate the next period. Phoenix is used until data for the desired time steps is obtained. These new raster files represent how much peat has subsided for the different time periods until 2100 for the climate scenario.

The output data from Phoenix that will later be used in ArcGIS is the ground surface (Fig. 12). By extracting the new ground surface from the current day, it is possible to determine the difference which represents how much peat that has subsided at a given period (Fig. 12).

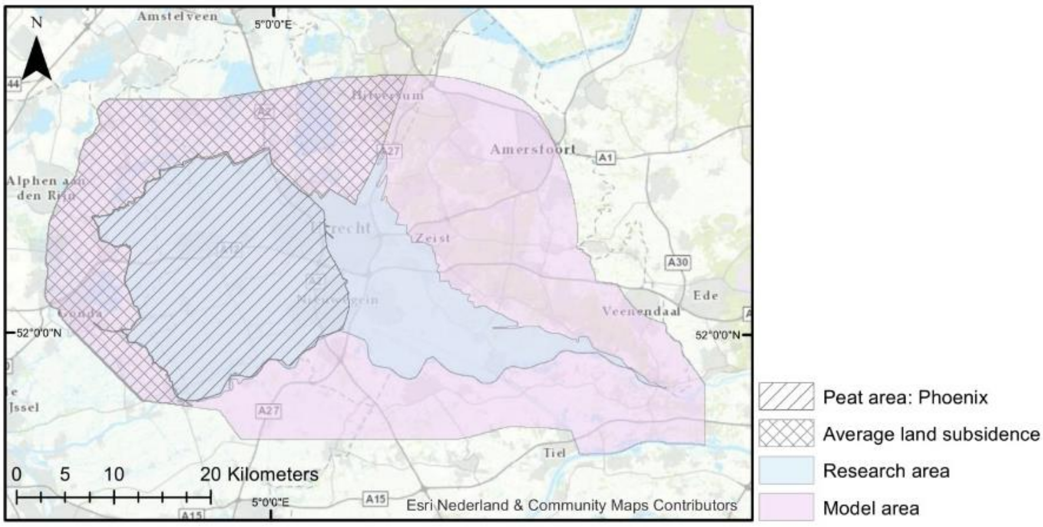


Fig. 13 For time interval 2050 and 2100 was input data available for the peat area which is marked as Phoenix in the figure to determine the land subsidence. For the area West of the peat area as part of the buffer zone was an average subsidence calculated based on the results from Phoenix. The other part of the research area and the buffer zone remained unchanged.

3.2 Step 2: Calculating the average land subsidence in the Western part of the buffer zone

The input data used in Phoenix is not available for the buffer zone nor the Eastern part of the research area (Fig. 13). To include areas where peat is present and avoid a sharp drop between the research area and the buffer zone an alternative path was chosen to obtain the new ground surface for these areas. The Western part of the buffer zone was selected (square pattern in Fig. 13) based on the physical geographic regions where peat is present (Fig. 2) (NGR 2013). An assumption was made that the rest of the model area wasn´t going to subside for the first two intervals, 2050 and 2100. The peat that is present in this part of the model area is left unchanged, it is located under at least one and a half meter of clastic material and not expected to subside within this time frame.

Step 2 is to calculate the new ground surface for the Western part of the buffer zone (Fig. 12). The first move is to identify areas in the peat area where peat and clay on top of peat is present (Fig. 6). The division into these two classes is made since previous research on peat soils indicate a difference in peat subsidence if clay is present on top of the soil column or not (van den Akker et al. 2008; Geisler 2014). The second move is to determine an average difference in the ground surface. It is done by converting the two identified classes into polygons to obtain an average value over how much the ground has been lowered for the areas where peat and clay on top of peat is present (Table 3). The next move is to apply the difference in ground surface to the buffer zone for areas that are classified as peat and clay on top of peat.

To results from Phoenix was used to get an indication of what the average rate of peat subsidence is for the different scenarios and the two classes. By taking the difference in ground surface divided by the number of years that have passed for a certain scenario could the rate of subsidence be calculated (Table 3).

Table 3 The average difference in ground surface and the rate of peat subsidence for two given time periods. To get a better understanding how the rate of peat subsidence relates to history and present day has a few more values been added.

<table>
<tr><td rowspan="3"></td><td colspan="6">W_H/w+</td></tr>
<tr><td colspan="2">Difference in ground surface</td><td colspan="4">Rate of peat subsidence</td></tr>
<tr><td>2045-2050</td><td>2095-2100</td><td>2070-2010 (Zegveld)</td><td>Present day</td><td>2045-2050</td><td>2095-2100</td></tr>
<tr><td>Peat</td><td>0.313 m</td><td>0.805 m</td><td rowspan="2">7.7 mm per year*</td><td rowspan="2">10 mm per year **</td><td>8.9-10.4 mm per year</td><td>9.4-10 mm per year</td></tr>
<tr><td>Clay on top of peat</td><td>0.203 m</td><td>0.501 m</td><td>5.8-6.7 mm per year</td><td>5.9-6.2 mm per year</td></tr>
</table>

*Geisler 2014
** RECARE 2017

3.3 Step 3: Calculating the new Holocene top layer resistance

3.3.1 Model theory of ArcGIS

In step 3 the computer program ArcGIS is used; ArcGIS is a computer-based geographic information system. The development of ArcGIS was done by Environmental Systems Research Institute (Esri) (Esri 2004; Hiller 2008). A system is a powerful tool that can provide information to analyze, display, store, capture and output geographic information. One of many advantages that it is possible to connect data in tables with geographically referenced data. The structure of the model is made up of three software products; ArcInfo, ArcEditor, and ArcView. The combination of these products improves the extent of functionality (Esri 2004; University of Maryland 2012).

GIS support three views of how to work with geographic information. The first view is the geodatabase view; Where there is a collection of data that is connected to a spatial database, such as rasters, features, and networks. The next view is Geovisualization view; where maps and features can be connected to each other as well as corresponding to the Earth's surface. It is also possible to visualize information that is linked to the maps, in connection with them. The third and last view is the Geoprocessing view; a tool where it is possible to derive new data from actual data. The three views mentioned above together create critical parts in ArcGIS and are used in various levels of applications in ArcGIS (Esri 2004).

In this step is the new vertical flow resistance determined. By using data obtained in step 1 and 2; difference in ground surface (Fig. 12) and vertical hydraulic conductivity table 4. For the worst case scenario has the new ground surface be calculated (Fig. 14). In this scenario has all the peat disappeared in the top Holocene layer.

3.3.2 Data used

To obtain a better overview of the data that were used in ArcGIS, see below.

- New ground surface (Fig. 12). The data represent the amount of peat that has subsided for the two time intervals; 2050 and 2100. The new ground surface is available for the peat area (striped area in Fig. 13) and the Western part of the buffer zone (square pattern in Fig. 13). The difference in ground surface: represent the thickness (D) of the Holocene layer that has subsided.
- The GeoTop subsurface model (TNO et al. 2016). The horizontal section with lithofacies. The file consists of raster files with a cell size of 25*25 m and a thickness of 0.5 m. Each cell contains information about sediment type at a certain location (Stafleu et al. 2011; TNO 2016). The classification of sediment in GeoTop is based on the description given by Westerhoff et al. 2003. The extent of the files is the research area for the Holocene layer from 6.25 m+ NAP to -14.25 m-NAP. To calculate the new vertical resistance when part/all of the peat is subsided the Geotop subsurface model (TNO et al. 2016) is used.
- Horizontal cross section maps. This file is to obtain sediment type for the buffer zone. The properties of the files are somewhat different than for the research area with a cell size 100*100 m with a thickness of 1 m but are still based on the subsurface model GeoTop. The sediments have been classified based on borehole logs into eight different classes (Table 4) (TNO 2016). The file is used to identify areas in the buffer zone where peat is present in the top Holocene layer

3.3.3 Implementation of ArcGIS

Firstly, the new vertical flow reistance will be calculated for time interval 2050 and 2100. The difference between present day ground surface and new ground surface represent the thickness (D) of peat that has subsided, equation 4 (Fig. 12). The vertical hydraulic conductivity (kd) for peat is 0.18 m/d (Table 4) (Gunnink et al. 2004; Weerts 1996). The calculations to obtain the decrease in vertical flow resistance as a result of land subsidence is made in raster calculator for each cell (Equation 4). The next step is to calculate the new resistance by extracting the decrease in vertical flow resistance from present day vertical flow resistance based on the digital geological model REGIS ll (Appendix B) (Borren et al. 2009; TNO et al. 2016). The vertical flow resistance represents the ratio between vertical hydraulic conductivity and the thickness of the Holocene layer and is calculated with:

$$[4] \qquad c = \frac{D}{kd}$$

c: Vertical flow resistance (d^{-1})

D: Thickness of Holocene layer (m)

kd: vertical hydraulic conductivity (m/d)

As previosly mentioned is the vertical flow resistance for the worst case calculated using a different approach (Fig. 12). For this case is all the peat removed that is present in the top Holocene layer. The Geotop model is imported into ArcGIS and contains information on the lithology for the individual layers. It has ten lithology classes of which two are peat (Table 4) (TNO et al. 2016). The data that are available for the buffer zone is classified slightly different (Table 4). The vertical flow resistance are necessary as input for Hydromedah as well as to answer the sub-question, how the vertical resistance in the top layer will be affected when the peat is subsided. To make the process quicker and more unified a model was built within ArcGIS. The Geotop data and Horizontal cross section maps mentioned above is used as input data in this model at two locations (Fig. 14)., including all steps taken in ArcGIS. The new resistance is calculated seprately for the research area (GeoTop data) and the buffer zone (Horizontal cross section maps) and then added together. In the flowchart presented below all intermediate steps are not given as it would make the flowchart too complex to understand. (Fig. 14). For the cells where peat is present was the input layer reclassified to zero, which generate a resistance of zero at this cell (Fig. 14). For the rest of the cells was the thickness of the layer unchanged (0.5 or 1 m) and the resistance was calculated. When all the peat had been removed was the layers summed together to obtain the new vertical flow resistance when all the peat is gone (Fig. 14).

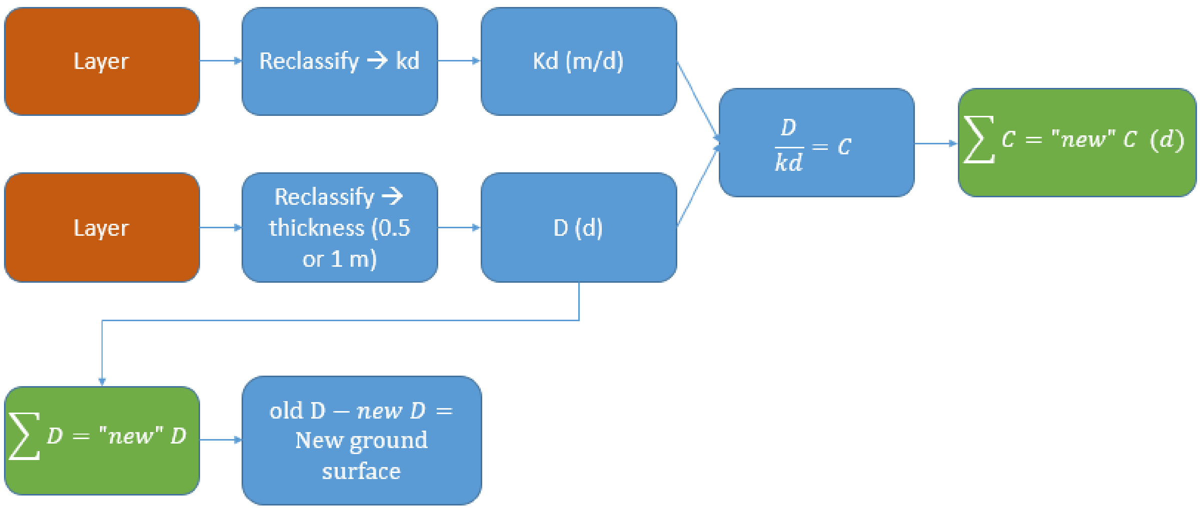


Fig. 14 The vertical flow resistance is calculated individually for each GeoTop and horizontal cross section layer using equation 7 and summed up to represent the new vertical flow resistance for the Holocene layer.

The vertical flow resistance for the Holocene layer is presented in Appendix B. To get a better understanding of how the resistance changes in different areas and scenarios difference maps have been created. This is done by extracting the new resistance from the current situation (original REGIS values) (Fig. 15). The difference maps for time-interval 2050 and 2100 have the extent of the peat area, and the Western part of the buffer zone, the remaining part of the modeling area, was unchanged.

The hydraulic conductivity in peat can vary significantly over a short distance, but it is often assumed that the conductivity decrease with depth (Holden & Burt 2003). This arises considerable differences in a vertical and lateral direction which generate preferential flow pathways with a high frequency. The significant variations in hydraulic conductivity allow for areas with a faster flow and can make it difficult to model an area containing peat (Holden & Burt 2003). The hydraulic conductivity has been classified in the same as the model parameterization for HDSR (Table 4) (Gunnink et al. 2004; Weerts 1996).

Table 4 Represent best available data for the research area and the buffer zone and their respective vertical hydraulic conductivity. ® Represent peat located under at least 1 meter of clastic materials.

Sediment	Research area	Buffer area	K_v (m/d)	Reference
Clay	x	x	9×10^{-4}	*
Peat	x		0.18	**
Sandy clay	x	x	1.6×10^{-3}	*
Marine clay	x		5×10^{-3}	*
Compacted peat ®	x		1.9×10^{-2}	*
Fluvial sand	x		16	*
Organic material		x	1.8	***
Clayey sand		x	2×10^{-3}	***
Fine sand		x	5	***
Moderate coarse sand		x	20	***
Coarse sand		x	25	***
Anthropogenic		x	9×10^{-4}	***

* Bierkens & Dagan 1994; Gunnink et al. 2004; Weerts 1996

** Gunnink et al. 2004; Weerts 1996

*** Bierkens & Dagan 1994

3.4 Step 4: Calculating the groundwater flow with the Hydromedah model

3.4.1 Model theory

The Hydromedah groundwater model will be use to answer the primary research question: How will the regional groundwater flow be influenced by peat subsidence and the sub-questions: What the influence will be in the hydraulic head and flux is the groundwater model Hydromedah. By combining data from the three previous steps (Fig. 12).

The groundwater model, Hydromedah (Borren et al. 2009; HDSR 2011), is site specific for the research area, and was made at the request of HDSR developed by TNO and Deltares and is an addition and extension of the software IMOD. Hydromedah is a numerical groundwater model in 2.5 D (Borren et al. 2009). The model is a combination of computer models where the core primarily consists of SIMulation of GROundwater (SIMGRO), Regis II, Meta SWAP, and MODFLOW. The model focuses on the water balance within the domain and how the different parameters are connected (Borren et al. 2009).

The integrated model code SIMGRO include sub-models and contains interactions between surface water, groundwater, soil moisture, and plant-atmosphere. SIMGRO is intended for modeling of the shallow subsoil and unconsolidated sediments and also for connecting the processes occurring in the groundwater and the unsaturated zone. The language of the model is Intel Fortran and shows the output through user files such as binary and ASCII (Vermeulen & Minnema 2015). Regis II is a subsurface model that contains information of the Dutch substrate. The compilation of data is from the DINO database and the national geological mapping of the Netherlands (Borren et al. 2009). The DINO database contains information from 430.000 boreholes, with 26.500 of these boreholes located in the research area. This data provide information about the thickness of the different geological units as well as a lithostratigraphic description (TNO et al. 2016).

The focus of Hydromedah will be on the Holocene layer, where the peat is present, and the first aquifer. The conditions in the deeper aquifers are not expected to change if part/all of the peat are subsided. Throughout the MSc. Research thesis the internal database of HDSR is available to obtain the best data for the computer modeling.

3.4.2 Data used

Input data that will be utilized in the groundwater model are;

- The initial vertical flow resistance is based on REGIS ll (Borren et al. 2009; TNO et al. 2016). The digital geological model (DGM) is used as a basis for REGIS II. The model extends to a depth of 500 m-NAP with a 100 *100-meter resolution (table 5). The vertical flow resistance is available for the seven aquitards including the top Holocene layer (Borren et al. 2009; TNO 2016; Deltares 2015). To not generate error messages within the model and to be able to conduct the calculations the no-data values are set to 0.1 (Borren et al. 2009). The focus is on the resistance for the Holocene layer.
  - New vertical flow resistance for the three time intervals; 2050, 2100 and the worst-case scenario (Fig. 12).
- Surface water levels and their bottom heights. These files contain information about the surface water within the model area and their relation to the ground surface. They are available for the Holocene layer and the first aquifer for primary, secondary and tertiary surface water systems (Borren et al. 2009; Deltares 2015). The difference in ground surface between present day and the three time periods is applied to these files to maintain their relation to the ground surface and each other (Fig. 12).
- The general head boundary is where the boundary conditions are set for the groundwater model. It is a constant head at the model boundary (Borren et al. 2009). The difference in ground surface is also applied to this IDF file for the three scenarios (Fig. 12).

The groundwater model uses IDF files. The ones that are not mentioned above are; anisotropy-factor, model boundaries, hydraulic head, hydraulic conductivity, groundwater abstractions, conductance and drainage for submerged drainage (Borren et al. 2009). These files are unchanged throughout the different simulations and for that reason no further description is made of these files. For more information, see Borren et al. 2009 (Appendix C).

3.4.3 Implementation of Hydromedah

In this research is the model run as a steady state model and is comprised of 2 720 columns, 1 600 rows, and eight layers. The cells have a size of 25 * 25 m. (Borren et al. 2009). The model contains eight layers where each layer contains an aquifer and an aquitard, except layer eight which only contains an aquifer. The vertical distribution is 0.4 m+ NAP to 198.5 m- NAP (Table 5) (Borren et al. 2009; HDSR 2011). The groundwater model that will be used has a schematization for the complete management area and it has divided the model area in eight aquifers and seven aquitards. The stratigraphy of the area is following; the first layer represents the top layer and phreatic water levels. In the Western part of the research area Holocene deposits are present such as peat and in the Eastern part of the research area the Boxtel formations. The sediments within the unit are composed of fine to medium coarse sand with elements of loam and calcareous deposits (Fig. 2). The second layer consists of the first aquifer and an aquitard. The first aquifer starts at 4.8 m- NAP with a thickness of 7 m in the Easter part up to 12.5 m in the Western and extends to a depth of approximately 20 m- NAP (Borren et al. 2009; Oude Essnik et al. 2010). The first aquifer is partly unconfined; the sediment is fluvial deposits and is classified to be part of the van Sterksel, van Urk, and van Kreftenheye Formation. The formations are composed of sand and gravel with layers of clay. Below the first aquifer is an aquitard present (Table 5) (Borren et al. 2009; HDSR 2011).

One of the major steps in Hydromedah is to create a run-file for 64-bits to execute in iMODFLOW_v3_2_1_METASWAP_SVN1044_X64.exe (appendix C). The rows marked with a red arrow are changed for the different scenarios. The groundwater model Hydromedah was used to run four simulations.

Table 5 Schematization for the complete model area, including hydrogeological units (Borren et al. 2009).

Hydrogeological units West	 Ridge + East	Hydrogeological model format	Model layer	Average depth (m+ NAP)	Average thickness (m+ NAP)
Holocene (Gunnink et al. 2004)	Boxtel	Topcoat layer +phreatic levels	1	0.4	5.7
Holocene (Gunnink et al. 2004)	Boxtel	Vertical flow resistance: Holocene layer			
Kreftenheye formation	Sand: Eem formation, partly driven complex	First aquifer	2	-4.8	7.1
Not present	Peat: woudenberg formation & clay: Eem formation	First aquitard		-8.1	5.5
Sand: Urk formation	Sand: Eem-, Urk-, and Sterksel formation	Second aquifer	3	-20.6	24.5
Clay: Sterksel formation	Clay: Drente Uitdam-, Drente Gieten-, Urk and Sterksel formation	Second aquitard		-33.8	5.3
Sand: Peize Waalre formation	Sand: Peize Waalre formation, partly driven complex	Third aquifer	4	-41.6	13.8
Clay: Waakre- & formation		Third aquitard		-52.1	10.1
Sand: Peize Waalre formation, partly driven complex		Forth aquifer	5	-68.5	26.1
Clay: Waalre- & Peize formation		Forth aquitard		-83.6	11.5
Sand: Peize Waalre- & Massluis formation		Fifth aquifer	6	-104.8	38.6
Clay: Waalre formation		Fifth aquitard		-125.8	12.9
Sand: Massluis- & Peize Waalre formation		Sixth aquifer	7	-135.7	16.9
Massluis formation		Sixth aquitard		-156.8	28.3
Sand: Massluis formation		Seventh aquifer	8	-198.5	58.6
		Hydrological base			

First run

The first simulation represents present day to have a starting point; the input files were not altered in any way with the original REGIS based values for the vertical flow resistance.

Second to the fourth run

The second to fourth scenario represent year 2050 and 2100 for climate scenario w+ and the worst case scenario where all the peat is gone. The amount of peat that is subsided has been calculated in Phoenix. The obtained data were used to determine the new vertical flow resistance, surface water levels and their bottom heights and general head boundary. The new files were added to the run-file (Appendix C).

- o The new vertical flow resistance for scenario 2050 and 2100 are a result of calculations in Phoenix and ArcGIS (Appendix B). As the peat is subsided there is a decrease in the resistance, and it takes a shorter time for the water to pass through the Holocene layer.
- o The relation between the bottom and surface water levels remains unchanged, the difference in ground surface level is applied to the surface water levels and bottom heights IDF files to not alter the relationship between them (e.g. surface water level current situation – difference = new surface water level for a certain climate scenario).

- For the general head, the boundary is the difference in ground surface level applied to the IDF file for layer two. As the surface level is lowered the general head boundary has to decrease with the same rate to avoid a steep drop in output of the hydraulic head.
- The groundwater model takes into account the recharge of an area by combining the precipitation and evaporation. Since the expected change in recharge is correlated for in Phoenix for the two scenarios 2050 and 2100 it is not correlated for in the groundwater model. For the worst case scenario is a change in recharge not possible to determine as there is not predictions that far in the future.

The results from the groundwater model are presented as maps. As mention in the beginning of this section was the importance of the buffer zone. The buffer zone prevents that the boundary conditions are affecting the model results (Vermeulen et al. 2016). For this reasons is the results presented in a way that the results from the buffer zone is part of the maps but not considered in the results. The calculations within the groundwater model affect the results in the buffer zone in that way that they are no longer reliable. The upward and downward flux figures represent the flux between the Holocene top layer and the first aquifer (Fig. 20). The hydraulic head represents the groundwater levels in the first aquifer. To get a better understanding/visualization of how the vertical flow resistance, hydraulic head, upward, and downward flux has changed compared to current day, maps with the difference have been made.

4. Results

4.1 Vertical flow resistance

As peat subsides, the vertical flow resistance decreases. Therefore it takes less time for the water to pass through the top Holocene layer. Within the research area the vertical flow resistance variates between <100 days up to >5000 days (Fig. 11, paragraph 2.3.5). The decrease in the vertical flow resistance does not have a large impact on the large-scale pattern (Appendix B). To answer the sub question of how the vertical resistance in the Holocene top layer differs in the different scenarios a map has been created to visualize the changes in a clear way (Fig. 15).

4.1.1 Difference map: Present day vs. W_H/w+ at 2050

A difference map of the vertical flow resistance has been created between present day and the time interval in 2050 (Fig. 15a). As mentioned above, a change in the vertical resistance was seen in the peat area as well as in the Western part of the buffer zone (striped area and squared in Fig. 13). The rest of the model area remained unchanged for this scenario (Fig. 15a). The results of Phoenix within the peat area lead to the more detailed scenario outcome conserning the amount of peat which has subsided. The difference in ground surface level obtained by calculations in Phoenix is used to determine the decrease in vertical flow resistance (Fig. 11; 15a).

For this difference, the map shows that the decrease in vertical flow resistance variates between 0.5 to 2.5 days. The large scale pattern for the vertical flow resistance does not change (Appendix A). It is important to point out that there is a difference in the rate of peat subsidence within the peat area. If the peat has clay on top or not, generates a different rate of peat subsidence. If clay is present on top of peat, the peat subsides does the peat subside with 5.8-6.7 mm per year (Table 3). In locations where no clay is present the rate of peat subsidence is higher and variates between 8.9-10.4 mm per year (Table 3). The difference in peat subsidence if clay is present or not is about 3 mm per year. It is already possible to see that where the fluvial deposits are present (Fig. 2; 6) no change in the vertical flow resistance has occurred (Fig. 15a).

4.1.2 Difference map: Present day vs. W_H/w+ at 2100

In this scenario more time has passed since current day and therfore more peat has subsided. The decrease of the vertical flow resistance in the top Holocene layer is between 0.1-6 days. The decrease in vertical flow resistance occurs in the peat areas that already have a low resistance in present day (Appendix A). In this time interval, the rate of peat subsidence is slightly lower (Table 3). For areas where clay is not present on top of the peat the subsidence will be 9.4-10 mm per year and where clay is present the rate of subsidence varies between 5.9-6.2 mm per year. However, the difference between the two rates is larger for this scenario and varies between 3.5-3.8 mm per year (Fig. 15b).

4.1.3 Difference map: Present day vs. Worst case scenario

For the worst-case scenario, all the peat has been removed from the Holocene top layer. There is also peat present further down in the soil profile in the entire model area, which also has been removed in this scenario (Fig. 15c). For certain areas in the model, this generated a decrease of the vertical flow resistance with up to 40 days. The largest decrease of the vertical flow resistance can be seen in the fields in the Western part of the model area where the peat thickness was significantly higher. The cells that were classified as peat by GeoTop have been removed which generates a decrease in the thickness of the Holocene top layer, resulting in a shorter time for the water to pass through the Holocene layer. The decrease in the vertical flow resistance in the top Holocene layer is just a few percent for the worst case scenario.

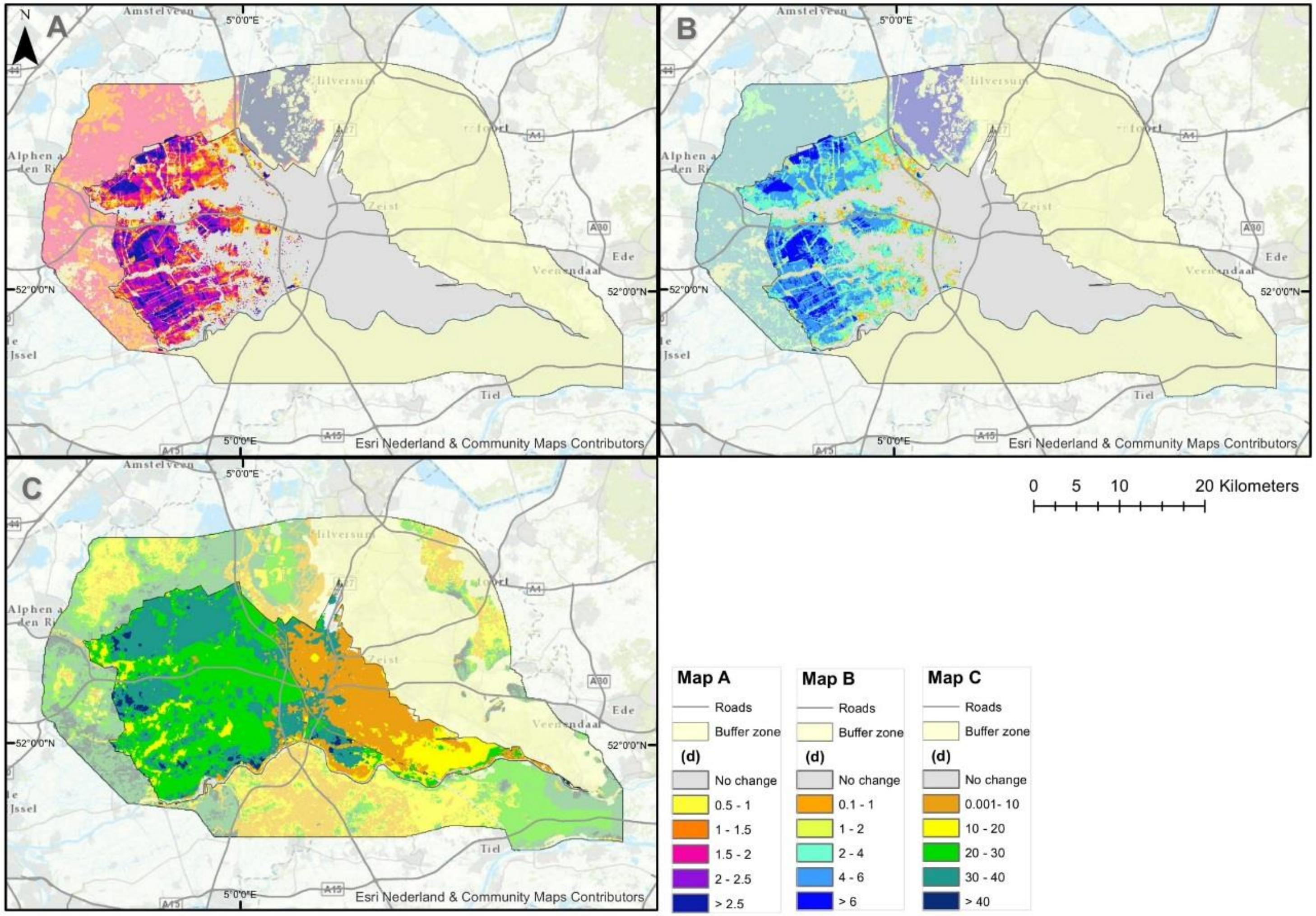


Fig. 15 Show the decrease in vertical flow resistance between current day and the interval in 2050, 2100 and the worst-case scenario. Map A represent the decrease in resistance between present day and 2050, map B the decrease between current situation and 2100 and map C the decrease in resistance between current day and the worst-case scenario. Different legends are used for the different maps to capture the small changes for the first two scenarios. The results from the buffer zone is located under a transparent polygon and is not taken into account in the results as these are affected by the model boundaries.

4.2 Groundwater flow and hydraulic Head

The driving force of groundwater flow is the irregular distribution of energy in the water. The irregularities result in that the water flows from regions with high energy towards those with lower energy. For this reason, it is possible to know that the water is always flowing from areas with a high hydraulic head towards areas with a low hydraulic head (Fitts 2002). The groundwater flow at present day is from southeast to northwest in the first aquifer as explained in paragraph 2.2.3 (Fig. 7; 16a) (Oude Essink et al. 2010). A deviation from the general groundwater flow at present day, is the flow towards the Prinses Irene sluices, the groundwater flow is perpendicular to the contour lines. The hydraulic head is higher in the eastern part of the research area. Moving towards the western part of the research area, the hydraulic head decreases as the land surface is lower in this area. The hydraulic head is lowered due to the continues lowering of the surface water levels to maintain the desirable freeboard. Prior to settlements in the Netherlands the hydrology and peat soils had a dynamic equilibrium, the water management, e.g. lowering of surface water and ground water extraction, offset the balance. By lowering the surface water levels to maintain a desirable freeboard and pumping surface water out of the system, it allows for a groundwater flow to these surface water systems and expose peat to drainage related processes. There is also an induced recharge from the first aquifer to the river systems (Brunke & Gonser 1997; Sophocleous 2002). The close connection between the different parameters in the hydrological cycle and their pursuit to reach a new state of equilibrium drives the lowering of the hydraulic head in the first aquifer, as a result of lowering the surface water levels, at the same rate as peat subside. It is the contour lines that represent the hydraulic head in the first aquifer. The hydraulic head is in direct connection with Prinses Irene sluices and it can be seen as a finger like shape pointing towards the sluice (Fig. 16).

4.2.1 Climate scenario W_H/w+ at 2050

The simulation from Phoenix indicated an average land surface drop of 20-30 cm until year 2050 in the western part of the research area (Table 3). The small change in surface level generates minor variations in the hydraulic head locally (Fig. 16b). Foremost located in the western part of the research area where the majority of peat is located. The round pattern in the peat area is the location of the pumping station Woerden where groundwater extraction created a cone of depression in the first aquifer.

In the eastern part of the research area, the water level in the Amsterdam-Rheine canal mainly determines the hydraulic head in the first aquifer (Fig. 17). There is only little resistance between the channel bottom and the aquifer. When the land subsidence continues, the contours get disconnected from the sluice and it generates a more gradual change in the hydraulic head, due to the groundwater table with equal elevation has moved in a westerly direction as the gradient increase. The location of Prinses Irene sluices can be seen as isolated circular patterns that are not longer connected with the rest of the contours (Fig. 16; 17). The regional groundwater flow follows the same large-scale patterns as it does today. However, the groundwater flow change direction locally at the Prinses Irene sluices from a flow towards the sluice in the previous scenario to a westward direction in the 2050 and 2100 scenario (Fig. 17).

4.2.2 Climate scenario W_H/w+ at 2100

The next scenario is another 50 years in the future, and the results give a simulation of what the hydraulic head might look like in 2100. At this scenario, more peat has subsided and the ground surface is lowered further, in average between 50-80 cm (Table 3). It is possible to start to see a pattern concerning the land subsidence, which drives a lowering of the surface water levels from the water authority which in turn affects the hydraulic head. To maintain the freeboard there is a continuous pumping of water out from the research area which affects the groundwater and the hydraulic head in the first aquifer. The regional groundwater flow continues to follow the same direction from southeast to northwest (Fig. 16c). The hydraulic head in the peat area has been lowered with 0.5 to 1 m (which correlates with the average range of ground surface decrease), and the lower hydraulic head has expanded towards the Eastern part of the research area (Fig. 16c). The groundwater extraction at Woerden and Prinses Irene sluices can be seen in the contours of the hydraulic head in the first aquifer.

4.2.3 Worst case scenario

In the worst-case scenario, all peat has been removed from the Holocene layer, this has large impacts on the hydraulic head in the first aquifer. As mentioned earlier in the text the difference in ground surface is applied to the files containing information of the surface water, their bottom heights and the general head boundary (Fig. 12). It gives rise to significant gradient drops over a relatively short distance within the whole research area. A side effect of peat subsidence and the lowering of surface water by water management the hydraulic head has considerably dropped, especially in the peat area in the western part of the model area (Fig. 16d).

An important result is that the hydraulic head decreases with the same rate as the peat subside, e.g. in areas where up to seven meters of peat is removed the hydraulic head is lowered by seven meters. As mention above the hydraulic head controls where the groundwater flows, directed from a high to a low hydraulic head. Keeping this in mind, for the worst-case scenario, the flow from East towards West is caused to slightly direction towards northwest after about 20 km in the research area (Fig. 16d).

The buffer zone is not sufficient, in the Eastern part of the model area. This results in that the calculations generate a large drop in the hydraulic head over a short distance. To improve the results within the buffer, a larger area would have to be modelled.

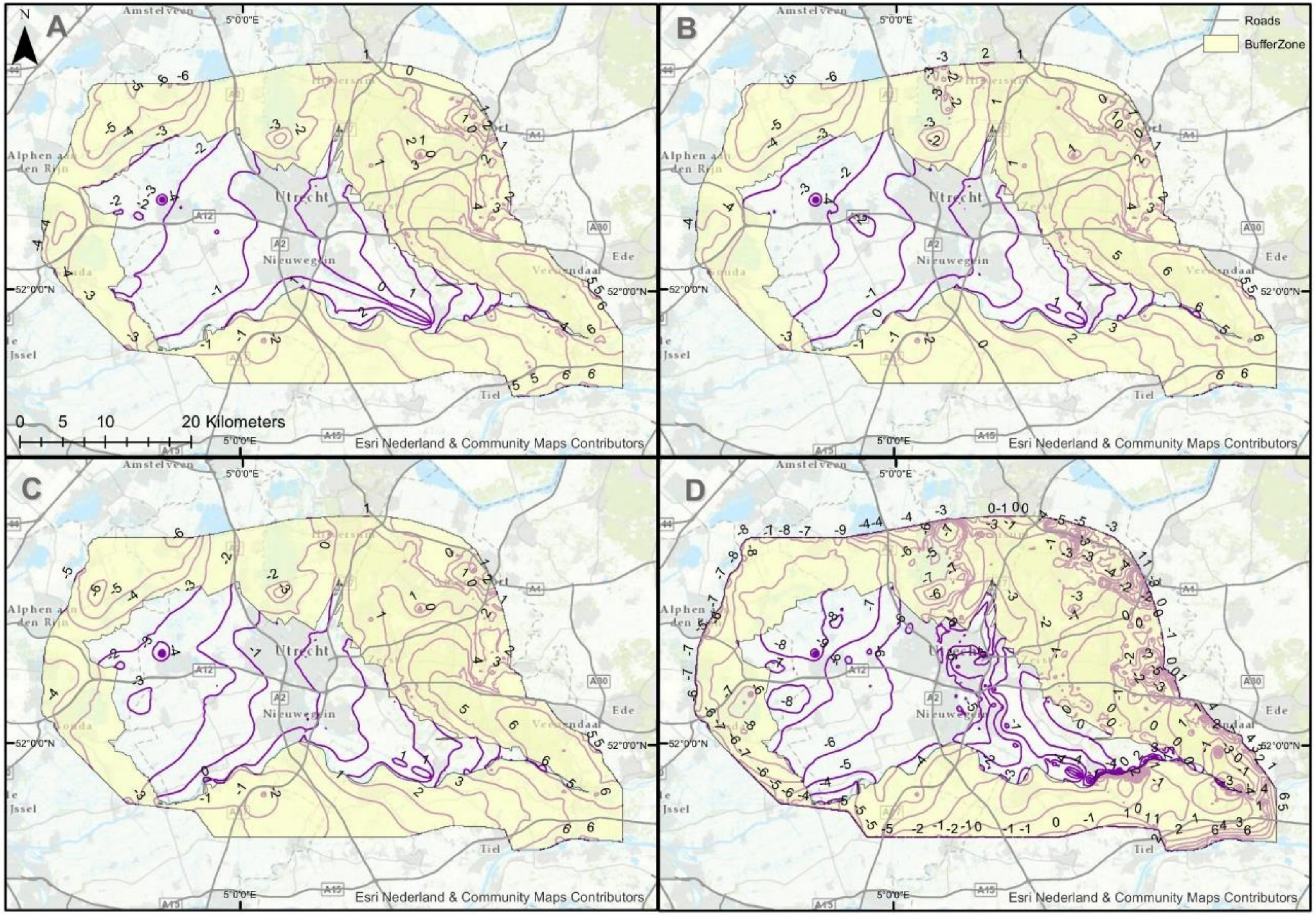


Fig. 16 Illustrates the hydraulic head as contour lines to get a better visualization of the groundwater flow in the first aquifer. Map A: Current day, Map B: Time interval in 2050, Map C: Time interval in 2100 and Map D: worst-case scenario.

4.2.4 Difference in hydraulic head

The hydraulic head will change as the land subsidence continues. After analyzing the difference maps between current day and the three different scenarios, important differences can be observed. For the scenario in 2050 and 2100 the vertical flow resistance. The general head boundary, the surface water level and their connecting bottom heights for the peat area and for the western part of the buffer zone were changed (Fig. 12; 13). The rest of the model area was unchanged. The surface water levels in the eastern part of the research area are maintained in the same way as present, the same goes for the water levels in the Amsterdam-Rhine canal. For these two scenarios (2050 and 2100), the difference in the hydraulic head in the peat area is a direct effect of lowering the surface water levels due to that the peat subsides (Fig 18a; 18b). The decline in the peat area (Fig. 13), where the subsidence has been calculated with Phoenix, varies between a 0.1-0.4 m decrease (Fig. 18a). The next difference map represents the change in the hydraulic head between current day and the scenario in 2100 (Fig. 18b). The large-scale pattern is the same as in the previous difference map. However, the alteration in the hydraulic head is big, especially for the peat area. The decrease in the hydraulic head, in the peat area, ranges between 0.2-1 meter.

The eastern part of the research area has been affected with an increase in the hydraulic head, this is due to the changes in the peat area. To get a better understanding of why the hydraulic head increases, from present day to 2050 and 2100, an enlargement of the area around the sluice has been created (Fig. 16; 17). The contour lines represent the groundwater table with equal elevation. During present day, the contour line for 0m and 1m+ NAP (red arrow and yellow arrow in Fig. 17) is strongly influenced by the sluice in the Amsterdam-Rheine canal and has a finger shaped pattern. The groundwater flow is perpendicular to the contour lines, with a flow towards the sluice. As the peat subsides (in scenario 2050 and 2100) the ground surface is lowered in the western part of the research area, and the contour line for 0 m NAP shifts in a westward direction (Fig. 17). The groundwater table between the contour line 0m NAP (red arrow) and 1m+ NAP (yellow arrow) ranges from > 0m NAP to < 1m+ NAP. As the pressure gradient increases, the groundwater table with equal elevation is relocated closer to the peat area. The relocation of the contour lines result in an increase in the hydraulic head in the eastern part of the research area, this can be seen in the difference map from present day to 2050 and 2100 (Fig. 16a; 16b). The increase in the hydraulic head in the eastern part of the research area is a direct effect of a westward shift of the contour lines. As the pressure gradient increase, the finger shaped pattern cannot continue and the contour lines shifts in a westward direction (Fig. 17). The groundwater table in the eastern part of the area will be affected as the contour lines change. This is visible as there is an increase in the hydraulic head in the eastern part of the research area (Fig. 16a; 17b).

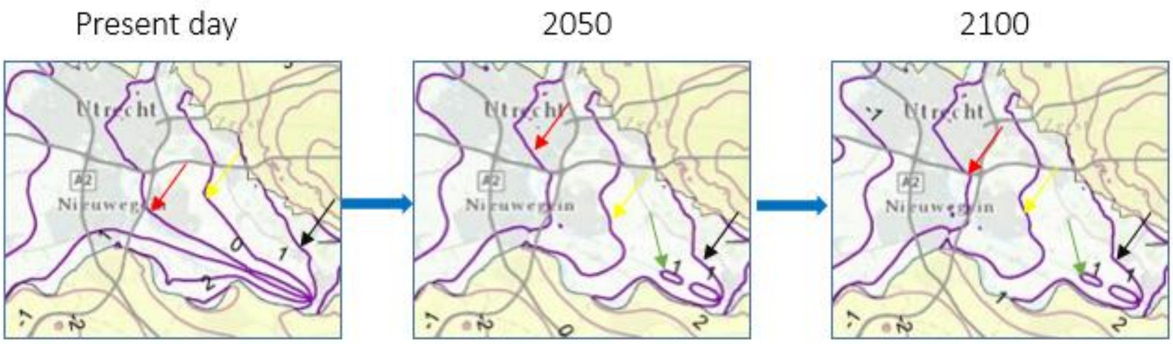


Fig. 17 Enlargement of the Prinses Irene sluices in the Amsterdam-Rheine canal, based on data presented in Fig.16, over the contour lines in the first aquifer. To get a better visualization of how the contour lines shifts from present day to 2050 and 2100, they have been assigned a colour in figure 17; red represent the contour line for 0 m NAP, Yellow 1 m+ NAP, Black 2 m+ NAP and Green >1 m+ NAP.

For the worst-case scenario, all the peat present in the Holocene top layer has been removed. The difference in ground surface was applied to the general head boundary, surface water and their bottom heights Fig. 12). The removal of all the peat has generated a different pattern for the hydraulic head in the first aquifer compared to the other two time-intervals (Fig. 18c). In figure 18c the difference in the hydraulic head between present day and the worst-case scenario is presented. The decline in hydraulic head is significantly larger and varies between 1 to 6 meters and has affected the whole model area (Fig. 18). The decrease correlates with the ground surface drop as a direct result of the removing of all the peat and the lowering of the surface water and their bottom heights in the whole model area. When all the peat has been removed in the Holocene top layer, the surface water has been lowered to the same extent. A lowering of the surface water levels, maintaining a desirable freeboard, is performed by pumping of water out of the system. This induces a groundwater flow to the surface water systems and an induced recharge from the first aquifer to the river systems and the hydraulic head is also lowered in the whole research area (Fig. 18c) (Brunke & Gonser 1997; Sophocleous 2002). The surface water level is lowered in the whole area, including the Prinses Irene sluices, this can explain why the elongated decrease downstream the sluice cannot be seen in this scenario.

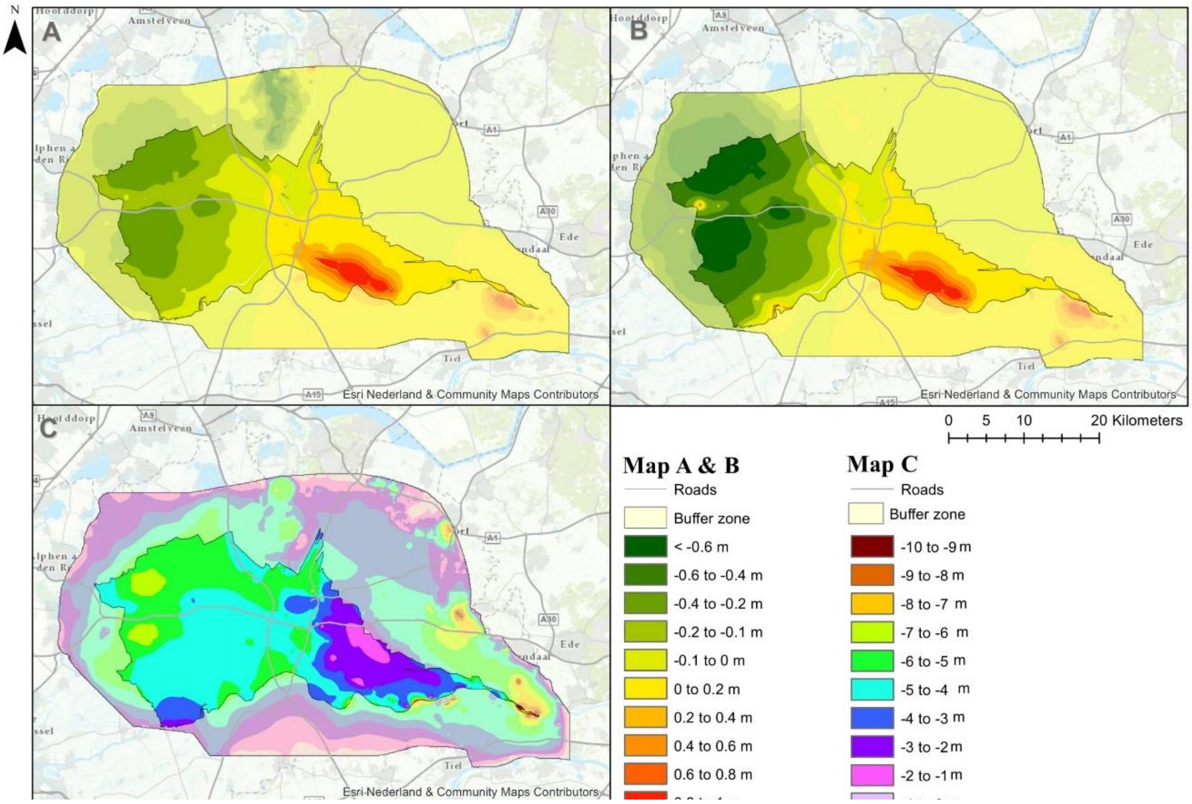


Fig. 18 Shows the change in the hydraulic head between current day and the three time intervals. Map A represents the change in the hydraulic head in the first aquifer between present day and the scenario in 2050. Map B shows the change between the current situation and the time interval in 2100. Map C shows the increase for the worst-case scenario compared with present day.

4.3 Upward- and downward flux

The results presented in this section will be used to answer the question of how the upward flux changes as land subsidence continues. Upward flux can occur when the hydraulic head in the first aquifer exceeds the phreatic water level in the Holocene top layer. An upward flux can also occur between different polders, due to groundwater flow from higher to lower lying polders (Schot & Van der Wal 1992). The rate of downward flux is determined by many parameters, such as sediment, precipitation and evaporation, vegetation cover, saturation level and topography. The maps represent the flux between the Holocene top layer and the first aquifer (Fig. 19).

4.3.1 Climate scenario W_H/w+ at 2050

The large-scale patterns for upward flux and downward flux in this scenario has not changed compared to the current situation. The majority of the downward flux occurs in the eastern part of the research area and the upward flux occurs in the western part of the research area. (Fig. 19b).

4.3.2 Climate scenario W_H/w+ at 2100

The results from the next scenario, the time interval in 2100 show that the large-scale patterns are still the same with a downward flux West of the ice-push ridge and an upward flux in the peat area. The upward flux from the first aquifer is moderate, but for this scenario, the yellow areas, with a 0-0.5 mm per day upward flux, starts to increase (Fig. 19c).

As the peat subside and the resistance in the Holocene layer decrease the flux between the first aquifer and the top Holocene layer does change where areas for upward flux increase and areas for downward flux decrease. The difference in the rate of peat subsidence, if clay is present or not, and different starting ground surface levels does this cause a difference in the surface water levels, which generate local systems of upward flux and downward flux.

4.3.3 Worst case scenario

The results from the worst-case scenario show a downward flux where the fluvial deposits are present. These sediments have not been exposed to subsidence and has remained in the landscape with present days ground surface. In the western part of the research area, where the peat was present, are the polders significantly lower than the present-day ground surface. In these low-lying areas does an increase in the upward flux occur. There are two possible reasons for the increase in the upward flux. The first suggestion is that the change is due to an increase in the difference between adjacent polders. This generates a larger groundwater flow from the higher lying polder to the lower lying polder. (Fig. 19d). In this area, there is an increase in both the upward-and the downward flux. The second explanation for the increase in upward flux is that the hydraulic head exceeds the surface water levels more frequently when the all the peat is gone (Fig. 19d).

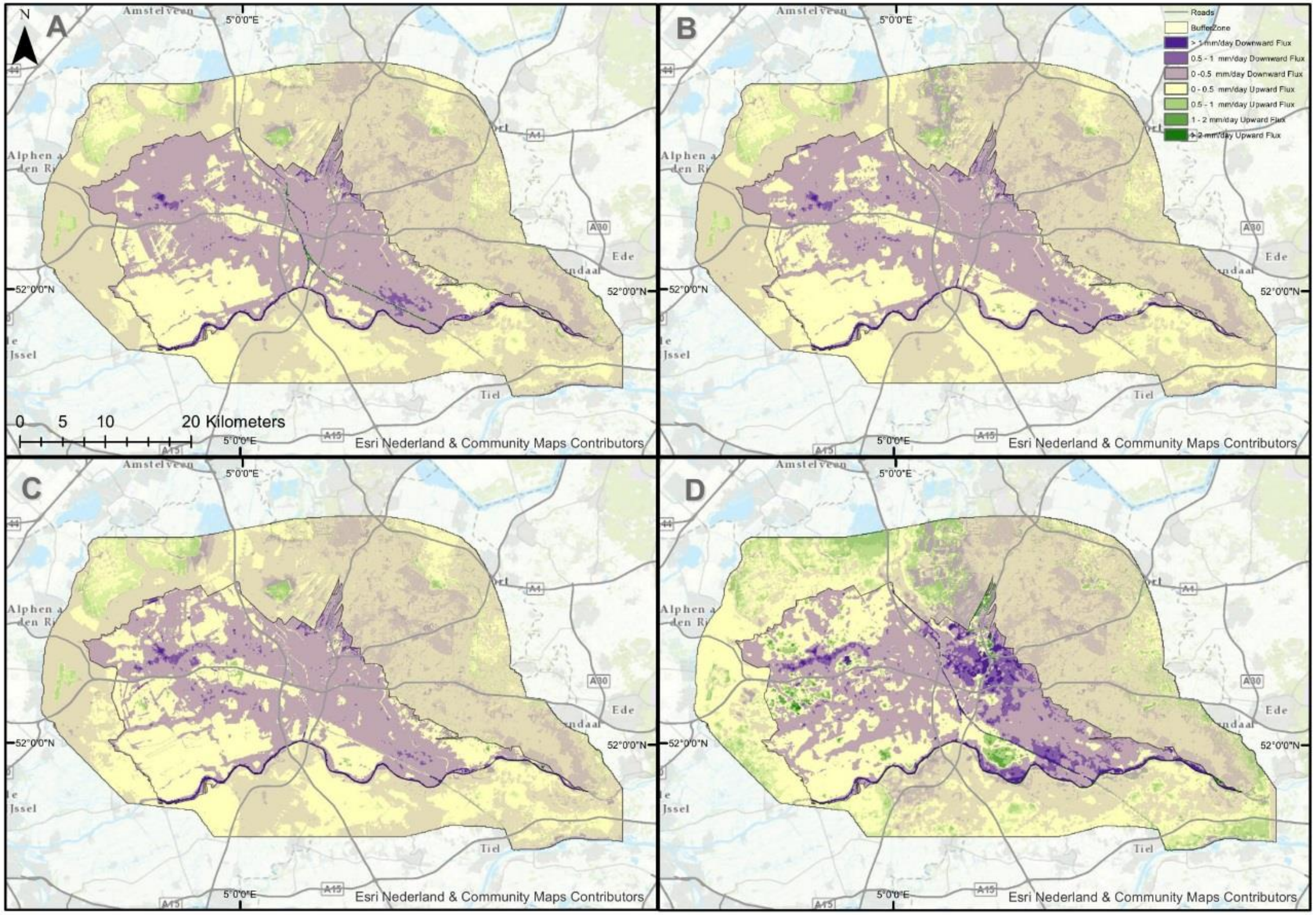


Fig. 19 Shows the flux between the top Holocene layer and the first aquifer. Map A: present day situation, Map B: Time interval in 2050, Map C: Time interval in 2100, Map D: worst-case scenario.

4.3.4 Difference in upward flux and downward flux

To get a better idea of how the fluxes change between present day and the three scenarios, the difference map has been divided into six classes; Increase in downward flux, decrease in downward flux, increase in upward flux, decrease in upward flux, change from upward to downward flux and change from downward to upward flux. The classification help comparing the present day with the three scenarios (Fig. 20).

It is not common that a change occurs from downward to upward flux or vice versa in the time interval 2050 compared to present day. In the Southwestern part of the research area there is an increase in upward flux, extensive light green area (Fig. 20a). The pattern of the light green area in figure 20a is similar to the pattern where the largest decrease in the vertical flow resistance occurs (Fig. 15a). That indicates that there is a correlation between areas with decrease in vertical flow resistance and areas with an increase in upward flux (Fig. 20a). In the Eastern part of the research area there is an increase in the downward flux, where more water is entering the first aquifer compared to present day (Fig. 20). In the Southeastern part of the research area, an increase in upward flux is present. It is a positive sign indicating that the nature area *Langbroekerwetering* is receiving a higher supply of fresh water from the first aquifer to the Holocene top layer.

The differences in upward and downward flux between present day and 2100 indicate that areas in the Northern part of the peat area have changed from upward to downward flux (Fig. 20b). Areas that previously had a downward flux will now have an upward flux. In the Southern part of the research area, there is a part where the upward flux has increased. The general pattern for areas with a decrease in downward flux within the peat area, (dark blue in Fig. 20a; 20b), is that the downward flux is correlated to fluvial deposits (Fig. 2; 6). It is interesting that the fluvial sediments in the Eastern part of the research area has an increase in the downward flux (turquoise in Fig. 20a; 20b). The new ground surface level in the time interval of 2050 and 2100 is lowered in the peat area and the rest of the research areas is unchanged. The surface water level in Prinses Irene sluices is not lowered, and a large increase in the hydraulic head can be seen (Fig. 17; 18). The change in the hydraulic head can also be seen in the flux difference between the Holocene top layer and the first aquifer (red area in Fig. 20a; 20b).

For the worst-case scenario, all the peat has been removed from the Holocene top layer. The location of the fluvial deposits is still possible to detect for this scenario (Fig. 2; 6). In 2050 and 2100 the fluvial deposits are blue; an increase or decrease in the downward flux (Fig. 20c). Locations where a change in the flux has occurred are more common. In the Northern part of the peat area, black color in figure 20c, the flux has changed from a downward -to an upward flux. A Part of the green area is still present in the Southern part of the peat area (Fig. 20c). However, in another part of the green area the flux has changed from an upward to a downward flux, red color in figure 20c. In the worst-case scenario, the flux has changed in the area Langbroekerwetering and when all the peat is removed a downward flux will take place. This swamp area will be negatively affected if extra measures are not reinstated. (Fig. 20c).

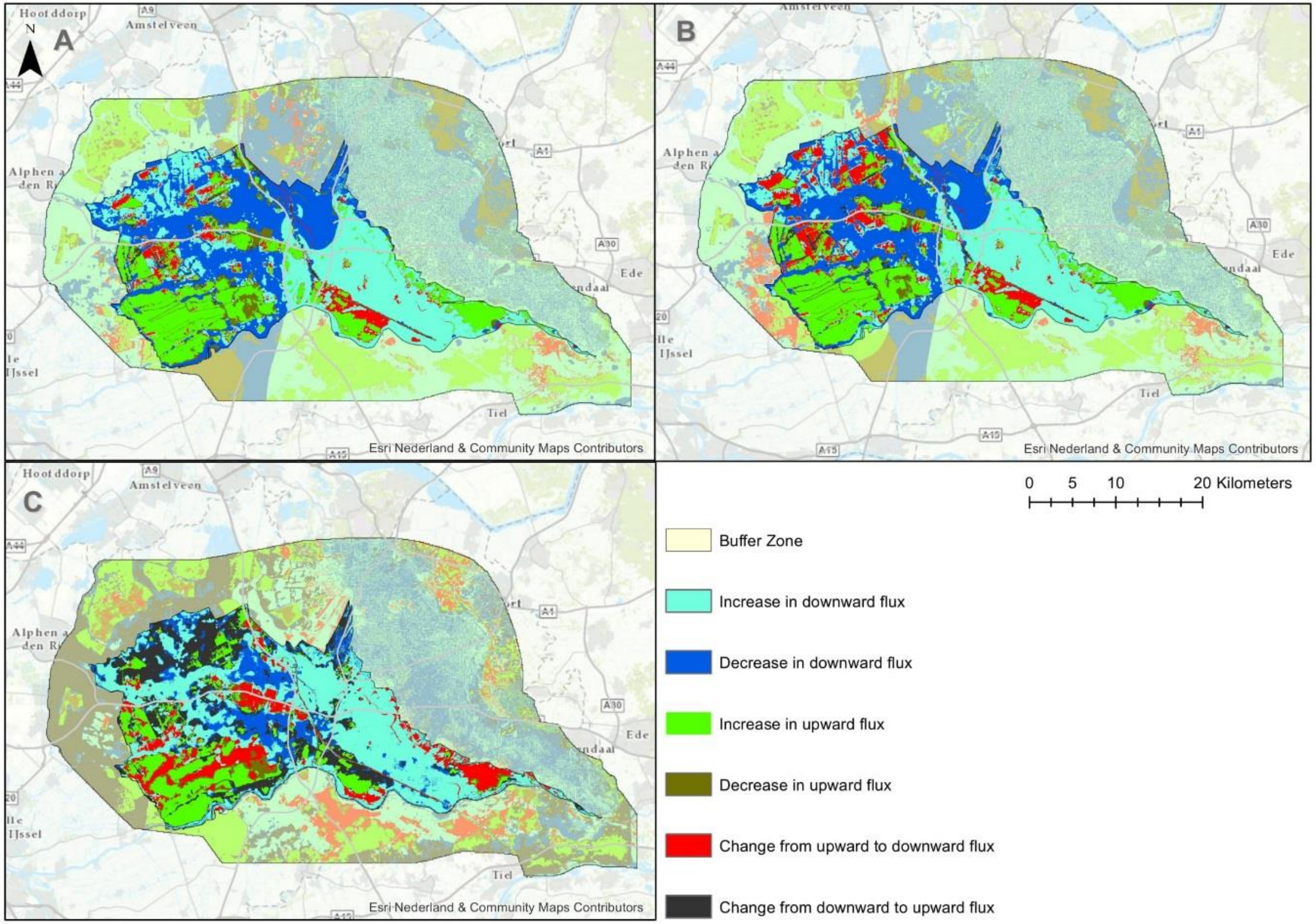


Fig. 20 Show the difference in areas for upward- and downward flux between the top Holocene layer and the first aquifer. Map A: Change between current day and 2050, Map B: display the difference in flux from present day and time interval 2100. Map C illustrates the change in the flux between current day and the worst-case scenario when all the peat is gone.

5 Discussion

The aim of the research was to investigate how the regional groundwater flow would be affected by land subsidence and a decrease in the vertical flow resistance in the Holocene top layer. As well as investigating how the hydraulic head and the flux between the first aquifer and the Holocene top layer would be affected when peat continues to subside. To get a better overview of the different discussion points this chapter has been divided into sections (paragraphs). The first section describes the model limitation/uncertainties. Section 2 uncertainties with available data. Section 3 impact of climate change. Section 4 local vs. regional changes. Section 5 recommendations.

5.1 Model limitations

When the non-stationary run-file did not work due to the limitations of cells that could be utilized and the time limiting factor, the decision was made to use old corrections. The correction file considers an expected change in precipitation and evaporation, in addition to Phoenix that model an expected temperature increase. As well as only being able to run Phoenix for the peat area (in the western part of the research area) to calculate land subsidence for different time periods and not the western part of the buffer zone. These circumstances have affected the outcomes of the groundwater model, since the input data of a model controls the quality of the result. In the discussion, these circumstances and decisions will be discussed to answer how much they affected the outcome.

The lack of available input data for Phoenix leads to the decision to apply an average rate of land subsidence for areas that have been classified as peat or peat with clay on top according to the soil map (Fig. 6). By determening an average subsidence, an indication of the land subsidence for different scenarios is given. The average rate of subsidence is then applied to sections of the buffer zone. With this method, it is not possible to generate a detailed view of how the subsidence would affect different polders. By converting the land subsidence into resistance, it gives unified areas with the same properties. The lack of data for the buffer zone and the usage of average values affects the results. It is particularly evident in the difference map illustrating the vertical flow resistance for the scenario in 2050 and 2100 compared to current day (Fig. 13). The lack of data in the western part of the buffer zone has a direct effect on the vertical flow resistance but is not expected to have a significant effect on the hydraulic head. To improve the results, point files have to be created containing all necessary information about the buffer zone and a correction file for the expected change in precipitation and evaporation. It is a time consuming process and was not managed within the frames of this MSc. Research thesis.

The old corrections were based on predictions regarding the changes in precipitation and evaporation from 2006. The available data concerned the climate scenario w+ for the peat area. The impact of using the old climate scenario for precipitation and evaporation are not expected to have a large impact on the results from the groundwater model, as the difference between the two predictions are just a few percent (KNMI 2014). The other climate scenario suggests a smaller change in the temperature, precipitation and evaporation compared to the w+/w_H scenario. By running the other climate scenarios, it would generate similar results as for 2050 and 2100. However, it would be interesting to see what the difference between the scenarios would be to get a better understanding of the role temperature, precipitation and evaporation has on the peat subsidence.

As mentioned in the beginning of the method a buffer zone is included in the model area to prevent the boundary conditions from affecting the results. For this reason, the results of the buffer zone from the groundwater modelling is not described in the results. It is interesting to mention the impact of the model boundaries; it is especially visible for the hydraulic head in the first aquifer in the worst-case scenario (Fig. 16d). The buffer zone is not sufficient, in the Eastern part of the model area. To improve the results within the buffer, a larger area would have to be modelled.

Another (not accurate) area that is located within the buffer zone is the area North of Utrecht (Fig. 15a; 15b). The difference in vertical flow resistance is significantly higher in this area. The only possible explanation is a model error in the way the new resistance was determined in this area. Due to time limitations within the frame of this project and as this area is part of the buffer zone and not the research area, the files are still used. It is important to point out that if the results from the buffer zone were meant to be used in further research, the new vertical resistance has to recalculated to obtain a more realistic decrease. The model error in the area North of Utrecht is not expected to have a large impact on the hydraulic head nor the groundwater flow in the research area.

The different methods of determening the new vertical flow resistance (Fig. 12; 14) illustrates that there is peat present in the whole area (Fig. 15c). The peat present in the eastern part of the model area is located further down in the soil profile and not exposed to oxygen during present day. The majority of peat is present in the peat area, further down, and is taken into account for the scenarios in 2050 and 2100. It is hard to say if the peat that has been neglected in this model will cause a land subsidence for the time intervals in 2050 and 2100.

5.2 Uncertenties with available data

In reality sediments are heterogeneous and contain a mix of different lithologies as well as macropores. The heterogeneity generates a preferential flow which speeds up the recharge of the groundwater and spreading of contaminations. These heterogeneities are not taken into account in GeoTop, where each cell is a homogeneous unit. At a larger scale the homogeneous units give a rough estimation of the land subsidence. These deviations are probably not affecting the output of the regional groundwater flow significantly, but it is important to keep in mind while conducting computer modeling on a smaller scale.

The decission to use Gunnink et al. (2004) values of the vertical hydraulic conductivity when calculating the new vertical resitance, influences the input data that was used in the groundwater model. If the hydraulic conductivity for peat would be assigned a lower value e.g. 0.018m per day instead of 0.18m per day, this would result in a larger decrease in the vertical flow resistance as the peat subside. On the contrary, if the hydraulic conductivity would be given a higher value e.g. 1.8 m per day instead of 0.18m per day the decrease in vertical flow resistance would be lower. It is difficult to determine the effect of the different values for the hydraulic conductivity on the resistance in the Holocene top layer and their effect on the groundwater simulations. To determine the impact of the hydraulic conductivity a sensitivity analysis has been conducted to investigate the influence on the groundwater modeling. It is a time consuming process but would give a better understanding of the role that the hydraulic conductivity plays.

In GeoTop each cell has been classified based on the majority of the sediment within the cell. So for a cell containing 70 % peat and 30% clay the cell has been assigned a lithology representing peat. In ArcGIS the reclassification is based on the data from GeoTop and their classification system. A cell that has been classified as peat is assumed to be completely gone, due to oxidation, shrinkage and loss of bouyancy, in the worst case scenario and that the new thickness of the cell is set to be 0 m. This is not entirely accurate since there is tecnically 30% clay left in this, as in the example above (TNO et al. 2016; TNO 2016). The data that is available, only show the data as homogenoius units as 100 % peat. The input data has a high resolution, to be able to capture heterogenities and local variation is a recommendation to use a smaller cell size to get a better classification, e.g. that corresponds better with reality. Another way to improve the data is to apply a field generator, that generates a range of possible vertical hydraulic conductivity for each cell which will reflect the heterogenites. However, It is possible that the classification cancel out, as there are some cells e.g. assigned the value 70 % peat and 30 % clay and other cells that contain 70 % clay and 30 % peat.

The flux between the top Holocene layer and the first aquifer is presented in the upward flux and downward flux maps. The groundwater simulations indicate that there will be an increase in the upward flux, especially in the peat areas. The interface between the Holocene top layer and the first aquifer is located about 4.8 m- NAP. It is not possible to say if the increase in upward flux is going to be noticeable at ground surface level and in turn if it will affect the crop yield. Most likely the polders are going to become wetter as the land subsidence continues provided that the areas are maintained in a sufficient way.

5.3 Impact of climate change

The rate of land subsidence in peat areas at present day indicates a lowering of the ground surface with 10 mm per year, depending on where the drainage is located (RECARE 2017). The Phoenix model simulation calculate a subsidence rat of 5.8-6.7 mm per year in locations where clay is present. In areas where the peat does not have a protecting clay cover the calculated subsidence rate is higher, with 8.9-10.4 mm per year (Table 3). What the results show is that the rate of peat subsidence will increase as the climate change, which corresponds to the studies conducted by Caro Cuenca et al. (2007). A possible explanation for this is a longer growing season where the soil does not reach field capacity and peat is exposed to oxygen, shrinkage and loss of buoyancy resulting in more peat subsidence (Fig. 9) (Holman 2006). For rural areas, such as grasslands the impact of land subsidence is going to be relatively small. It is a different matter when it comes to infrastructure within the peat area, such as roads and buildings. A ground surface drop of 50-80 cm until 2100 will result in cracks in constructions due to different rates of peat subsidence. As well as the loading from infrastructure will result in further subsidence. In the long run, the cost to maintain the constructions in the peat area will start to escalate and it will be too expensive to maintain a good quality.

In this thesis the w_H/w+ scenario was investigated based on the RCP 8.5. This is one of the four suggested directions that global warming can take, based on present day research. If the greenhouse emissions are not stabilized an even larger climate change is to be expected. This would generate a higher rate of peat subsidence. It would also drive a further lowering of surface water in the research area, which will affect the hydraulic head in the first aquifer. One of the milder climate predictions is possible but not likely as all the measurements indicate a steady increase in greenhouse emissions. If the new ground surface would be calculated for this scenario, the rate of subsidence would be lower as less peat would have subsided. It is not possible to determine what difference the scenarios would yield. A sensitivity analysis would have to be conducted to determine the range of possible future scenarios.

The calculations show a higher rate of subsidence as the precipitation, evaporation and temperature change due to climate change. The surface water and their bottom heights must be lowered with the same rate as the peat subside to maintain the desirable freeboard. The lowering of surface water drives the hydraulic head in the first aquifer to decrease. HDSR must invest in more efficient pumping stations to pump away the water, if the water management continues in the same manner as now. If this is not done, this is going to affect the crop yield as well as the safety of the dikes. By pumping more and more fresh water out of the system drinking water with a good quality is flushed away to the Sea. Ideally, the fresh water could be used for drinking water or in the submerged drainage.

The change in the hydraulic head says something about the groundwater velocity for the different scenarios. The pressure gradient (the difference in the hydraulic head over a distance) is increasing as peat subside. In the same time, the other parameters in the first aquifer are unchanged such as the porosity, hydraulic conductivity, and the area the water flows through. The increase in the pressure gradient results in an increase of groundwater velocity. This is important to keep in mind, leakages of contaminations will spread faster in the future as the difference hydraulic head increase.

5.4 Local vs. Regional changes

The magnitude of the regional changes presented in this thesis is quite small at year 2050 and 2100. Concerning changes such as the vertical flow resistance, the flux over the interface between the Holocene layer and the first aquifer, hydraulic head and groundwater flow. The large-scale pattern shows the same trend as at present day (Appendix B, Fig. 16; 19). With a higher hydraulic head in the eastern part of the research area and a lower hydraulic head in the western part of the research area where peat is present, and with a regional groundwater flow from southeast to northwest (Oude Essink et al. 2010).

When looking at local scale patterns, the result shows considerable changes. By analyzing local variations of the resistance, a patchwork of polders where local difference in peat subsidence is present (Fig. 15) (de Vries 2007; Schothorst 1977). The calculations in Phoenix, to obtain the new ground surface

(Fig. 12), allows a high level of detail in the files. The details from the subsurface model are transferred into the vertical flow resistance (Fig. 15). The decrease in the resistance can be seen in the local patterns in the peat area for the change in the flux. The areas with the largest decrease in the two scenarios correspond with an increase in the downward and upward flux (Fig. 20a; 20b). A sensitivity analysis could help to get a better understanding of how the vertical flow resistance is related to the flux between the Holocene top layer and the first aquifer. By assessing the relevance of these two parameters, their importance for the hydrological system can be evaluated (Fitts 2002; Saltelli et al. 2000).

A change that occurs in the whole research area is the increase or decrease of the downward flux where fluvial sand is present. This result indicates that when peat is subsiding and the ground surface is lowered the downward flux changes. In some areas (Eastern part of the research area) the downward flux increases (Fig. 20). For the two five year intervals, during 2050 and 2100, the downward flux in areas with fluvial sediment decreases.

A change that has a large local impact is Prinses Irene sluice. The sluice has a big impact on the hydraulic head in the first aquifer (Fig. 16; 17; 18). As peat subside the contour pattern changes because of that the pressure gradient increases. This generates an increase in the hydraulic head downstream from the sluice (Fig. 18a; 18b). As the contour lines shift, westward for time interval 2050 and 2100, the groundwater flow change direction from towards the sluice at present day to a northwest direction. The location of the sluice also affects the flux between the Holocene top layer and the first aquifer (Fig. 20a; 20b). If the surface water would be lowered in the sluice the effect on the hydraulic head and the flux would decrease. However, this could lead to other changes in the areas in close proximity to the sluice. To get a better idea of what the impact of a lowering of the surface water in the Amsterdam-Rhine canal would be, new simulations of the groundwater model would have to be done. Let's say that the sluice in the Amsterdam-Rheine canal would not be attendant in the present day. It is likely that the contour lines would be similar to the time interval 2050 and 2100. If this where the case, there would not have been an increase in the hydraulic head in the eastern part of the research area. The impact of the sluice generates an increase in the hydraulic head as the groundwater table with equal elevation is relocated westward in the research area.

Another area where local changes are visible is the nature area *Langbroekerwetering* (HDSR 2017). At present day upward flux occurs. For the two following scenarios the upward flux increases compared to present day, which indicates a benefit for the swamp area (Fig. 20a; 20b). On the contrary, for the worst-case scenario the flux changes from an upward flux to a downward flux (Fig. 20c). This alteration in the flux will affect the ecosystems in the area if no extra measurements are made. A few suggestions for extra measurements; additional pumping stations and limitations for water use for the area surrounding the wetland (Joyal et al. 2001; Saunders et al. 2002).

It is interesting to speculate; what if the Phoenix model could have been applied for the whole model area or e.g. an installation of new groundwater extraction (as the demand of fresh water will increase). The hydraulic head in the first aquifer would have been affected and local differences would arise. The effect also depends on the location of where a future well would be placed. The hydraulic head for the worst-case scenario (Fig. 18d) has been lowered in the whole research area because of lowering the surface water levels. It is possible to use the water that is pumped out of the system as drinking water. However, it is important to remember that the availability of the fresh water source might vary throughout the year due to dry and wet periods. The changes in the peat area illustrates the same pattern as previous scenarios, but with a larger decrease since all of the peat has been removed. The surface water and their bottom heights have been lowered in the whole model area, including the water level in sluice.

5.5 Recommendations

It is quite clear after living in the Netherlands for some time that stop maintaining the freeboard in the peat areas is not an option, as the land would become peaty swamps. The water management is going to continue in such a way that the land is going to continue to evolve. By combining literature and research from the thesis it is possible to increase the knowledge of peat soils and ways to decrease the rate of subsidence. Previous research indicates that the rate of subsidence depends on on the drainage depth; shallow drainage (< 0,5 below land surface) result in a rate of 2 mm per year and deep drainage (> 0,5 m below land surface) results in a rate of 6 mm per year (Schothorst 1977). RECARE (2017) shows that the rate of peat subsidence has increased over the last decades and is on average 10 mm per year at present day. It also denotes a difference in peat subsidence if clay is present on top of the soil column or not (Geisler 2014). The research in this MSc Research Thesis confirms the difference in peat subsidence. Based on the knowledge obtained during this project, it is not feasible to continue with the present management in the long run. Below are three suggestions/ options discussed;

- To reduce the amount of peat subsidence and associated emissions of greenhouse gasses from peat soils an alternative would be to keep a high ditchwater level. However, this would not be economically possible to sustain traditional farming on the organic soil due to the high surface and groundwater levels. A method that is under investigation and under testing in parts of the research area, is the use of a submerged drainage to operate the subsurface irrigation. This would raise the groundwater levels during the summer months via ditchwater that is infiltrated (van den Akker et al. 2008). There are continuous to investigate different drainage systems and pilot tries are being conducted. The idea is to find a way to slow down the rate of peat subsidence. It is a big problem in the Netherlands and a national collaboration would be the best way to find a drainage system that is suitable. If the research succeeds it should be possible to maintain the land usage in the peat area. The maintenance cost of infrastructure would also be possible to keep on a feasible level.
- A possible solution to decrease the rate of peat subsidence is to combine the application of a shallow drainage with a drainage depth of < 0.5 m below land surface and to create a clay cover on top of the peat areas lacking clay at present. However, the issue of where to obtain enough clay with a high enough mineral content which enables the continues growth of crops as today.
- Another suggestion would be to change the land usage, by growing crops that are adapted for a wetter soil. By changing the land usage, the freeboard can be altered so that the unsaturated zone is decreased. The processes described in chapter two is then affecting a smaller volume. This option would result in a different land usage and most likely affecting the crop yield. However, the rate of peat subsidence would decrease. A land usage change would also generate less maintenance as the surface waters would not have to be lowered in same extent as previous. The hydraulic head in the first aquifer would not be affected in the same extent if the surface water levels are kept high. Another recommendation is to focus new constructions in the research area with fluvial sediment present to reduce the risk of peat subsidence and thereby reducing future reparation costs.
- The last option that is suggested in this report is; to conserve peat in some places. By conserving some peat by maintaining high water levels. This would allow less subsidence in these areas as well as in larger natural areas. The question is how these areas should be picked, since it will affect the land usage as well. It will generate a larger groundwater flow from the higher lying polder, where peat is conserved, to the lower lying polder. By conserving some areas, there will be a local difference in the hydraulic head and a change in the areas with the downward and upward flux.

The water authority HDSR should focus on different drainage systems to find ways to reduce the subsidence. Working together at a national level, would improve the prospect to find tools to decrease the subsidence. it is of great importance to conduct research to find a way to inhibit the subsidence otherwise it will have a large impact on society. Different rates of subsidence will affect the stability of infrastructure in urban areas. An alternative freeboard should be investigated as an alternative to the different drainage systems. By reducing the unsaturated zone the rate of subsidence would decrease, lowering the rate of the subsidization. The advice would be to start investigating areas where a change in land usage would be possible. Before the decision to conserve some peat is made, more research should be conducted. The research would help to give a better understanding of how the local hydrology would be affected.

6 Conclusion

If the water management is continued in the same manner as it presently is (using the same techniques) and lowering the surface water levels to maintain the freeboard as the peat subsides, the hydrological system will not reach equilibrium resulting in new peat present above the groundwater level. The decrease in the hydraulic head leads to an increase in the pressure gradient. This results in an increase of groundwater velocity. For the two time intervals in 2050, 2100 and the worst-case scenario the regional groundwater flow in the first aquifer continues to follow the same flow direction, from southeast to northwest, as it does at present day. With a local change in the flow pattern at the sluice, from a flow towards the sluice at present day to a flow towards northwest for 2050 and 2100.

The vertical flow resistance in the Holocene layer does not change a lot for the different scenarios. The decrease in the vertical flow resistance seems to have little influence on the hydraulic head. However, it is possible to detect a correlation for the decrease in vertical flow resistance and the areas with an increase in upward flux within the peat area.

The hydraulic head in the first aquifer changes a lot from present day to the three scenarios and is mainly caused by lowering of the surface water levels. Prior to settlements in the Netherlands the hydrology and peat soils had a dynamic equilibrium, by lowering the surface water levels to maintain a desirable freeboard and pumping surface water out of the system, it includes a groundwater flow to these surface water systems and expose peat to drainage related processes. There is also an induced recharge from the first aquifer to the river systems. The decline in the peat area, varies between a 0.1-0.4 m decrease for the 2050 interval and 0.2-1 meter decrease in 2100. With an increase in the hydraulic head in the eastern part of the research area due to a westerly shift of groundwater table with equal elevation as the pressure gradient increase. The hydraulic head is lowered in the whole research area for the worst-case scenario.

The large-scale pattern of upward and downward flux does not change from present day to the worst-case scenario, the majority of downward flux takes place in the Eastern part of the research area and the majority of the upward flux takes place in the Western part of the research area. However, a decrease and increase in downward flux arises where fluvial deposits are present. It is possible to detect a correlation for the decrease in vertical flow resistance and the areas with an increase in upward flux within the peat area. The combination of research concerning submerged drainage, a potential change in land usage and an alternative freeboard the ideal way forward in finding a sustainable way to manage the research area. If these actions are not considered the subsidence will continue and even an increase in the rate can be expected as the climate change continuous.

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8 Appendix

A. The correction file that is required as input data in Phoenix, it was not possible to calculate within the frames of this project due to limitation with the non-stationary run file. It is an important step to understand the Phoenix model so the model theory is described below.

Phoenix works within ArcGIS where the model considers which effect an expected increase in temperature has on land subsidence for different time periods. The expected change in precipitation and evaporation must be correlated separately through iMOD as these two parameters affect the groundwater levels, which in turn influence the rate of peat oxidation. Historical data over precipitation and evaporation are available as input data in software package iMOD (interactive MODeling) (Stowa 2009; Vermeulen et al. 2016), after they have been altered to the expected change for the different climate scenarios (KNMI 2014). The hydrological data comprise of the mean lowest groundwater levels (Dutch GLG) and mean highest groundwater levels (Dutch GHG). It is possible to enter information of techniques that are presently used as well as future policies for the water management

The idea is to use the groundwater levels that were calculated to determine the new correlated GLG and GHG to use as input data in Phoenix. The GLG and GHG are based on a period of a minimum of eight years. Equation 5-8 represent how to calculate the new GLG and GHG (Wesseling 1991; Van Heesen 1971).

[5] $$GHG = \frac{1}{nr\ of\ years} \sum_{y=1997}^{2005} HG_3^y$$

[6] $$GLG = \frac{1}{nr\ of\ years} \sum_{y=1997}^{2005} LG_3^y$$

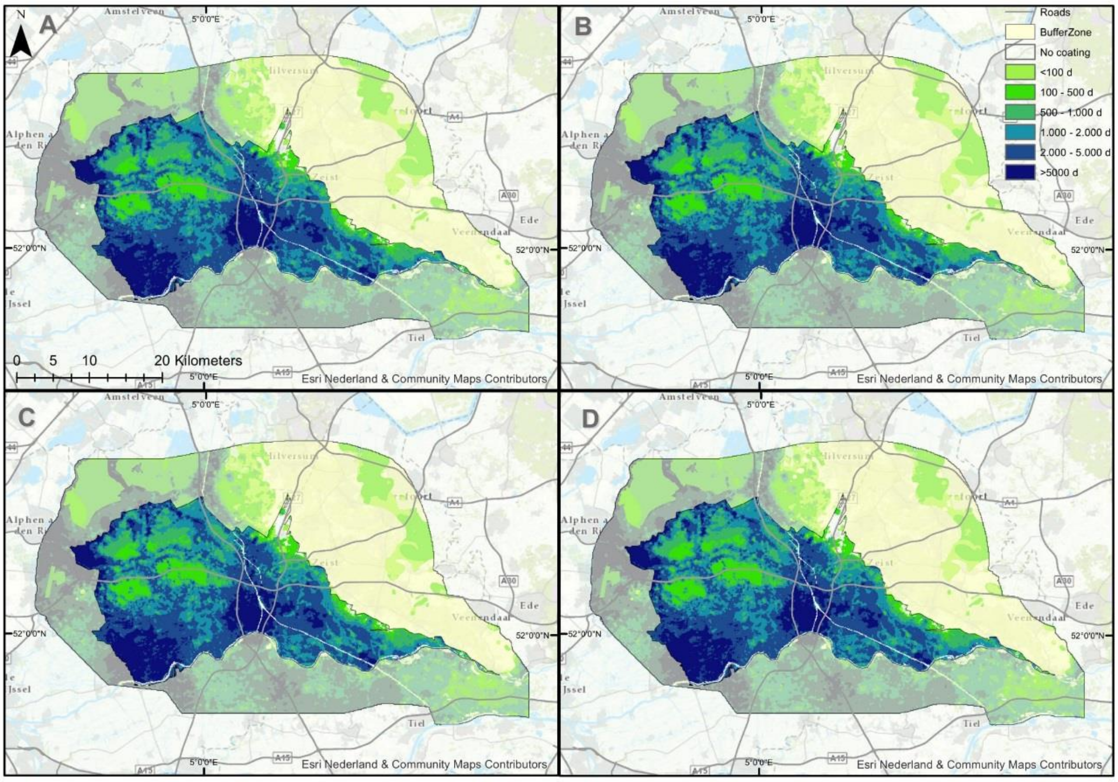
HG_3^j: Mean value of the three highest groundwater levels in a year (y)

LG_3^j: Mean value of the three lowest groundwater levels in a year (y)

[7] $$HG_3^j = \frac{\vartheta_{\max 1}^y + \vartheta_{\max 2}^y + \vartheta_{\max 3}^y}{3}$$

[8] $$LG_3^j = \frac{\vartheta_{\min 1}^y + \vartheta_{\min 2}^y + \vartheta_{\min 3}^y}{3}$$

B. In Appendix A is the results from the groundwater model when it comes to the vertical flow resistance, for the current situation and for the three-chosen time-windows. Map A: Present day, Map B: scenario 2050, Map C: scenario 2100 and Map D: worst case scenario. Present day are the original vertical flow resistance value, so is the time interval 2050 and 2100. The worst case scenario is based on GeoTop data.



C. In appendix B is the stationary run-file that was created to run the computer model Hydromedah presented. The run-file where used for the worst-case scenario and the climate scenario W+ for time period 2050 and 2100. For more information about the description of different lines and values see Vermeulen et al. (2016). The file below shows the original file for the present situation. The lines that are followed by a red arrow below represent the files that has been changed for the different scenarios. The focus of the thesis has been on the first aquifer and for that reason has the alterations only been done on the files that are connected with the Holocene layer and the first aquifer. The files that has been altered is the vertical flow resistance, general head boundary (which represent the boundary conditions of the model), ground surface level, surface water levels and bottom level of the surface water. The file-names were kept in Dutch as the internal database of HDSR are in Dutch to easier to keep track of the files.

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     150      50     0.0001     1.0    0.998
 105000.00 433000.00  173000.00 473000.00    25.00     250.00
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        0         0 (cap)
        1         0 (bnd) BOUNDARY
        1         8 1 2 3 4 5 6 7 8 (shd) GROUNDWATERHEAD
        1         0 (kdw)FLUX FRONT/RIGHT FACE
        1         0 (vcw)FLUX LOWER FACE
        1         0 (wel)WELLS
        1         0 (drn)(DRAINAGE
        1         0 (riv)RIVERS
        0         0 (evt)EVAPOTRANSPIRATION
        1         0 (ghb)GENERAL HEAD BOUNDARY
        1         8 1 2 3 4 5 6 7 8 (rch)RECHARGE
        1         0 (olf)OVERLAND FLOW
        0         0 (chd)CONSTANT HEAD
        0         0 (isg)ISG
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-STATE_L4.IDF
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2,1.0,0.0,E:\HYDROMEDAH\DBASE_HYDROMEDAH\ghb\ghb_head_laag2.idf
3,1.0,0.0,E:\HYDROMEDAH\DBASE_HYDROMEDAH\ghb\ghb_head_laag3.idf
4,1.0,0.0,E:\HYDROMEDAH\DBASE_HYDROMEDAH\ghb\ghb_head_laag4.idf
5,1.0,0.0,E:\HYDROMEDAH\DBASE_HYDROMEDAH\ghb\ghb_head_laag5.idf
6,1.0,0.0,E:\HYDROMEDAH\DBASE_HYDROMEDAH\ghb\ghb_head_laag6.idf
7,1.0,0.0,E:\HYDROMEDAH\DBASE_HYDROMEDAH\ghb\ghb_head_laag7.idf

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8,1.0,0.0,E:\HYDROMEDAH\DBASE_HYDROMEDAH\ghb\ghb_head_laag8.idf
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0,(chd)
0,
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