EFFECT OF SURFACE WATER MANAGEMENT MEASURES ON A GROUNDWATER FED WETLAND

KUZIVAKWASHE PATRICK NYARUGWE
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ABSTRACT

Wetlands provide important eco-hydrological services and functions but have historically been altered by mankind to meet their needs and wants. Wetland restoration now being pursued as part of broader sustainability goals. In the Netherlands, wetland reconstruction projects are in progress and the Aamsveen wetland has been restored. River channel restoration and establishment of a reservoir were done as surface water management measures to re-establish prior hydrological functioning but it is not known whether the surface water management measures have improved surface-groundwater interactions and the water balance components.

The aim of this study was thus to understand the impact of surface water management measures on the Aamsveen wetland hydrologic system through focusing on surface-groundwater interactions. A steady state groundwater modelling approach was applied. A detailed local scale model was developed that captures the spatio-temporal dynamics of the 4 Km^2 wetland to quantify the wetland fluxes and states. MODFLOW-2005 under the ModelMuse environment was chosen to implement the wetland conceptual model. Two gauges were implemented in the inlet and outlet of the wetland area model as hydrological forcings of the model. The steady state model was manually calibrated. Considering that the water management measures were implemented in the year 2011, that year was chosen as the demarcation period to assess the changes in the wetland water balance. Thus, two scenarios were implemented for the pre-2011 and post-2011 scenarios. Furthermore a second calibration of the pre-2011 scenario was done using exported heads. The modelling work was supported by fieldwork measurements of: saturated hydraulic conductivity on the peat and sandy soils, stream discharge and meteorological data from KNMI.

Field measurements showed that stream discharges were between 0.04 m^3s^{-1} and 0.09 m^3s^{-1}, and the hydraulic conductivities were in the region of 0.02 md^{-1} for peat and 1.19 md^{-1} for sand. Calibrated horizontal hydraulic conductivities were in the ranges of 0.04 md^{-1} to 30 md^{-1} for the first layer and 0.001 md^{-1} to 100 md^{-1} for the second layer. The model was sensitive to horizontal hydraulic conductivities and stream depth. The model performance from the calibration results was satisfactory as shown by R^2 values of 0.96 for the post-2011. The calibrated conductivities, when imported into the pre-2011 scenario resulted in a R^2 value of 0.8 and there were large residuals showing that there was excess water in the model. Thus a second calibration of the model was done for the pre-2011 scenario which produced satisfactory results with an R^2 value 0.86 for the pre-2011. The results showed that the pre-2011 scenario has 25.5% less water than the post-2011 period. After the 2011 changes, the behaviour of groundwater flows in the wetland changed as more water was being discharged into the wetland system. Only 21% of the inflows are lost in the post-2011 scenarios as lateral transfer whereas such losses amounted to 62% in the pre-2011 scenario.

It is concluded that the water management measures that are part of the Aamsveen wetland restoration project have led to positive changes in the water balance. The wetland is becoming wetter. However, it is recommended that further studies be carried out in the wetland such as transient modelling. Data from the German side needs to be accessed and intensive measuring of the hydraulic conductivities on the peat and sandy soils needs to be done for better model parameterization.

Key words: Aamsveen wetland, Groundwater modelling, wetland restoration assessment, MODFLOW

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ACRONYMS

NDVI	Normalised Difference Vegetation Index
GPI	Global Polynomial Interpolation
ET	Evapotranspiration
GIS	Geographical Information System
RS	Remote Sensing
SVD	Singular Value Decomposition
DEM	Digital Elevation Model
SAC	Special areas of conservation
SPA	Special protection areas
KNMI	Koninklijk Nederlands Meteorologisch Instituut
HOF	Hortonian overland flow
SOF	Saturation overland flow
SFR	Stream flow routing package
HOB	Head observation package
PEST	Parameter estimation
ME	Mean error/bias
MAE	Mean absolute error
RMSE	Root mean square error
FAO	Food and Agriculture Organization
GIW	Geographically isolated wetlands

1. INTRODUCTION

1.1. Background

Wetlands are one of the world's most important environmental assets, containing a diversity of flora and fauna. However, their diversity makes them vulnerable to over-exploitation because of the abundance of water, fuel, and fish (Wetlands International, 2015). They exist where there is a positive water balance at or near the surface for a significant amount of time and thus their widespread coverage in humid, tropical, subtropical, and temperate regions (Humphries et al., 2011). Wetlands have various functions that include flood control, pollution filtration, nutrient recycling, sediment accretion, groundwater recharge and water supply and erosion control (Hartig et al., 1997). Since wetlands are characterised by water, hydrological processes such as runoff have an impact on the wetland functioning. Alterations to the wetland hydrology and spatial extent that may occur due to human activities and climate change may induce negative impacts. These impacts can be mitigated by management measures such as establishing buffer areas, promoting sustainable use of wetlands, and restoration of altered wetland areas (Hartig et al., 1997).

Water management involves complex designs and ideas that enable one to modify systems to ease on water resources, ecology and ecosystem services related hazardous impacts. The Netherlands is famed for its alterations on the rivers in order to manage the hazards associated with them. Such plans like "Room for the river" (Ruimte voor de Rivier) are intended to address flood protection, master landscaping and the improve environmental conditions in the riverine/riparian areas (Royal Haskoning DHV, 2015). These efforts are focused on returning these ecosystems to a state that is close to the pristine conditions. Most threats to the Netherlands wetlands, excluding long-term threats that are largely climate-change related, comprise: changes in hydrology leading to changed discharges, currents and desiccation (Best et al., 1993).

One of the important gazetted wetlands under Natura 200 in the Netherlands is called the Aamsveen wetland. This wetland is a remainder of a peat area stretching from north to south along the Dutch-German border. Armandine Les Landes et al. (2014) in their research noted that abstractions or anthropogenic activities on wetlands can affect the area of wetlands. The Aamsveen wetland ecology and water quality are sensitive to fluctuations in water level as caused by natural fluctuations and human intervention. A decrease in the area occupied by wetlands portrays a reduction in the amount of water in the wetland and vice versa. The Aamsveen wetland has experienced these changes and with the area being gazetted under Natura 2000, continuous monitoring to these volatile environs becomes of paramount importance. The wetland restoration efforts in Aamsveen wetland at local scale thus need to be studied and monitored to assess the water management efforts on wetland restoration.

Studies have been done on wetlands/peatlands focusing on climate change and other impacting drivers (Armandine Les Landes et al., 2014; Bradley, 2002; Elçi & Molz, 2008; Santos et al., 2014). Elçi & Molz (2008) focused on the understanding of saturated groundwater flow in wetland soils in relation to its effects on hydrological, geochemical, and ecological functions on the ecosystems. Other studies have focused on climate change coupled with other anthropogenic activities, their effect on the amount of water present and the spatial extent of peatlands. In the study by Armandine Les Landes et al. (2014), they concluded that the extent of peatlands is decreasing across the world because of anthropogenic activities such as drainage for agriculture or groundwater abstractions in underlying aquifers. A previous study on the Aamsveen peatland by Xing (2015) focused on the effects of wetland reconstruction on vegetation and nutrients variation and used the NDVI and the Global Polynomial Interpolation algorithm for hydrological analysis of the measured groundwater levels in monitoring piezometers.

Wetland restoration is an environmental sustainability strategy that is recommended and applied (Stromberg, 2001; Verhoeven, 2014)(Verhoeven, 2014). However, the impacts of wetland restoration on the hydro-dynamics are scantily known and they vary from wetland to wetland. Several measures have been taken in the Netherlands and Germany to conserve the Aamsveen area without negatively affecting agriculture. The last reconstruction/alteration on this peatland was a water diversion program in 2011. Past studies on wetlands (Best et al., 1993; Kentula, 2000; Whigham, 1999; Young, 2000) focused on ecological aspects of the wetlands. Proper management of water systems requires a definite account of the interaction between surface and groundwater (Rassam et al., 2013). Uncertainties regarding the impact of the changes in the surface water management (water diversion and wetland reconstruction) of the Aamsveen wetland have made it necessary to monitor the impacts on groundwater resources thereof.

1.2. Research problem

The Aamsveen wetland has undergone various changes for water management purposes but the hydrologic impacts of the water management driven changes on the wetland system are not fully understood. To be able to observe the effect of these changes and in part, determine the success of the wetland reconstruction, there is urgent need to understand the surface and groundwater processes of this system. For these groundwater processes to be understood, there is need for measuring and monitoring in order to diagnose the complex wetland hydrologic processes involved (Kazezyılmaz-Alhan et al., 2007; Verhoeven, 2014) but this is not trivial.

Field based monitoring of wetland hydrology is essential and can be used to address this problem but it is expensive, time-consuming, gives only time limited scope for studying different scenarios (Acremanet al., 2007) and provide space-time limited snapshots of the processes (state or rate variables). However, use of models provides the possibility of simulating these processes especially where there is coupled effect of surface hydrological changes impacting on the groundwater and vice versa. Modelling also presents an opportunity to explore changes in conditions that would be difficult to impose in the field. Therefore the study responds to the Aamsveen wetland case by applying a modelling approach to simulate the changes made to the wetland and support monitoring.

1.3. Research objectives

1.3.1. Main objective

To assess groundwater-surface water interactions in the Aamsveen wetland system for management purposes with support of groundwater modelling.

1.3.2. Specific objectives

1. To develop and calibrate the steady state groundwater model of the Aamsveen and its catchment, based on an existing regional model.
2. To estimate the water balance of the wetland.
3. To determine the effects of the 2011 changes on the water fluxes in the wetland.

1.4. Research questions

1. How to simulate the surface and groundwater system by modifying the regional groundwater model of the Vechtstromen Water Authority?

2a. To what accuracy can the model close water balance?

2b. What are the spatial-temporal key water balance components (recharge, ET)?

3a. How to capture the changes made to the wetland in the model?

3b. Can the model simulate the effects of the water management interventions?

1.5. Relevance of the research

As described in section 1.1, the Aamsveen is a remainder of a peat area stretching from north to south along the Dutch-German border. The wetland ecology and water quality are sensitive to fluctuations in water level as caused by natural fluctuations and human intervention. Several measures have been taken in the Netherlands and Germany to conserve the area without negatively impacting agriculture. The Aamsveen wetland has undergone a transition to restore it, thus the hydrology of the area has to be properly monitored. This study aims to understand the interaction between the groundwater and the surface water in the Aamsveen wetland.

The effects of water resources management measures in this wetland have to be monitored and assessed. This study proposes a management tool in form of a local scale model that can be used for decision making on water use and water allocations. There is currently no model with appropriate details available for monitoring the hydrology of the wetland. Restoration of this wetland remains to be modelled and monitored. There are few studies in the literature on wetland restoration effect modelling, hence this study will provide methodologies to assess performance of restored wetlands. Figure 1 shows the images from Aamsveen for different years.

21/09/2006

31/12/2009

04/06/2012

08/02/2015

Figure 1: Images showing the history of the Aamsveen (source: Google earth images from 2006, 2009, 2012 and 2015)

2. LITERATURE RELATED TO THIS STUDY

This chapter briefly describes the main aspects of groundwater modelling and use of satellite remote sensing products on wetlands.

2.1. Wetland hydrology

The primary component in wetland restoration projects is wetland hydrology. An understanding of the dynamics of the relationship between coupled hydrology and vegetation systems in wetlands is required to be able to assess their responses to engineering work and climate change (Chuiet al., 2011). This entails the surface and the subsurface hydrological constituents and the interaction between them. The groundwater quantity in wetland ecosystems is important to be investigated and studied, however, the success of wetland restoration is not always entirely dependent on groundwater quantity and quality (Susilo et al., 2012).

This study, however will focus on peatlands. Studies on the flow of groundwater in peatlands and its maintenance of a high water table is necessary especially in reconstructed wetlands. One of the field-based methods of monitoring groundwater dynamics is to directly measure the groundwater in piezometers/monitoring wells. The use of field data and with system modelling is a frequently used method for predicting the effect of changing a hydrological parameter on the groundwater levels. Hydrological models provide potentially a useful tool in modelling future scenarios in areas targeted for wetland restoration (Boswell & Olyphant, 2007). Modelling can either be used to describe past events based on a phenomenon, schematic description or theory of a system with different data (Susilo et al., 2013) or it can used for predictive purposes.

2.2. Groundwater modelling

The Dutch province of Overijssel has a regional model that includes the Aamsveen wetland. However, this model does not include the peat and the local effects of the wetland. It is a regional model and the level of detail in the model does not contain data on the wetland details to be able to assess the impact of changes on the wetland. The regional model has a spatial resolution of 25*25 m grid size but it cannot capture the processes in the wetland since some layers are not represented in this model, some drains and streams are also not modelled. According to Michot et al. (2011), fine scale hydrodynamic models can be utilized as a tool to evaluate potential changes in water flow and water quality. Therefore, to fully model the dynamics of wetlands as coupled surface and ground water systems, careful consideration must be given to the three-dimensional transient nature of the flow systems as well as the complexities of inconsistently-saturated media and the response of the porous media to infiltration and evapotranspiration (Boswell & Olyphant, 2007).

Groundwater level rise in low-lying areas results in wetlands when the water table rises very close to or above the land surface. Modelling surface water and groundwater interactions can be done using various approaches in MODFLOW and is termed as integrated modelling. These approaches represent a surface water body either as a head-dependent boundary using the River package or stream flow routing (SFR) package. Gusyev & Haitjema (2011) present a method to represent a surface water body using

MODFLOW's wetland package. Milzow et al. (2009) describe the use of the SFR2 package for stream-flow routing in the delta wetlands of the Okavango. Vermuelen et al. (2013) used iMOD to develop a coupled surface and groundwater model in the Mekong delta. The difference is on how each package simulates leakance between the surface water and groundwater, with the SFR package offering routing of water into and out of lakes and reservoirs and also has a time delay effect in the leakance caused by unsaturated conditions between the stream and the groundwater which cannot be offered by the river package. Thus one can employ different packages for representing surface water bodies in groundwater depending on the prevailing conditions.

2.3. Model Calibration

Model calibration is one of the step of groundwater modelling. Li et al, (2009) described calibration as traditionally done by comparison of simulated and observed piezometric/well heads at a limited number of observation points. A good fit between the observed and simulated values is achieved by adjusting a number of model parameters in order to minimize the residual between observed and simulated heads by means of a trial and error method (Li et al., 2009). Parameter estimation (PEST)(Doherty, 2000) is another method that has been used for calibration of different models. PEST offers a highly parameterized inversion process and speeds up the calibration process by using mathematical regularization techniques like jacobian matrix, tikhonov regularization and SVD-assist to obtain parameter estimation values(Doherty, 2015). Thus there are various ways and algorithms that can be used in parameter optimization. Care should be taken when calibrating parameters so as not to have an over-parameterized groundwater model with little or no predictive value (Li et al., 2009). The calibrated model should be able to simulate the past events and also to have predictive value and assist in decision making.

2.4. Spatial data products

Remote sensing (RS) data products can help in setting up and validating a groundwater model. Through RS image interpretation, one can get spatial data in contrast to the traditional limited number of point data (Li et al., 2009). Novel datasets like high resolution satellite images with their multi-spectral properties and increasing global coverage have become increasingly popular due to their numerous advantages and qualities (Dar et al., 2010). GIS and RS techniques allow generation of spatially and temporally distributed data that can be used to create and validate hydrological models. Compared to the usual limited amount of head data observed in points, the spatial distribution of RS data provides a complete areal coverage (Li et al., 2009). This information is very essential for monitoring the sensitive reconstructed wetlands. RS data can also provide a good source for the elevation model (DEM) using high resolution imagery and this can be further manipulated to extract catchments and sinks in these catchments. RS data can be used to monitor the surface water coverage or inundation occurring on wetlands. These methods combine two or more spectral bands using various algorithms to increase the difference between water bodies and their surroundings (Feyisa et al., 2014 and Xing, 2015).The use of indexes like NDVI has been used to monitor the vegetation on wetlands. Xing (2015) used NDVI to monitor the vegetation changes of the Aamsveen wetland.

3. RESEARCH METHODS

This section entails details on the Aamsveen study area, the data products to be used for the modelling exercise, the groundwater model and the model performance evaluation. It details on the various applied methods, including a flow diagram.

3.1. Study area

The Aamsveen (Figure 2) is a bog on the border of the Netherlands and Germany. The Aamsveen (centre coordinates: 52"10'N, 6"57'E) is situated about 5 km SW of Gronau and about 5 km SE of Enschede. The catchment of the study area is 36 km^2 and the area of the Aamsveen wetland is 4 km^2. The area has an average daily mean temperature of 9.6 °C and a yearly average precipitation of 749 mm. The surface geology of this raised bog area consist of aeolian sand deposits of the Late Weichselian age (coversands) (Kuhry, 1985) and peat from partly decomposed biomass formed under waterlogged conditions in a process called paludification (Andriesse, 1988). The neighbourhood is characterised by agriculture while the wetland is a nature reserve with protected vegetation/forest on both the German and the Dutch side.

The Aamsveen is part of the European Union initiative on nature conservation called Natura 2000. This is a network of nature protection areas, including Special Areas of Conservation (SACs) and Special Protection Areas (SPAs), designated respectively under the Habitats Directive and Birds Directive. The network includes both terrestrial and marine sites (Natura 2000, n.d.). The Aamsveen is a presently a Natura 2000 site, but it has undergone through various changes in the past. Formerly, peat from this bog was extracted and used as a source of fuel. The most recent changes on the wetland are:

In 2006, minor raises were done on the bottom level of the Glanerbeek to reduce the amount of water that was draining from the wetland.

In 2011, the central canal was closed and a weir was built to restore the water course to the original stream, (the Glanerbeek) which is found along the side of the wetland. The Glanerbeek is the main stream that drains water from the wetland

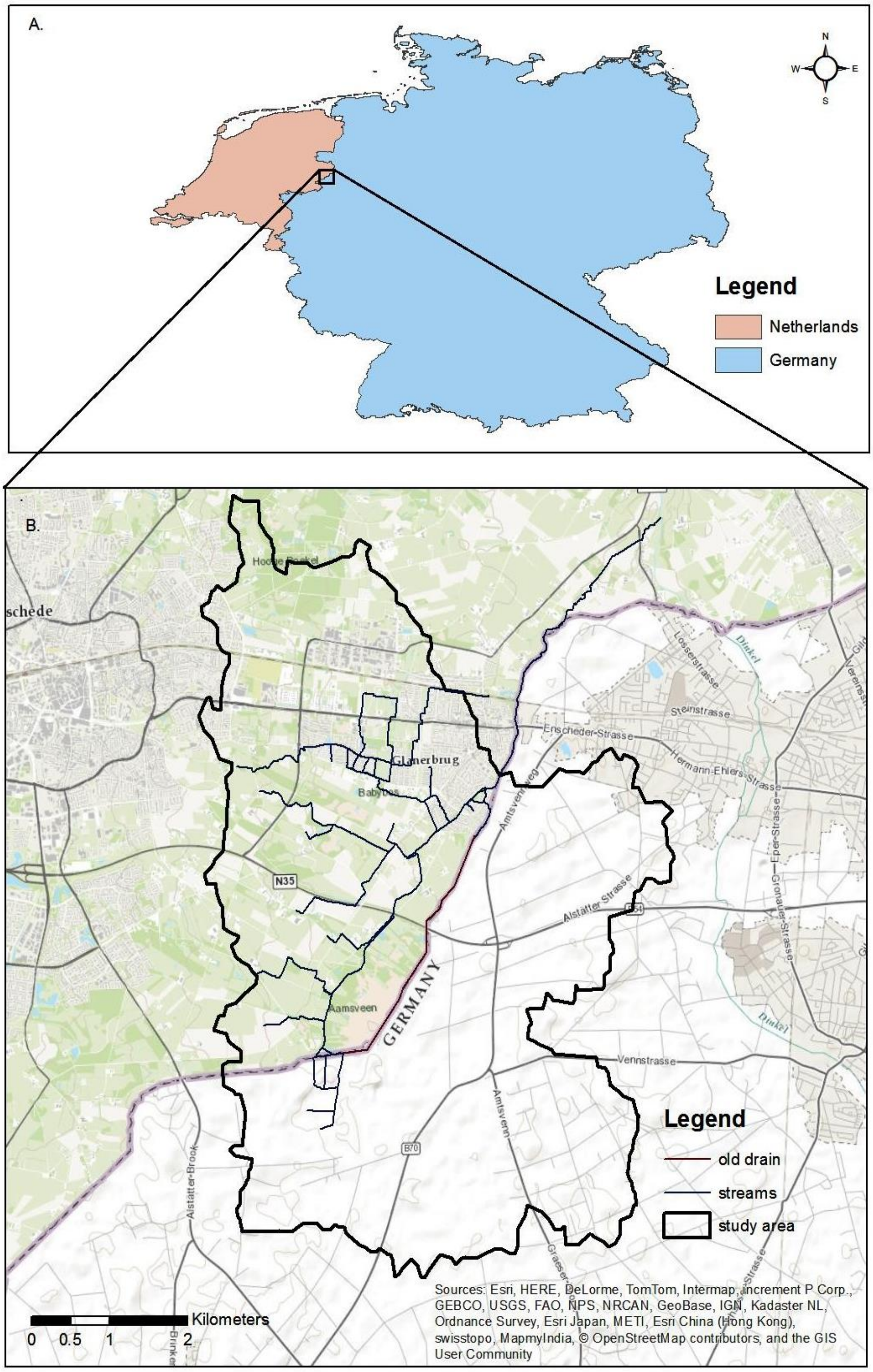


Figure 2: location of the Aamsveen wetland a) The Netherlands and Germany b) The Aamsveen wetland study area

3.2. Previous research on the Aamsveen wetland

3.2.1. NDVI

A study by Xing (2015) on the vegetation characteristics and change detection on the Aamsveen wetland showed that the vegetation greenness increased from 2002 to 2012. These various changes on the vegetation are both natural and anthropogenic including areas where humans have reduced agricultural practice in fields close to the wetland. From the histograms (Figure 3) of the maps created by Xing, (2015) for the year 2004 and 2014, it can be seen that there is a marked increase in vegetation and that the wetland is become greener in 2014 (second peak) than in 2004.

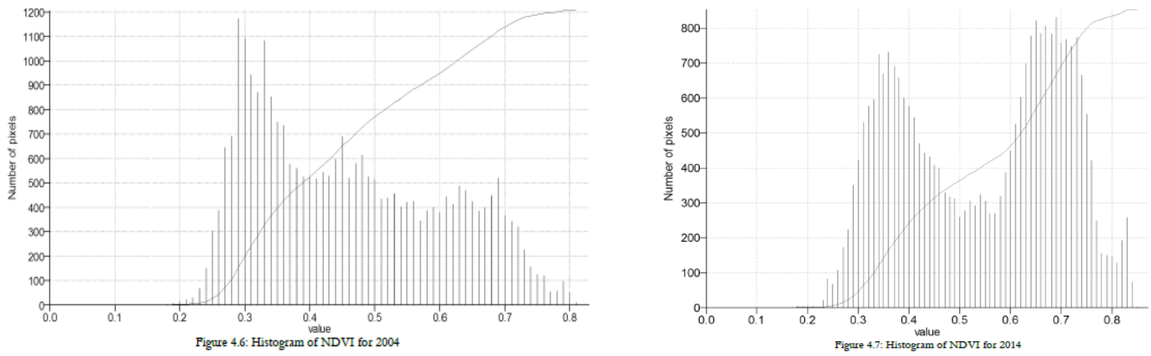


Figure 3: Histograms showing the change in values for the NDVI in April 2004 and April 2014. Source(Xing, 2015)

3.2.2. Groundwater

The study by Xing (2015) also focused on the hydrology and groundwater assessment of the Aamsveen with the help of various methods including the global polynomial interpolation (GPI) with the first and second order polynomials. This study focused on seasonality of the groundwater heads. Key findings included observations that there was no significant changes in the groundwater level in both the dry and the wet season. After using the GPI, no change could be seen with the use of the first order or the second order polynomials. This was attributed to the changes being less than the RMSE. Xing, (2015) also looked at the spatial patterns of the Aamsveen hydrology and concluded that in the dry season, the groundwater would become lower at the streams than at the old drain, and that there were no spatial differences in the wet season.

3.3. Original regional model

The regional model was developed for the Vechtstromen water board which manages water in the Netherlands province of Overijssel. The regional model is an iMOD model extending into Germany (Figure 4) to follow hydrological boundaries. The model is a steady state model with seven layers but peat which is characteristic of the Aamsveen area is not present. The spatial scale of the model is 25*25 m which falls under high resolution but the level of detail on the regional model concerning the hydrology of the Aamsveen wetland is very poor. The surface hydrological activities found in the Aamsveen were not present in the model.

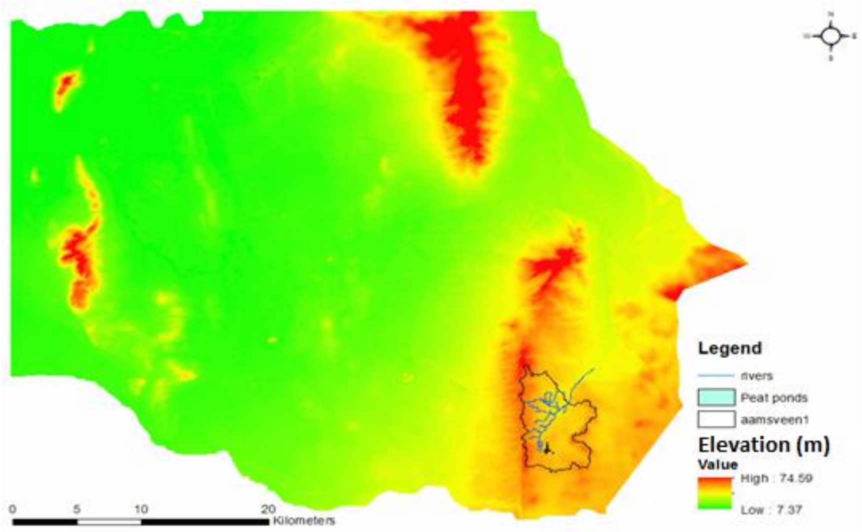


Figure 4: Regional model area

3.4. Data activities in the modelling process

This study was carried out by modifying a regional groundwater model to simulate the local-scale effects of water management measures carried out in the Aamsveen wetland. One layer, a detailed land cover map and the most important streams were added to the regional model to model the surface and groundwater interactions. Figure 5 outlines the modelling steps used in this study.

The regional flow model data was used to define the model top as it was consistent with the model top from the area. The layer was then refined to a 10*10 m model in ModelMuse. Other input data were added into the model after processing the data and exporting it into the required input parameterization in the model. Recharge data was parametrised from precipitation and interception. Field measurements were done to determine the saturated hydraulic conductivities of the modelled layers. Two steady state model cases were created for the pre and post-2011 scenarios and calibrated. The groundwater budget from these two scenarios were then used to determine the flux and volumetric differences in the two modelling cases.

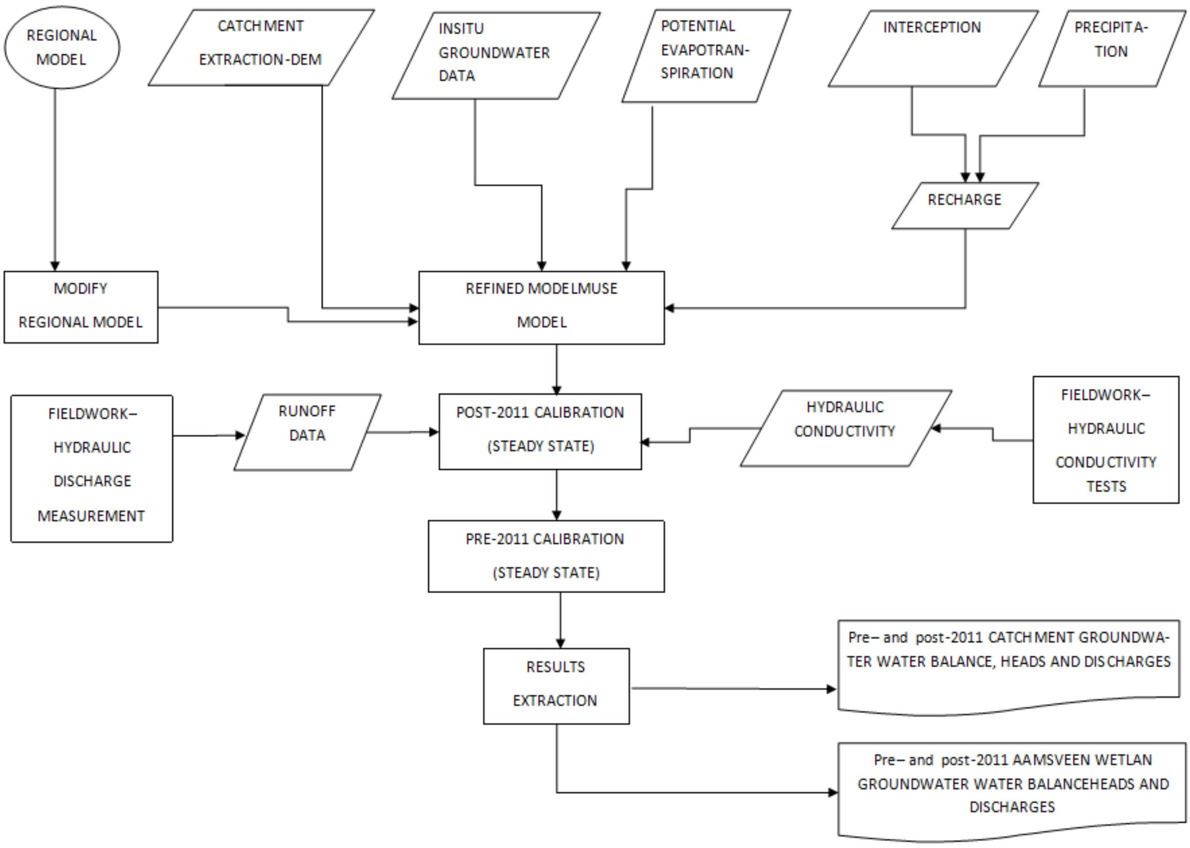
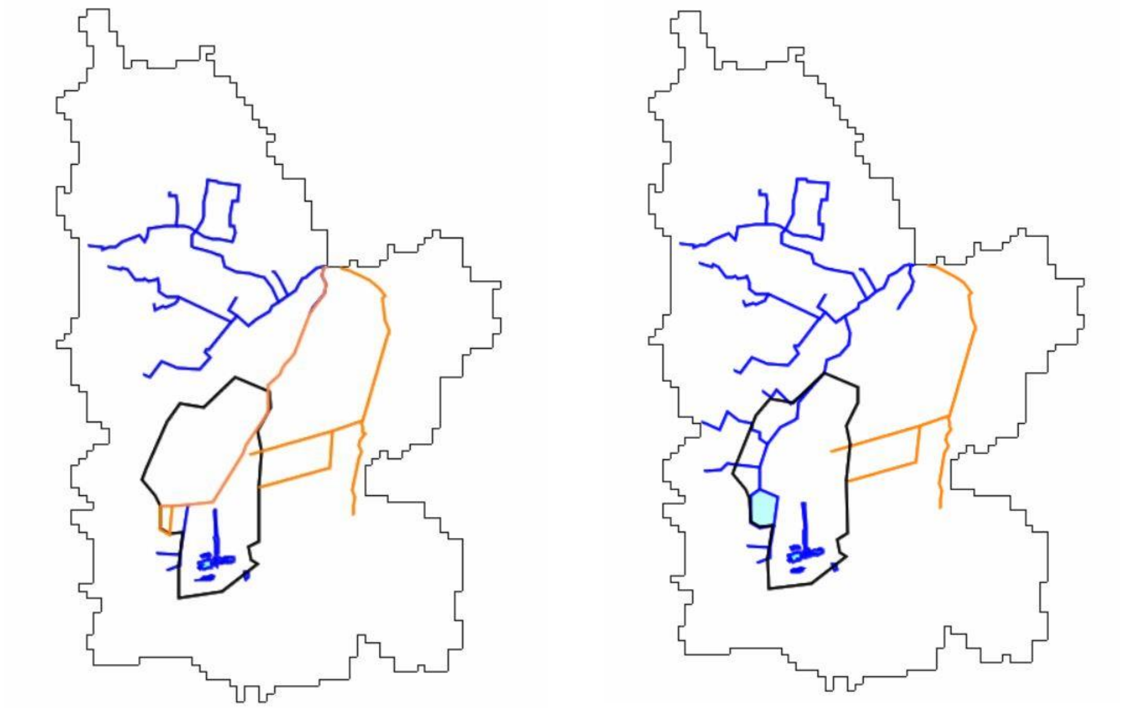


Figure 5: Schematic representation of the work-flow.

3.5. Conceptual model

The conceptual model is the pictorial or the descriptive representation of the Aamsveen groundwater system. The conceptual model encompasses the following main four aspects: hydrostratigraphic units, boundary conditions, flow system analysis and preliminary water balance. Two scenarios are being modelled that is the pre and post-2011 scenarios to evaluate the effect of the water management measures. Figure 6 6 shows the two scenarios as they are in the model with the main difference being a drain in the wetland in pre-2011 scenario and a stream being in the wetland in the post-2011 scenario.

The pre-2011 scenario has a drain/tube that was used to route water from the wetland. This drain was implemented in the model as a drain together with other surface drains that are present in the German side of the Aamsveen wetland. The post-2011 scenario was implemented into the model by removing the drain and diverting the water through a gauging weir. In this scenario, a reservoir was introduce and the gauging weir is used for measuring discharge from the reservoir. The surface drains are used to drain the German side of the catchment. Figure 6 shows the pictorial implementation of the two scenarios in the model.



a) Pre-2011 scenario b) Post-2011scenario

Figure 6: The two modelled scenarios used to depict the prevalent conditions instituted as a way of wetland restoration a) depicts when the Aamsveen wetland was drained by a tube/drain pre-2011 b) depicts the post-2011 state after management measures to restore the wetland by addition of a reservoir and streams.

3.5.1. Hydrostratigraphic units

There are two modelled hydrostratigraphic layers that are present in the Aamsveen area, bounded from below with the lower boulder clay being treated as a lower impermeable boundary because of its low hydraulic conductivity. Anderson et al. (2015) justifies the placing of a no-flow boundary when the underlying hydrogeological unit has a transmissivity two or more orders of magnitude lower, so it conveys less than 1% of the flow, which in most cases is sufficiently small to be neglected. Figure 7 shows the stratigraphic layers that are present in the Aamsveen area. Hydrostratigraphic layers are not always of uniform hydraulic properties. The existing regional model of the water authority depicts the boulder clay as the top hydrostratigraphic layer and does not represent the overlying thin sand layer. In this study, the further developed model includes this layer as well as the peat where it developed on the top of the sand. This way, the sand is becoming the main aquifer and the boulder clay represents a no-flow boundary.

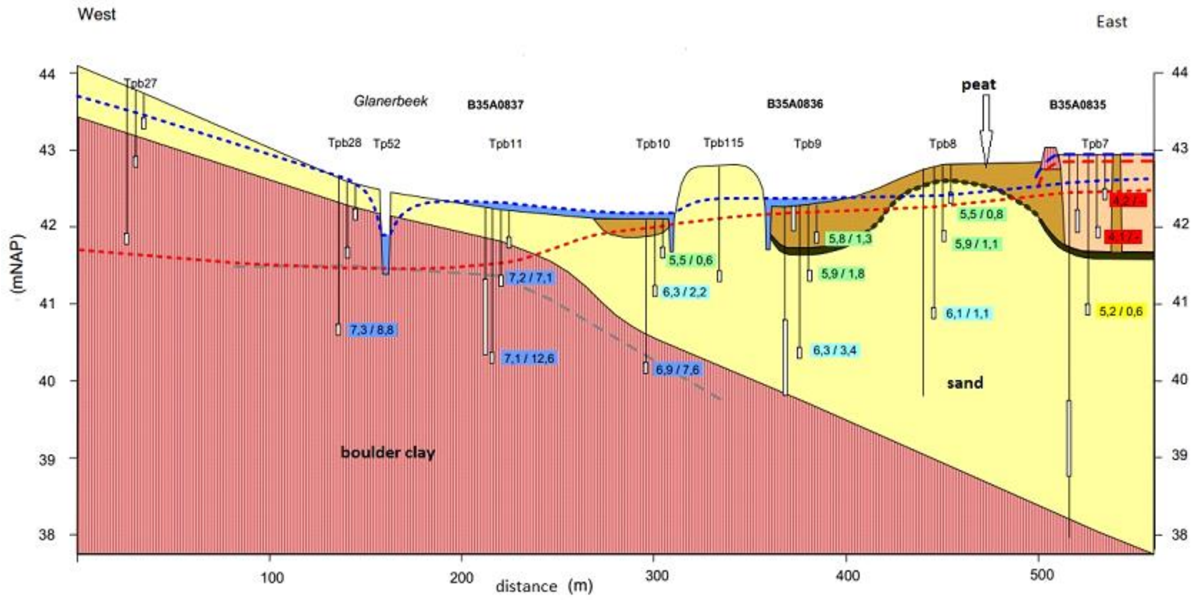


Figure 7: Cross section of the Aamsveen wetland showing the different layers (peat, sand and boulder clay). Source (Bell Hullenaar, 2015)

3.5.2. Flow system pattern and Preliminary water balance

The area is characterised by a shallow aquifer system that is recharged by precipitation and lateral groundwater flows. The groundwater outflows from the study area are groundwater evapotranspiration and lateral groundwater flow on the eastern and north eastern boundary. Flow direction in this basin is from the south going towards the north such that it is from Germany and into the Netherlands. On the western and eastern side, flow movement is restricted by a no-flow boundary. There is a surface water divide at the southern side which also translates into a groundwater divide.

3.5.3. Boundary conditions

The model area has two layers that were used to simulate the Aamsveen area. The first layer is a confining layer of peat. This first layer just embeds into the rest of the model layers. The second layer is sandy soil layer which is a convertible layer. There is a no flow boundary around the study area and as the rest of the area is extended to meet areas which are physical boundaries.

The area circled in red in Figure 8 is the area that harbours the Aamsveen wetland and the external model boundaries were determined along the higher areas using the DEM hydro-processing tool in Streams, reservoirs and drains represent internal model boundaries.

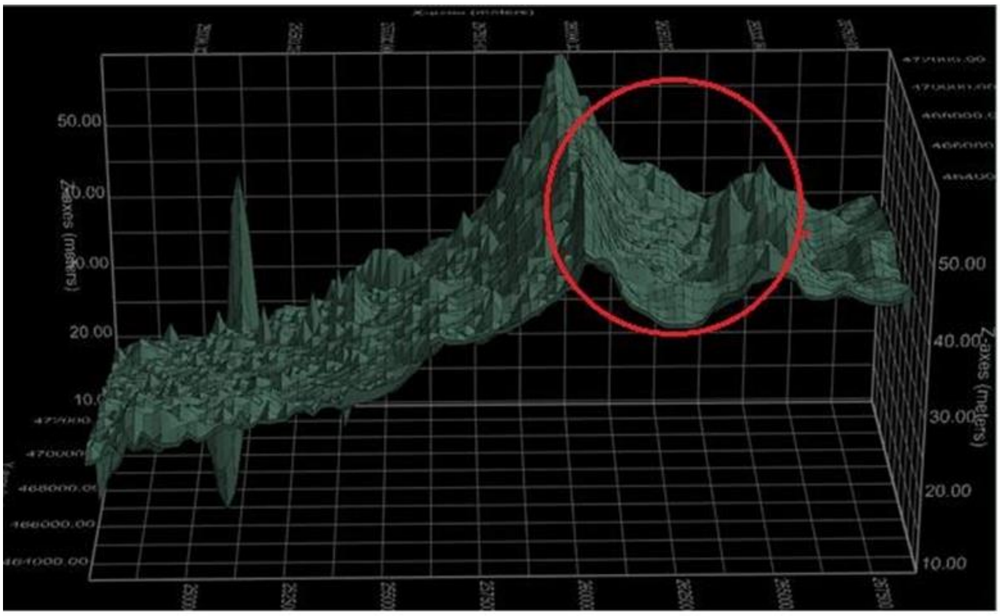


Figure 8: Birds eye view of the modelled area defined on the DEM

3.6. Field work

Field work was carried out to define parameter values related to soil hydraulics and stream/river hydraulics. There are various methods to carry out hydraulic conductivity tests especially in unconsolidated material or regolith. There is a need to understand the depth of the water table and knowledge of the various soil layers in the area and their distribution. To measure saturated hydraulic conductivity, this study applied the inverse auger-hole method in the sandy soils and the double ring infiltrometer in the peatlands as outlined in Oosterbaan & Nijland (1994) for calculating saturated hydraulic conductivity. For discharge measurement, floats were used to estimate stream velocity at chosen sections of the streams. These methods have been used before and are also ideal in situations involving limited time resources.

3.6.1. The inverse auger-hole method for saturated hydraulic conductivity

The inverse auger hole method is suitable for measurements of saturated hydraulic conductivity in areas where the water table is shallow (Noshadi et al., 2012) as in the Aamsveen wetland. To implement this method, firstly a hole equivalent to the thickness of the top soil layer (~1m) was augured with an 8cm auger bit. As explained in Hoorn, (1979) the bore-hole was filled with water and the rate of fall of the water level is measured. Using the field data and eqautions1-3, saturated hydraulic conductivity was calculated.

The surface which water infiltrates at a given time

$$A_t = 2\pi r h_t + \pi r^2 \qquad [1]$$

Where, h_t is head cm, t is time in seconds, r is radius in cm; A_t is the surface area in cm^2

Assuming a hydraulic gradient of 1, according to Darcy Law

$$Q_t = KA_t = 2K\pi r\left(h_t + \frac{r}{2}\right) = -\pi r^2 \frac{dh}{dt} \qquad [2]$$

And then finally integrating the limits of time and head gives

$$K = 1.15r\frac{\log\left(h_0+\frac{r}{2}\right)-\log\left(h_t+\frac{r}{2}\right)}{t} = 1.15r\ \tan\alpha \qquad [3]$$

Where K is hydraulic conductivity cm/s, h_0 are heads cm, t is time in seconds, r is radius in cm

The graph that was produced was not always a straight line in the first observations. This non-linearity is attributed to unsaturated flow and a hydraulic gradient greater than one (1) (Hoorn, 1979). Figure 9 shows part of the fieldwork on determining the hydraulic conductivity of the sandy soil using the inverse auger-hole method.

Figure 9: Fieldwork on inverse auger-hole method to determine saturated hydraulic conductivity. Left: the measuring apparatus used in the field. Right: the sandy soil core laid next to the bore-hole and time being taken by the Author (black jacket), whilst Mr. Sammy Njuki records the notes.

3.6.2. Double rings method for saturated K

Double rings were used to measure the saturated hydraulic conductivity of peat (Figure10). The peat was in a semi-saturated state and the two rings were hammered into the ground. The inner ring is used to measure the rate of water movement downwards while the outer ring is used to control the movement of water in the inner ring by confining it in the vertical dimension. The outer ring controls the directional properties of the movement of water from the inner ring by acting as a saturated barrier and assuring that the movement of water in the inner ring is restricted in the vertical direction.

Figure 10: Use of the double rings infiltrometer to determine saturated hydraulic conductivity in the peat soils

3.6.3. Discharge measurement

Discharge measurement sites were selected on the main stream called the Glanerbeek as a way to monitor the discharge into and out of the wetland. Selection of measurement points in the catchment was based on the location of the site, the type of flow at the site (laminar flow was preferable to turbulent flow) and also accessibility of the site. Discharge measurement was calculated using the velocity-area method as expressed in Hudson (1993):

$$Q = \bar{v} . A \qquad [4]$$

Where Q is discharge (m^3/s), $\bar{v}$ is average flow velocity in the section at the moment (m/s) and A is the wetted area of the cross section at that moment.

In order to measure velocity, various methods were used i.e. float, current meter and a gauging weir depending volumes and nature of the streams. However the float methods was applicable in the high and low flow conditions, making it a viable option. When using a float for estimation of stream velocity, the value derived is multiplied by a factor of 0.85 to cater for the wind action on the float (Chow et al., 1988). The values derived from the discharge estimation were compared to the discharges derived from the gauging stations and the results were correlated. The correlated result was then used as a model forcing on the amount of water leaving the wetland in the streams. Figure 11 depicts photographs of gauging places that were used to carry out discharge measurement in the Aamsveen wetland area.

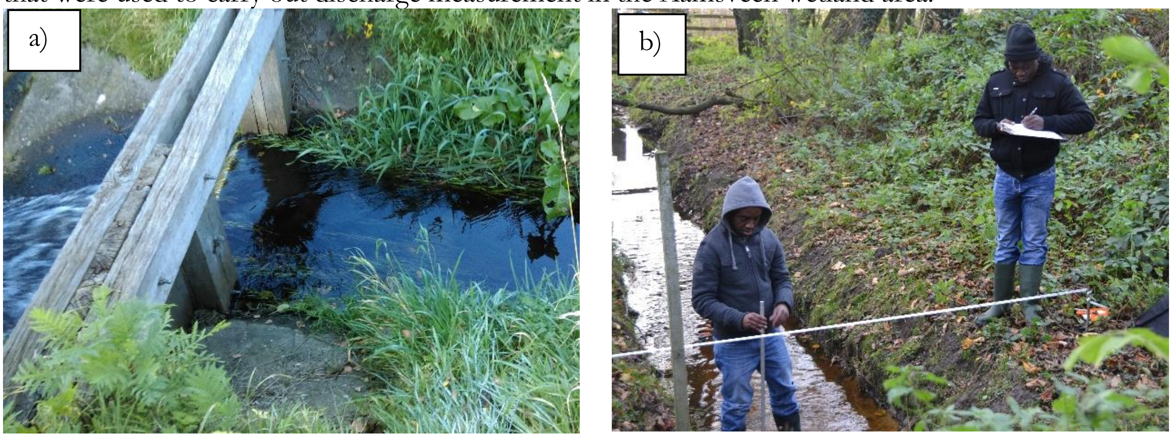


Figure 11: Different types of measuring discharges were used and correlated. a) Shows the gauging weir at the outlet from the wetland and b) the discharge measurement by floats at the main stream from the reservoir

3.6.3.1. The manning's roughness coefficient

The Manning's equation is embedded in the model that was used for calculating stream velocity in the implemented reaches. During field work, surveys of the stream channels were done to determine the manning's n coefficient as input into the model. The manning's equation embedded in the model can be expressed as (Chow et al.,1988; Van der Molen et al., 2007):

$$V = \frac{k}{n} R^{2/3} S^{1/2} \qquad [5]$$

Where V is average velocity in the cross section (m/s); k is 1.0 for metric units; n is Manning's roughness coefficient; R is hydraulic radius (meters) and S is energy slope (m/m) (water-surface slope for uniform flow)

The Aamsveen wetland and the modelled area were characterised by different flow conditions. The Manning's roughness coefficient (n) and cross sectional area vary along natural channel reaches as shown in Figure 12. Field visual inspections of the river channels were used to determine the Manning's n with the help of published tabulated values (Chow et al., 1988)

Figure 12: Streams showing different roughness conditions prevalent in the streams.

3.6.4. DEM hydro-processing

A Shuttle Radar Topography Mission (SRTM) 30 m digital elevation model (DEM) was acquired from NASA's for the Aamsveen area. The DEM was used to determine the catchment boundaries (Figure 13) using the DEM hydro-processing tool in ArcGIS. The DEM was thus used to extract the physical boundaries on the of the study area. Flow patterns and flow direction were determined by use of the topographical map. The catchment area was derived from physical boundaries and it is larger than the Aamsveen wetland area. This catchment area was then used to derive the catchment area water balance which was used to assess the catchment interaction with the Aamsveen wetland area. Thus the Aamsveen wetland is only a portion of the area shown in Figure 13.

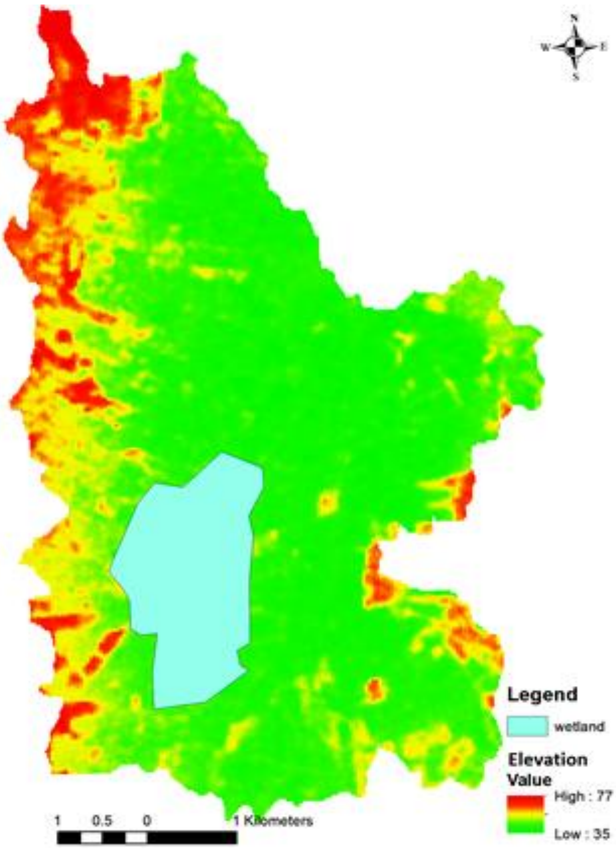


Figure 13: DEM of the Aamsveen area used for catchment extraction and surface elevation

3.6.5. Precipitation

Precipitation data was acquired from the Twente weather station run by KNMI as it is the closest to Aamsveen. The precipitation data is part of the weather data that was derived from the KNMI database for the Twente station. The Recharge package in MODFLOW requires precipitation as an input into the calculations for infiltration. Figure 14 shows the precipitation and potential evapotranspiration data for the Twente station that was used in this study.

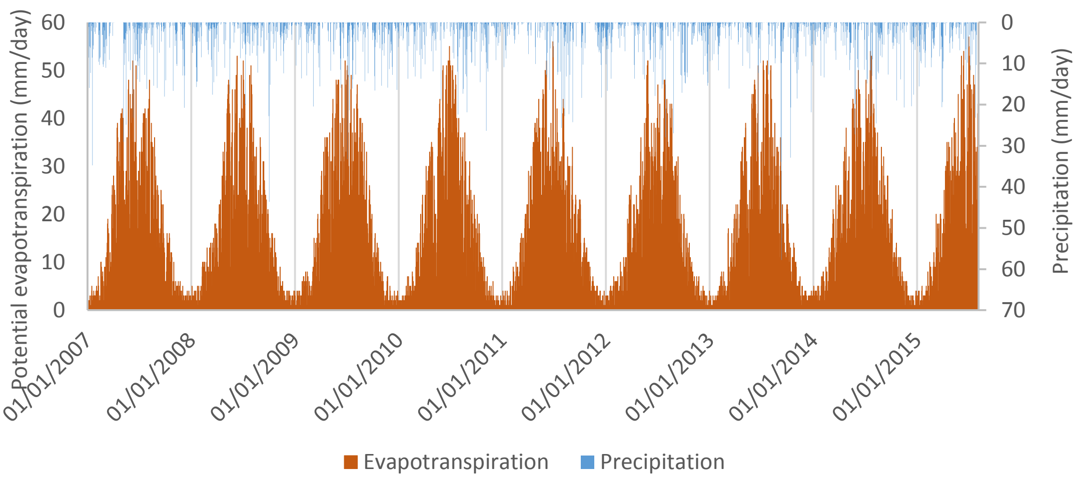


Figure 14: Precipitation and Evapotranspiration data

3.6.6. Potential Evapotranspiration

The data was obtained from the KNMI database and is based on the Makkink which is a radiation based derivative of Penman-Monteith equation (Allen et al., 1998). The method applied for deriving potential evapotranspiration follows the derivations made from equation 6 in a methodology by Makkink (Hiemstra & Sluiter, 2011; Xu & Singh, 2002).:

$$\lambda ET = \frac{\Delta(Rn-G)+\rho_a.c_p.\frac{e_s-e_a}{r_a}}{\Delta+\gamma.\left(1+\frac{r_s}{r_a}\right)} \qquad [6]$$

Where λET is the latent heat flux standing for evapotranspiration, Rn is net radiation, G is the ground heat flux, (e_s - e_a) represents the air vapour pressure deficit, ϱ_a is the air density under constant pressure, C_p is specific heat capacity of air, Δ is the slope of the saturation vapour pressure to temperature relationship, γ is a psychometric constant, and r_a and r_s are the aerodynamic and surface resistances.

Xu & Singh (2002) showed how the Makkink potential evapotranspiration equation is a simplified radiation based version of the FAO Penman-Monteith equation that includes solar radiation only instead of the whole radiation balance. Xu & Singh (2002) further elaborated the Makkink equation performance to be second after the Priestley-Taylor equation. The advantage of the Makkink equation is that it is easy to parametrise as only solar radiation is needed (Xu & Singh, 2002).

$$PET = c1\frac{\Delta}{\Delta+\gamma}\left(\frac{R_S}{\lambda}\right) - c_2 \qquad [7]$$

$$PET = 0.7\frac{\Delta}{\Delta+\gamma}\frac{R_S}{\lambda} \qquad [8]$$

Where *PET* is potential evapotranspiration after Makkink, Δ is saturation slope vapour pressure curve, γ is psychrometric constant, *Rs* is measured or calculated solar radiation, L is special heat of evaporation, *C1* is Makkink coefficient (0.61) and *C2* is Makkink coefficient (-0.12)

3.6.7. Evapotranspiration depth

The model setup had two major rooting depth categories based on the dominant species in the catchment. The method applied variable root depths for the dominant landcover types which are forest and heath. Therefore spatially variable root depths were implemented in this study as used by Vekerdy et al. (1996) and Shah et al. (2007) since different vegetation types have varying root depth. Lubczynski & Gurwin (2005) discussed about parameterising groundwater evapotranspiration to the best possible knowledge. Thus, applying variable rooting depths helps in partitioning vadose zone evapotranspiration and groundwater evapotranspiration (Shah et al., 2007). Boolean expressions were used to segment the root depth of heath and trees extracted in a GIS environment and thus, 3 m was used for cells with trees and 0.3 m for heath.

3.6.8. Interception

Interception is a part of total precipitation that is captured by vegetation (leaves, branches and trunks) preventing it from reaching the soil and is eventually lost to evaporation. In order to compute recharge, interception from the Aamsveen area had to be estimated. Wang et al. (2007) estimated interception loss to be in the range of 5% to 42% in their global analysis of interception by canopy of forests. A study by Barrientos (2007) showed heath interception to be 15% of the rainfall with 85% as throughfall. The Aamsveen wetland area is characterized by heath vegetation, therefore literature values were used for the calculations in the model. The values of 15% for heath were used and 25% for forest (Barrientos, 2007).

3.6.9. Infiltration rates

Infiltration rate was required in the model as input to the Recharge package. The infiltration component is percolated and becomes recharge or can be routed as stream runoff. According to Niswonger et al., (2006), the throughfall component is the water that becomes the infiltration component and is the input for modelling the unsaturated zone. This input is then further divided into different components including runoff, evapotranspiration, unsaturated-zone storage, and groundwater recharge (Niswonger et al, 2006). Thus, infiltration is influenced by either Hortonian overland flow (HOF) or saturation overland flow (SOF) or even both processes. HOF occurs when the rainfall intensity is greater than the infiltration capacity. SOF from saturated soils occurs where the ground is saturated and the water table coincides with the ground surface. When the infiltration rate is greater than the vertical hydraulic conductivity, then percolation will be limited and the excess water will be routed as runoff to the streams using the SFR package. The infiltration rate used in this model was derived from the precipitation minus interception. The Recharge package is the boundary package that provides water from infiltration into the model. Infiltration in the settlements is neglected as most of the settlements have dominantly impermeable surfaces and water is routed offsite in drains.

3.6.10. Stream flow discharge measurement

Discharge data from the Glanerbeek was used as channel flow input and output from the wetland system. The discharge data and the Manning's coefficients were assessed during fieldwork on the most important reaches and tributaries of the Glanerbeek as described in section 3.4.3.1. The model required streambed thickness, streambed elevation, stream width, channel roughness and runoff volume. The discharge measurements from the field work and observations were compared and correlated. The weir at the outlet of the reservoir provided continuous hourly data that was used to correlate the discharge at the Aamsveen wetland outlet.

3.7. Numerical model

Numerical models are computer-based representations that provide the quantified flows and water levels for the analysis of groundwater systems. Numerical models are used for the simulation of groundwater movement based on groundwater measurements. There are two types of approaches in numerical modelling. The steady state and transient (non-steady state) modelling modes. Steady state flow occurs when the hydraulic head is constant in time. This is equivalent to long-term average conditions Equation 9 is based on Darcy's law and is used in numerical modelling for unconfined and confined conditions under steady state scenario (Anderson et al., 2015).

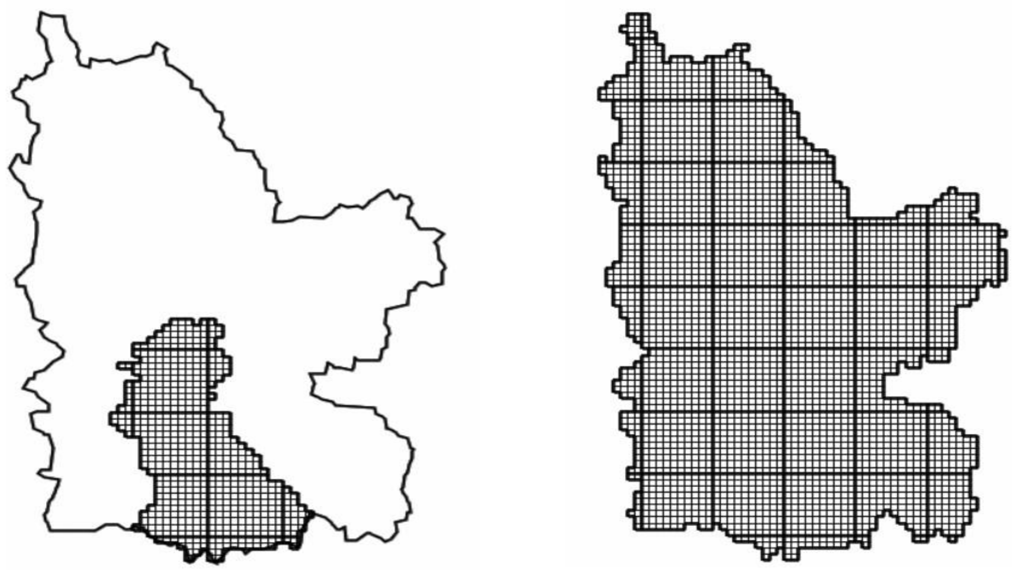
$$\frac{\delta h}{\delta t} = \frac{\delta}{\delta x}\left(K_x \frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta y}\left(K_y \frac{\delta h}{\delta y}\right) + \frac{\delta}{\delta z}\left(K_z \frac{\delta h}{\delta z}\right) + W = S_y \frac{\delta h}{\delta t} \quad [LT^{-1}] \qquad [9]$$

For steady state flow $\frac{\delta h}{\delta t} = 0$

Where: W is a source or a sink; S_y is specific yield for unconfined conditions; K is hydraulic conductivity in x, y and z orthogonal cartesian-plane coordinate directions

3.7.1. Grid design

The model has two grid layers (Figure 15) with the top confining peat layer and the bottom convertible sandy layer. The model area had uniform grid cells of 100m by 100m and the grid network had 80 rows and 50 columns giving a total of 3578 active grid cells. The grid was consistent with the RD-New Royal Dutch coordinate system.



a) Top layer b) 0.

Figure 15: The study area and the modelled layers a) shows the top layer (peat) and b) the second layer (sand)

3.7.2. Driving forces

The simulated flow in a parameterized model is affected by the various model forcings. The Aamsveen wetland model was affected by potential evapotranspiration, stream runoff, precipitation and interception. These driving parameters affected the model output as observed in the water balance of the model. These driving forces were mostly hydro-meteorological in nature. These model driving forces formed the surface boundary conditions. The water table in this case was shallow and trees and vegetation could draw water for transpiration from both the saturated and the unsaturated zone.

3.7.3. Software selection description

The model used in this study ran under the ModelMuse environment based on the MODFLOW-2005 model code with the Layer Property Flow package (LPF) for specifying properties controlling flow between cells (Harbaugh, 2005). MODFLOW model is a three-dimensional (3D) finite-difference groundwater model (Harbaugh, 2005). Separate modelling components were used to represent the separate individual flow components for studying the surface-groundwater interactions. The developed Aamsveen model makes use of the for Stream Flow Routing (SFR) package, Drain package, and Head observation package (HOB), Evapotranspiration package, Recharge package, Reservoir package and Zone budget as a post processor.

3.7.3.1. Streamflow Routing Package

The streamflow routing package (SFR) helps to evaluate the interaction between streams and aquifers and the strong influence that streams can have on the flow through many aquifers (Prudic et al., 2004). The manning's equation method was employed using a rectangular channel, for simulating streams. Streamflow routing within the SFR Package is based on the continuity equation and constant-density streamflow that volumetric influx and discharge rates are the same hence no water is added to or removed from storage in the surface channels (Prudic et al., 2004). This package was used to represent the various streams that route to the Glanerbeek and the Glanerbeek River itself. The SFR package relies on the premise that flow is dependent on the head difference between the stream and the aquifer. When the aquifer head is greater than the stream stage then we have a gaining stream and when the aquifer head is lesser than the stream stage then we have a losing stream. Ground water flow between streams and aquifer systems is based equation 10 in (Prudic et al., 2004).

$$Q_L = \frac{KwL}{m}(h_s - h_a) \qquad [10]$$

Where Q_L is a volumetric flow between a given section of stream and volume of aquifer [L3T-1], K is the hydraulic conductivity of streambed sediments [LT-1], and w is a representative width of stream [L], L is the length of stream corresponding to a volume of aquifer [L], m is the thickness of the streambed deposits extending from the top to the bottom of the streambed [L], h_s is the head in the stream determined by adding stream depth to the elevation of the streambed and h_a is the head in the aquifer beneath the streambed [L].

3.7.3.2. Drain package

The Drain package was a head-dependent boundary package. The drain removes the water but does not return the water to the aquifer but rather routes it out when the groundwater table elevation is above the drain elevation. The drain package has an effect when the groundwater is above the drain elevation. The drain is only active when the groundwater head in the aquifer is higher than the drain elevation (Anderson et al., 2015). The drain package is an internal boundary used in this model as there are some surface unlined drains and a tube which was a lined drain. The rate of removal is dependent on elevation differences between the drain ground water-level and affected by the drain conductance (Harbaugh et al, 2000).

$$Qd = Cd\,(H - De) \qquad [11]$$

Where *Qd* is drain flow, *Cd* is the drain conductance, *H* is the head of the water in the aquifer and *De* is the drain elevation.

3.7.3.3. Head Observation package (HOB)

The head observation package was used to input observations of piezometric heads for use in the modelling process. MODFLOW then computes simulated heads in the same locations used for comparison with the observed piezometric/well heads. The observed heads from the piezometers in the wetland were used as observation points for the overall assessment of the model. A total of eight piezometers were used in this study. These observed heads and the simulated heads were used in the calibration process to fine-tune the hydraulic conductivity. The model compared simulated and observed values for these eight defined observations during calibration.

3.7.3.4. Reservoir package

The Reservoir package is a MODFLOW boundary package in that simulates leakage between a reservoir and the ground-water system (Council, 1997; Fenske et al., 1996). The reservoir package was used in the model to represent surface water bodies that are present on the wetland. The main reservoir was constructed after 2011 and other reservoirs that have been put in the model have been present in areas were peat mining took place.

3.7.3.5. ZONEBUDGET

ModelMuse provides the overall groundwater balance for the modelled catchment area after a successful MODFLOW model run. This postprocessor is available in the ModelMuse modelling environment was used to get the water balance of Aamsveen wetland and thus was been used to derive the interaction between the catchment area and the Aamsveen wetland. This tool was used to create a zone around the

Aamsveen wetland and the water balance that is estimated from the zone. It should be noted that lateral groundwater movement is derived from this tool as an interaction between two zones that is the catchment as a composite zone and the Aamsveen as another zone contained in the catchment.

3.7.4. Initial potentiometric heads

Initial heads were derived and imported from the regional model of the area from Deltares. These heads were created from the regional model of the Netherlands from measurements on piezometers. The heads were also used in formulating the hydraulic conductivities. When the transmissivity is lower, the gradient is high and when the transmissivity is high then the gradient is low. Water flows from high hydraulic head to a region with the lowest hydraulic head. Groundwater movement is from unconfined aquifer to a confined aquifer if the confined aquifers head is lower than the unconfined thus recharging it and if the confined aquifers head is greater than the unconfined head, this results in discharge (Fetter, 2001). The potentiometric map is incorporated into ModelMuse as a raster (ASCII) file and assigned as initial heads. Figure 16 shows the image showing the contour map used in the model as initial hydraulic head conditions. It can be obtained from Figure 16 that the western side of the catchment has a steeper gradient. From equation 12 and 13 that the higher the slope then the lower the hydraulic conductivity and this equation was used in the background of the formulation of the hydraulic conductivity.

$$T_1 I_1 = T_2 I_2 \qquad [12]$$

$$KD_1 I_1 = KD_2 I_2 \qquad [13]$$

Where KD = T; T is transmissivity, I is the slope/gradient, K is hydraulic conductivity and D is depth

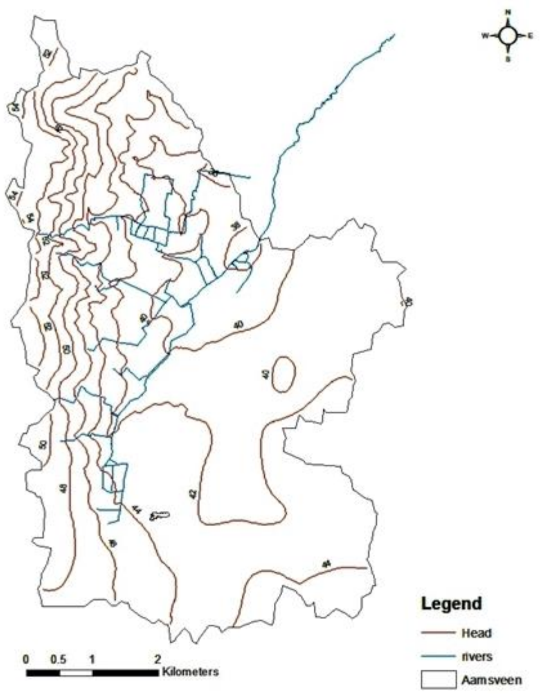


Figure 16: Map showing the heads that were used as the initial heads

3.7.5. Steady state groundwater model

This study applied steady-state flow modelling of the Aamsveen wetland in which there is no change in head with a change in time system. Thus, there is a change in head with time in a transient state model and but not in a steady state flow where the change in head is equal to zero. Anderson et al. (2015) stated that "a steady-state solution alone is often sufficient to address many modelling objectives, such as analysing average groundwater flow patterns and flow rates; estimating average annual leakage from a losing stream; calculating regional water-table gradients; simulating flow directions influenced by long-term pumping". Thus a steady state model was used to simulate overall conditions in the study of the Aamsveen wetland.

3.7.5.1. Steady state model calibration

Model calibration refers to the procedure of adjusting model parameters to match observed data. There are various calibration techniques that area used in groundwater modelling among them is the trial and error method and the parameter estimation (PEST) (Doherty, 2000). This study used the trial and error method and time constraints did not allow the use of any other approach. Observed piezometric heads were tested against simulated heads in a process that Anderson terms as history matching (Anderson et al., 2015). The parameter that was used for calibration was mainly hydraulic conductivity defined in a number of zones.

3.7.5.2. Hydraulic conductivity

There are various field and laboratory methods that can be used to assess the hydraulic conductivities for use in groundwater modelling. A good network of hydraulic conductivity monitoring sites has to be developed to be able to parameterise the hydraulic conductivity and two efficient methods exist the pilot point method and the zonal method (Anderson et al., 2015). The zonal method was used in this study and few hydraulic conductivity tests were carried out in the Aamsveen area. Hydraulic conductivity tests from the dominant soils in the wetland were taken, that is the peat and the sand soil. The inverse auger-hole method was used to measure hydraulic conductivity in the sandy soils and the double ring method used for the peat land.

3.7.5.3. Error assessment

The Geometric multigrid package solver was used in this study and error assessment was carried out using the Mean Error (ME) which helped in assessing the bias of the model; the Mean Absolute Error (MAE) and the Root Mean Square Error (RMSE). The equations for the assessment methods are listed in Equations 14-16. The regression correlation and the residuals were used for the graphical assessment of the calibrated results.

$$ME = \frac{1}{n}\sum(H_{obs} - H_{sim}) \quad [14]$$

$$MAE = \frac{1}{n}\sum |H_{obs} - H_{sim}| \quad [15]$$

$$RMSE = \sqrt{\frac{1}{n}\sum(H_{obs} - H_{sim})^2} \quad [16]$$

Where: *Hobs* is the observed head, *Hsim* is the simulated head and *n* is the number of observations.

3.8. Sensitivity analysis

Sensitivity analysis was carried out by incrementally changing model parameters, mainly the vertical and horizontal hydraulic conductivity by a percentage factor of +30% to -30% whilst holding other parameters constant. There are two methods of carrying out calibration, that is the trial and error method and the PEST automated method which can evaluate statistical influence (Anderson et al., 2015) thereby relating the importance of observation to calibration. The trial and error method of model calibration has its limitations when compared to PEST which thoroughly evaluates parameter sensitivities. The trial and error method was used to calibrate as it allows the researcher to carry out reasonable parameterisation of model area especially if a good set of hydraulic conductivity observations are available.

4. RESULTS AND ANALYSIS

4.1. River discharges

Stream flow gauging was carried out at various strategic places in the catchment as a form of hydrological monitoring on the modelled area. Two sites were used for hydrological forcing of the model in the Aamsveen wetland catchment that is at the gauging weir at the reservoir and at the outlet of the wetland. The data in Figure 17 were taken on three different occasions with reading 1 taken in a low flow period and readings 2 and 3 taken in moderate to high flow periods. The reading used was taken from the averages of the data at the weir that measures the discharge from the reservoir and the correlation used to compute a value at the outlet of the wetland.

Table 1: Discharge measurement carried out in the field at two points in the wetland

	Discharge at gauge 1	Discharge at gauge 2
Reading 1	0.089 m^3s^{-1}	0.182 m^3s^{-1}
Reading 2	0.17 m^3s^{-1}	0.386 m^3s^{-1}
Reading 3	0.12 m^3s^{-1}	0.31 m^3s^{-1}
Values put in model	**3456 m^3d^{-1}**	**8294 m^3d^{-1}**

The measured discharge values between the two gauging sites were compared to the field values measured by the automatic recorder gauge and the following values were derived based on the correlation of the datasets. The average from the automatic recorder at gauge 1 (X = 261268; Y = 466910) was 0.04m^3s^{-1} and the correlated values of the second gauging site (X = 262240; Y = 468588) was 0.09m^3s^{-1}.

The final values used in the model were taken from the correlation factor of 2.4 as seen in Figure 17. The data has a regression correlation of 0.92 which validates the usage of the correlation factor 2.4 between the gauges 1 and 2 data. This correlation was used as there was no continuous data for the gauge point 2.

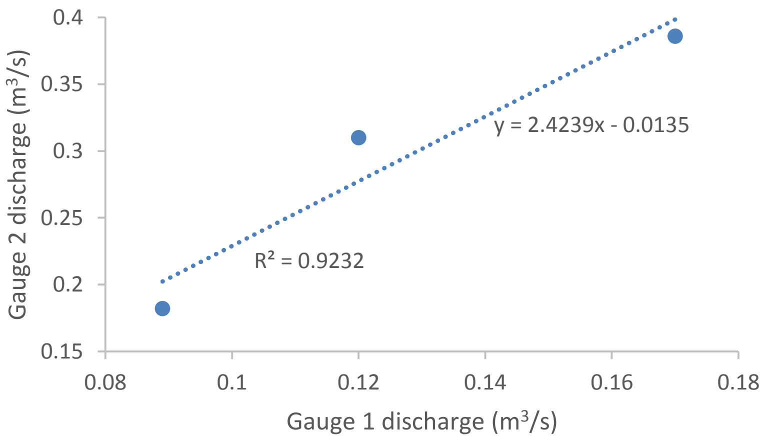


Figure 17: Correlation between first gauge and second gauge

The values shown in Figure 18 show the discharge that was derived from the gauging weir and used in the formulation of the correlation that was used to derive the downstream discharges. The weir crest minimum is the lowest discharge measurement level on the weir that accommodates low flow measurement from the while the weir crest maximum is the highest discharge measurement level on the weir accommodating high flows from the reservoir. The data from Figure 18 was used to derive average inflow rate into the model.

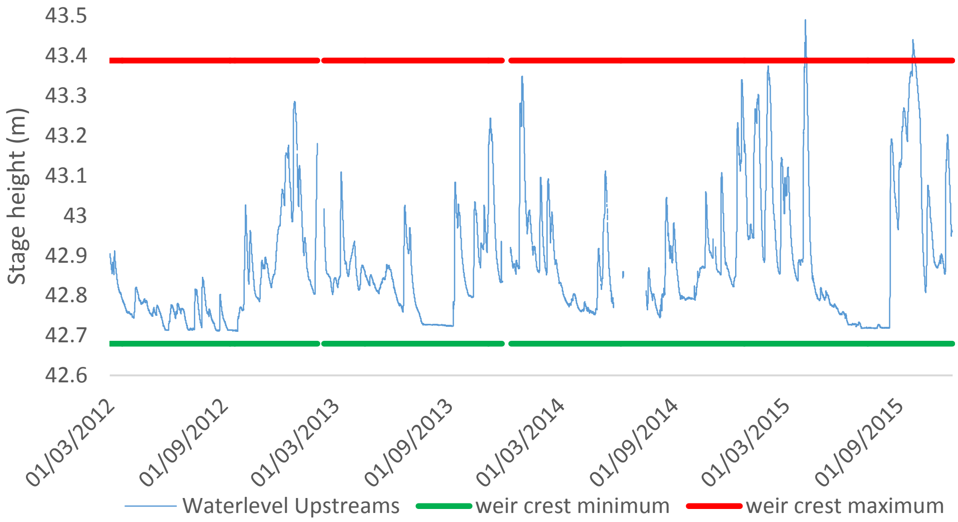
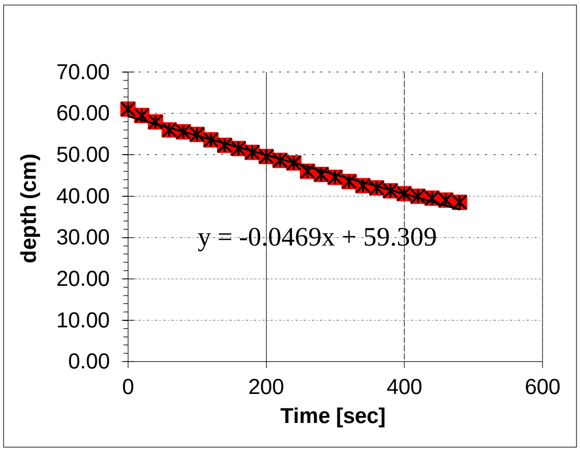


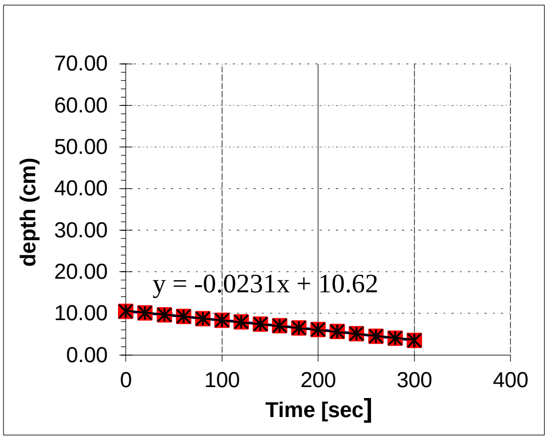
Figure 18: stage height values from the gauging weir discharging from the reservoir

4.2. Hydraulic conductivity tests

Hydraulic conductivity tests were carried out on the dominant soils in the wetland i.e. the peat and the sandy soil. The values derived from the tests are shown in Table 2 and they are consistent with the values found in Ala-aho et al. (2015) where the values of sand and peat have a difference of two orders of magnitude with the peat having a lower hydraulic conductivity than sand. Figure 19 shows part of the formulation used in the derivation of the gradient of the saturated part of the curve where the gradient is used to give the saturated hydraulic conductivity.



a)



b)

Figure 19: Saturated hydraulic conductivity test results of the a) inverse auger hole showing plot of level and time b) plot of time and level using the double rings method

Table 2: Hydraulic conductivities measured in the field using the inverse auger-hole method and double ring methods

Soil	**Saturated Hydraulic conductivity (K) md^{-1}**
Peat	0.02
Sand	1.19

4.3. Steady state model post-2011

Steady state model calibration for the post-2011 scenario was carried out using the information for the last known management measures which include a reservoir and a weir in the year 2011. The model calibration was carried out with the recent data and then checked whether the model is depicting the situation before the changes in 2011.

4.3.1. Head calibration

According to Figure 20 the modelled and the observed groundwater heads in the piezometers in the Aamsveen wetland have a regression coefficient of 0.96 after model calibration. Figure 20 shows the scatterplot of the observed and the simulated heads from the piezometers. These observation points are in the two modelled layers (peat and sand). Averages of the observed vales over the represented period were used for this calibration of the steady state model.

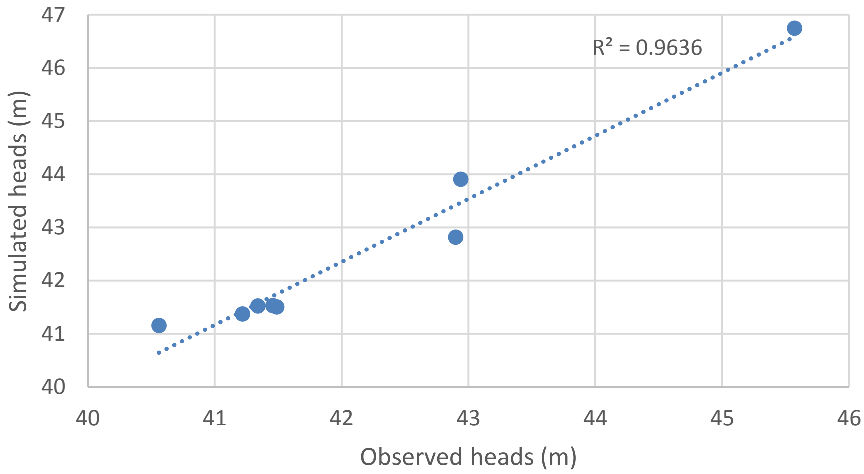


Figure 20: Comparison of calibrated and observed heads for the steady state model of post 2011 period

Table 3 shows the error assessment of the model. The bias of the model is slightly negative, so further calibration could be done on the model for the reduction of this bias, but this was not allowed by the time constraints of the present research. The mean absolute error and the root mean square error are satisfactorily good. It should be noted that the model has a good simulation of the piezometers with low to medium heads and a difference can be observed from piezometer B35A0194 which has a high head. This discrepancy is further analysed in section 4.3.2.

Table 3: Error assessment for the post-2011 period

Well ID	Observed	Simulated	(Obs - Sim)	|Obs – Sim|	(Obs - Sim)^2
B35A0194	45.570	46.745	-1.175	1.175	1.381
B35A0189	42.900	42.815	0.085	0.085	0.007
B35A0184	42.940	43.907	-0.967	0.966	0.934
B35A0187	41.460	41.530	-0.070	0.070	0.005
B35A0192	41.220	41.376	-0.156	0.156	0.024
B35A0191	41.490	41.504	-0.014	0.014	0.000
B35A0196	40.560	41.160	-0.600	0.600	0.360
B35A0197	41.340	41.525	-0.185	0.185	0.034
Assessment method			**ME**	**MAE**	**RMSE**
Result			**-0.237**	**0.250**	**0.127**

4.3.2. Residuals

Figure 21 shows the plot of the residuals of the simulated piezometric heads of the calibrated model. Piezometer B35A0194 is the one with the most deviation from the rest of the piezometers. It is the piezometer with the highest heads and the rest of the observation boreholes have residuals less than a meter. Piezometer B35A0194 is next to the holiday area where unknown subsurface drainage is prevalent. The area tends around this piezometer is surrounded by surface drains that drain water from the recreation place. The residuals from the rest of the piezometers are within 0.6 m from the observed value rendering them a good approximation to the observed

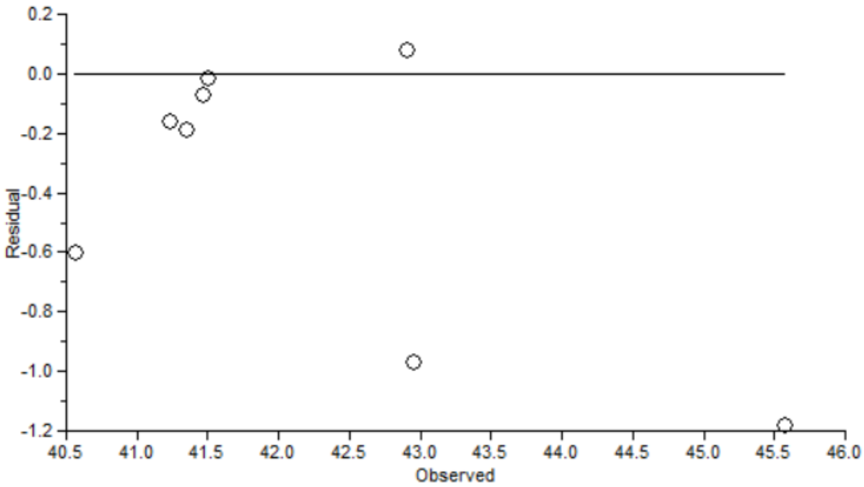


Figure 21: Plot of the residuals of the calibration in the post-2011 period

4.3.3. Hydraulic conductivities

The horizontal hydraulic conductivity (Kx)and the vertical hydraulic conductivity (Kz) were linked by an equation whereby Kz=Kx/10, that is in the range for unconsolidated material (Fitts, 2012). The hydraulic conductivity the values for the first layer are 0.0001 mday^{-1} to 27 mday^{-1} in the first hydrostratigraphic layer and 0.0001 mday^{-1} to 80 mday^{-1} in the second hydrostratigraphic layer.

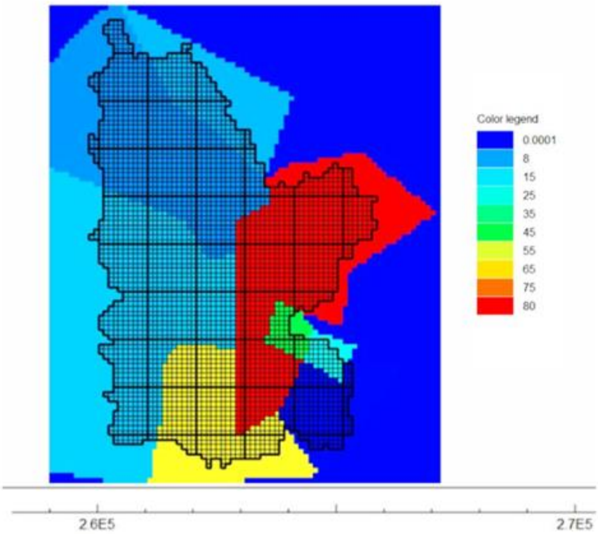


Figure 22: Hydraulic conductivity map of the second layer (sand)

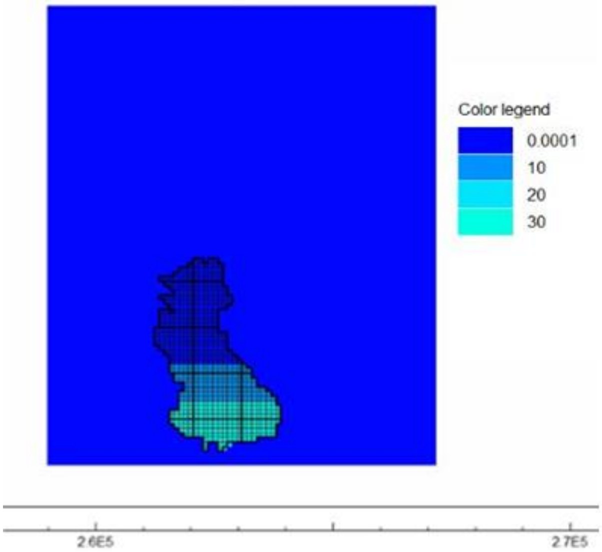


Figure 23: Hydraulic conductivity map of the first layer (peat)

The peat being of very low hydraulic conductivity is underlain by a very thin layer of clay that is the interface that was deposited on top of the sand and then started accumulating this organic matter forming the peatlands. The hydraulic conductivity values of 80 $mday^{-1}$ can be observed on the discharge area of the catchment to the outlet of the modelled area.

The values obtained by the study of Ala-aho et al. (2015) in Finland show sand to have 1.728 m day^{-1} and peat to have 0.0086 $mday^{-1}$ which is close by one order of magnitude to 0.04 $mday^{-}$1 calibrated for peat and sandy soils which range from 1 $mday^{-1}$ to 80 $mday^{-1}$ in the Aamsveen. The values for the peat area (Figure 23) are also influenced with the high water table in the area which sometimes results in parts of the wetland to be inundated thereby forming more peat as mostly peat is formed in anaerobic conditions (Andriesse, 1988). Peat swells when wet and acts like a sponge. The sandy area values can be compared to the FAO values in Figure 24 of (Van der Molen et al., 2007) where we have medium textured sand in the western side of the modelled area outside the Aamsveen area. The Aamsveen wetland has also medium textured sand with a hydraulic conductivity of 13 m day^{-1} as can be seen on the western side of Figure 22

K and μ values according to the soil texture and structure

Texture (USDA)[1]	Structure	μ	K (m/d)
C, heavy CL	Massive, very fine or fine columnar	0.01–0.02	0.01–0.05
	With permanent wide cracks	0.10–0.20	> 10
C, CL, SC, sCL	Very fine or fine prismatic, angular blocky or platy	0.01–0.03	0.01–0.1
C, SC, sC, CL, sCL, SL, S, sCL	Fine and medium prismatic, angular blocky and platy	0.03–0.08	0.1–0.4
Light CL, S, SL, very fine sL, L	Medium prismatic and subangular blocky	0.06–0.12	0.3–1.0
Fine sandy loam, sandy loam	Coarse subangular block and granular, fine crumb	0.12–0.18	1.0–3.0
Loamy sand	Medium crumb	0.15–0.22	1.6–6.0
Fine sand	Single grain	0.15–0.22	1.6–6.0
Medium sand	Single grain	0.22–0.26	> 6
Coarse sand and gravel	Single grain	0.26–0.35	> 6

[1] C: clay; L: loam; S: silt; s: sand.
Source: Adapted from FAO, 1980, with further elaboration.

Figure 24: FAO table on texture, structure and hydraulic conductivity. Source: (Van der Molen et al., 2007)

4.3.4. Water balance

The water budget of the model is shown in Table 4 showing the total inflows and outflows from the study area. The various fluxes are divided into inflows and outflows. The recharge into the area is 59994 m^{3}day^{-1} which complementary to the input into the area. MODFLOW then channels the water into various constituents of the processes in the study area. Reservoir leakage is small in the inflow 216 m^{3}day^{-1} compared to 374 m^{3}day^{-1} in the outflow. Stream leakage plays a big role in regulation of levels in this wetland as it has an inflow of 36866 m^{3}day^{-1} and an outflow of 66765 m^{3}day^{-1}. Surface drains were put in the German side as the area is characterised by surface drains that drain water from the Aamsveen and the agricultural fields in the area and their discharge is 15234 m^{3}day^{-1}. The discrepancy between the inflows and the outflows is 0.003% which falls within the tolerable limits of less than or equal to 1%. From these results it can be noted that in the out fluxes, evapotranspiration has lower amounts as compared to stream leakage and drains which give a combined flux of 81999 m^{3}day^{-1} which is a form of routing water away from the wetland. These values were hydrologically forced with the discharge data that is from a gauging station in the Aamsveen.

Table 4: Groundwater budget for the post 2011

FLOW BUDGET COMPONENTS	INFLOW (m^{3}d^{-1})	OUTFLOW (m^{3}d^{-1})
RECHARGE	59994	0
EVAPOTRANSPIRATION	0	14706
RESERVOIR LEAKAGE	216	374
DRAINS	0	15234
STREAM LEAKAGE	36866	66765
Total	97076	97079
IN – OUT	-3	
Percent Discrepancy	0.00%	

4.4. The pre-2011 period

The calibrated results were then taken to the pre-2011 period were the reservoir and some of the streams in the Aamsveen were not present. This was the time period were the tube/drain was the means of draining water from the nutrient rich wetland as shown in the water quality results of the study by Xing (2015) in the Aamsveen wetland. Two scenarios were observed and assessed in the pre-2011 water resources management measures that were carried out in the Aamsveen area. The two scenarios are outlined and described in the section 4.5 (imported heads from the post-2011 case but not calibrated) and section 4.6 (calibrated heads for the pre-2011 case). This was done after the results showed that there was a change in hydraulics between the two modelled period of pre- and post-2011.

4.5. Steady state model results - Drain without calibration (pre-2011)

The model results that were obtained in the calibration process for the post-2011 period were then transfered to the pre-2011 period. The surface water routing streams that are present in the post-2011 period were removed together with the main reservoir that has also been put in the Aamsveen wetland. A drain/tube that was draining water away from the Aamsveen was included on the boundary between Netherlands and Germany. Therefore the aim of creating this scenario is to create the conditions prevalent before the naturalisation of the wetland in 2011. The other parameters were left as they were except piezometric heads that were changed to the mean of the 2007-2011 period.

4.5.1. Hydraulic conductivities

The hydraulic conductivities were left as they were in the post-2011 scenario as shown in Figure 22 and figure 23. The original surface water courses were included in the model i.e. the closed drain along the German-Dutch border was included, and the reservoir was removed. The main water course was diverted from the side of the wetland into the closed drain.

4.5.2. Comparison of the modelled and observed Heads

The results obtained from the model run under the imported conditions has a regression coefficient of $R^2=0.8$ portraying a good correlation in the data as shown in Figure 25. This plot in Figure 25 shows a comparison of the observed heads and the calibrated heads. The other assessment criterion used for the assessment of this model showed unsatisfactory results as shown in Table 5. The results shows that the model is over-simulating the heads for many of the piezometers in the wetland and that there is a lot of water that is not being routed away from the wetland.

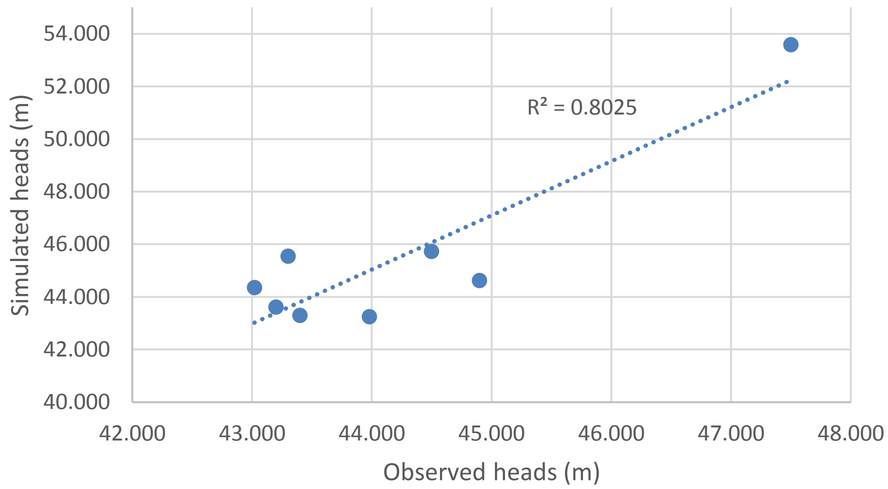


Figure 25: Steady state observed and calibrated heads for the pre-2011 period with imported parameters

Piezometer B35A0194 has the largest discrepancy between the observed and the simulated heads with a head difference of 6.01m and piezometer B35A0197 has the least head difference of about 11 cm. there is a lot of water in the model that needs to be routed away from the wetland area and the rest of the model area that is why there is such a poor performance of the model as the hydraulic and the drainage properties in this scenario are not being well represented.

Table 5: Error assessment for the pre-2011 period (with imported hydraulic conductivity)

Well ID	Observed	Simulated	(Obs - Sim)	|Obs – Sim|	$(Obs - Sim)^2$
B35A0194	47.500	53.588	-6.088	6.088	37.068
B35A0189	44.500	45.726	-1.226	1.226	1.503
B35A0184	44.900	44.612	0.288	0.288	0.083
B35A0187	43.300	45.539	-2.239	2.239	5.011
B35A0192	43.200	43.608	-0.408	0.408	0.167
B35A0191	43.980	43.248	0.732	0.732	0.536
B35A0196	43.020	44.350	-1.330	1.330	1.769
B35A0197	43.400	43.288	0.112	0.112	0.012
Assessment method			**ME**	**MAE**	**RMSE**
Result			**-0.782**	**0.956**	**0.523**

4.5.3. Residuals

The plot of the residuals shows that the majority of the residuals are within 2 metres from the observed heads denoted by the zero line. Most of the piezometers are over-simulating the piezometric heads. Figure 26 shows the plot of the residuals and the model needs to be recalibrated for the pre-2011 scenario.

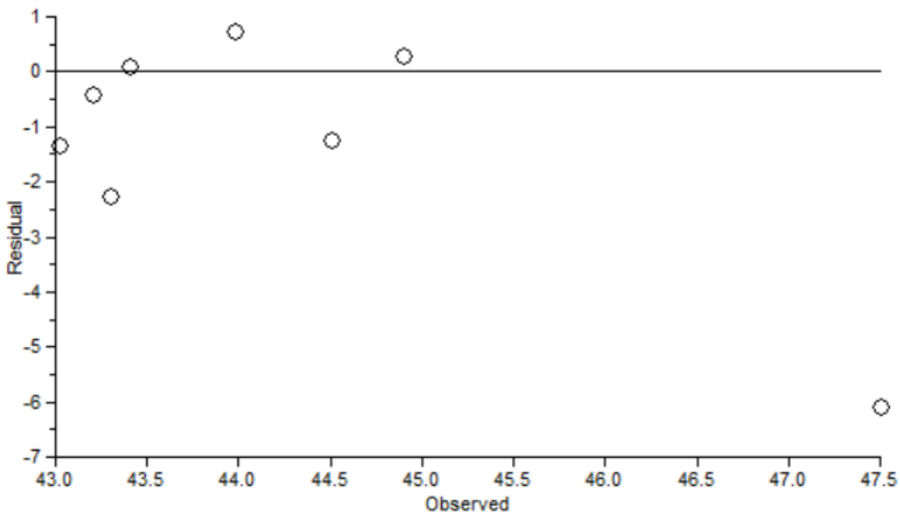


Figure 26: Plot of the residuals of the pre-2011 uncalibrated results from imported hydraulic conductivities

4.5.4. Water balance

Table 6 shows the uncalibrated model groundwater budget for the period before 2011 and because of the errors in the hydraulic heads, the water balance will not be accurate though percent discrepancy of the inflow and the outflow fluxes is 0.01%.

Table 6: Water balance for the imported uncalibrated pre 2011 scenario

FLOW BUDGET COMPONENTS	INFLOW (m^3d^{-1})	OUTFLOW (m^3d^{-1})
RECHARGE	59994	0
EVAPOTRANSPIRATION	0	15106
RESERVOIR LEAKAGE	0	686
DRAINS	0	17783
STREAM LEAKAGE	27378	53807
Total	87371	87382
IN – OUT	-11	
Percent Discrepancy	0.01%	

4.5.5. Analysis of the findings

The groundwater model used for the post-2011 scenario was used to assess the pre-2011 scenario. Though the model performance evaluation for the post-2011 scenario was satisfactory, when the model was used to evaluate the pre-2011 scenario performance, the results showed through residuals that there was more water in the model. The totals from the two scenarios show that there the post 2011 scenario has more water (97076 m^3d^{-1}) than the pre-2011 scenario (87371 m^3d^{-1}) even though the recharge is the same value. There is more water in the model in the post-2011 scenario that cannot be routed out from the model with the drain without changing the hydraulic conductivities of the zones containing the drain.

Anderson et al. (2015) talked of model verification as used by streamflow modellers, will not lead to increased confidence in the models performance but rather focus should be directed at parameter estimation and forecast analysis. Doherty & Hunt (2010) and Anderson et al. (2015) argued that while in model validation, a calibrated model is able to reproduce certain aspects of the system response under field conditions, all the data should be used in calibration. As this study is about studying the effects of water management measures on a wetland, the effect of the measures could not be carried out with one model without affecting the model performance to assess the other scenario. According to Anderson et al. (2015) different time periods and data types comprise information relevant to different aspects of the modelled groundwater system. The changes that were done on the Aamsveen wetland altered the hydraulics of the system. Calibration from one scenario and changing the surface water courses, reservoirs and position within a modelled scenario and exporting the parameters to function in another scenario with a different set of surface conditions is difficulty especially with manual methods used in this calibration.

Leijnse & Hassanizadeh (1994) in a review on model validation and stated that validation of prediction models is an almost impossible task in typical geo-hydrological application. Anderson & Woessner (1992) after analysis of five post-audits/validation advocated on the difficulty in trying to validate groundwater models as it is probably impossible to characterize the field setting in adequate detail. It should be noted that the peat and sand layers are thin thereby making the model very sensitive. Data from the Germany side should be sourced and more hydraulic conductivity tests should be done for better parameterization of the hydraulic conductivity as few tests were done. There is also need for more piezometric data from both the Germany and Netherlands side to aid in the calibration. A second calibration using the drain parameters for the pre-2011 scenario could yield better results for use in the comparison of the two scenarios and was carried out to further improve the model in section 4.6.

4.6. Steady state model results - Second calibration, (based on pre-2011 data)

A second steady state model calibration for the pre-2011 period that had in some instances big differences in hydraulic heads was done to achieve a better overal accuracy of the model. Hydraulic head data from 2007 to 2010 was used in this scenario. From the previous scenario (section 4.5. with imported heads in the pre-2011 scenario), the model was over-simulating the hydraulic heads as the observed piezometric heads were greater by up to 6 metres. The streams were removed, the drain was implemented in this calibration, as it was in the wetland before 2011. A reservoir was also removed from the model in the second calibration. Thus, the reservoir and the gauging weir which acts to control discharge from the reservoir was absent in the second calibration

4.6.1. Hydraulic conductivities

Figure 27 shows the hydraulic conductivities map of the second layer based on the pre-2011 period after the second calibration of the hydraulic conductivity zones. The majority of the zones were not changed but changes were in the zones containing the wetland and the discharge drain. The hydraulic conductivity was increased since the excess water had to be drained by the single drain. The hydraulic zones after the calibration range from 0.001 mday^{-1} to 100 mday^{-1} in the second layer and little changes were done on the first layer. The lowest hydraulic conductivities were observed on the south western part of the study area and the highest observed hydraulic conductivities were from the southern part of the study area. The zone which discharges out of the catchment had hydraulic conductivity of 70 mday^{-1}.

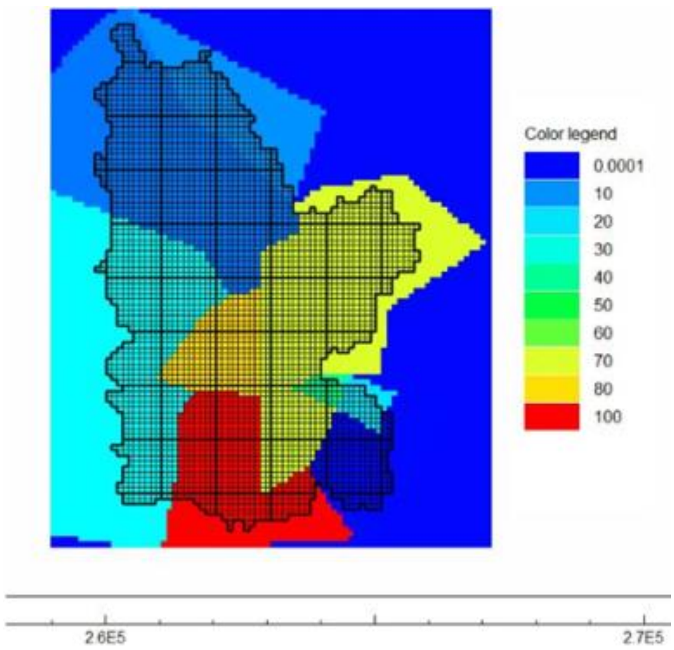


Figure 27: The horizontal hydraulic conductivity map for the second layer (sand)

The sandy area in layer 2 overlain with peat has an increased hydraulic conductivity of 80 mday^{-1} whilst the peat has a horizontal hydraulic conductivity of 0.04 mday^{-1}. The hydraulic conductivity results are corresponding to Figure 16 and equations 12 and 13 where the low hydraulic conductivities on the western side results in the high slope or gradient of the groundwater table and the higher hydraulic conductivities on the eastern side result in low gradient.

There is a marked difference in the hydraulic conductivities of pre-2011 in Figure 27 and of post-2011 in Figure 22 where there is higher conductivities in the pre-2011 than the post-2011 especially in the zones containing discharge channels(rivers and drains). Samsó et al. (2016) studied on a constructed wetland talked of the reduction of both porosity and hydraulic conductivity resulting in the proliferation of overland flow. They simulated a reduction in hydraulic conductivity as being a result of bio-clogging in wetlands. Therefore bioclogging can be the cause of a reduction in hydraulic conductivities in the post-2011 scenario, thus requiring continous monitoring of the soil hydraulic properties in the wetland. The wetland is inundated and had overland flow in the post-2011 scenario and yet the hydraulic conductivity of the zones within discharge channels is lower than the pre-2011 scenario.

4.6.2. Head calibration

The hydraulic heads after calibration for the pre-2011 period showed an increase in the regression coefficient with an R^2 value of 0.86 as shown in Figure28. The graph shows the comparison of the calibrated head results between the observed and simulated hydraulic heads. There is a good distribution of the heads where there are some piezometers on both sides of the trend line.

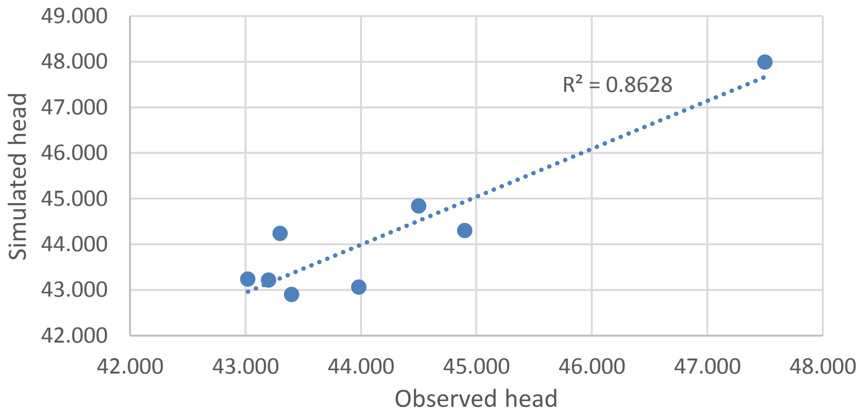


Figure 28: Comparison of calibrated and observed heads for the steady state model of the pre-2011 period

The results from Figure 28 and table 7 show both satisfactory results in the regression coefficient as well as the other methods of error assessment that include the bias = -0.067, MAE = 0.321 and RMSE of 0.127.

Table 7: Error assessment for the pre-2011 period (second calibration)

Well ID	Observed	Simulated	(Obs - Sim)	|Obs – Sim|	$(Obs - Sim)^2$
B35A0194	47.500	48.068	-0.568	0.568	0.323
B35A0189	44.500	44.940	-0.440	0.440	0.194
B35A0184	44.900	44.392	0.508	0.508	0.258
B35A0187	43.300	44.332	-1.032	1.032	1.064
B35A0192	43.200	43.330	-0.130	0.130	0.017
B35A0191	43.980	43.180	0.800	0.800	0.640
B35A0196	43.020	43.374	-0.354	0.354	0.125
B35A0197	43.400	43.053	0.347	0.347	0.120
Assessment method			**ME**	**MAE**	**RMSE**
Result			**-0.067**	**0.321**	**0.127**

The piezometer with the highest deviation from the observed value is B35A0187 which has a deviation of approximately 1 m. The piezometer with the lowest difference is B35A0192 which has a difference of 13 cm. piezometer B35A0194 which was not performing well previously in another scenario has a satisfactory difference of 56 cm. the majority of the piezometric head differences between the observed and the simulated heads is below 50 cm. The model results show a slightly negative bias showing that the overall model performance is slightly over-simulating with a small margin and the result is acceptable.

4.6.3. Residuals

The graph in Figure 29 shows a plot of the residuals after model calibration in the pre-2011 scenario. The majority of the heads are within 0.5 m and there is only one outlier which is a piezometer with a residual of slightly above 1 m.

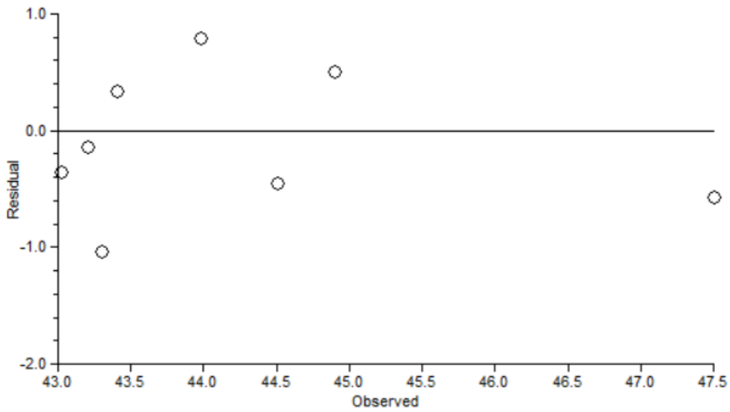


Figure 29: Plot of the residuals of the pre-2011 calibrated heads

Three of the piezometers are under simulating that is piezometer B35A0184, B35A0191 and B35A0197. The rest of the piezometers (five) are over-simulating giving a good balance in the model as there are no systematic errors that are largely negative or positive.

4.6.4. Water balance

The groundwater budget of the model is shown in Table 8 with the inflow and the outflow fluxes. The recharge is 59994 m^3d^{-1}. Stream leakage is present because of streams in the rest of the model area outside the Aamsveen wetland and they have an inward flux of 27883 m^3d^{-1} and outward flux of 53796 m^3d^{-1} from the downstream part of the catchment. Evapotranspiration has an outward flux of 14631 m^3d^{-1} and reservoir leakage out of the groundwater is 224 m^3d^{-1}. This reservoir leakage is from areas where peat harvesting was carried out and there is little or no inward flux from these reservoirs. Drainage out of the groundwater system in drains is 19233 m^3d^{-1}. The difference between the inward and the outward flux is -7 m^3d^{-1} which results in a discrepancy percentage of 0.01% which is within the acceptable limits of less than 1%.

Table 8: Groundwater budget for the pre-2011

FLOW BUDGET COMPONENTS	INFLOW (m^3d^{-1})	OUTFLOW (m^3d^{-1})
RECHARGE	59994	0
EVAPOTRANSPIRATION	0	14631
RESERVOIR LEAKAGE	0	224
DRAINS	0	19233
STREAM LEAKAGE	27883	53796
Total	87877	87884
IN – OUT	-7	
Percent Discrepancy	0.01%	

4.7. Analysis of the modelled catchment area and the Aamsveen wetland

The groundwater budget for the pre-2011 and the post-2011 scenarios are shown in Table 9 for comparison of the preliminary result based on two models (where the model is the same and the forcings are different) in the modelled catchment area. The results are good for understanding the system qualitatively, but not for drawing quantitative conclusions. The groundwater budgets differ between the two cases with the post-2011 scenario having a total inflow flux of 97076 m^3d^{-1} (referring to a wetter period after 2011 than before 2011) as compared to the inflow of 87877 m^3d^{-1} in the pre-2011 case. Evapotranspiration is slightly less in the pre-2011 case with a value of 14631 m^3d^{-1} as compared to the post-2011 case were it is simulated to be 14706 m^3d^{-1} with a difference of 75 m^3d^{-1}. In the post-2011 case, the recently constructed reservoir discharges 216 m^3d^{-1} as compared to 0 m^3d^{-1} that is discharged into the groundwater system by the pre-2011 model. Stream leakage is also greater in the post-2011 case with a value of 66765 m^3d^{-1} whilst in the pre-2011 the value is 53796 m^3d^{-1} and the difference amounts to 12969 m^3d^{-1}. This large difference can be attributed to the absence of streams in the Aamsveen wetland in the pre-2011 case. The total amount of water leaving the catchment through surface streams and drains in the post-2011 case is 81999 m^3d^{-1} as compared to 73029 m^3d^{-1} in the pre-2011 case and the difference is 8970 m^3d^{-1}. The percentage discrepancies from both cases are within acceptable limits of less than 1%.

Table 9: Key water balance difference in the catchment groundwater balance

FLOW BUDGET COMPONENTS OF THE CATCHMENT AREA	RIVER AND RESERVOIR (Post-2011)		DRAIN (Pre-2011)	
	INFLOW (m^3d^{-1})	OUTFLOW (m^3d^{-1})	INFLOW (m^3d^{-1})	OUTFLOW (m^3d^{-1})
RECHARGE	59994	0	59994	0
EVAPOTRANSPIRATION	0	14706	0	14631
RESERVOIR LEAKAGE	216	374	0	224
DRAIN	0	15234	0	19233
STREAM LEAKAGE	36866	66765	27883	53796
Total	97076	97079	87877	87884
IN – OUT	-3		-7	
Percent Discrepancy	0.00%		0.01%	

The groundwater budget for the Aamsveen wetland area was created through the ZONEBUDGET post processor to quantify how the wetland interacts with the surroundings. The results of the groundwater budget in the wetland is shown in Table 10 for the two models (pre and post-2011). The comparisons are of indicative nature. The totals for the two cases are 13838 m^3d^{-1} for the post-2011 case and 10304 m^3d^{-1} for the pre-2011 case with a difference of 3534 m^3d^{-1}. This shows that the post-2011 period has more water in the system than the pre-2011 period. Since this study was based on the hydraulics of the area, climatic factors were of little influence on the result. The same recharge volume in both cases amounting to 5127 m^3d^{-1} which is 50% and 37% total water in the system for the pre-2011 and post-2011 case respectively.

There is slightly more evapotranspiration in the pre-2011 case (6242 m^3d^{-1}) in the wetland than in the post-2011 case (6200 m^3d^{-1}) due to the climatic driving factors as there was less rain and a bit more ET before 2011 than after it. Recharge in both scenarios in the Aamsveen wetland is 8.5% of the total amount received in the study area but comparing it with evapotranspiration, where it is 42.2% in the post-2011 and 42.7% in the pre-2011 /of the total evapotranspiration experienced in the study area. It is profound to note that the Aamsveen wetland receives less water as recharge but is responsible for almost half (42%) of the delineated catchment evapotranspiration losses. This can be attributed to the high water table level and the vegetation in form of trees and heath and other flora in the area as seen in the study by (Xing, 2015) where she noted the increase in the values of the NDVI in the wetland over the years. Streams and reservoirs allow for the interaction of the wetland with the groundwater through processes that either recharge it or extract via leakage. Evenson et al. (2015) in their study on geographically isolated wetlands ranked evapotranspiration losses as second among the lateral and vertical losses which is experienced in the post 2011 case, while it is different from the pre-2011 case where ET is the dominant water loss.

The wetland interaction in Table 10 determines the lateral transfers that occurred in the model between the wetland and the rest of the modelled study area. It should be noted that inflow transfers between the two cases show a higher value of 4970 m^3d^{-1} in the pre-2011 case than the post-2011 case with a volume of 4287 m^3d^{-1}. The period in the post-2011 receives less groundwater from the rest of the model area than the pre-2011 case. The outflows of the lateral transfers show a reduction from 4287 m^3d^{-1} getting into the Aamsveen wetland system and 924 m^3d^{-1} exiting the wetland system constituting about 21.6%. This value from the Aamsveen wetland system, when compared to the pre-2011 case where the inflows were 4970 m^3d^{-1} and the outflows are 3058 m^3d^{-1} which is 61.5% is very small. In the post 2011 scenario some of this water is lost through stream runoff but ultimately the wetland is getting wetter than previously as the groundwater balance in the post 2011 has more water than in the pre-2011 case.

Table 10: Key water balance difference in the Aamsveen wetland groundwater balance

FLOW BUDGET COMPONENTS OF THE AAMSVEEN WETLAND	**RIVER AND RESERVOIR (Post-2011)**		**DRAIN (Pre-2011)**	
	INFLOW (m^3d^{-1})	OUTFLOW (m^3d^{-1})	INFLOW (m^3d^{-1})	OUTFLOW (m^3d^{-1})
RECHARGE	5127	0	5127	0
EVAPOTRANSPIRATION	0	6200	0	6242
RESERVOIR LEAKAGE	216	374	0	0
DRAIN	0	23	0	779
STREAM LEAKAGE	4204	6317	200	0
WETLAND INTERACTION	4287	924	4970	3058
Total	13834	13838	10297	10304
IN – OUT	-4		-7	
Percent Discrepancy	-0.02%		0.07%	

From the physical setup of the study area as shown in Figure 8 the Aamsveen is a low lying area which is bounded by areas of slightly higher topography. The areas of higher topography are recharge zones in this area as the Aamsveen top layer is characterised by low hydraulic conductivity thus groundwater recharge occurs from the areas of unconfined conditions and discharges at the area confining conditions. The results of Table 10 show that the wetland receives 4287 m^3d^{-1} and discharges only 924 m^3d^{-1} as also shown in Figure 30. The lower discharge implies it's a discharge point of the catchment (Fetter, 2001). Water quality results from the study by Xing (2015) on the place of the new and old canal/drain have high values of phosphates, nitrites and nitrates within 500m of the new and the old canal. These nutrient values are attributed to come from the Aamsveen wetland and thus showing that groundwater discharges in this area come through the wetland making it a source of water. The peatlands are characterised as nutrient-rich ecosystems from the decomposition of heath and other vegetation species prevalent in the area and thus the nutrients are carried as the water drains away from the wetland.

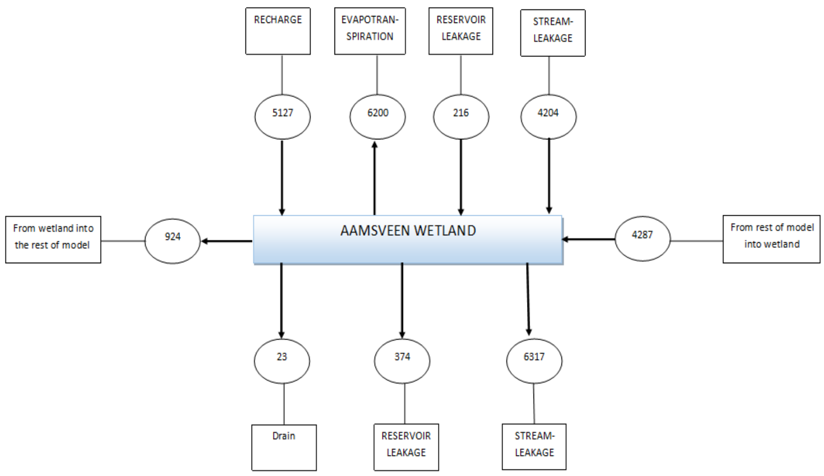


Figure 30: Diagrammatic illustration of the fluxes in the Aamsveen wetland in the post 2011scenario.

The wetland is thus supplied by recharge, from the upper boundary and lateral groundwater transfers. Fetter (2001) talks about non-completely impervious layers on top of an aquifer, that there will be some discharge from the aquifer in the form of upward leakage in the area of upward hydraulic gradient. This is exacerbated by the presence of streams and another reservoir in the area which are responsible for and interaction between groundwater and surface runoff through leakage. Water from the catchment is routed as surface runoff and conveyed using streams and these streams depending on the season can be gaining or losing water from the groundwater system. The drain in the pre-2011 period did not allow for such an interaction but rather was a way of only removing nutrient rich waters away from the peatlands for agricultural use downstream of the catchment. According to Andriesse (1988), the water balance of a peatland site can be characterised as equation 17 which is the same as what is observed for the Aamsveen wetland. In Aamsveen, water retention is also available in the reservoirs and other inundated areas and outflows are through streams and drains and lateral groundwater flows as shown in l.

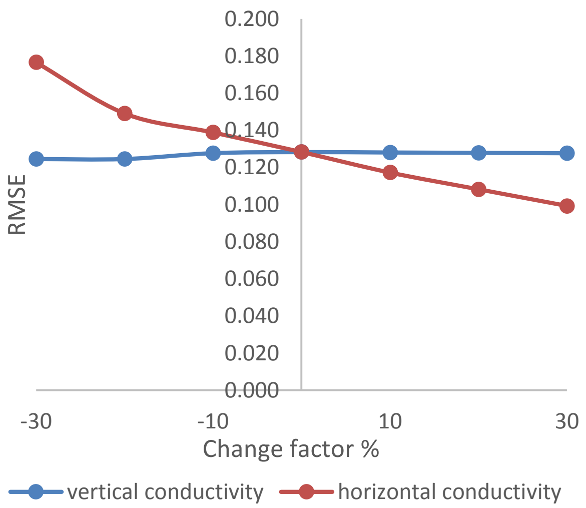
$$Qin + P = Qout + ET + \Delta S \qquad [17]$$

Where: Qin is inflows; P is precipitation; Qout is outflows, ET is evapotranspiration and ΔS is change in storage which are equal to zero in a steady state model.

This study shows that due to the water management measures implemented in the Aamsveen wetland, the wetland is become wetter and supporting these findings, a past study by Xing (2015) using the global polynomial interpolation and correlation analysis showed that there was an increase in the piezometric head levels of the Aamsveen wetland. The study and computations by Xing (2015) in the Aamsveen wetland on the differences between precipitation and evaporation for the two scenarios of the pre-2011 and post-2011 periods showed in a majority of the piezometers that there is a significant increase in the average values of the observed heads.

4.8. Sensitivity analysis

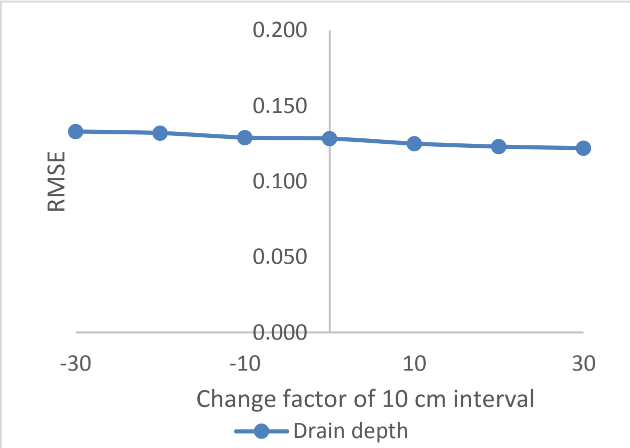
A sensitivity analysis was carried out to define how sensitive the model is to changes (e.g. errors) in the model parameter definition. As Figure 31 shows, the model is less responsive to the changes in the vertical hydraulic conductivity than to the horizontal conductivity. The comparison on the gradients shows the influence and helps in finding the parameter of the model that is most sensitive (Anderson et al., 2015).



Factor	Vertical conductivity	Horizontal conductivity
-30	0.125	0.177
-20	0.125	0.149
-10	0.128	0.139
0	0.128	0.128
10	0.128	0.117
20	0.128	0.108
30	0.128	0.099

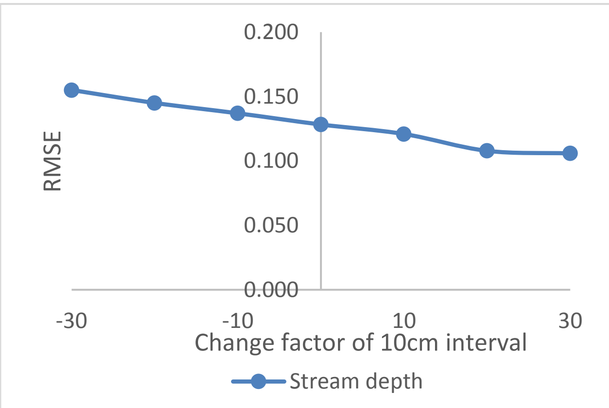
Figure 31: Sensitivity analysis of the vertical and horizontal hydraulic parameters

A sensitivity analysis was carried out to define how sensitive the two models are to drain and stream depth. The influence of the model by the drain depth is also minimal. The conductance of the water in the drain and streams which are influenced by the horizontal conductance and thus of paramount importance to the model. As shown in Figure 32 and 33, the model is less responsive to the changes in the drain depth than to the stream depth. The parameters that are sensitive can be used to help achieve better model performance during the calibration process. Thus the horizontal hydraulic conductivity and stream depth were used to try and achieve better model performance.



Factor	Stream depth
-30	0.133
-20	0.132
-10	0.129
0	0.128
10	0.125
20	0.123
30	0.122

Figure 32: Sensitivity analysis of the drain parameters



Factor	Stream depth
-30	0.155
-20	0.145
-10	0.137
0	0.128
10	0.121
20	0.108
30	0.106

Figure 33: Sensitivity analysis of the stream parameters

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The objective of this study was to assess groundwater-surface water interactions in the Aamsveen wetland system for management purposes with support of groundwater modelling. The starting point was an existing regional model, which contained the Aamsveen area, but at a low level of detail. Based on a more detailed representation of the aquifers, steady state models for the pre-2011 and post-2011 conditions were built and calibrated. This local model of the Aamsveen wetland system was created under a different modelling environment (ModelMuse) than the regional model (iMod). The steady-state model of the post-2011 period simulated heads in comparison to the observed heads had an R^2 of 0.96. A new, slightly modified calibration was needed for the simulation of the pre-2011 situation. The steady state model of the pre-2011 period simulated heads in comparison to the observed heads had an R^2 of 0.86.

The Aamsveen wetland system has been shown to be a discharge area of the catchment. The water management changes of restoring the wetland are fruitful as the wetland is becoming wetter as shown in Table 10. The modelling of the two situations of the post and pre-2011 cases was carried out according to the surface water management measures introduced to the wetland in 2011, resulting in a change of the hydraulics of it. Long term averages of the meteorological forcings of the two modelled periods in the Aamsveen area (precipitation and evapotranspiration) were used to study the hydraulic aspects of the management changes.

To capture the changes made to the wetland in the model and to estimate the groundwater water balance of the wetland, the ZONEBUDGET postprocessor was used to delineate the Aamsveen wetland from the catchment. In order to determine the effects of the 2011 changes on the water fluxes in the Aamsveen wetland, two models were created. The groundwater balance of the two periods (before and after 2011) were assessed in a bid to assess the wetland restoration exercise. The difference between the pre-2011 and the post-2011 case amounts to 25.5% with the latter having more water in the wetland system. This means that that the pre-2011 scenario has 25.5% less water than the post-2011 period in the Aamsveen wetland. The study found that the wetland is now getting wetter due to the hydraulic changes made to the area by removal of the canal/drain and replacing it with a stream and by putting a reservoir controlled by a weir. The wetland is a discharge point for the groundwater system where groundwater is discharged on the wetland surface through reservoirs, drains and surface streams (48.5%) where previously it was just 7.6%.

The model was capable of simulating the water management interventions at the local scale. The Aamsveen wetland model is capable of simulating the main aspects of the local conditions because of its high spatial resolution and the level of details in its parameterization. The key water balance components are recharge/infiltration from precipitation, evapotranspiration, stream leakage and lateral transfers (termed wetland interaction). The results represent a good start, but there is still room for further improvements, which are detailed in the next section.

5.2. Recommendations

More hydraulic conductivity tests in the wetland and the model area are needed. This will enable more accurate parameterisation of the hydraulic conductivity, and enable a unified conductivity field, which allows the study of the pre-2001 and post-2011 situations as scenarios of the same model. Furthermore, liaison with the Germany water authority is recommended for acquiring more data that allows better parameterisation of hydraulic conductivity on their side. The presence of a low permeability layer (peat) has the ability to form perched water tables which can result in surface ponding which is not well captured in the recent model, thus there is a need to carry out further thorough hydrogeological examination of the wetland.

Peat hydraulics needs to be further assessed as there are very few recent studies on the behaviour of peat in terms of the vertical and horizontal hydraulic conductivity. The values of peat hydraulics can be divergent and thus the need to be able to assess the peat soil hydraulics. A timely requisition should be made to the proper authorities to be able to sample in the peat area in summer and winter when the peat is unsaturated and when it is saturated respectively.

A transient model for the area would mean the next step that can be best calibrated with the help of remote sensing data for the parameterisation of evapotranspiration and precipitation. Remote sensing based data has a good advantage of spatial and temporal coverage of these dynamic forcings. The transient model can then be used to determine how the wetland responds to the changes in weather/climate and human management interactions.

Peat hydraulics needs to be assessed as there are very few recent studies on the behaviour of peat in terms of the vertical and horizontal hydraulic conductivity. The values of peat hydraulics can be divergent and thus the need to be able to assess the peat soil hydraulics. A timely requisition should be made to the proper authorities to be able to sample in the peat area in summer and winter when the peat is unsaturated and when it is saturated respectively.

The parameter estimation using manual method has shown that the model is the most sensitive to the horizontal hydraulic conductivity. The use of PEST for calibration of the transient state model is thus recommended together with the help of improved hydrogeological knowledge, as recommended above, to have a model for reliable forecasting.

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7. APPENDIX

Appendix 1

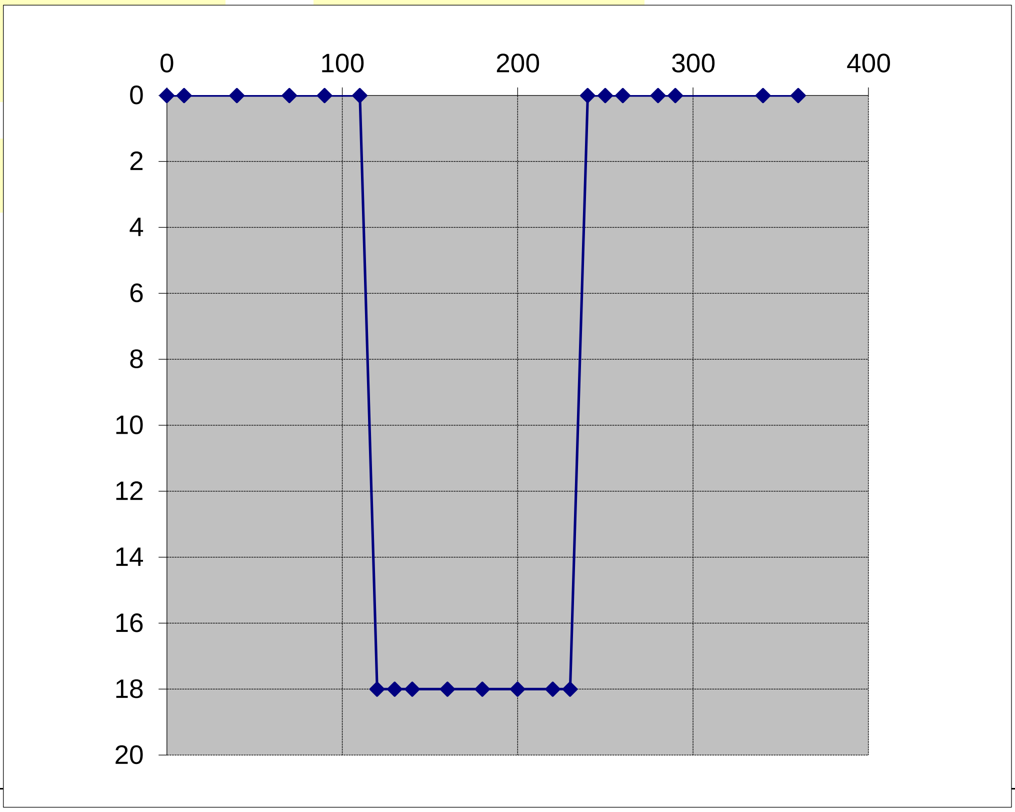
***** DISCHARGE MEASUREMENTS *****

River:	Out of wetland	Photo Nr:	
Cross num:		Sheet name:	
		UTM Zone:	
		UTM Y:	
		UTM X:	

Total number of verticals: 21

Total discharge [m3/s]: **0.18238**

Vertical Number	**Distance from base [cm]**	**Width [cm]**	**Depth [cm]**	**Veloc. 0.2 depth [cm/s]**	**Veloc. 0.8 depth [cm/s]**	**Area [cm2]**	**Discharge [m3/s]**	**Average Velocity [cm/s]**
1	0	2	0	0	0	0.0	000.0E+0	0.00
2	10	4	0	0	0	0.0	000.0E+0	0.00
3	40	14	0	0	0	0.0	000.0E+0	0.00
4	70	23	0	0	0	0.0	000.0E+0	0.00
5	90	34	0	0	0	0.0	000.0E+0	0.00
6	110	48	0	0	0	0.0	000.0E+0	0.00
7	120	60	18	28.50	0	1080.0	15.4E-3	14.25
8	130	88	18	28.50	0	1584.0	22.6E-3	14.25
9	140	95	18	28.50	0	1710.0	24.4E-3	14.25
10	160	96	18	28.50	0	1728.0	24.6E-3	14.25
11	180	96	18	28.50	0	1728.0	24.6E-3	14.25
12	200	95	18	28.50	0	1710.0	24.4E-3	14.25
13	220	94	18	28.50	0	1692.0	24.1E-3	14.25
14	230	87	18	28.50	0	1566.0	22.3E-3	14.25
15	240	83	0	0	0	0.0	000.0E+0	0.00



Appendix 2

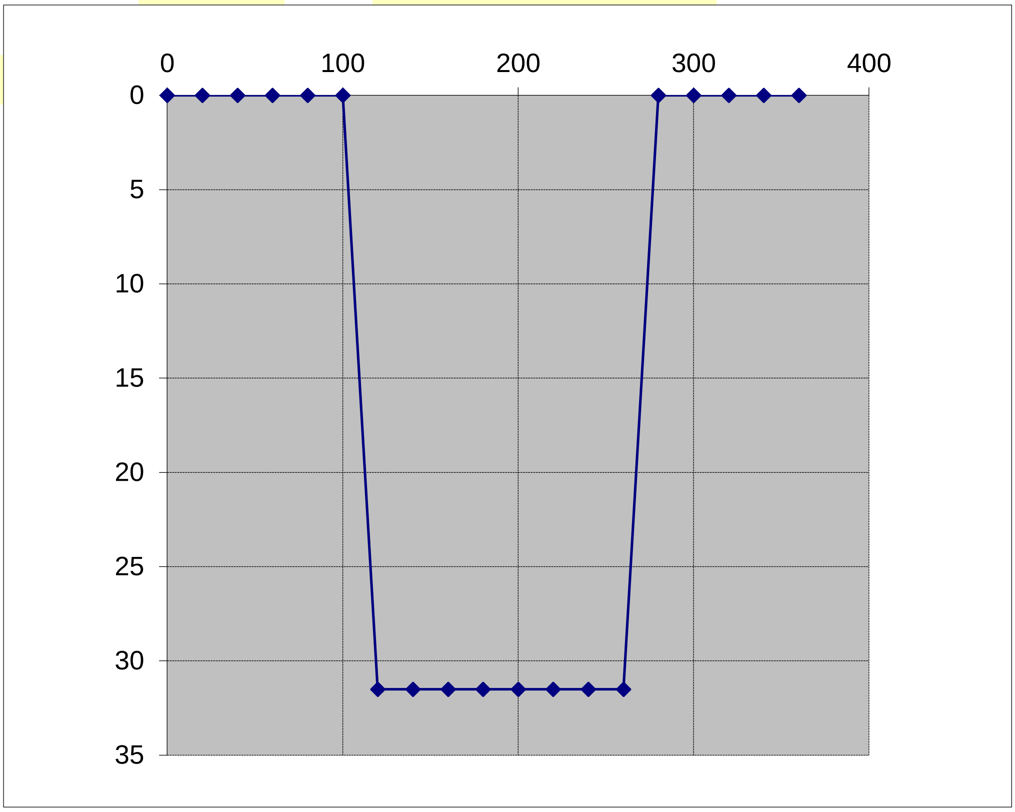
***** DISCHARGE MEASUREMENTS *****

River:	main river, out of wetland	Photo Nr:		
Cross num:		Sheet name:		UTM Zone:
				UTM Y: 262240
				UTM X: 468588

Total number of verticals: 19

Total discharge [m3/s]: **0.38608**

Vertical Number	Distance from base [cm]	Width [cm]	Depth [cm]	Veloc. 0.2 depth [cm/s]	Veloc. 0.8 depth [cm/s]	Area [cm2]	Discharge [m3/s]	Average Velocity [cm/s]
1	0	0	0	0	0	0.0	000.0E+0	0.00
2	20	22	0	0	0	0.0	000.0E+0	0.00
3	40	31	0	0	0	0.0	000.0E+0	0.00
4	60	45	0	0	0	0.0	000.0E+0	0.00
5	80	65	0	0	0	0.0	000.0E+0	0.00
6	100	78	0	0	0	0.0	000.0E+0	0.00
7	120	87	31.5	31.63	0	2740.5	43.3E-3	15.81
8	140	103	31.5	31.63	0	3244.5	51.3E-3	15.81
9	160	105	31.5	31.63	0	3307.5	52.3E-3	15.81
10	180	105	31.5	31.63	0	3307.5	52.3E-3	15.81
11	200	105	31.5	31.63	0	3307.5	52.3E-3	15.81
12	220	98	31.5	31.63	0	3087.0	48.8E-3	15.81
13	240	90	31.5	31.63	0	2835.0	44.8E-3	15.81
14	260	82	31.5	31.63	0	2583.0	40.8E-3	15.81
15	280	71	0	0	0	0.0	000.0E+0	0.00
16	300	59	0	0	0	0.0	000.0E+0	0.00
17	320	39	0	0	0	0.0	000.0E+0	0.00
18	340	24	0	0	0	0.0	000.0E+0	0.00
19	360	12	0	0	0	0.0	000.0E+0	0.00



Appendix 3

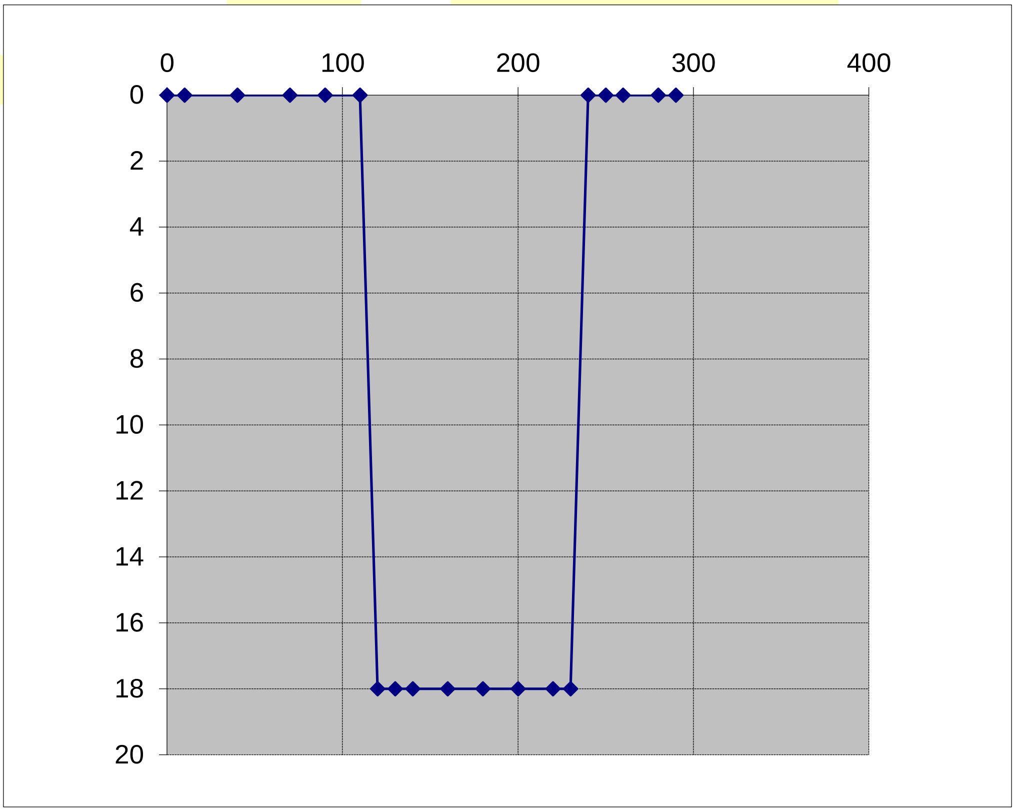
***** DISCHARGE MEASUREMENTS *****

River:	weir at wetland	Photo Nr:			
Cross num:		Sheet name:		UTM Zone:	
				UTM Y:	262240
				UTM X:	468588

Total number of verticals: 19

Total discharge [m3/s]: **0.18034**

Vertical Number	**Distance from base [cm]**	**Width [cm]**	**Depth [cm]**	**Veloc. 0.2 depth [cm/s]**	**Veloc. 0.8 depth [cm/s]**	**Area [cm2]**	**Discharge [m3/s]**	**Average Velocity [cm/s]**
1	0	2	0	0	0	0.0	000.0E+0	0.00
2	10	4	0	0	0	0.0	000.0E+0	0.00
3	40	14	0	0	0	0.0	000.0E+0	0.00
4	70	23	0	0	0	0.0	000.0E+0	0.00
5	90	34	0	0	0	0.0	000.0E+0	0.00
6	110	48	0	0	0	0.0	000.0E+0	0.00
7	120	60	18	28.18	0	1080.0	15.2E-3	14.09
8	130	88	18	28.18	0	1584.0	22.3E-3	14.09
9	140	95	18	28.18	0	1710.0	24.1E-3	14.09
10	160	96	18	28.18	0	1728.0	24.3E-3	14.09
11	180	96	18	28.18	0	1728.0	24.3E-3	14.09
12	200	95	18	28.18	0	1710.0	24.1E-3	14.09
13	220	94	18	28.18	0	1692.0	23.8E-3	14.09
14	230	87	18	28.18	0	1566.0	22.1E-3	14.09
15	240	83	0	0	0	0.0	000.0E+0	0.00
16	250	52	0	0	0	0.0	000.0E+0	0.00
17	260	45	0	0	0	0.0	000.0E+0	0.00
18	280	35	0	0	0	0.0	000.0E+0	0.00
19	290	33	0	0	0	0.0	000.0E+0	0.00



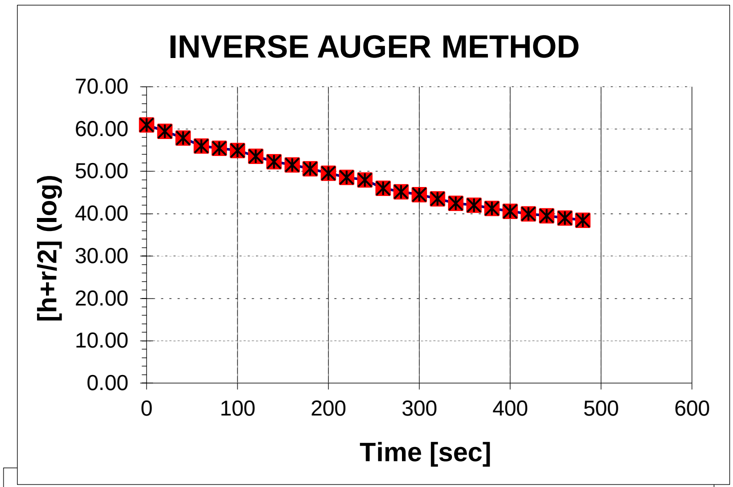
Appendix 4

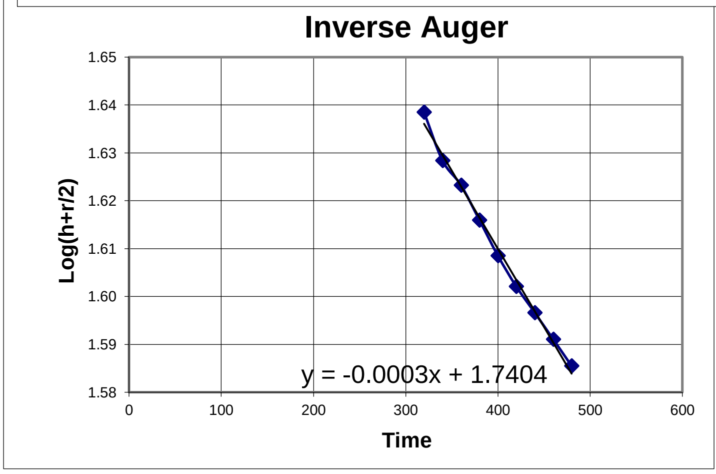
******** INVERSE AUGER METHOD ********

Site:	sandy	TMU:		UTM X:	261400
Sample n:	1	Lithology Unit:		UTM Y:	467066
Photo Nr:		Toposheet name:			
UTM Zone:					

Hole diam. [cm]:	8
Hole depth [cm]:	80
point-surface [cm]:	30
K[cm/day]:	119.2

Time [sec]	**Level [cm]**	**(h+r/2) [cm]**	**log(h+r/2) log[cm]**
0	51	61.00	1.79
20	52.5	59.50	1.77
40	54.1	57.90	1.76
60	56	56.00	1.75
80	77	35.00	1.54
100	57.1	54.90	1.74
120	58.4	53.60	1.73
140	59.7	52.30	1.72
160	60.5	51.50	1.71
180	61.4	50.60	1.70
200	62.4	49.60	1.70
220	63.4	48.60	1.69
240	64	48.00	1.68
260	66	46.00	1.66
280	66.8	45.20	1.66
300	67.5	44.50	1.65
320	68.5	43.50	1.64
340	69.5	42.50	1.63
360	70	42.00	1.62
380	70.7	41.30	1.62
400	71.4	40.60	1.61
420	72	40.00	1.60
440	72.5	39.50	1.60
460	73	39.00	1.59
480	73.5	38.50	1.59





Appendix 5

******** INVERSE AUGER METHOD ********

Site:

TMU:

UTM X:

UTM Y:

Sample n:

Lithology Unit:

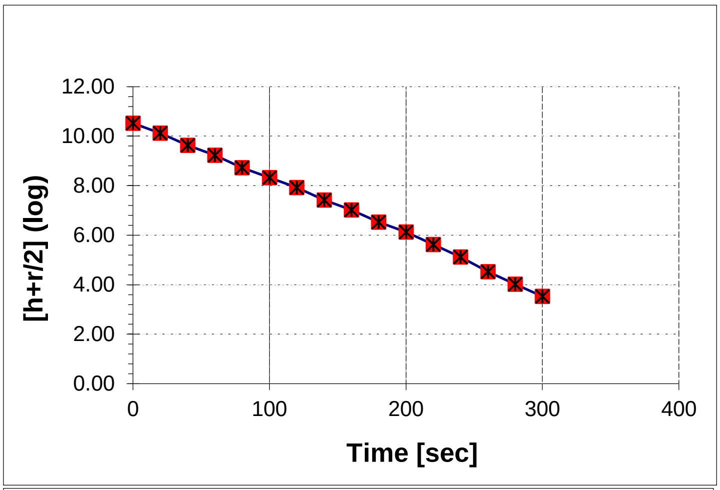
Photo Nr:

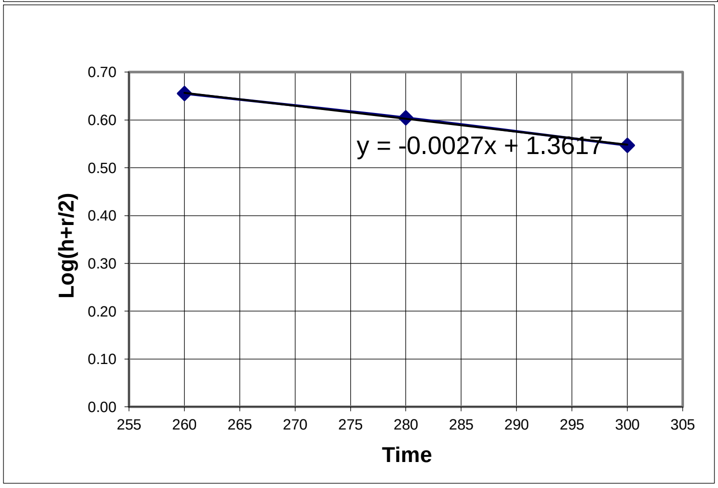
Toposheet name:

UTM Zone:

Hole diam. [cm]:	11.7
Hole depth [cm]:	15.6
point-surface [cm]:	0
K[cm/day]:	2.34

Time [sec]	Level [cm]	(h+r/2) [cm]	log(h+r/2) log[cm]
0	8	10.53	1.02
20	8.4	10.13	1.01
40	8.9	9.63	0.98
60	9.3	9.23	0.96
80	9.8	8.73	0.94
100	10.2	8.33	0.92
120	10.6	7.93	0.90
140	11.1	7.43	0.87
160	11.5	7.03	0.85
180	12	6.53	0.81
200	12.4	6.13	0.79
220	12.9	5.63	0.75
240	13.4	5.13	0.71
260	14	4.53	0.66
280	14.5	4.03	0.60
300	15	3.53	0.55





3000.00

Appendix 6

Table B.2. Manning's Roughness Coefficients for Various Boundaries.

Rigid Boundary Channels	Manning's n
MINOR STREAMS (top width at flood stage < 30 m)	
Streams on Plain	
1. Clean, straight, full stage, no rifts or deep pools	0.025–0.033
2. Same as above, but more stones and weeds	0.030–0.040
3. Clean, winding, some pools and shoals	0.033–0.045
4. Same as above, but some weeds and stones	0.035–0.050
5. Same as above, lower stages, more ineffective slopes and sections	0.040–0.055
6. Same as 4, but more stones	0.045–0.060
7. Sluggish reaches, weedy, deep pools	0.050–0.080
8. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075–0.150
Trees	
1. Dense willows, summer, straight	0.110–0.200
2. Cleared land with tree stumps, no sprouts	0.030–0.050
3. Same as above, but with heavy growth of sprouts	0.050–0.080
4. Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080–0.120
5. Same as above, but with flood stage reaching branches	0.100–0.160
MAJOR STREAMS (Topwidth at flood stage > 30 m)	
The n value is less than that for minor streams of similar description, because banks offer less effective resistance.	
Regular section with no boulders or brush	0.025–0.060
Irregular and rough section	0.035–0.100
Alluvial Sand-bed Channels (no vegetation)	
Tranquil flow, Fr < 1	
Plane bed	0.014–0.020
Ripples	0.018–0.030

Dunes	0.020–0.040
Washed out dunes or transition	0.014–0.025
Plane bed	0.010–0.013
Rapid Flow, Fr > 1	
Standing waves	0.010–0.015
Antidunes	0.012–0.020
Overland Flow and Sheet Flow	
Smooth asphalt	0.011
Smooth concrete	0.012
Cement rubble surface	0.024
Natural range	0.13
Dense grass	0.24
Bermuda grass	0.41
Light underbrush	0.40
Heavy underbrush	0.80