A comparison of groundwater level estimation methods

Luc Dekker

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UNIVERSITY OF TWENTE.

hoogheemraadschap
Hollands
Noorderkwartier

Preface

In this report, the results of my thesis project for the BSc Civil Engineering Programme at the University of Twente are presented. The research was conducted in cooperation with the water authority Hoogheemraadschap Hollands Noorderkwartier, as part of the work in the hydrology department, which are tasked, among other things, with estimating and predicting the risk of financial damage due to extreme rainfall events. This study, therefore, focuses on this application in comparing several estimation methods for the groundwater level.

I would like to give special thanks to Lara Wöhler, assistant professor at the University of Twente for her critical look during the course of the research. Also, the help and expertise from the hydrologists at Hoogheemraadschap Hollands Noorderkwartier, in particular Wouter van Esse, Jeroen Hermans and Doeke Dam, has been essential to kickstart the research and to turn the results into knowledge. I hope that this report contributes to the understanding of the implications of using a particular type of groundwater level estimation method.

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Summary

Inundation models, which serve to estimate the risk of damage as a result of pluvial floods, rely on a large number of input parameters. One of the most important ones is available soil storage, which is in turn very dependent on groundwater level. There are various different methods to estimate groundwater level. In this research, four of these are compared in order to assess/evaluate their strengths and weaknesses.

The main research question is: Which sources of groundwater level are most accurate under which circumstances? To address this overarching question, two sub-questions have been formulated: 1) Which hydrological conditions are responsible for/influence the deviations between the estimates? 2) How can the identified deviations be explained through the sources' calculation method?

The four groundwater sources assessed were WDM, LHM, Alterra and Acacia. WDM and Alterra are interpolations of measured values, while LHM and Acacia are complete, complex hydrological models, which describe the flow of water in the soil. The outputs of these sources is expressed in terms of mean lowest water table (MLW) and mean highest water table MHW), which correspond to the lower and upper bound of the annual trend line of the water table in any specific location. Together, these parameters are called MxW. The study area is the territory of Hoogheemraadschap Hollands Noorderkwartier, one of the 21 water authorities of the Netherlands.

The study's results show, among other things, that in the higher sandy areas the measurement-based sources, WDM and Alterra, give too shallow estimates of the groundwater level because the estimates depend on measurements taken outside of the study area. Moreover, these sources overestimate the depth of the MHW in peaty areas, in the south of the study area. This is likely caused by the linear regression used. In addition, it was shown that the measurement-based sources are generally closest to the genuine values, but do not portray the variation of the groundwater level with respect to the surface through space as well as the simulation-based sources do. This makes sense because the measurement-based sources only use measured (so realistic) values, but describe the whole area based on these measurement locations, despite the fact that they could be subject to local, special circumstances. Conversely, however, the simulation-based sources do have extreme, unreliable values in more locations, LHM has a too shallow MHW estimate on the island of Texel and Acacia varies too extremely on a local level.

1. Introduction

Inundation models are important tools in flood risk policy. They give an indication of the damage to be expected in case of an inundation and the influence that counter-measures have on it. This way, understanding about the current risk and the forecast risk after counter-measures can be combined with the costs of said measures in order to take informed decisions. For the sake of the quality of the decisions as well as the transparency towards the many citizens who are affected by the flood risk, it is critical that these inundation models are as accurate as possible.

As with every model, however, there are sources of uncertainty. In inundation models, one of the most uncertain parameters is available soil storage. It expresses the amount of water that can infiltrate into the soil until it is completely saturated. It varies from place to place and it is difficult to measure, so it has to be estimated instead. There are many ways to estimate the soil storage, but the groundwater level plays an important role in each of them as it determines the depth of the soil layer that is not yet saturated.

The groundwater level itself, however, is also subject to much uncertainty. There are many estimates across space, based on complete hydrological models or on measured values interpolated with respect to soil characteristics. Each of these methods has strengths and weaknesses, depending on the method's purpose, assumptions and underlying methods. Therefore, this research assess different methods with the goal of xxx. The overarching question is: which groundwater level sources are most accurate under which conditions?

This can be dissembled into two sub-questions: which hydrological circumstances predict the differences between the sources and how can those differences be explained through the source's calculation process? In order to answer these questions, the differences between the sources are plotted in the form of maps. Subsequently, the relation between these maps and a range of geohydrological parameters is assessed. Moreover, an analysis of the procedure behind the groundwater sources and their implications is conducted through literature study and expert interviews. Finally, the accuracy of these sources is assessed by comparing them to the surface water level in the area and to the few measured values that there are. The study area spans the territory of the water authority Hoogheemraadschap Hollands Noorderkwartier (HHNK), which covers all land north of the IJ and the Noordzeekanaal (which connect the city of Amsterdam to the North Sea) in North Holland, the Netherlands.

In the next chapter, the theory behind groundwater is described, and a quick description of each source is given. Subsequently, the methods used in this research are outlined, before their results are presented in chapter 4. A discussion and the ensuing conclusions follow, which provide a critical view on and an interpretation of the results. Finally, in chapter 7, the recommendations are given, both for current action and for future research.

2. Theory

The groundwater level is the elevation of the top of the saturated layer. It can be measured by digging a hole into the ground and measuring the level of the water that flows in. If one wishes to document the groundwater level during a longer period of time, however, the hole needs to be stable, so a pipe is inserted into the ground, with a filter attached on the low end. The water can enter through the filter, but if the top of the filter is lower than the groundwater level, the pipe functions as a piezometer (Bouma, Maasbommel, & Schuurman, 2012). Therefore, the water level inside the pipe is equivalent to the hydraulic pressure head at the top of the filter, which is a quantity that describes the flow pattern of water; water flows towards a lower hydraulic pressure head (hence, the water will rise to the hydraulic pressure head inside the pipe; above that level, the hydraulic head is higher than that at the top of the filter). Its definition is based on the elevation and the pressure at a certain point. The hydraulic pressure head is usually, but not always lower at deeper depths, so filters that are too deep record too low a groundwater level.

2.1. Groundwater dynamics parameters

However, the groundwater level is difficult to quantify, because it fluctuates extremely through time (as shown by the grey lines in Figure 1). Interpolation through space constitutes another complicating factor. In order to overcome this issue and represent the groundwater level as a more steady variable, the mean highest water table (MHW) and the mean lowest water table (MLW) are used by researchers to describe groundwater level (Knotters, sd). These parameters again differ across space, but not throughout the year. First of all, the three highest and three lowest water tables measured in one specific location during each hydrological year (starting April 1st) are averaged. These average values are called the HW3 and LW3 respectively. These values from thirty consecutive years (a climate period), in turn, are averaged, provided no major changes in water management policy that influence the groundwater level at the location are made in this period (Knotters, sd). This measuring procedure for the MLW and MHW is designed such that they are roughly equal to the upper and lower bound of the annual trend line of the groundwater level, known as the 'regime curve' (see the dotted line in Figure 1). The regime curve increases relatively quickly to its highest level late autumn, and decreases relatively slowly to its lowest level late summer (van der Gaast, Vroon, & Massop, 2010). Also note that the time of year in which the minimum and maximum groundwater levels occur is highly variable. As a result, the day-by-day average (shown in black in Figure 1) bears little resemblance to the regime curve. Due to the complicated nature of these parameters, truly measured values of the MxW (an acronym henceforth used to denote the MLW and MHW at once) are very rare. Instead, researchers depend on estimation methods.

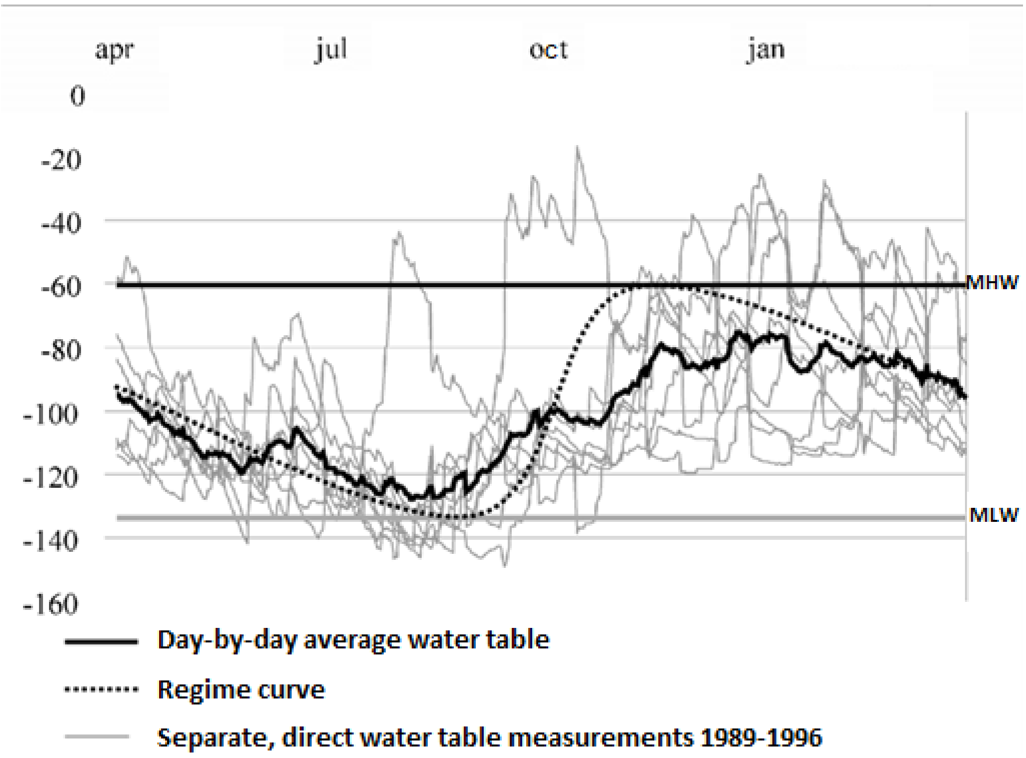

Figure 1 The groundwater level measured in eight years directly (grey), averaged day-by-day (black) and the regime curve (dotted) (van der Gaast, Vroon, & Massop, 2010)

When expressed with respect to the surface, the positive direction is downwards, so numerically high values correspond to physically low (deep) water tables. Regardless of this, 'high' and 'low' are understood to mean physically high or low in this report. Terms like 'overestimate' or 'increase' are used in accordance to this definition. Sometimes, 'shallow' and 'deep' or 'wet' and 'dry' are used instead.

2.2. Sources

Four estimation methods that are used to calculate or interpolate values of the MxW were used in this research and are discussed below; WDM, LHM, Alterra and Acacia. WDM and Alterra are based on measurements, LHM and Acacia are models of the flow processes.

First of all, WDM is a measurement-based calculation method for the whole of the Netherlands, freely available on the government-run BROloket (*Basisregistratie Ondergrond*, basic subsurface registry). WDM has existed since 2004, but the most recent update in the study area was made in 2014. A large number of permanent measuring locations, subject to several requirements concerning location, depth and time, were selected (Hoogland, Knotters, Pleijter, & Walvoort, 2014). The measured water tables were entered into a physical time series model, which incorporates the measured values and meteorological data to extend the measurements to a 30 year period. This way, both of the MxW values and their uncertainties were documented. The density of measurements was increased by measuring the water table twice in many locations, once in summer and once in winter. The water tables of the permanent locations on that day were compared to that location's MxW values (MLW for the summer measurement, MHW for the winter measurement) and using linear regression, the MxW in the one-off locations and their uncertainties were determined. In the dune areas (see Figure 3), this dense grid of measurements was interpolated using another linear regression model, with respect to elevation, relative elevation (defined as the difference between the elevation and the mean elevation of a specified radius around the point), the *drooglegging* (a word that does not appear to have an English equivalent, which denotes the difference between the surrounding surface water level and the surface elevation), the drainage density (the fraction of 25x25 metre cells in a 100 metre radius that include a waterway) and the previous estimates of groundwater level or its corresponding available soil storage estimate, based on CAPSIM, a model for flow in the unsaturated zone. Within each hydrogeologically homogeneous area, called 'stratum' (see *Figure 2*), a different combination of factors could be used in the regression analysis, depending on the quality of its approximations (de Gruijter, van der Horst, Heuvelink, Knotters, & Hoogland, 2004). In the rest of the area (see Figure 3), this second regression was not conducted. Instead, the MxW was assumed to be uniform in the surroundings of the one-off measurement (Hoogland, Knotters, Pleijter, & Walvoort, 2014). In each linear regression model, the measurements were weighted according to their uncertainty.

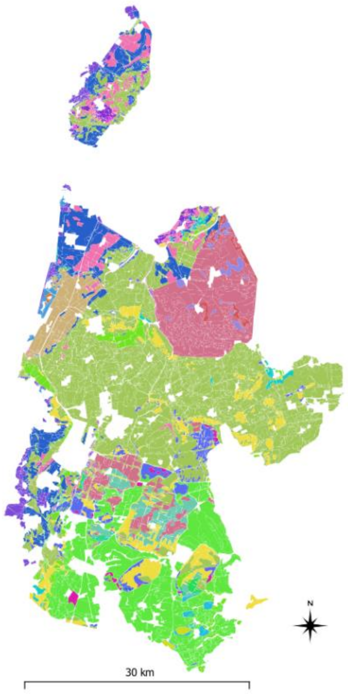

Figure 2 Stratification in the study area (the legend is not included, because it is meant illustratively). Note that the stratums also include sections from other parts of the Netherlands.

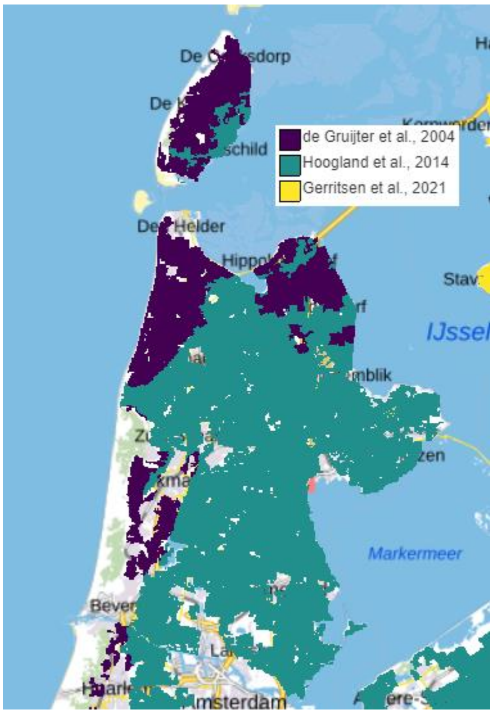

Figure 3 Division between the two methods of WDM

Secondly, the *Landelijk Hydrologisch Model* (National Hydrological model, LHM) was established in 2012 to replace the many different water-related models that were in use in Dutch governmental organisations before (Delsman, Veldhuizen, & Snepvangers, 2012). The model in turn consists of at least two sub-models: MODFLOW is used to determine the groundwater flow in the saturated zone (deeper than the water table) and MetaSWAP is used to calculate the behaviour of the water in the unsaturated zone (between the water table and the surface). In addition, the surface water flow model MOZART/DM can be added for some purposes, but it is irrelevant for the calculation of the MxW. MODFLOW combines Darcy's law (relation between the water flow pattern and the *hydraulic gradient*, the derivative of the hydraulic head across space) and the water balance (the total amount of water in the system remains unchanged), two theoretical equations, with an empirical relation between pressure and moisture content (Guo & Langevin, 2002). MetaSWAP, similarly, is based on Richards' equation (similar to Darcy's law, but it includes root water uptake), the water balance and the empirical Van Genuchten parameters, which express the relation between soil moisture and hydraulic head (van Walsum, Veldhuizen, & Groenendijk, SIMGRO 7.1.0 - Theory and model implementation, 2010). If the deviation between MODFLOW's and MetaSWAP's water table is too large, the border between the sub-models is changed and certain parameters are exchanged. This is repeated until the groundwater levels have sufficiently converged, which tends to happen very quickly (van Walsum & Veldhuizen, Integration of models using shared state variables: Implementation in the regional hydrologic modelling system SIMGRO, 2011). The model was run, based on measured weather data, for a long period. The time series of water tables from April 1st 2011 to March 31st 2018 were used to create the MxW maps of the whole of the Netherlands.

Thirdly, the Alterra KK2010 map was evaluated, which dates to 2010. It was meant as a relatively fast update of the existing WDM map (van der Gaast, Vroon, & Massop, 2010). As there was a lack of available permanent measuring locations, new, one-off measurements, initially conducted for local mappings of the water table, were used. The locations of these local measurements are shown in Figure 4. These local mappings, which had a very high density of measurements, but spanned only small areas, were overwhelmingly made in sandy areas. The existing *Grondwatertrappen*, categories based on the values of the MxW, were fitted with new distributions of the MxW values, which were transformed to relations with several mappable characteristics (KK in KK2010 is short for *Karteerbare Kenmerken*, which translates to mappable characteristics). This enables the nation-wide mapping of the groundwater level.

Figure 4 Locations of the local mappings (van der Gaast, Vroon, & Massop, 2010)

Finally, the fourth source of MxW values used in the research is Acacia, which results from the model *Leven met Zout Water* (living with salt water, LMZW). This model was created in 2012 by the consultancy company Acacia Water specifically for the study area, excluding the island of Texel. Its focus was the ratio between fresh and salt water. Therefore, the SEAWAT model was used (van Staveren & Velstra, 2012). SEAWAT builds on MT3DMS, a solute transport model, and a modified version of MODFLOW (Guo & Langevin, 2002). MODFLOW was adapted such that it allows for a variable density, because salt water has a higher density than freshwater. The density of the groundwater was approximated by a linear, empirical relation to the salt concentration. However, the hydraulic conductivity, the hydraulic head and the specific storage were all simplified to that of freshwater, for the benefit of shorter computation time. Once the groundwater flow pattern was calculated, it was possible to determine the solute transport through a mostly theoretical equation. The modelled period spans from 2000 to 2010. Again, the time series of groundwater levels was converted to MxW values.

3. Methods

In this research, a series of methods were used: 1) literature study was used to compare the theory and procedure behind the sources mentioned in Section 2.2. 2) Pearson's correlation test and the t-test were used to compare the results of the groundwater level sources. For this purpose, the data was first processed so as to express the difference to the other sources' results (rather than the difference within one source) before these tests were conducted. 3) The sources were compared to each other, to the target levels and to recent measured values in order to gain insight into the accuracy of the sources, rather than only their numerical differences.

3.1. Comparison of methods

Literature study and expert interviews were conducted to compare the theory behind the sources to each other. A literature study of the sources' documentation and validation was used to gain insight into the calculation procedure that supports each of the sources. In the case of the hydrological models (LHM and Acacia), these were often user guides, patch notes and validation documents. In the case of the calculation methods (WDM and Alterra), it was the report of the study that produced the map in question.

3.2. Comparison of MxW values

Secondly, the values in the sources were compared. First of all, the maps had to be harmonised such that they are comparable; the unit was changed to metres below surface and the resolution was changed to 250x250 metres (the coarsest of the raw grids). The values along the dykes (with a buffer of a single cell's width) were excluded from the dataset, because these values are highly dependent on the resolution and alignment of the original grids. As a means to isolate the differences between the sources and exclude spatial variability of the groundwater level itself, the groundwater level of each source in each grid cell was expressed with respect to the median value between the sources in the relevant location (see top row in Figure 5). The median is preferred over the mean, because it is less sensitive to outliers. The resulting maps show the way in which the sources are distinctive more clearly than the maps with absolute values do. Additionally, cumulative distribution functions, which show the value of each percentile, were plotted in an effort to reveal any striking statistical properties of the datasets. This includes the central tendency and the spread, but also specific patterns like bimodality, overrepresentation of one specific value etc.

Subsequently, the goal is to relate this difference map to the hydrological conditions, in order to find structure behind the differences. To achieve this, correlation coefficients were calculated between the difference maps and each of the hydrological conditions that are included in the research (these conditions are further elaborated later in this section). The correlation coefficient can range from -1 to 1 and indicates the strength and direction of a correlation. The further away from 0, the stronger the correlation is and the direction of the correlation corresponds to the sign of the coefficient. This way, patterns in the difference maps can be discovered, even if they are not immediately visible. The condition with the strongest correlation is excluded through linear regression; first of all, a linear formula that approximates the relation between the value of the condition and the value on the difference map is drafted. Secondly, the difference map is expressed with respect to the expected value based on this formula before, finally, the correlation coefficients between the normalised difference map and the remaining conditions are calculated. The soil type is an exception, because it is a qualitative, not a quantitative condition. Instead of calculating correlation coefficients, the mean value of the difference map was calculated within every soil type and these values were compared.

A different kind of difference map was used for this purpose; instead of the median, it was based on the mean. This way, values that would otherwise be close to zero are distinguished based on which way the outliers go furthest (compare the top row of Figure 5 to the middle row). This is deemed preferable, because the accuracy of the sources is unknown, including that of the outliers. Therefore, it would be dismissive to use the median.

Moreover, particular extreme values were taken out (see the bottom row of Figure 5), because these differences can not be attributed solely to the hydrological conditions, but would still greatly influence the correlation coefficients. For example, one particular source could have a positive correlation between the difference map and elevation, but the correlation coefficient would be negative if, at a high elevation, there is such an area with extremely low values in the difference map. Instead of fully incorporating these areas into the statistical analysis, the circumstances shared between the areas were identified and treated as a separate observation.

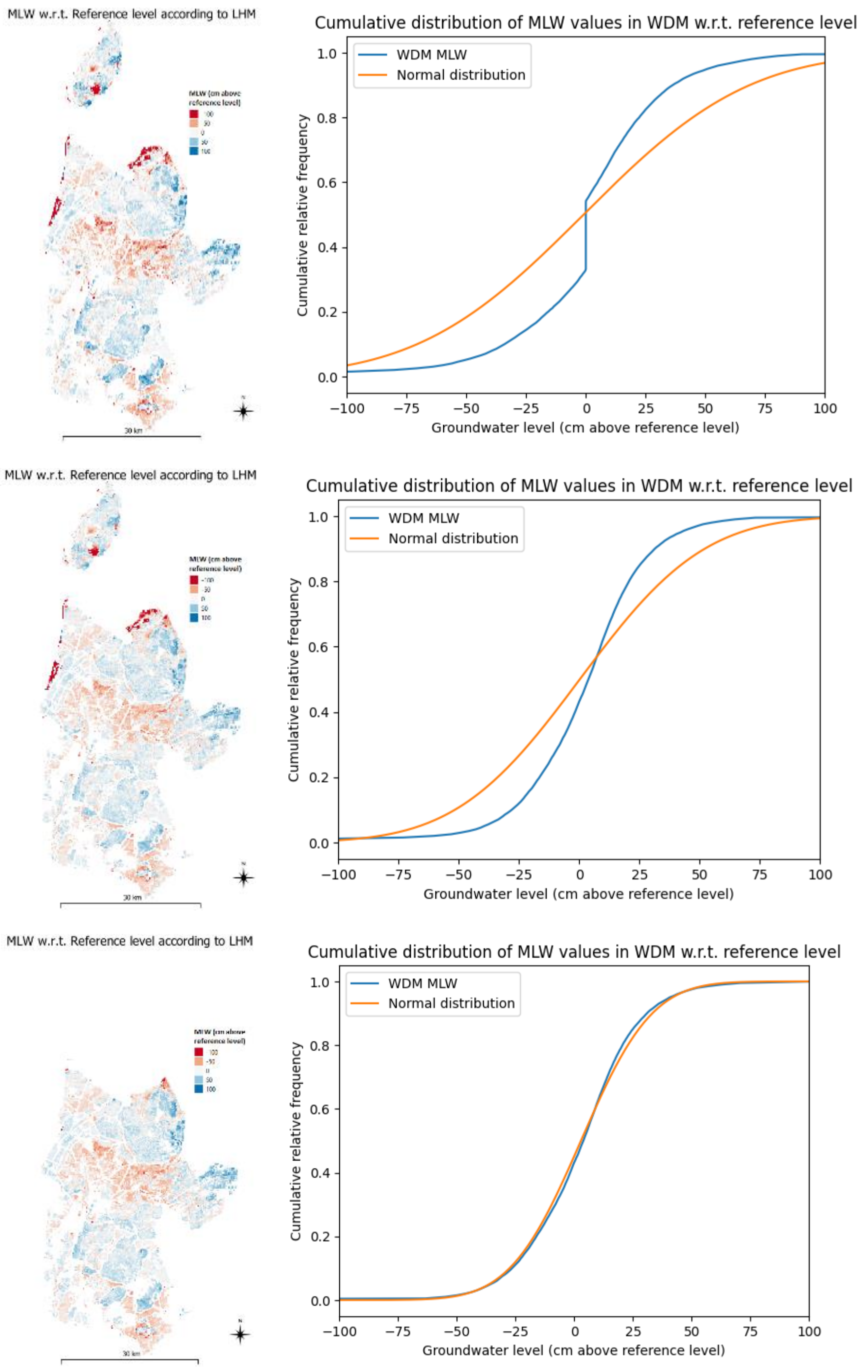

Figure 5 Difference maps and cumulative distribution functions of the MLW values according to LHM. From top to bottom: median as the reference grid, mean as the reference grid, mean as the reference grid without extreme values.

The conditions that were tested for correlation, were inputs used by the sources, as well as several other quantities. A description of these conditions and the way they were obtained follows. As indicated in section 2, the parameters used to calculate the MxW in the WDM are the surface elevation, the relative surface elevation, the *drooglegging*, the drainage density, the groundwater values of a previous mapping and, finally, the corresponding soil storage. The last two were excluded from correlation testing, because they do not actually express a property of the water system, like the other inputs, but are merely a different, older estimates of the groundwater level itself and an abstract variable derived from it. *Actueel Hoogtebestand Nederland* (Current Elevation Model Netherlands) was the source of the elevation map. For the relative elevation, a radius of 300 metres was used (that means, the elevation at a certain point was reduced by the mean elevation in a 300 metre radius around that point), as an arbitrary but reasonable value, because it is in the middle of the range of radii that was used by WDM (de Gruijter, van der Horst, Heuvelink, Knotters, & Hoogland, 2004). The *drooglegging* is equivalent to the grid of target levels with respect to the surface; the winter target level is used during comparisons of the MHW, the summer target level during those of the MLW (mind that these two maps are nearly identical). The drainage density map was constructed for the purpose of this research, based on a nation-wide map of water-ways and lakes and other topographic features (Kadaster, sd). Its vector file of waterways was rasterised to a 25x25 metre grid, and the percentage of cells within a radius of 100 metres that contained water was inserted. However, in order to compare it to the much coarser difference map, this grid had to be represented in a 250x250 metre grid. This was done by taking the average value in each of the new cells. LHM, in addition to the elevation, uses the root zone depth, soil type, land use, precipitation, infiltration and evaporation. Location-specific data for the root zone depth across North Holland is unavailable. Soil type, on the other hand, is available in HHNK's own database. Land use, precipitation, infiltration and evaporation were not used in the research, because their time-dependency makes them too complicated for the time frame of the research. Furthermore, the shortest distance to salt water (North Sea or Wadden Sea) and the shortest distance to one of the major freshwater lakes (IJsselmeer or Markermeer) were used as conditions. Finally, seep, the amount of water that flows from a less permeable layer into the saturated zone ($mm\ d^{-1}$), was provided and checked for correlation with the difference maps.

3.3. Plausibility assessment

The found correlations do not disclose anything about the accuracy of the sources, but only about the differences between them. Therefore, it is important to assess the plausibility of the sources' values. After all, the actual values of both groundwater level parameters and the available soil storage are unknown, which is the very reason that estimates are necessary. First of all, several locations where groundwater level is measured were compared to the results from the sources in that location. The filters of the pipes had to be at most 3 metres below the surface and the measuring frequency had to be at least twice per month. However, such locations are limited in number (see Figure 6) and present a bias themselves. Most of them are located in natural reserves, where the groundwater level is essential to the environment and therefore kept at a higher level compared to agricultural land. Therefore, the measuring locations in the high dunes were excluded. Another class of measuring locations is placed near road construction sites in order to assess the stability of the soil below the road. These measurements are often taken very close to the edge of a wet ditch, which influences the groundwater level. Therefore, these were likewise excluded. Secondly, target surface water levels present another method to validate groundwater level estimates, as became clear from the expert interviews. After all, any estimate of MLW that is higher than the surface water level next to it, is unrealistic. Thirdly, the standard deviation between the estimates from the sources in the same locations was mapped. A low value implies that the sources are close to each other, which suggests that the actual value is close as well.

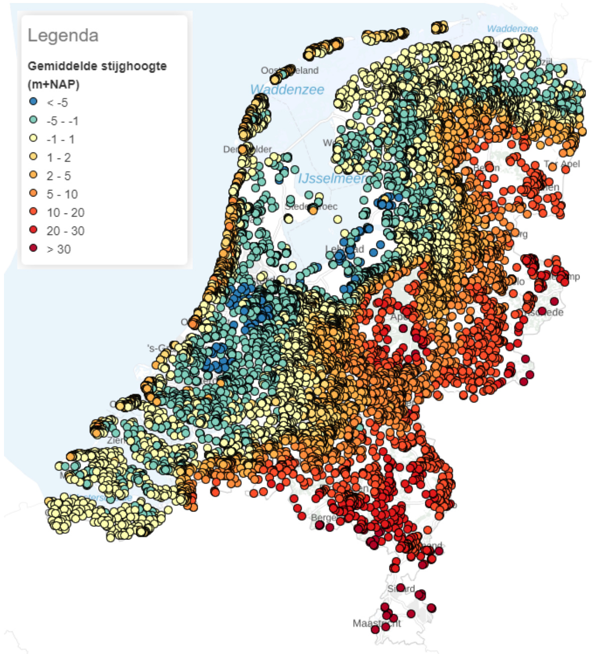

Figure 6 Groundwater level measuring locations with a filter between -8 and 3 m +NAP in the Netherlands (GDN, 2023). Note that the eastern and southern parts of the country are situated higher (deeper filters are more common, but not usable for this project), but even comp ared to the other low, coastal areas, North Holland is relatively empty on this map.

In Table 1, all data maps used in the research are listed, including, if applicable, their sources, operations that were done before they were used and the calculation procedure.

Table 1 List of geographical data used in the research

Blue: Conditions that were tested for correlation with the difference maps		
Orange: Difference maps that were tested for correlation with the conditions		
Raw Data		
Name	**Source**	**Operations**
WDM MLW	WDM	Harmonise the units (cm below surface) and resolution (250x250 m), cut out the study area and remove dykes.
LHM MLW	LHM	
Alterra MLW	Alterra	
Acacia MLW	HHNK	
WDM MHW	WDM	
LHM MHW	LHM	
Alterra MHW	Alterra	
Acacia MHW	HHNK	
Summer target level	HHNK	Harmonise the units (cm below surface) and resolution (250x250 m)
Winter target level	HHNK	
Elevation	AHN	
Water bodies	BRT	
Soil type	PAWN	Divide the 21 soil types into three broader categories
Seep	HHNK	
Processed Data – statistical analysis		
Name		**Calculation**
MLW Reference grid		Cell-by-cell mean of each of the sources' MLW estimates
MHW Reference grid		Cell-by-cell mean of each of the sources' MHW estimates

WDM MLW Difference map (1)	WDM MLW subtracted from the MLW Reference grid
LHM MLW Difference map (1)	LHM MLW subtracted from the MLW Reference grid
Alterra MLW Difference map (1)	Alterra MLW subtracted from the MLW Reference grid
Acacia MLW Difference map (1)	Acacia MLW subtracted from the MLW Reference grid
WDM MHW Difference map (1)	WDM MHW subtracted from the MHW Reference grid
LHM MHW Difference map (1)	LHM MHW subtracted from the MHW Reference grid
Alterra MHW Difference map (1)	Alterra MHW subtracted from the MHW Reference grid
Acacia MHW Difference map (1)	Acacia MHW subtracted from the MHW Reference grid
Relative elevation map	Subtract elevation of each cell by mean elevation of all cells within a 300 metre radius
Drainage density map	Relative number of cells within a 100 metre radius that contains a waterway
Distance to salt water	Shortest distance to either the North Sea or the Wadden Sea
Distance to freshwater	Shortest distance to either the IJsselmeer or the Markermeer
Processed data – visual purposes	
Name	**Calculation**
MLW Reference grid (median)	Cell-by-cell median of each of the sources' MLW estimates
MHW Reference grid (median)	Cell-by-cell median of each of the sources' MHW estimates
WDM MLW Difference map (2)	WDM MLW subtracted from the MLW Reference grid (median)
LHM MLW Difference map (2)	LHM MLW subtracted from the MLW Reference grid (median)
Alterra MLW Difference map (2)	Alterra MLW subtracted from the MLW Reference grid (median)
Acacia MLW Difference map (2)	Acacia MLW subtracted from the MLW Reference grid (median)
WDM MHW Difference map (2)	WDM MHW subtracted from the MHW Reference grid (median)
LHM MHW Difference map (2)	LHM MHW subtracted from the MHW Reference grid (median)
Alterra MHW Difference map (2)	Alterra MHW subtracted from the MHW Reference grid (median)
Acacia MHW Difference map (2)	Acacia MHW subtracted from the MHW Reference grid (median)
MLW Standard deviation map	Cell-by-cell standard deviation between each of the sources' MLW estimates
MHW Standard deviation map	Cell-by-cell standard deviation between each of the sources' MHW estimates
WDM MLW w.r.t. target level	WDM MLW subtracted from summer target level
LHM MLW w.r.t. target level	LHM MLW subtracted from summer target level
Alterra MLW w.r.t. target level	Alterra MLW subtracted from summer target level
Acacia MLW w.r.t. target level	Acacia MLW subtracted from summer target level
WDM MHW w.r.t. target level	WDM MHW subtracted from winter target level
LHM MHW w.r.t. target level	LHM MHW subtracted from winter target level
Alterra MHW w.r.t. target level	Alterra MHW subtracted from winter target level
Acacia MHW w.r.t. target level	Acacia MHW subtracted from winter target level

4. Results

4.1. Mean lowest water table

Figure 7 shows the MLW values generated with the four different sources assessed in the present research. Note that the resolutions of the grids differ (50x50 m for WDM, 250x234 m for LHM, 25x25 m for Alterra, 100x100 m for Acacia). Also, the difference between the study areas is visible: WDM excludes both the dunes and urban areas, Alterra excludes only urban areas, LHM includes the entirety of the Netherlands (even negative values in the IJsselmeer and Markermeer were provided, but they were removed) and Acacia provides values across all of the mainland in the study area.

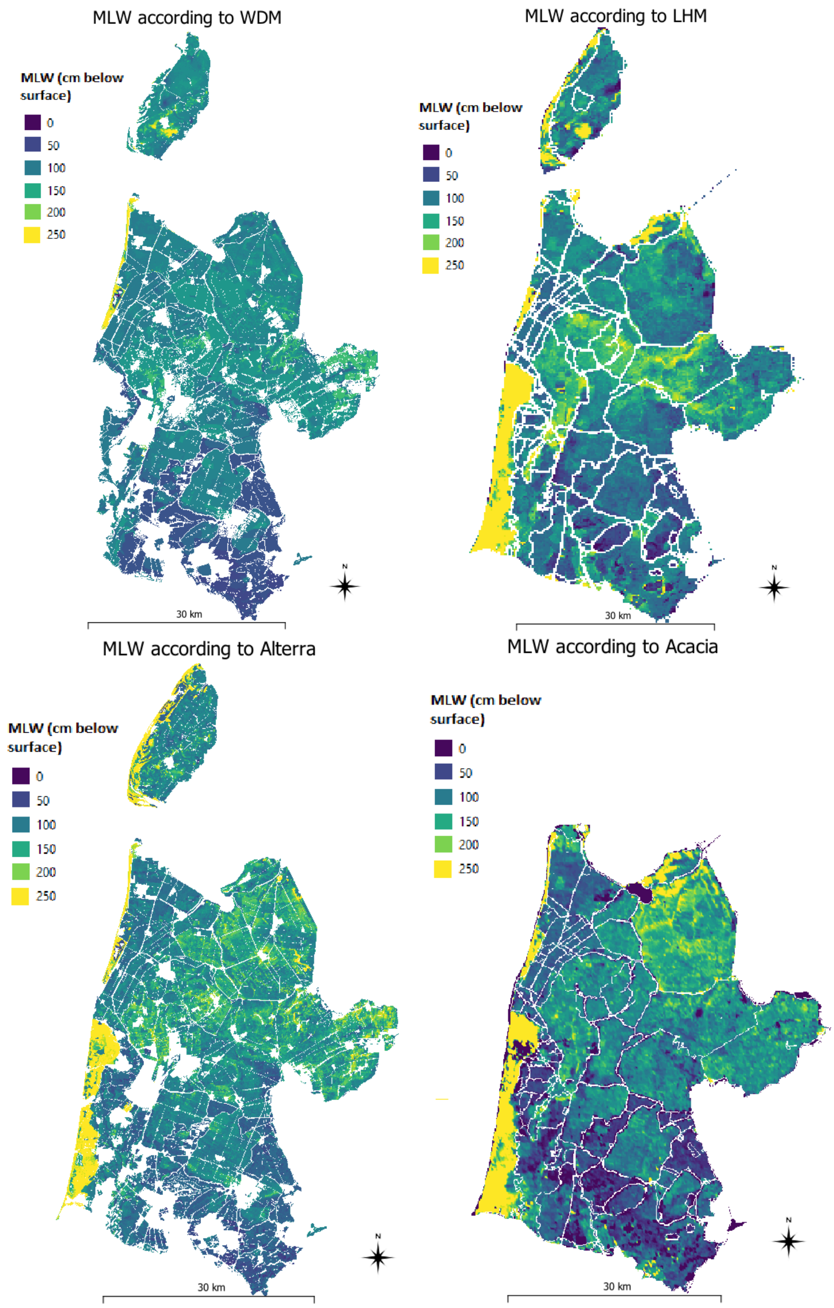

Figure 7 The MLW values in the various sources, after removing the dykes.

In Figure 8, the difference maps based on the median values are shown for the mean lowest water table, in which all area is included where all four sources have a value. Immediately, it is striking that the colours on the maps of LHM and Acacia are darker, which means they have more extreme values, whether higher or lower. This is also visible in the cumulative distribution functions, shown in Figure 9; they show that the spread of these sources is bigger. This graph also shows WDM's assumption of a uniform MxW value in each one-off measurement's surroundings, as a number of values is shown to occur very often. Moreover, the areas with higher sandy soils (compare Figure 10) have the most extreme values; they are estimated to be lower in the simulation-based sources (LHM and Acacia) and higher in the measurement-based sources (WDM and Alterra). This is a result in itself, but for the benefit of a fair analysis of the rest of the results, these areas were removed from the dataset (see Chapter 3). Furthermore, Acacia estimates low MLW values in the Wieringermeer and other deep-lying polders in the study area: Schermer, Beemster, Wijde Wormer and Purmerend (see Figure 11). These polders also have remarkably high MLW estimates in LHM. Finally, Acacia's estimates are well above the surface close to certain dykes (visible as thin blue strips in the right bottom map of Figure 8). It is certainly striking that this pattern only appears to influence the eastern side of each dyke, which suggests that the grid cells that were excluded are misplaced. However, the data was checked and the original values in the excluded cells deviated even more than those just east of them.

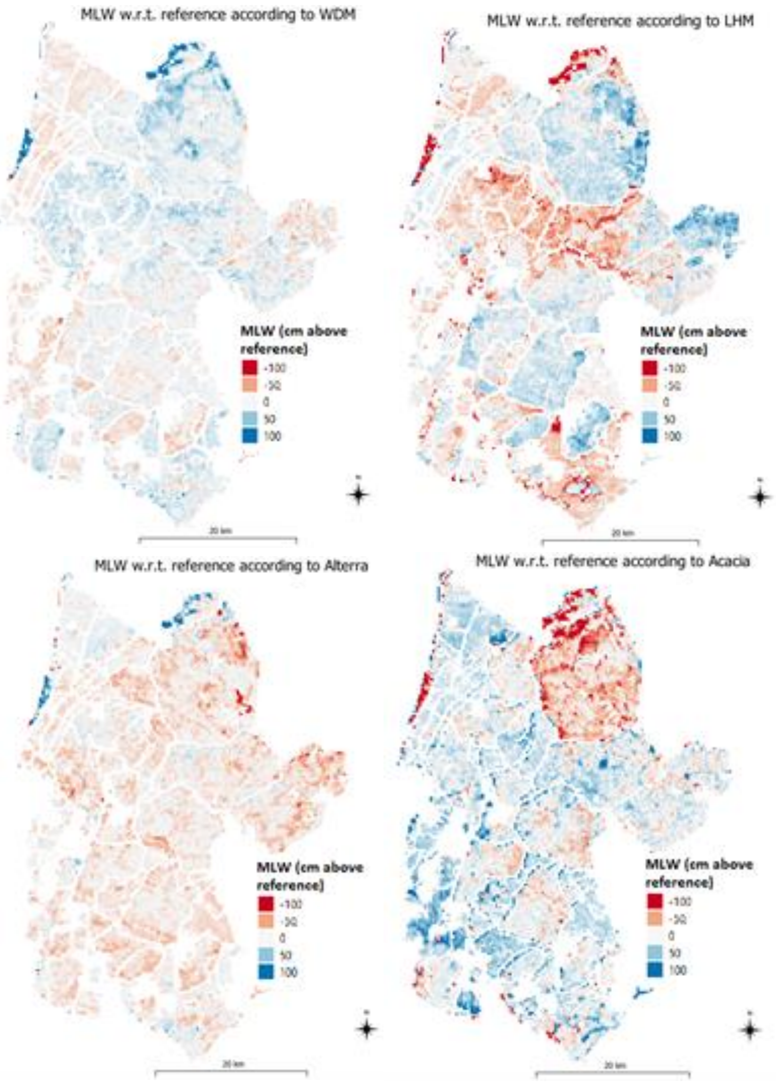

Figure 8 Difference maps (based on median) of the MLW values in the various sources

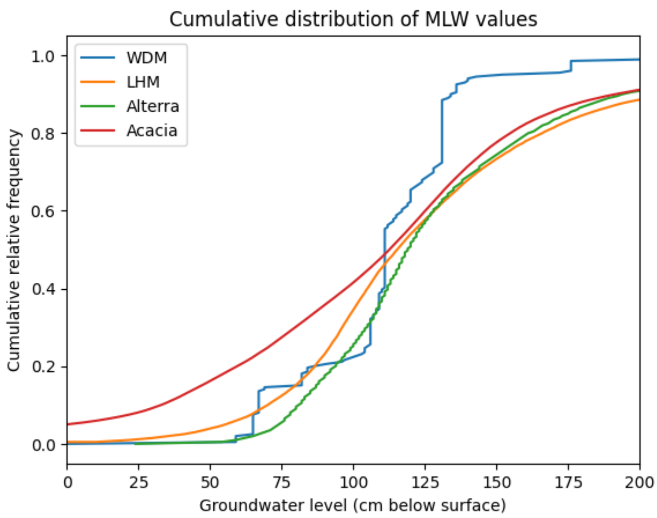

Figure 9 Cumulative distribution functions of the MLW sources.

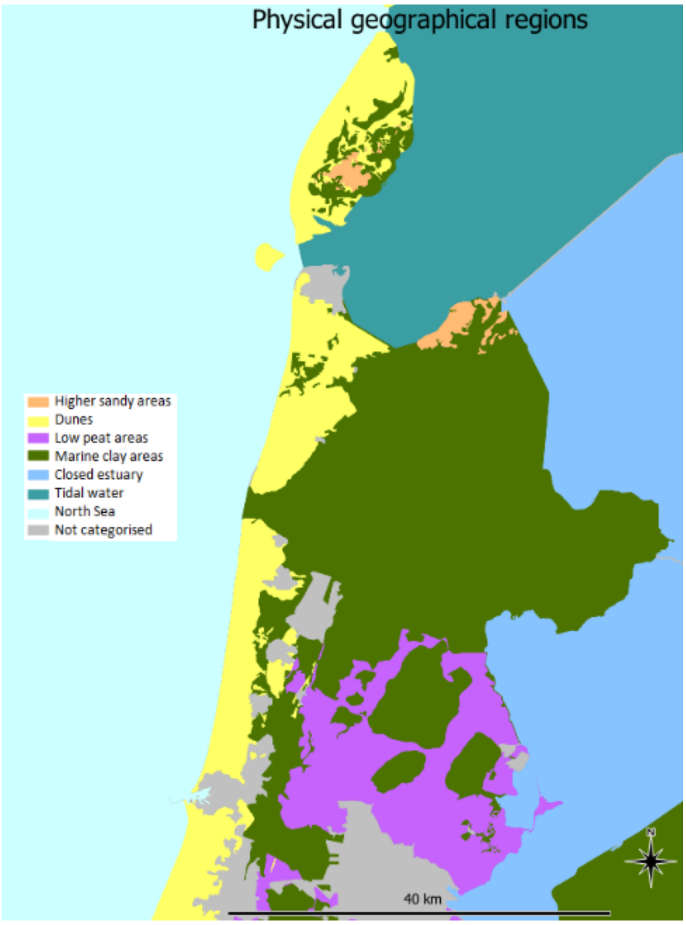

Figure 10 Physical Geographical Regions of North Holland

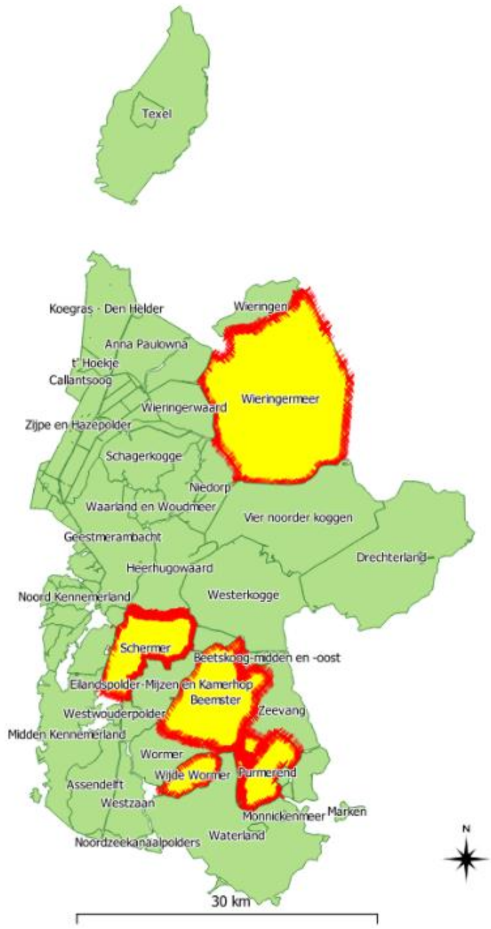

Figure 11 Names of the polders in the study area. The marked polders are low-lying.

As described in section 3.2, the correlation coefficients between the difference maps and a selection of hydrological conditions were calculated. These coefficients are shown in Table 2. Elevation has the strongest correlations with the deviation from the reference grid. This is also visible in the scatter plots in Figure 12. LHM dominates with a negative correlation; the lower the elevation, the higher the MLW estimate is with respect to the other sources. As a result, the correlation is inverted for the other sources, but out of them, only Acacia's correlation is significant, based on the scatter plot (Figure 12).

Because the number of data points in the scatter plot is large, they have been grouped into groups of 6 or 7 and the values averaged. If this was not done, multiple dots would have occupied the same place, which would, by comparison, have shifted more attention to the outliers. This method, on the other hand, has the disadvantage that it makes the data appear more congruent than it is.

Table 2 Correlation coefficients of the quantitative conditions with the MLW sources

MLW	Elevation	Relative Elevation	Summer target level	Drainage density	Distance to salt water	Distance to freshwater	Seep
WDM	0,06576	0,094684	0,312975	-0,14959	-0,03601	-0,13127	-0,01182
LHM	-0,54155	-0,26572	-0,26379	-0,05412	-0,00084	-0,14531	0,288773
Alterra	0,169913	0,009816	-0,03123	0,001937	-0,07046	0,105135	-0,08902
Acacia	0,26006	-0,00079	-0,3447	0,265656	0,050988	0,209113	-0,28235

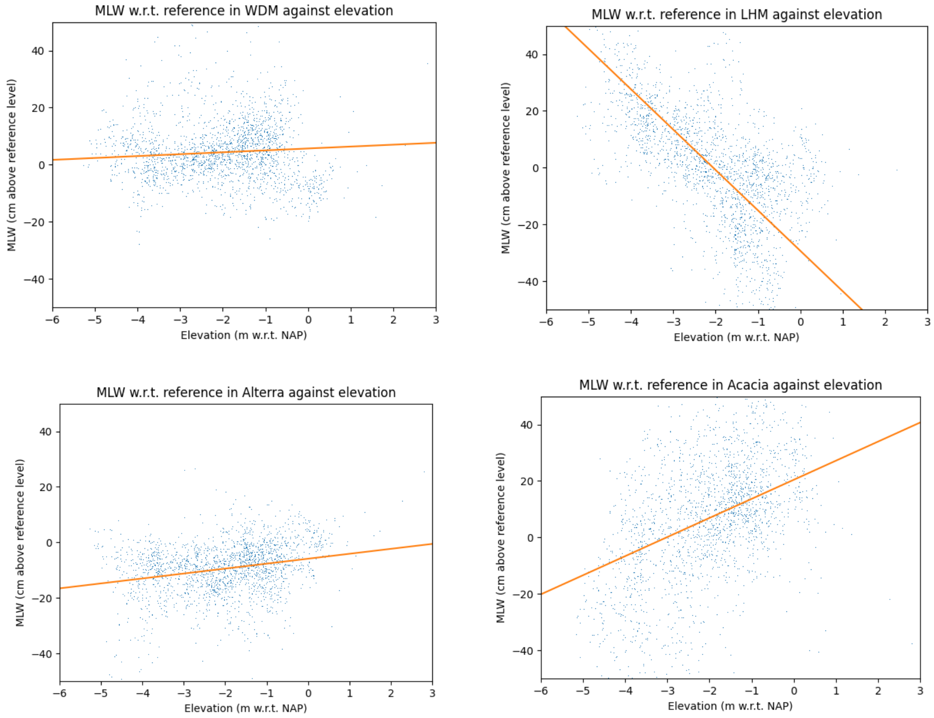

Figure 12 Scatter plots of the various groundwater sources against the elevation. Note that each dot represents a group of cells from the maps.

Subsequently, the data was normalised (see section 3.2) and the results are shown in

Table 3. The only condition with strong correlation coefficients, is the summer target level. In particular, the deeper the target level is, the deeper the MLW estimate of Acacia is. WDM, on the other hand, becomes shallower as the target level becomes deeper.

The correlation coefficients with seepage show a decrease, which suggests that seepage is itself correlated with elevation. This is important, because there is a possibility that seepage is the true cause of the deviations, but elevation showed the largest correlation coefficients by coincidence. These scatter plots are shown in Figure 13. The normalisation process was repeated once again, with the results shown in Table 4, but yielded no additional results.

Table 3 Correlation coefficients between the normalised MLW grids and the remaining conditions.

	Relative Elevation	Summer target level	Drainage density	Distance to salt water	Distance to freshwater	Seep
WDM	0,072014	0,307184	-0,13197	-0,02647	-0,16758	0,012765
LHM	-0,09248	-0,25053	-0,04534	-0,09376	0,112595	0,000711
Alterra	-0,04989	-0,04862	0,035215	-0,04072	0,029915	-0,00788
Acacia	-0,0943	-0,38343	0,221806	0,087386	0,108938	-0,14492

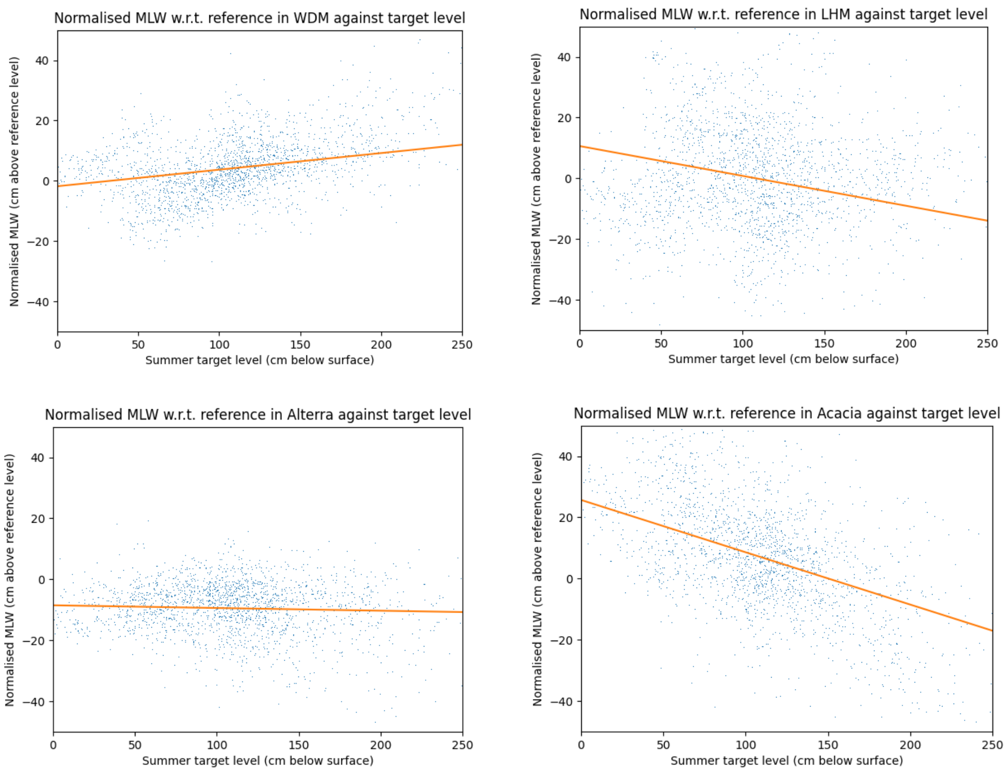

Figure 13 Scatter plots of the various groundwater sources against the summer target level. Note that each dot represents a group of cells from the maps.

Table 4 Correlation coefficients between the twice-normalised MLW grids and the remaining conditions.

	Relative Elevation	Drainage density	Distance to salt water	Distance to freshwater	Seep
WDM	-0,10116	-0,01914	0,028199	-0,12832	-0,08517
LHM	0,046246	-0,14266	-0,14176	0,078003	0,079769
Alterra	-0,02328	0,017233	-0,04922	0,022747	0,006974
Acacia	0,125331	0,086428	0,02257	0,056509	-0,03012

Finally, the only qualitative condition used in this research, the soil type, is assessed (see *Figure 10* for the used categorisation). In Figure 14, confidence intervals of the mean deviation from the reference grid are shown by soil type. However, the 95% confidence intervals are shown to be tighter than they should be, because each grid cell was treated as an independent observation (see chapter 0). The statistical tools for a more accurate assessment of the uncertainty are unavailable.

For two of the sources, trends could be observed: Acacia estimates a higher value in all soil types except clay, while LHM estimates a lower value for peat in particular. It should be noted that clay is so ubiquitous in the study area that it dominates the mean of the total study area. Moreover, Alterra is much lower than the others in the clayey areas and Acacia is much higher than the others in sandy areas, whereas the remaining sources are close to each other in terms of the mean. In the peaty areas, conversely, no one source stands out, but all sources differ considerably between each other.

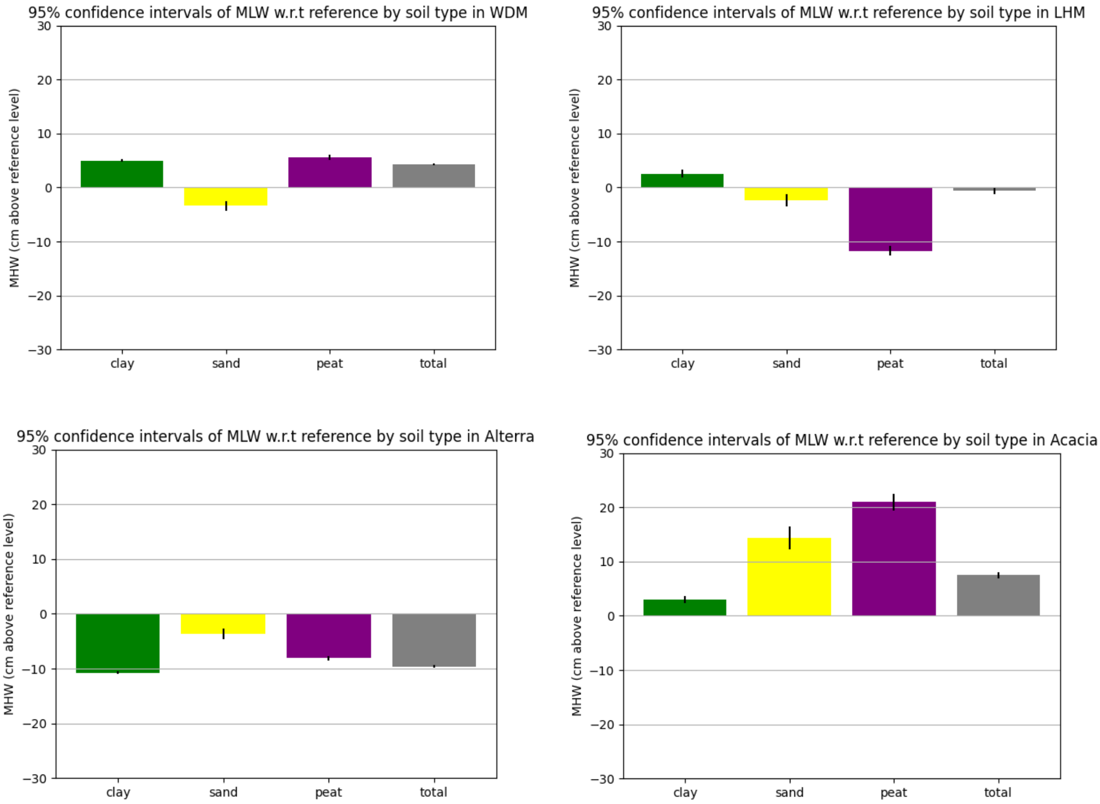

Figure 14 95% confidence intervals of MLW deviation from the reference grid per soil type.

4.2. Mean highest water table

Figure 15 shows the MHW values generated with the four different sources assessed in the present research. Note that the resolutions of the grids differ (50x50 m for WDM, 250x234 m for LHM, 25x25 m for Alterra, 100x100 m for Acacia). Also, the difference between the study areas is visible: WDM excludes both the dunes and urban areas, Alterra excludes only urban areas, LHM includes the entirety of the Netherlands (even negative values in the IJsselmeer and Markermeer were provided, but they were removed) and Acacia provides values across all of the mainland in the study area.

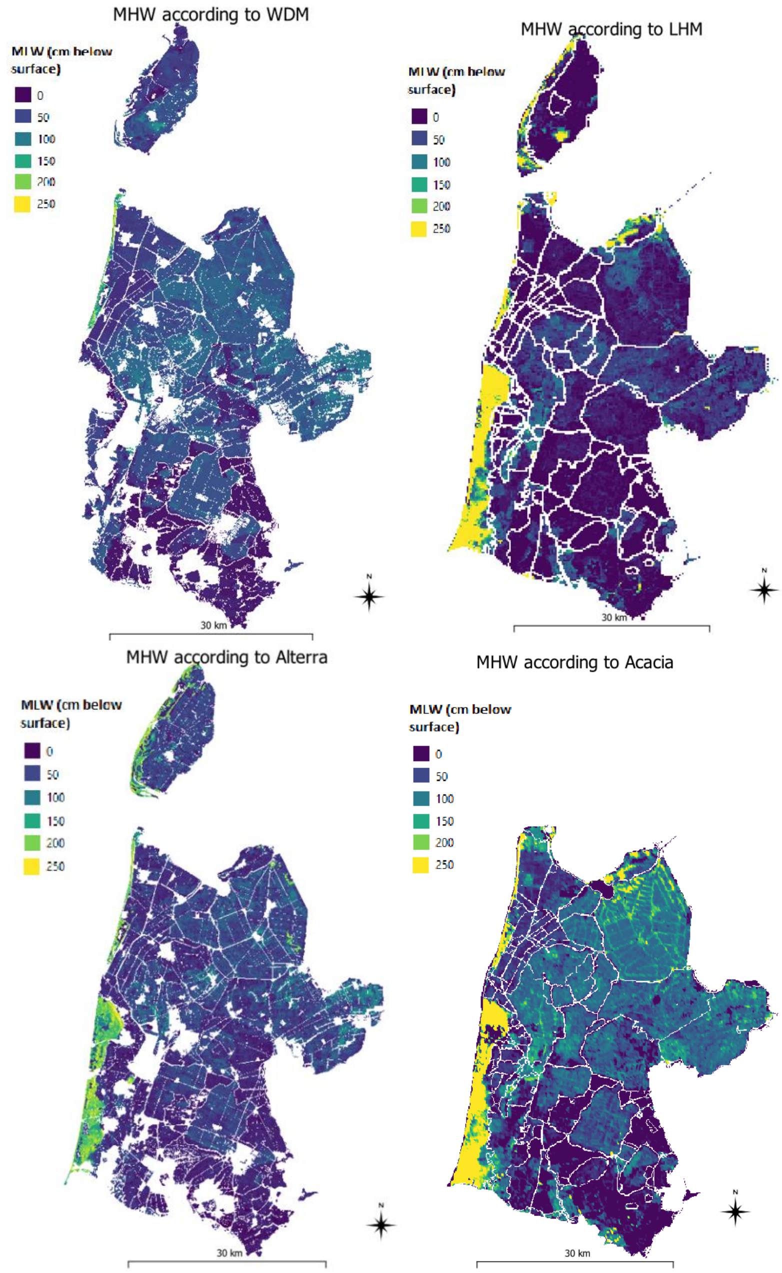

Figure 15 The MHW values in the various sources, after removing the dykes

The difference maps in Figure 16 again show the large deviations in the higher sandy areas. The same polders highlighted with the results of the MLW in section 4.1 are again notably wet according to LHM. Also, the tendency toward the extremes of the LHM and Acacia models are visible and the surroundings of the dykes are wet in the Acacia map. Other than that, however, the most striking observation is that LHM's difference map is almost entirely blue (signifying a higher level than the other sources) and WDM is almost entirely red (lower level). Also, when compared to *Figure 10*, it seems Acacia structurally makes higher groundwater level estimates in peaty areas, while LHM and Alterra both show a lower estimate in these areas. The cumulative density function in Figure 17 also shows the clear hierarchy between WDM, LHM and Alterra, while Acacia stands out in its spread. In particular, Acacia contains negative values (groundwater level above the surface) in almost 20% of the area and even a considerable number of values below -20 cm. These values are clearly unrealistic and suggest that Acacia does not distinguish between groundwater flow and surface water flow.

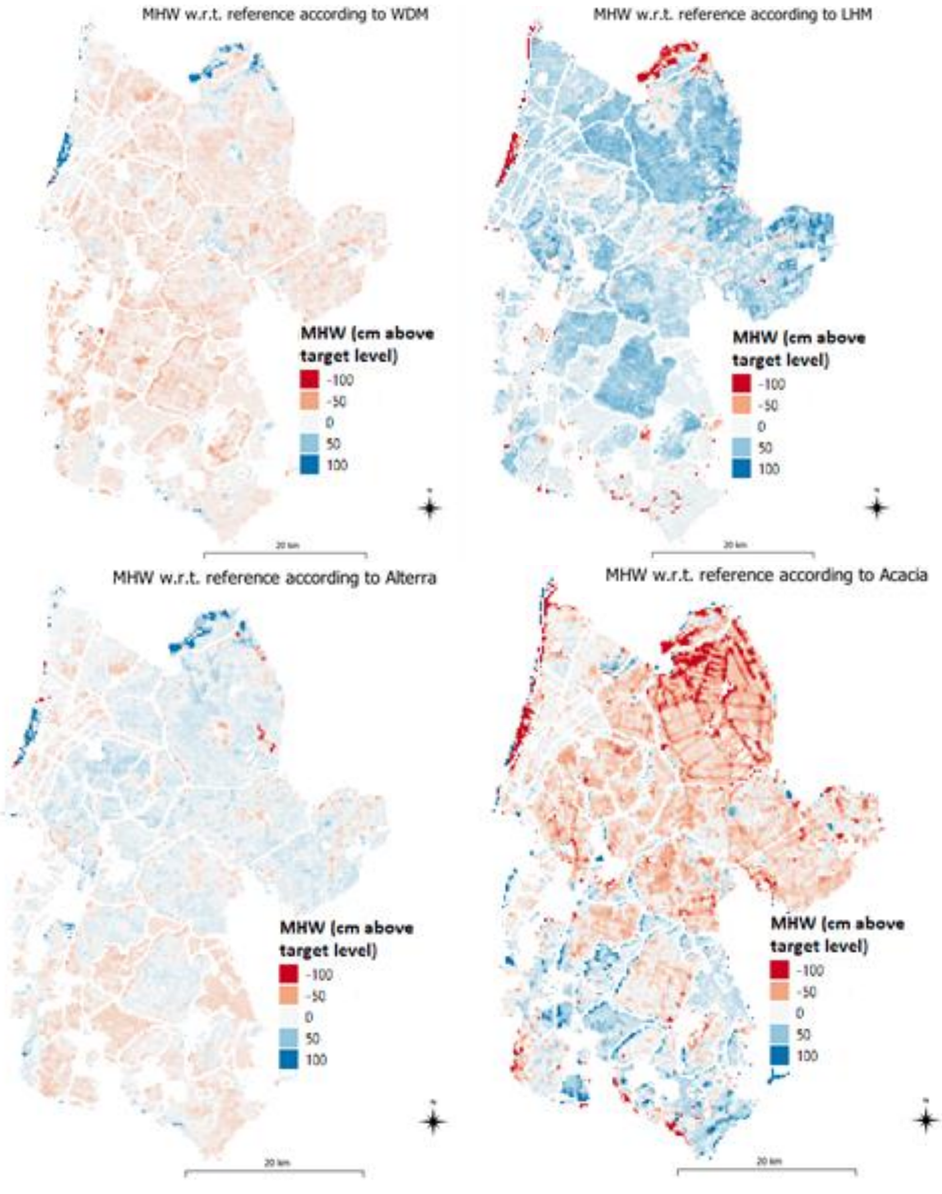

Figure 16 Difference maps (based on median) of the MHW values in the various sources

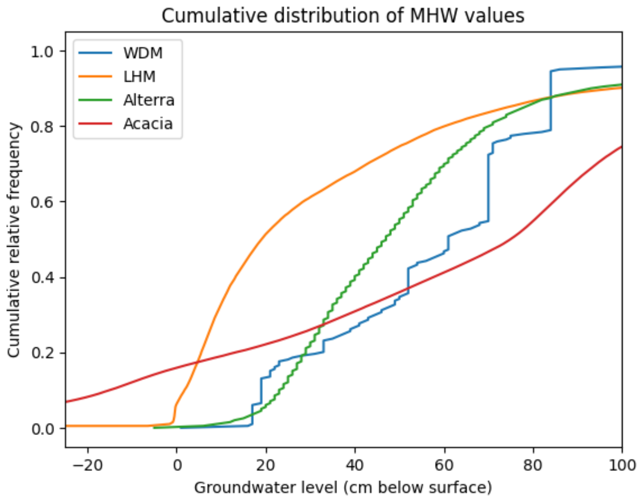

Figure 17 Cumulative distribution functions of the MHW sources.

In contrast to that of the MLW, the statistical analysis of the MHW points to the target level as the condition most strongly correlated to the differences between the sources (see Table 5 and Figure 18). The directions of the correlations are identical to those of the MLW; WDM is wetter as the target level is deeper, while Acacia is drier in those places. However, Alterra correlates more strongly than it did for the MLW, showing a similar correlation as WDM. Also note that the trend line and the correlation coefficient of LHM, in particular, is skewed by extreme values, as is visible from Figure 18. The scatter plot itself actually appears to show a positive correlation, whereas the trend line's gradient and the correlation coefficient are negative.

Table 5 Correlation coefficients of the quantitative conditions with the MHW sources

MHW	Elevation	Relative Elevation	Winter target level	Drainage density	Distance to salt water	Distance to freshwater	Seep
WDM	0,271	0,166	0,416	-0,057	-0,0577	-0,0636	0,0253
LHM	-0,401	-0,256	-0,184	-0,25	-0,084	-0,0638	0,18
Alterra	0,133	0,126	0,478	-0,238	-0,117	-0,0195	0,148
Acacia	0,166	0,0873	-0,305	0,384	0,168	0,101	-0,256

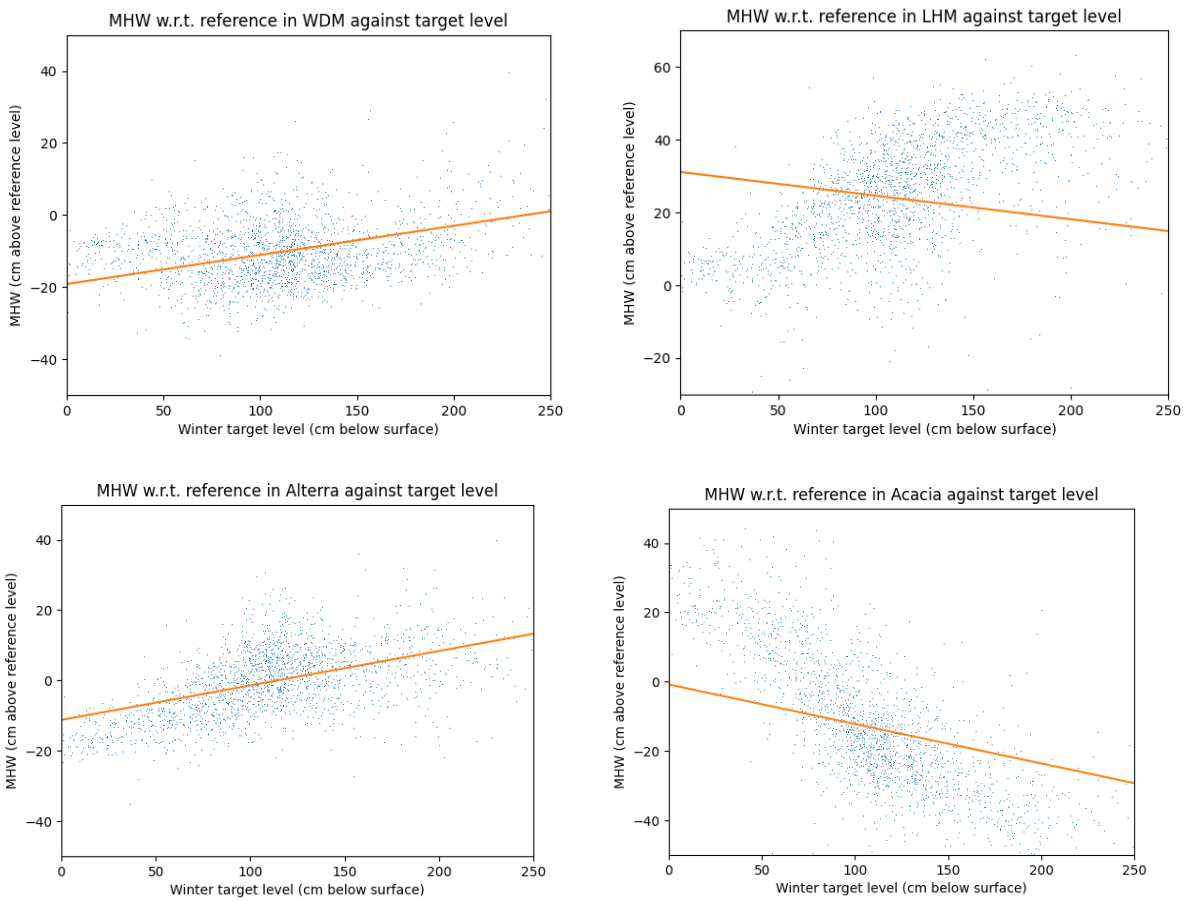

Figure 18 Scatter plots of the various groundwater sources against the target level. Note that each dot represents a group of cells from the maps.

After normalising the data with respect to target level (see section 3.2), the elevation proved to be a predictor variable of the deviation with the reference grid, similar to the MLW (Table 6). Again, LHM is drier with respect to the other sources at higher elevations. The scatter-plots in Figure 19 confirm the correlations, although a much larger spread from the trend line is visible than in previous plots.

Table 6 Correlation coefficients between the normalised MHW values and the remaining conditions.

	Elevation	Relative Elevation	Drainage density	Distance to salt water	Distance to freshwater	Seep
WDM	0,236	-0,0605	0,123	0,0194	-0,0173	-0,111
LHM	-0,382	-0,161	-0,29	-0,119	-0,0865	0,229
Alterra	0,0779	-0,146	-0,0424	-0,0243	0,0378	0,000655
Acacia	0,217	0,262	0,244	0,119	0,074	-0,169

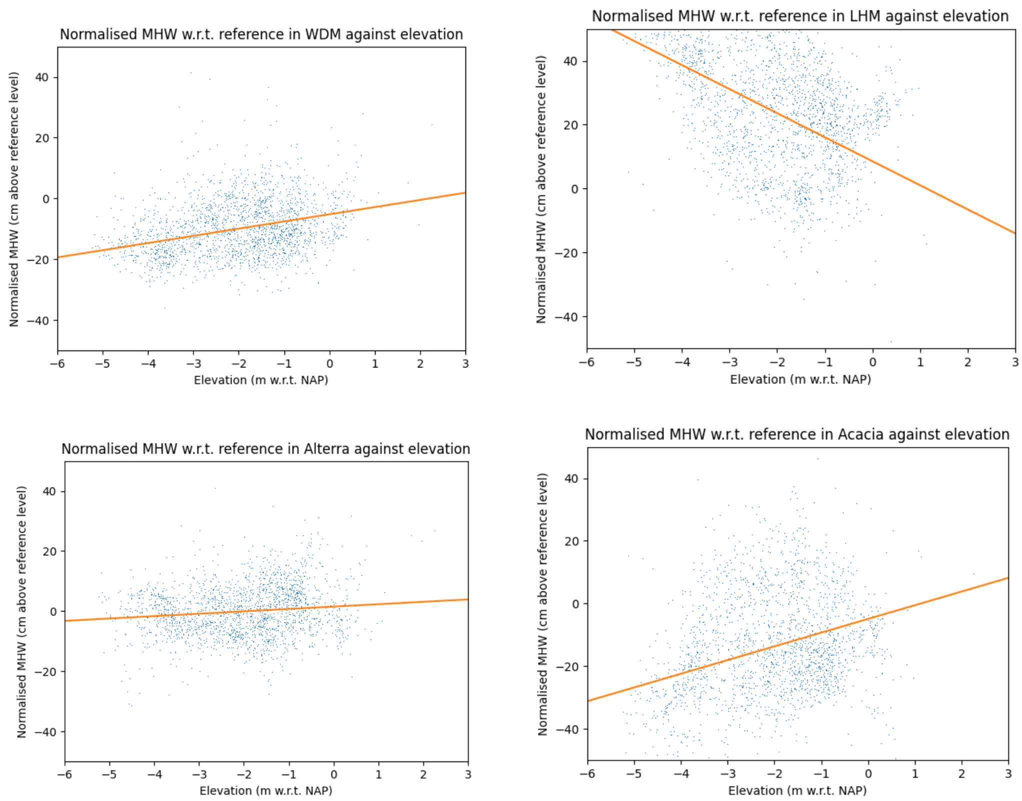

Figure 19 Scatter plots of the normalised MHW values against elevation. Note that every dot represents a group of cells on the maps.

After the second round of normalisation, a notable correlation appears between drainage density and the deviation of LHM and Acacia to the reference grid (Table 7 and Figure 20). The other two sources show to be indifferent, though it should be noted that this is the result of the normalisation; before normalisation, Alterra correlated negatively, to almost the same extent as LHM did. When comparing the scatter plots with the target level, in Figure 18, Alterra fits most closely to the trend line, whereas LHM and Acacia fit least closely. Also, the directions of the correlations are identical to those with elevation. All this suggests that drainage density is positively correlated with elevation, but the normalisations of LHM and Acacia were so unsuccessful that the correlation coefficient with drainage density did not weaken as much. Therefore, the results do not provide enough evidence to deem the correlation genuine.

Table 7 Correlation coefficients between the twice-normalised MHW values and the remaining conditions.

	Relative Elevation	Drainage density	Distance to salt water	Distance to freshwater	Seep
WDM	-0,142	0,114	0,0572	-0,127	0,0126
LHM	-0,0397	-0,293	-0,193	0,0915	0,0316
Alterra	-0,171	-0,0466	-0,0124	0,00302	0,0415
Acacia	0,195	0,239	0,156	-0,0236	-0,057

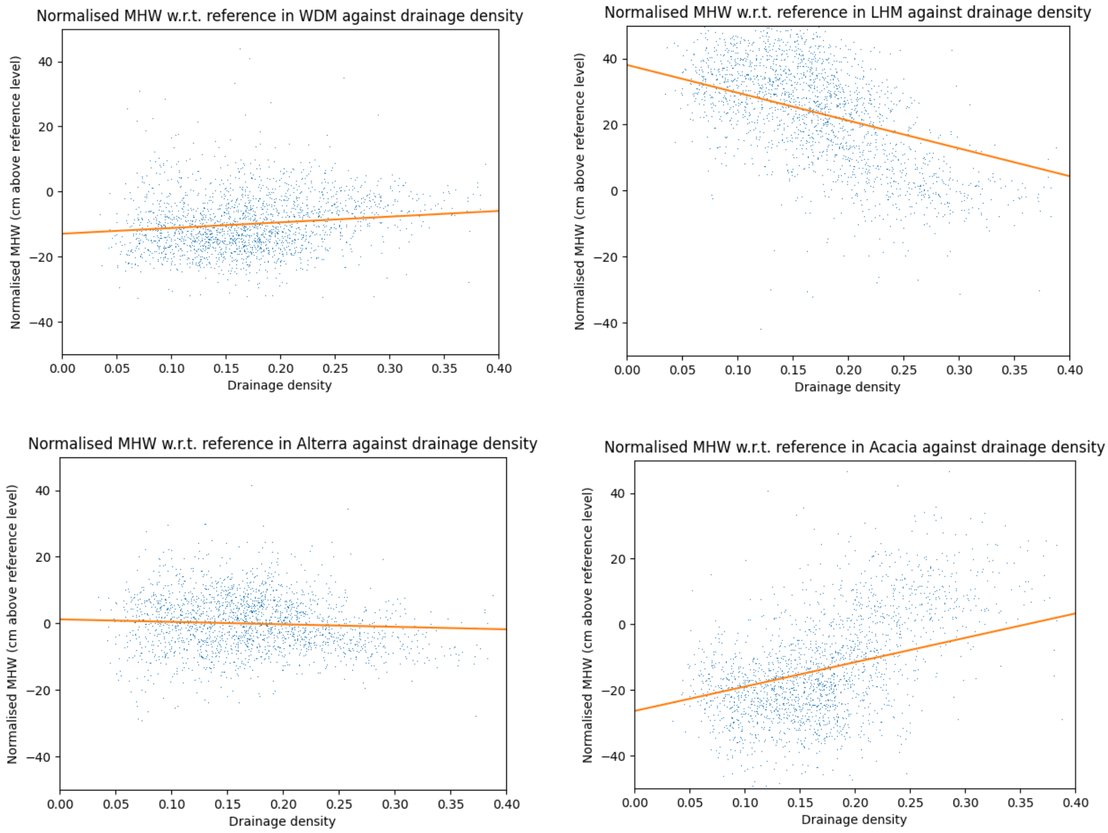

Figure 20 Scatter plots of the twice-normalised MHW values against drainage density. Note that every dot represents a group of cells on the maps.

A third normalisation was conducted, with the results shown in Table 8. The relative elevation is shown to have the strongest correlation, but a visual inspection of the scatter plots showed that the correlation is coincidental.

Table 8 Correlation coefficients between the thrice-normalised MHW values and the remaining conditions.

	Relative Elevation	Distance to salt water	Distance to freshwater	Seep
WDM	-0,13982	0,026055	-0,12322	0,033254
LHM	-0,04865	-0,11705	0,084533	-0,0219
Alterra	-0,17275	0,000415	0,001324	0,033161
Acacia	0,206858	0,093296	-0,01542	-0,01448

The results from the comparison between the soil types (Figure 21) reflect the large difference between the mean MHW of the sources. The clayey and sandy areas follow this hierarchy, but the peaty areas appear to be independent. Acacia estimates high groundwater levels in peaty areas, and LHM estimates low levels (although still greater than the reference level itself). In contrast to the MLW analysis, Alterra shows much lower levels in peaty areas.

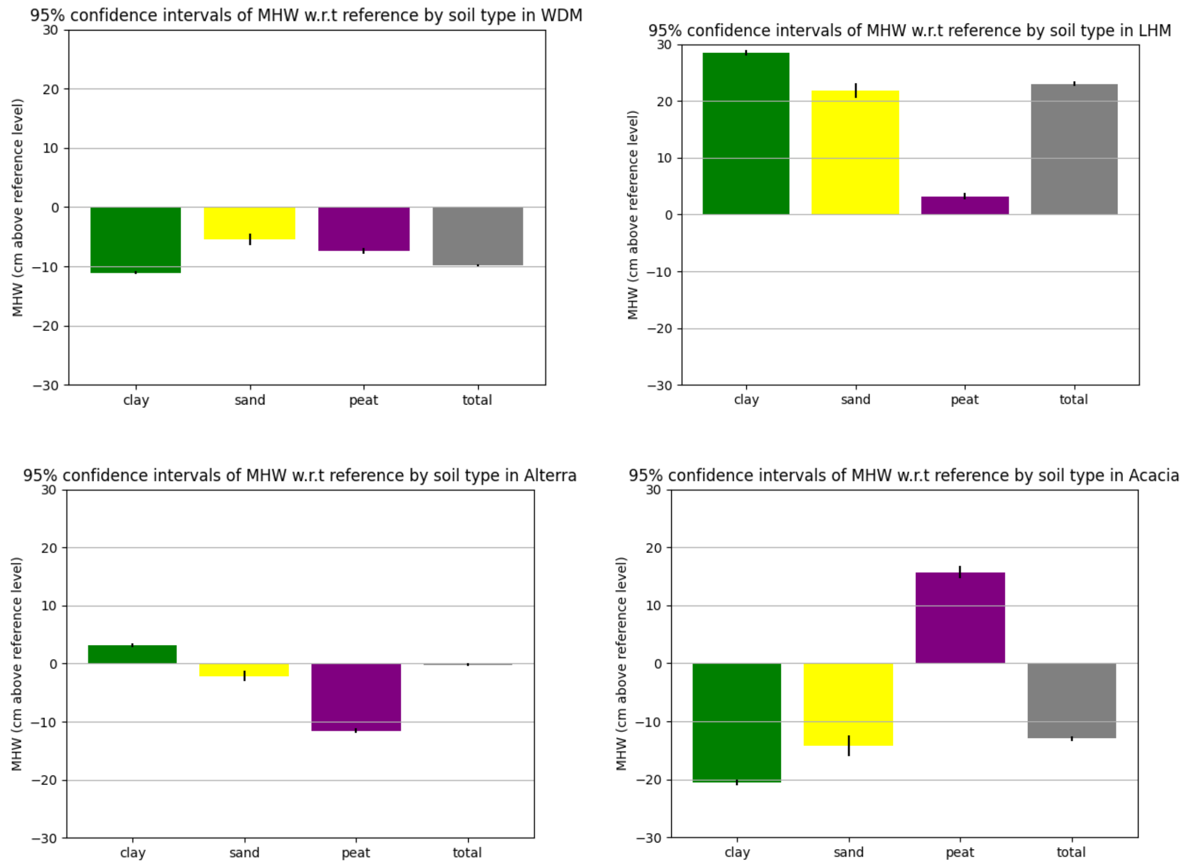

Figure 21 95% confidence intervals of MHW deviation from the reference grid per soil type

4.3. Plausibility assessment

As the first step of the plausibility assessment, the MHW with respect to the target level was mapped. The groundwater drains to the surface water, so in wet conditions, such as the MHW, the groundwater level is always higher than the surface water level. An MHW lower than target level is implausible. It is plausible, on the other hand, that the MLW might be higher than the target level. The results are shown in Figure 22. A few very dark-red dots are visible, which can be explained by diverging water management. In some areas, the surface water level is not managed by the water authority, but by the owners of the land themselves. In these places, the target level is either old or set to the default level of NAP (Normal Amsterdam Level, the Dutch sea level reference), which, in much of the area, is several metres above the surface. This does not apply to the sandy areas in the west of the study area, where LHM and Acacia show a large deviation.

The peaty areas stand out in the WDM and Alterra maps (Figure 22), suggesting their MHW estimates in peaty areas are unrealistically low. Acacia does not show any particular polder where the MHW is structurally underestimated, but they are present all around the study area. Therefore, it can be concluded that the local variation (within one polder) in Acacia's MxW estimates is unrealistically large.

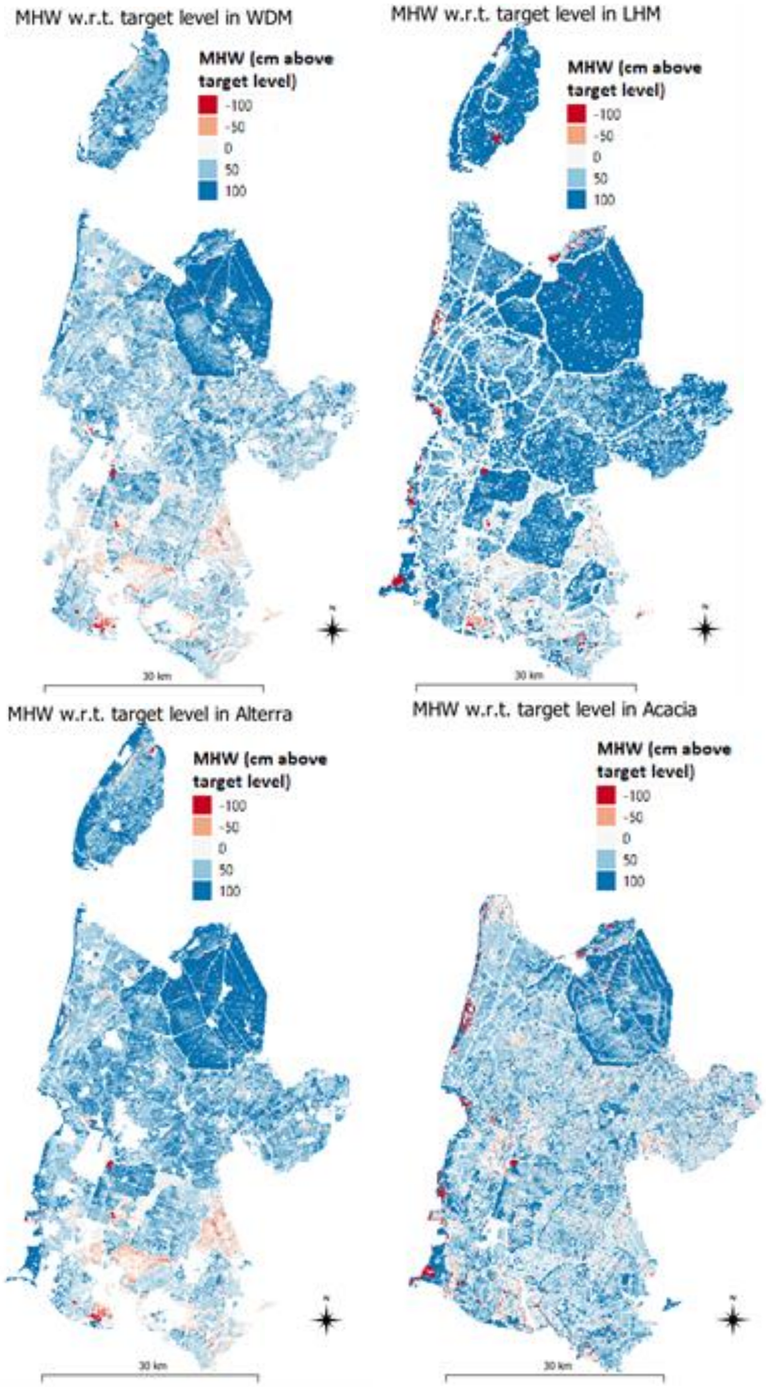

Figure 22 MHW with respect to target level in the various sources

The second method of plausibility assessment is the assessment of the likeness between the sources. This is expressed in standard deviation, as is shown in Figure 23. The lower the standard deviation, the closer the sources are to each other. The areas with a large standard deviation, the Wieringen, Wieringermeer and the dunes, are largely the same between MLW and MHW, but between the moderate values, there is little resemblance between them; for peaty areas, the sources are closer regarding the MHW and for clayey areas, the sources are closer regarding the MLW. In the sandy areas in the Northwest, meanwhile, the sources are quite congruent. The large deviations close to the dykes disappear when Acacia is ignored (as indicated at the start of section 4.1, Acacia is remarkably wet in a narrow strip along the dykes) but in the Wieringermeer, specifically in the east, substantial differences remain.

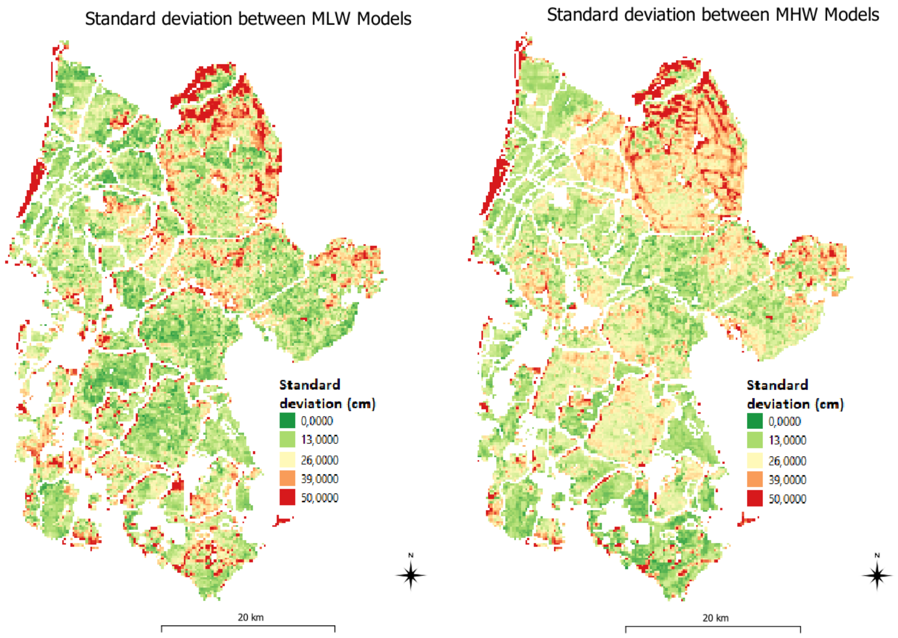

Figure 23 Standard deviation between sources of MLW and MHW

Finally, as a means of plausibility assessment, the MxW values were either taken or calculated from a total of 43 measuring locations. All of them are younger than the Alterra map and at most three years older than the most recent update of WDM in the study area, so these same locations could not have been included in these sources. It should be noted, however, that all available, suitable measurements were mostly taken in sandy areas, which makes the comparison less robust for other soil types. The majority of measurements were taken on the island of Texel and of the remaining locations, almost all were taken close to the dunes. A few measurements were taken in urban parks. Also, many of the measurement pipes' filters (see Chapter 2) were deeper than the groundwater level, which means that the measured value corresponds to the hydraulic head of the soil at the filter, not to the groundwater level itself.

The filters were never deeper than 3 metres below the surface, but it still resulted in several negative measured values. In Figure 24, the values from the sources are plotted against the measured values. Although the two measurement-based sources, WDM and Alterra, are generally closer to the measured values than the other two sources, they appear to underestimate the range of MxW across space, because their trend lines are much flatter. Furthermore, for the MHW, the large number of LHM estimates close to the surface, most of them on Texel, is striking. Clearly, LHM does not provide accurate MHW values on Texel. A bias towards too deep estimates is clearly visible and measurable: on average, the MLW is estimated 30,7 cm too deeply and the MHW is estimated 11,5 cm too deeply. By the criterion of the average square of the deviation from the measured values, Alterra is the closest fit (1909 cm^2), and WDM the second-closest (2477 cm^2). There is a considerable gap to LHM (16 169 cm^2), which is in turn more accurate than Acacia (25 924 cm^2). Mind that Alterra is largely based on local mappings in sandy areas (Section 2.2), so this result is not representative. In appendix A, all locations, measured values and modelled values can be found.

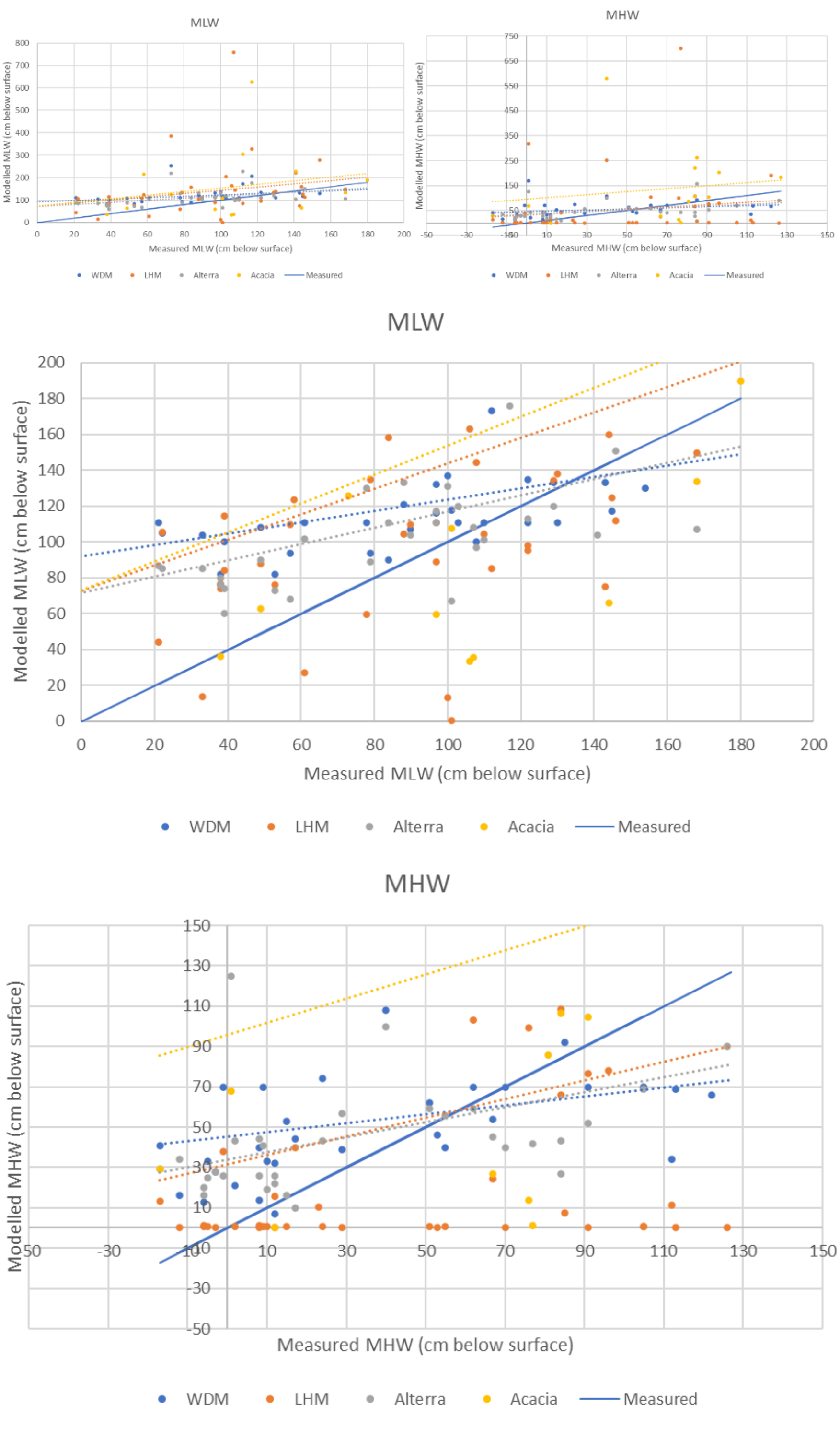

Figure 24 Measured against modelled MxW values, coloured by source. The full view is visible as a smaller graph on top, and on the bottom, the graphs are zoomed in.

5. Discussion

The results of this research are copious, but have limitations that are important to mention. As mentioned in section 4.3, is difficult to assess the plausibility of the estimated groundwater levels. Therefore, it is necessary to compare them to each other, through the means of the reference grid, but it is important to remember that there is no indication that the reference grid itself is plausible. To allow a more rigorous assessment of the accuracy of the models, more independent, long-standing measurement series in suitable locations are needed.

Moreover, the correlations with each of the conditions is highly sensitive to intercorrelation. Most noticeably, seepage and, to a lesser extent, drainage density, was strongly correlated with elevation. Theoretically, however, it is possible that, for example, seepage and drainage density each correlate with the difference map independently, but the correlation with elevation is shown to be stronger than each of them as a result. To distinguish each independent variable would have required a highly detailed analysis of the relations between the variables.

Also, it is important to note that the confidence intervals of the mean MxW value in each soil type are tighter than they should be due to autocorrelation. Autocorrelation means that two values that are spatially (or chronologically) close to one another are likely to be similar. However, for the determination of the confidence interval width, it was assumed that each grid cell was an independent observation. Additionally, there was no normalisation beforehand, so the influence of other parameters, independent of soil type, is not excluded. As a result, the influence of the soil type alone is uncertain.

Finally, the locations of the usable measurement results present a bias. The majority of them were on the island of Texel and none of them were in the eastern half of the territory. Also, the measurements were mostly taken in areas with sandy soil types. As a result, it is difficult to derive specific conclusions from the measuring locations. A larger number of measurement locations that are more representative of the study area would enable a fairer comparison. Despite this and the previous nuances, some interpretation of the results is possible, and is presented below.

5.1. Interpretation

First of all, a striking observation is the larger spatial variation of the MxW in the simulation-based sources (LHM and Acacia), compared to the measurement-based sources. As mentioned in section 4.3, during the comparison to the results from measurement locations (almost all of them in sandy areas), the measurement-based sources tend to be closer to the measured values, but is more uniform than them. This is likely due to the fact that WDM and Alterra automatically incorporate local circumstances, whereas LHM and Acacia miss some of them. However, the measurement-based sources proceed to project the local circumstances around the measuring locations across the whole area, which results in an overly uniform MxW grid. The simulation-based sources, on the other hand, are more accurate about the variation between large areas, because they simulate the whole process of groundwater flow. However, local circumstances are not taken into account and as a result, they are likely to be less accurate in a very specific location.

Secondly, peaty areas stand out in several results. For the MLW in particular, the groundwater level estimates in sandy and clayey areas are relatively close to each other, whereas the peaty areas show a high degree of uncertainty. Among the MHW values, the deviation from the reference grid in the sandy and clayey areas largely correspond to each other and, therefore, to the average deviation for that particular source. Furthermore, WDM and Alterra estimate the MHW of peat to be lower than the target levels, which is unrealistic. From expert opinion, it follows that the measurements in peaty areas are scarce and peat is very heterogeneous in terms of soil characteristics such as hydraulic conductivity, which explains the large uncertainty. In addition, WDM used linear regression to predict the MxW value in a one-off measuring location. For every day on which measurements were taken, for every region (in this case, North Holland and Flevoland), a linear approximation was made of the relation between the water table on that day and an MxW value (Hoogland, Knotters, Pleijter, & Walvoort, 2014). This linear approximation was not specific to any soil type. Based on this, one would expect that the 'fluctuation', the difference between MLW and MHW (represented by the term a in $y = ax + b$), is set, such that, in soil where fluctuation is low, like peat, the fluctuation is overestimated, which would mean that the MHW is overestimated. In addition, however, the minimum groundwater level depth (the term b in $y = ax + b$) could be overestimated in soil types that have a very shallow groundwater level, like peat, which would mean that the MHW is underestimated. As results from the plausibility assessment, the effect of the latter is stronger than that of the former.

Thirdly, Acacia's MxW grids show particular patterns. First of all, the Wieringermeer is estimated to be much drier than it is in any of the other sources. Secondly, it negatively correlates with the depth of the target levels very strongly. Thirdly, it is wetter than the other sources near waterways and finally, according to the comparison between the MHW and the target levels, the local fluctuation is too large. As leads from chapter 2, the two main differences between LHM and LMZW (from which Acacia derives) are the fact that LMZW takes the salt concentration of the water into account and that LHM includes a sub-model for the unsaturated zone, with which it harmonises the groundwater level. The former explains the behaviour of Acacia near waterways; the waterways, which are composed of freshwater, influence the salt concentration of the groundwater, such that the groundwater dynamics change. In both the case of the MLW and that of the MHW, this results in a higher water table. The fact that this effect is directed mostly in one direction, can, with only limited certainty, be explained through the fact that one side of each waterway has a lower elevation, and therefore a lower hydraulic head, than the other, meaning more of the freshwater flows that way. Conversely, one would also expect that near the North Sea and Wadden Sea, the groundwater level would be drier. This is visible only in a very thin strip along the coast (the dunes themselves are excluded from the difference maps, because WDM does not include them). Moreover, the lack of a separate unsaturated zone sub-model suggests that LMZW is less reliable when the unsaturated zone is thick, i.e. when the target levels are deep. Apparently, this results in a structurally deeper estimate of the groundwater level in those areas, suggesting that the water storage in the unsaturated zone is underestimated by the saturated zone model (SEAWAT). This is most visible in the Wieringermeer, which has the deepest target levels in the study area.

Finally, experts were consulted about the large difference in MxW estimates in higher sandy areas. It is their opinion that, in this particular case, it is more likely that the measurement-based sources are inaccurate than the simulation-based ones, because measurements from elsewhere in the Netherlands had to be used and extrapolated into the study area.

6. Conclusion

The first sub-question of the research was: Which hydrological conditions are responsible for/influence the deviations between the estimates? Many such patterns in the groundwater sources were found. First of all, higher sandy areas contained the most extreme values: WDM and Alterra give very high MxW values, LHM and Acacia give very low MxW values. In the remainder of the area, two hydrological conditions were found to be the best independent predictors of the differences between the sources. In areas with a high elevation, LHM gives a lower estimate of the MxW. Also, the deeper the target level, the lower the estimates of Acacia were with respect to the others. Conversely, WDM and Alterra, the measurement-based sources, correlated positively. Moreover, in peaty areas, Acacia gives the highest estimates among the sources, while LHM, relatively, gives lower estimates. In terms of MLW, Alterra is exceptionally dry in clayey areas and Acacia is exceptionally wet in sandy areas, but the remainder of the sources are similar. For MHW, on the other hand, the differences are substantial and the hierarchy is the same between clay and sand: LHM is wettest, then Alterra, then WDM and Acacia is driest.

The second research question, on the other hand, was more difficult to answer: How can the identified deviations be explained through the sources' calculation process? The large uncertainty and distinctiveness of peaty areas can be credited to peat's natural heterogeneity, which makes the outcome of the sources largely dependent on the soil data used, which is less accurate and more variable than those of other soil types. Acacia's strong negative correlation with the depth of the target level is likely connected to the fact that, in contrast to LHM, Acacia does not model the saturated zone and the unsaturated zone separately, but uses the equations for saturated flow in the unsaturated zone.

The main research question was: Which groundwater sources are most accurate under which circumstances? Unfortunately, it is impossible to answer this question directly from the results of the research. However, it is possible to conclude that certain sources are inaccurate in specific areas. First of all, WDM and Alterra are too dry in peaty areas. These sources are also unreliable in higher sandy areas, where they are based on the measured values in similar areas elsewhere. In addition, Acacia fluctuates too much on a local level, for unknown reasons. The comparison to measured data, on the other hand, although all usable measuring locations were in sandy areas, led to the conclusion that the measurement-based sources are generally closer and have fewer values that deviate extremely than the simulation-based sources, but are too uniform. In addition, the literature study into the theory behind the sources reveals that it is likely that Alterra is accurate in sandy areas and that, as alluded to in the previous paragraph, Acacia becomes less reliable as the unsaturated zone becomes thicker.

7. Recommendations

In this chapter, recommendations for action as a result of the findings in this research are given. This is divided into two categories. First of all, the implications for the calculation process of the pluvial flood risk is discussed. Secondly, directions of further research are proposed.

7.1. Flood risk modelling

The conclusions of this report can be used by water authorities (and specifically HHNK) to choose a method for determining the risk of financial damage from pluvial flooding. Currently, the map of target levels is used to determine the available soil storage, which is in turn an input in the used inundation model. However, there are several locations in the study area where groundwater sources estimate an MLW that is higher than this level, meaning that the available soil storage is overestimated when using the target level grid. Therefore, it is highly recommended to revise this aspect of the current method.

The research does not suffice to declare any of the sources most accurate in any section of the study area. However, there are several areas where certain sources are clearly unreliable. First of all, WDM and Alterra have unreliable (structurally too low) MHW estimates in peaty areas. Secondly, these same sources structurally have too high estimates of both the MLW and the MHW in higher sandy areas (Figure 10). Moreover, Acacia is overpredicting groundwater in surroundings of the large canals. The comparison with measurements has shown that LHM overpredicts groundwater levels on the island of Texel. Therefore, these sources should not be used in the respective areas. Also, although Alterra is based in large part on local mappings mostly made in sandy areas, and therefore, it is likely that it is more accurate than the others in sandy soils, there is too little proof of that from this research to warrant an advice. In the same way, it is likely that Acacia is too dry in areas with a deep target level, but this can not be said with certainty.

Furthermore it is advisable to treat groundwater level as a stochastic variable in the calculation process of the flood risk. This way, the areas where the groundwater level is highly uncertain, like the peaty areas, are treated differently than the areas where it is very certain. At the same time, it enables the joint usage of the MLW and the MHW. After all, the regime curve gives a probability distribution of the groundwater level at every time of year under known MxW values. The probability distributions of each MxW value, as well as that of the occurrence of an extreme rainfall event throughout the year, can be used to transform this to the probability distribution of the groundwater level at the start of an extreme rainfall event in each grid cell. In this regard, it is also interesting that WDM includes an uncertainty analysis (Hoogland, Knotters, Pleijter, & Walvoort, 2014).

Finally, it is recommended to decrease the uncertainty of the MxW values by expanding the measurement net. This way, a more proper validation of the sources is possible and more insight could be provided into the MxW values and their uncertainties. Alternatively, the measurement-based sources could be updated with more certainty, or a completely new source based on the measurements could be established.

7.2. Further research

First of all, this research could be expanded upon in several ways. For example, more sources could be included in the comparison. Other than Acacia, the maps used in this research were open-source, nation-wide grids. However, there are many paid, fundamentally different modelling modules that can be used to estimate groundwater level and once they are made, they could be compared in the same way. Likewise, it is likely that more measuring locations will be established in the near future, which would significantly improve the validation in Section 4.3. Also, more conditions could be compared against the difference maps, including land use, precipitation and evaporation, which were excluded from this research due to their complicated, time-dependent nature in combination with time constraints.

In such upcoming research projects, it is advisable to separate the analysis within each major soil type. In this research, the relation with soil type was investigated after the quantitative conditions were. However, the sources turned out to behave very differently in each of the soil types, with peat being particularly distinctive. Therefore, it would beg little surprise if the other correlations significantly differed in strength or even in direction between the soil types. Moreover, assessment of the standard deviation of between the estimates of different sources was carried out late in the research, as part of the validation, but would have served well immediately after the comparison. That way, it would have immediately become clearer where the sources differed most, which helps to focus more attention on the areas with the greatest uncertainty.

Secondly, the correlations with elevation were found and are difficult to miss, but they are also complicated to analyse. After all, elevation is itself correlated with seep, drainage density and even certain soil types. A deeper research into the causes of this correlation would be interesting. Other open questions from the results of this research include the reason that the sources had a clear hierarchy from wet to dry with the MHW, but not with the MLW, and the cause of the large difference between measured MxW values and the mean of the modelled values (Section 4.3).

Thirdly, the groundwater level is important in the determination of available soil storage, which is, in turn, important in inundation models, but it is unknown how sensitive the outcome of an inundation model is to the values of the groundwater level and how these relate to each other. This is another interesting direction of research, specifically with relevance to the recommendation to treat the groundwater level as a stochastic variable.

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Appendix A – Measurement results

In Table 9, each of the measurement locations are provided with the measured values for the MxW (in the second and third columns) and their estimates from each of the four models. The codes that define each of the locations correspond to those given in Figure 25.

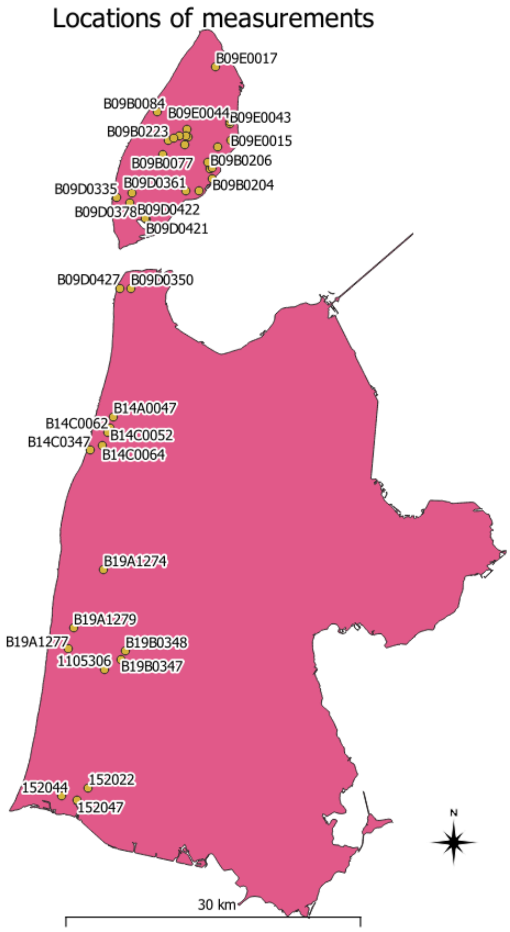

Figure 25 Locations of each of the measurement pipes, including the associated code

Table 9 The measured and estimated MxW values at each measurement location

Code	MLW	MHW	MLW (WDM)	MLW (LHM)	MLW (Alterra)	MLW (Acacia)	MHW (WDM)	MHW (LHM)	MHW (Alterra)	MHW (Acacia)
1105306	180	127	-	-	-	189,81	-	-	-	182,57
152022	168	84	-	149,71	107	133,89	-	65,89	27	106,37
152044	141	84	-	221,61	104	228,98	-	108,46	43	220,02
152047	101	81	-	-	-	107,65	-	-	-	85,82
B09B0049	145	112	117	124,87			34	11,34		
B09B0077	97	55	132	110,82	117		40	-0,67	56	
B09B0084	39	17	100	114,53	60		44	39,82	10	
B09B0092	129	51	133	134,51	120		62	0,68	59	
B09B0204	21	-1	111	44,26	87		70	37,93	26	
B09B0205	38	-5	82	73,92	80		33	-0,59	25	
B09B0206	53	10	82	76,26	73		33	-0,58	19	
B09B0207	39	-6		84,33	74			-0,50	20	
B09B0215	57	-6	94	109,60	68		13	1,12	16	
B09B0216	90	2	107	109,67	104		21	-0,50	43	

B09B0218	108	-12	100	144,45	97		16	-0,41	34	
B09B0219	84	8	90	158,17	111		14	-0,42	44	
B09B0223	79	-3	94	134,60	89		28	-0,47	28	
B09B0224	110	70	111	104,28	101		70	-0,33	40	
B09D0335	-19	23		120,03				10,23		
B09D0350	58	96		123,52		214,73		78,15		202,10
B09D0361	103	62	111	204,38	120		70	103,33	59	
B09D0362	78	105	111	59,85	130		70	-0,48	69	
B09D0378	88	29	121	104,26	133		39	-0,12	57	
B09D0421	33	8	104	13,92	85		40	-1,09	26	
B09D0422	22	12	105	105,59	85		32	-0,37	26	
B09D0427	73	1	254	386,65	219	125,59	169	317,49	125	68,09
B09D0696	130	105	111	138,24			70	-0,65		
B09E0015	122	91	111	98,15	113		70	-0,35	52	
B09E0017	122	53	135	95,33			46	-0,37		
B09E0028	146	126		111,78	151			-0,16	90	
B09E0043	61	9	111	27,23	102		70	-0,70	41	
B09E0044	100	24	137	13,31	131		74	-0,76	43	
B09E0045	101	15	118	-0,38	67		53	-0,90	16	
B14A0047	49	-17	108	87,78	90	62,91	41	13,32	29	29,30
B14C0052	154	122	130	279,58			66	191,16		
B14C0062	143	113	133	75,11			69	0,40		
B14C0064	112	85	173	85,43	228	305,67	92	7,26	158	262,73
B14C0347	117	40	207	329,17	176	626,00	108	251,70	100	580,14
B19A1274	144	91		159,79		-66,02		76,35		-104,58
B19A1277	106	76		163,02		33,61		99,49		13,93
B19A1279	107	77		758,73	108	35,69		699,67	42	1,02
B19B0347	97	67	116	89,10	111	59,84	54	24,42	45	26,82
B19B0348	38	12	76	76,70	76	36,37	7	15,62	22	0,12