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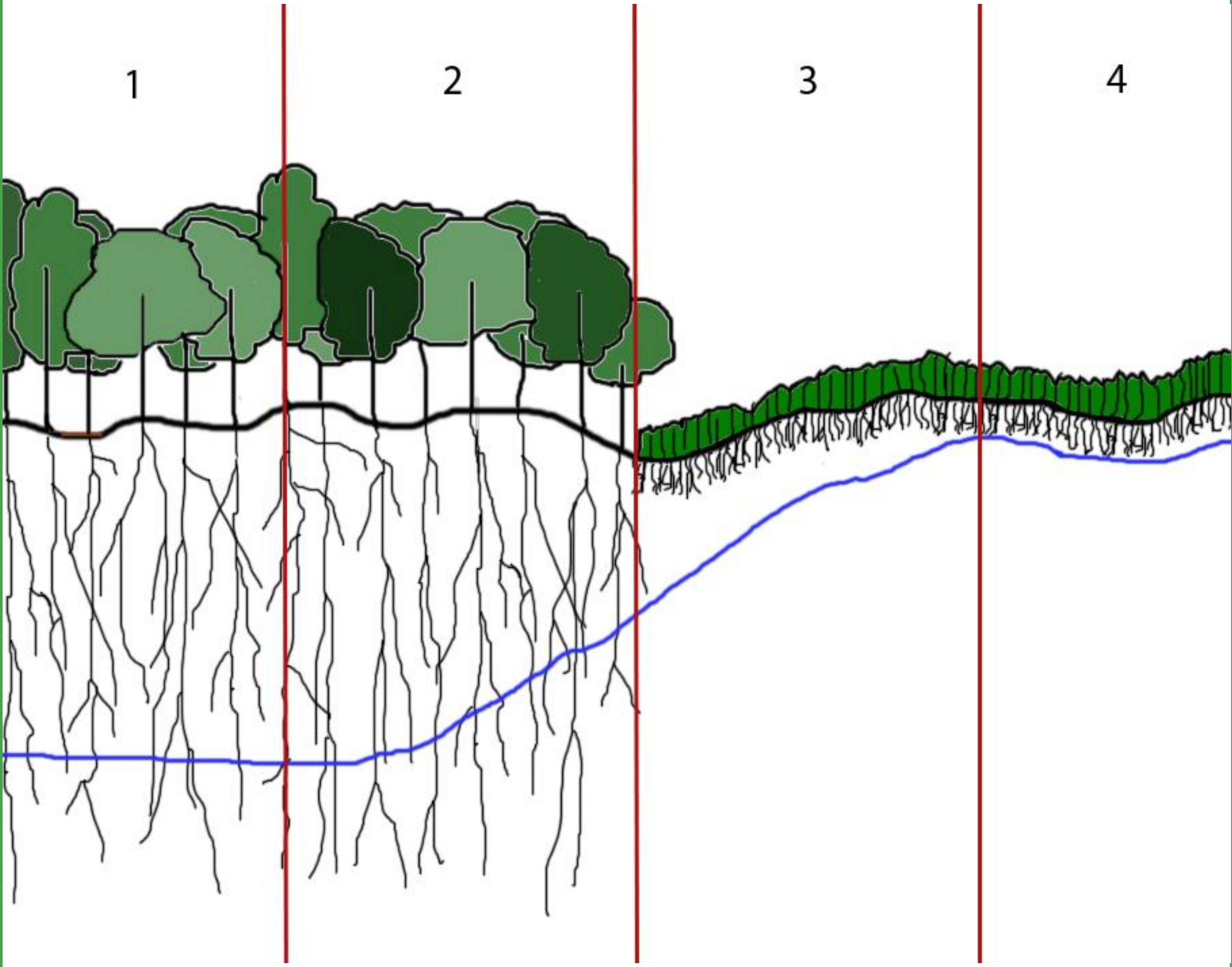

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A MODELLING STUDY ON THE EFFECT OF GROUNDWATER ON VEGETATION AND THE EFFECT OF VEGETATION ON GROUNDWATER IN THE PANTANAL OF MATO GROSSO, BRAZIL

Msc Thesis Hydrology | Arent Floris Zevenbergen

A modelling study on the effect of groundwater on vegetation and the effect of vegetation on groundwater in the Pantanal of Mato Grosso, Brazil

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Track: Earth Surface Hydrology

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Abstract

This report focuses on the interaction of vegetation and groundwater in a study area in the Pantanal of Mato Grosso, Brazil. This area is a mosaic of patches of different vegetation types. Many studies have focused on the effect of the inundation that occurs every summer and depending on the elevation inundates the vegetation zero to nine months. From these studies it is apparent that the vegetation distribution is influenced by inundation. However, during the annual dry season the surface water recedes almost entirely and the groundwater can drop up to 5.6 m below soil surface. The effect of this drought has not been investigated further.

To study the effects of groundwater on the vegetation distribution a groundwater model is created using PCRasterMODFLOW. Using the vegetation distribution and a digital elevation map created from 230 elevation points, three scenarios are modeled in which only the evaporation varies per scenario. In the first scenario the evaporation does not decrease when the groundwater drops and the evaporation is uniform over space. In the second scenario the evaporation decreases linearly with falling groundwater levels. In this scenario all the vegetation has a root depth of 3 m . This indicates that the vegetation has no influence on the evaporation. In the third scenario the evaporation again decreases linearly with falling groundwater levels, however the root depth depends on the vegetation. This indicates that the evaporation is dependent on both root depth (thus vegetation) and groundwater depth.

The results show that the vegetation distribution is not affected by the groundwater. However, the vegetation has a strong influence on the groundwater distribution. Deep rooted vegetation decrease the groundwater level up to 2 m lower than shallow rooted vegetation does. This causes groundwater to flow in the direction of the deep rooted vegetation. Deep rooted vegetation immediately adjacent to shallow rooted vegetation benefits most, for the shallow rooted vegetation immediately adjacent to deep rooted vegetation it is most disadvantageous. Further, it can be shown that deep rooted vegetation is least stressed by the drought and therefore the deep rooted vegetation is not limited by groundwater. A different environmental variable will more likely be responsible for the patchiness of this area.

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1. Introduction

1.1. Pantanal

The Pantanal is one of the largest wetlands in the world, located in Brazil, Paraguay and Bolivia. The total area covers approximately 140 000 km^2 of the upper Paraguay River and most of its major tributaries (Hamilton, 2002). It is an immense lowland or alluvial depression that becomes extensively flooded during the rainy summer season from November to April (Hamilton, 2002). Approximately 80% of the annual precipitation (800 – 1600 mm) falls during the wet season (Brasil Ministério do Meio Ambiente 1997) and in this season 70 – 80% of the Pantanal is inundated (Junk and Silva, 1995). The annual inundation imports nutrient-rich sediments, which ensures the floodplain wetland system is highly productive. This productivity supports both a large number of species, and a high concentration of these species (Swarts, 2000a).

The Pantanal is not only a pristine and biologically rich ecosystem, it also supports diverse economic activities such as cattle ranching, mining, tourism and fishing. Many of these activities affect the Pantanal vegetation (Swarts, 2000b), cattle ranching being the most extensive, with an estimated 3 million cattle, followed by fishing and ecotourism. Although cattle ranching has a documented effect on the ecosystem, authorities do not see it as a big environmental problem, as it is generally presented as a long-term activity that developed in harmony with the environment or which at least poses minimal negative impacts (Swarts, 2000b).

The larger threats to the Pantanal come from big construction projects either being built or proposed to be built. Among these projects are a gas pipeline from Bolivia to Brazil, dams for hydro-electric power and the creation of the Paraguay-Parana Waterway, a project that proposes to deepen the River Paraguay for transportation (Swarts, 2000a). Especially the latter projects will have a significant impact on the hydrological regime of the wetland.
In general wetlands provide innumerable economic, ecological, cultural, recreational and aesthetic values (Swarts, 2000a). The Pantanal may now be in a pristine state, but changes can occur in the near future.

1.2. Rationale for creating a groundwater model

The relationship between vegetation and hydrodynamics has been studied extensively in the Pantanal. Many ecological studies in the Pantanal have shown the impact of surface water on vegetation distribution (Zeilhofer and Schessl 1999, Nunes da Cunha et al. 2001, Arieira and Nunes da Cunha 2006, Damasceno-Junior *et al.,* 2005).

As mentioned above, the Pantanal has a severe water deficit in the dry winter months. In this time the groundwater table can drop significantly, possibly below the reach of the roots of plants. The impact of water deficit during the dry season on vegetation distribution in the Pantanal is not known so far. In a wetland undergoing desertification the fall of the groundwater table favors different species (Stromberg *et al.,* 1996). However results from Stromberg *et al.,* (1996) also indicate that different forest types were located on areas with a groundwater depth which was more than 1 m deeper than shrublands. Although it is well known that vegetation differs in their ability to adapt to deep groundwater, for the Pantanal it is unknown how influential this effect may be.

Furthermore, the effect of the vegetation on the groundwater itself has to be considered. Studies on soil-vegetation-atmosphere transfer show that vegetation influences climate and water budgets through evapotranspiration (Arora, 2002). An example of this is a study by Rietkerk *et al.,* (2004), which found that bog vegetation is patterned, i.e. patches of dense vegetation alternate with patches of sparse vegetation, due to the transport of nutrients (which is the growth limiting factor in this study) in groundwater towards the patches of high vascular plant biomass. This is a result of increased transpiration rates in these patches. Although this article is focused on the nutrient flux, it shows that groundwater is influenced by the vegetation, flowing in the direction of the patches with the highest evapotranspiration. If this occurs in the Pantanal, the vegetation towards which the groundwater flows can benefit from this phenomenon in the dry season. This mechanism may indicate that the during the dry season the Pantanal can become a self organizing vegetation system, where patches of higher evapotranspirating vegetation are created and maintained due to the positive feedback, i.e. the groundwater flows towards the vegetation with higher evapotranspiration and the vegetation then has an increased amount of water to evapotranspire, which can benefit their growth and reproduction.

A difference between the Pantanal and the bogs from the study done by Rietkerk *et al.,* (2004) is the groundwater table. Bogs generally have high groundwater tables, which is unlike the Pantanal during the dry season. The ability for plants to evapotranspire will depend on their ability to reach the groundwater table. A literature study by Stone and Kalisz (1991) states that roots can remain in contact with the groundwater table from depths of 1.5 m to 35 m depending on the vegetation. Rooting depth may thus support the self organization.

1.3. Hypothesis

The groundwater in the study area is subject to the annual variations in precipitation and run on, although it is possible the study site is located too far from a river to be subject to the latter. Due to the lack in slope of the area, the recharge of groundwater will most likely occur from precipitation and not from horizontal groundwater flow.

In the dry season the evapotranspiration will result in a drop of the groundwater table. In the grassy areas the groundwater will become unavailable for the grass-roots. In these areas evapotranspiration will stop as upwards transport of water by the plants vascular system has ceased. In areas with vegetation with deeper roots the groundwater table drops further as evapotranspiration can continue. The difference in groundwater level and associated hydraulic head creates horizontal flow in the direction of the vegetation with the deeper roots. This will be beneficial for the deep rooted vegetation, decreasing the impact of the drought.

As this mechanism increases the available groundwater for deep rooted vegetation, an increase in this vegetation would therefore also decrease the amount of water available for a single plant in the dry season, because the available groundwater must then be shared with a greater number of individuals. The drought can therefore create an equilibrium amount of vegetation with deep roots, as too many deep rooted individuals can limit or eliminate the advantage.

1.4. Research questions

To investigate the gap in the scientific knowledge and to test the hypothesis the research questions are stated as follows. The main research question for this research will be:

What is the effect of the groundwater level on the vegetation pattern and does the vegetation pattern affect the groundwater distribution?

The following questions are answered as part of the main question:

What is the behavior of groundwater in the study area over time?
What are the groundwater levels relative to the soil surface?
Is there difference in evapotranspiration between the different vegetation types?

1.5. Thesis objectives

The objectives of this study are:

1. Model groundwater in space and time for 3 different scenarios.
2. Calculate from this the groundwater level relative to the surface elevation.
3. Compare the spatial variation of groundwater level and groundwater depth relative to the soil surface with the spatial distribution of the root depth.
4. Investigate the effects of the groundwater on the vegetation and the effects of the vegetation on the groundwater.

1.6. Approach

In this thesis the objectives will be obtained by creating a spatio-temporal model of the study site. In this model groundwater will be mathematically simulated using inputs based on the natural situation of the study area. Elevation, precipitation, temperature, humidity will be collected and used in the making of the model. Three different scenarios will be modeled and the results will be used to formulate answers to the research questions. These results will be compared to results of other literature study of this type.

1.7. Thesis outline

This thesis contains a methodology (chapter 2) in which the study site (2.1) is discussed with more information on the Pantanal. Also the data assembly (2.2) is described. In section 2.3 more information is given on the vegetation and how it is incorporated in the model. In section 2.4 this is done for the hydrological processes significant for the model and more about the model and the creation of the model is given in section 2.5. In chapter 3 the results will be presented per model scenario. In chapter 4 these results and the model behavior will be discussed. Finally the thesis will be concluded and recommendations will be made for further research (chapter 5).

2. Methods

2.1. Study Site

This study is set in the Pantanal of Brazil (see figure 1, approximately 16˚–22˚ S and 55˚-58˚ W). Situated in the centre of the South-American continent, the Pantanal makes up approximately one third of the Upper Paraguay River basin. The other two thirds of the basin are the surrounding uplands: the Planalto to the north and east and the flat plains to the west. In between these highlands the Pantanal forms a subsided depression of circa 200,000 km^2, although the total size of the Pantanal is debateable as the borders are not well defined (Swarts, 2000; Hamilton, 2002). The elevation of the Pantanal is between 75 and 200 m. above sea level. The area is flat, but slightly undulating and the typical gradient is approximately 6-25 cm km^{-1} from east to west and 1-2 cm km^{-1} north to south (Ponce and Nunes Da Cunha, 1993).

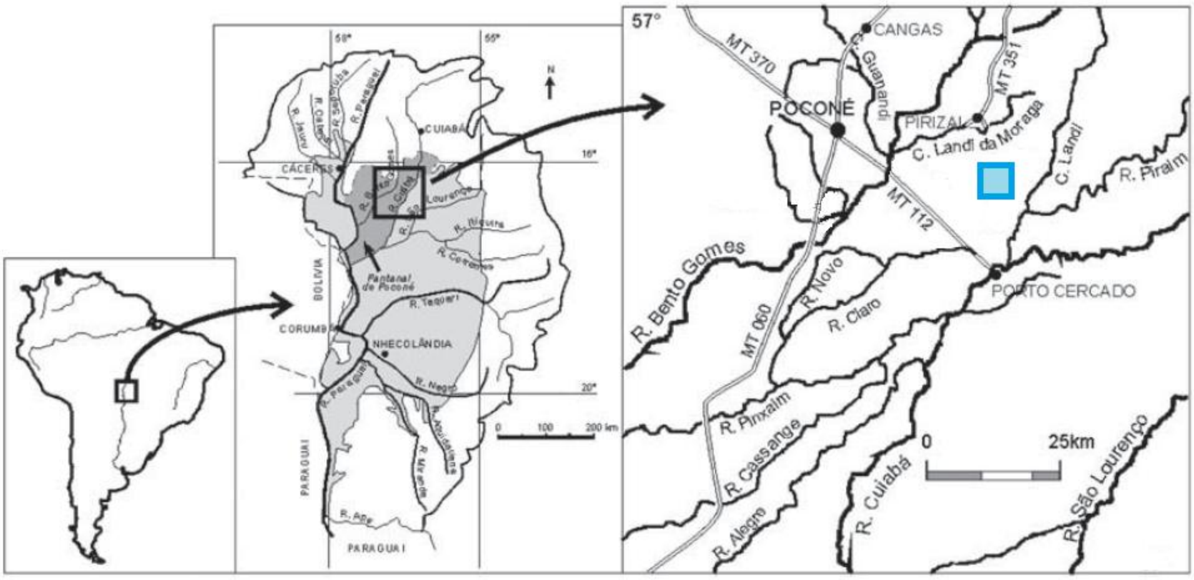


Figure 1. In the lower left corner: The location in the centre of South America. In the centre: The Upper Paraguay River Basin, the Pantanal (in light grey) and the Pantanal of Poconé (darker shade of grey). To the Right: The study site in blue approx. 30 km east of Poconé. The thick black lines are the major rivers flowing through the area. Figure modified from Nunes da Cunha and Junk (2004)

The Pantanal originates from a precambrian geological region and may have been a coastal lowland at what would presently be the Pacific Ocean. When the Andes mountainrange was uplifted during the Cretaceous, the Pantanal became a depression in the centre of South America (Heckman, 1998). Due to its low elevation much sediment was transported and deposited in this area. This resulted in a layer of unlithified sediments of up to 500 m. deep (Ussami *et al.,* 1999). The upper layers of these sediments are alluvial deposits, but beneath these layers there appear to be wind formed dunes. The Pantanal seems to have been a paleo desert, where rainfall could temporarily decrease to nearly nothing. During this arid phase in the Cenozoic these dunes were formed due to increased weathering of the uplands (Klammer, 1982). Apparently the Pantanal has only recently, in the quartenary, come under the present, strongly seasonal climate, which formed the the alluvial plain in its present state (Assine and Soares, 2004; Klammer, 1982).

The dominant force in controlling the structure and function of the present day flood-plain ecosystems is the flood pulse (Junk *et al.,* 1989). The inundation and dessication are defined by the seasonality in this region. In the dry winter months from May to October the Pantanal appears to be a savanna, similar to the cerrado of the Planalto. In the wet summer months from November to April the floodplain is inundated as upstream discharge and precipitation peak and the rivers and floodplains are unable to discharge the large quantity of water, due to the lack of gradient (Junk and Silva, 1995). Of the 356 000 km^2 of upland area that contributes to the discharge of the Pantanal, most lies to the north and north east. In these areas precipitation can also exceed that of the Pantanal. These large quantities of water from the north and east, in combination with the gradient, can explain why the major tributaries in the Pantanal flow from east to west until they merge with the Paraguay River. The Paraguay River flows in the west of the Pantanal wetland, north to south eventually merging with the Parana River, almost 700 km downstream (Swarts, 2000; Hamilton, 2002).

The rain falling in the uplands, which have a steeper gradient, quickly discharges to the bordering Pantanal areas. There, discharge slows due to the minimal slope and the flood wave slowly moves downstream, taking 3 to 4 months to reach the outflow at the southern end of the Pantanal (Por, 1995). Exemplary of this, is the river level of the Paraguay River, which peaks in February in the north and peaks in May at the southern end of the Pantanal (Hamilton, 2002; Junk and Nunes da Cunha, 2005).

The landscape is formed by the dynamic rivers and their alluvial fans (Klammer, 1982). The main rivers in this area are braided with many connected rivers, called “corixos” (Nunes Da Cunha and Junk, 2004). These corixos are (usually smaller) side rivers which can be cut off from the main river during the dry season, but can also be nearly the same size as the main river. Due to the dynamics, small differences in discharge and/or sedimentation can change a corixo into a main channel (Heckman, 1998).

Because the top sediment layers are alluvial deposits, sediments near the main rivers are different from those further away from the rivers. Three subareas can be indicated based on the soil type: sandy soils with less than 15% clay, mixed soils with 15% to 35% clay and the clay soils with more than 35% clay (Por, 1995). The soils in the north of the Pantanal contain more laterites (rusty-red soils with high iron and aluminium contents) and planosols (light colored soil with coarse texture) than more to the south, because most river water passes through the north first. the topsoil layers are thin with little detritus, even under stands of trees, because the moist tropical climate accelerates the breakdown.

The studied location is a 5 by 5 km area in the Pantanal of Poconé, 11 km south-southeast of Pirizal. This area is chosen for the available data from previous studies conducted here (Nunes da Cunha and Junk, 2004). These studies have chosen this location for the high diversity of wetland habitats, such as seasonally flooded forest and different physiognomies of Brazilian savanna.

2.2. Data Assembly

2.2.1. Available data

A lot of the data used in this modelling study was available from different studies done by dr. Nunes da Cunha, dr. Arieira and colleagues at the UFMT and INAU. In table 1 the available data is shown along with the number of data points and the date it was taken.

The groundwater levels were measured at 30 points. These points were distributed in a grid-formation in the 25 km^2 study area (see figure B1 in Appendix B). They were situated on lines (A – F), evenly spaced 1 km from each other. Groundwater levels were measured monthly over a period from December 2009 until August 2011 using the piezometer at that point. Surface flooding water levels were also measured at the above mentioned groundwater level data points as well as 30 additional surface water points distanced 50m from a piezometer. The Cuiaba River level was measured daily at a station in Cuiaba, which is approximately 100 km upstream. The meteorological data was also collected in Cuiaba by the Instituto Nacional De Meteorologia (INMET). At an altitude of 145 m (only slightly above the study site elevation) precipitation (mm), relative humidity (%) and minimum, maximum and average temperature (°C) was measured.

Table 1: available data from the study site, along with the number of data points, the measured variable and the date of measurement. Data is available from studies done by dr. Nunes da Cunha, dr. Arieira and colleagues at the UFMT and INAU.

Data type	Number of data points	Variable	Date
Flooding	60	water table	from december of 2009 to june of 2011
Flooding	30	duration	from december of 2009 to june of 2011
Ground water	30	ground water level	from december of 2009 to june of 2011
River water	1	water level	from 1969 to 2007
Precipitation	1	precipitation	from 1961 to 2010
Temperature	1	temperature	from 1961 to 2011
Relative humidity	1	moisture	from 1961 to 2012
Topography	200	elevation	
Vegetation	continuous	class	

The vegetation data was collected using remote sensing techniques. A vegetation map of the study site resulted from supervised classification of Landsat TM5 images, with 30 meters resolution, providing vegetation classes at each 30 x 30m pixel (see figure C1 in Appendix C).

For an accurate ground water model, high resolution elevation is a necessity. Terrain elevation was measured using a geodetic GPS. Approximately 200 elevation data points were collected with x, y and z coordinates with 1 cm precision. Many elevation data points correspond to the points where other data was measured, such as groundwater level data points. To increase the accuracy of the elevation for the model, additional elevation points were measured (see section 2.2.2.).

2.2.2. Data Collection

To increase modelling accuracy additional elevation data was necessary, as was data on soil texture and grain size to gain insight in the hydraulic conductivity. The positions of the additional data points were proposed using Google Earth. The additional elevation data points were proposed to be in three transects all running in a northeast to southwest direction, as it is likely that the general ground water flow will be in that direction, due to the slope in the study area (see figure A1 in Appendix A). These elevation points were also measured using a geodetic GPS.

To gain insight in the hydraulic conductivity the nine drills were made using an extendible hand auger. The drilling sites were chosen based on the vegetation (see figure B1 in Appendix B). In all abundant vegetation types one or more sampling sites are located. Sampling was done each 20 cm, estimating the clay and sand content by hand (and mouth) at the location of drilling. Drilling continued until the hand auger reached maximum length (5m.) or until the groundwater table was reached, which hindered drilling.

2.2.3. Drilling results

The table in appendix D presents the results of the drillings in the study area. The drills are done for different vegetation types and different locations to see whether there might be a correlation to allow for extrapolating the soil textures throughout the entire study area. Due to the variation of the soil texture samples within the vegetation types it is not possible to indicate a pattern. This is also the result for the correlation over space. It could have been convenient if the texture might be distributed as often is in a meandering river channel and floodplain. However, the gradient of coarse to fine soil texture correlating with the distance to the river channel was not visible in the measurements. Therefore the soil texture and hydraulic conductivity are modeled as homogeneous throughout the model area.

2.2.4. Groundwater measurements

The groundwater was measured once a month on initiative of the UFMT. The available data for the study area was measured at the 30 points indicated in figure B1 of appendix B (points A1-F5). The measurements are between 0 and 5 m depth below soil surface, where 0 is equal to the soil surface and 5 m is the maximum depth of the piezometers. The variation within one month of measuring is quite large. In many months both the minimum and the maximum value have been measured. The box plots (figure also clearly indicate that during the wet season when the study area is largely inundated, the groundwater levels are still between 4 and 5 m depth. During my stay in the study area, the groundwater was measured at a few of these points and these values were quite average (between 1.5 and 3.4 m). In conversation with a student of UFMT, I learned that a few points were too difficult to reach and this may also explain a few missing values in the data set.

The general observation of other Pantanal studies, states that in the wet season the water level rises to near or above soil surface levels (Girard & Nunes da Cunha, 1999; Heckman, 1998 & Hamilton, 2002). In the data for this study however, maximum groundwater depth for every month is at least 3.5 m and only in 3 months (February 2010-April 2010) the median groundwater depth is 0 m below the soil surface. Also contrary to the literature is the rise in average groundwater level from April 2009 – October 2009. Under natural circumstances the groundwater level falls when precipitation is low and evaporation is high, as is in the dry season which ranges from April/May to October/November in the Pantanal. For these reasons the data was not used for calibration, but only to get an indication of the water levels.

2.3. Vegetation

The vegetation in the Pantanal is complex and rich. It has been described as “the Pantanal complex” (Sanchez, 1977), a “mosaic” of different communities (Prance and Schaller, 1982), a “savanna parque” without gallery forest ([Loureiro *et al.,* 1982] in Nunes da Cunha and Junk, 2004). The mixture in vegetation is primarily determined by the topography and the hyperseasonality (Prance and Schaller, 1982; Heckman, 1998). In this thesis the focus lies on an area with almost no permanently inundated areas. Therefore this chapter will focus on the terrestrial vegetation of the Pantanal and the study site.

The Pantanal floodplain has a few dominant landscape units. Of these, the major geomorphological units are flat savanna areas that are inundated seasonally: “Campos limpos”, “Campos sujos” and “Campos de murunduns”, translated to english as grassland savanna, grassland savanna with low trees and shrubs and vegetated earth mound savanna, respectively (Nunes da Cunha and Junk, 2004, Nunes da Cunha *et al.,* 2006). In these areas multiple vegetation formations are situated: grasslands, shrubby savanna, low tree and shrub savanna (“Savanna arborizada”), alluvial low forest (flooded forest), and *Vochysia divergens*-dominated forest called “Cambarazal”. The “Campos de murunduns” are flat savanna areas with equally spaced vegetated termite mounds, similar to islands in a sea of herbaceous plants. In each mound one or more trees grow in a symbiotic interaction. The trees benefit from the protection of waterlogging and savanna fires and provides the termite with wood (Nunes da Cunha and Junk, 2004; Por, 1995).

The other landscap units are depressions with marshes, “Cordilheiras” (paleo levees) and levees. In the depressions in the Pantanal area grow marsh vegetation communities, which have adapted to the regular inundation or saturation. The raised levees along the major rivers are covered by dry forest and alluvial forest. These elevations are usually dry and are only inundated in years of extreme precipitation and high water levels. The paleo levees are similar to the levees, usually dry and often similarly elevated, yet these areas do not border water all year round. Vegetation communities covering these areas are low tree and shrub savanna, savanna forests (“Cerradão”), dry forests and carvoal (Nunes da Cunha and Junk, 2004; Por, 1995).

Table 2: The different vegetation types encountered in the study area accompanied by a short description, the landscape unit they are mostly found and the inundation regime they are mostly adapted to (source is from a personal conversation with Dr. J. Arieira).

Vegetation type		Landscape unit	Inundation regime
Cambarazal	seasonally flooded evergreen forests dominated by *Vochysia divergens* Pohl	Plain	Seasonally flooded
Landi	semi-evergreen flood forest dominated by *Calophillum brasiliensis* Cambess	Plain	Seasonally flooded
Grassland	Seasonally flooded grassy-woody savanna	Plain	Seasonally flooded
Shrubby Savanna	seasonally flooded low tree and scrub woodland	Plain	Seasonally flooded
Vegetated Earth Mound Savanna	seasonally flooded savanna parkland	Plain	Seasonally flooded
Marsh		Depression	Regularly flooded
Dry Forest	savanna forest also known as cerradão	Levee or Mound	Usually dry
Alluvial Forest	Alluvial seasonal semideciduous forest	Plain or Levee	Seasonally flooded or usually dry
Savanna Forest	Similar to dry forest	Levee or Mound	Usually dry
Carvoal	deciduous forest dominated by *Callisthene fasciculata* MART	Levee or mound	Usually dry

The Pantanal has, due to its dynamic character, a limited number of endemic species, especially among the higher terrestrial vegetation (Prance and Schaller, 1982). Therefore, most of the vegetation finds its origin in the surounding regions, thus consisting of elements of the nearby floristic regions: “Cerrado”, “Chaco”, Amazonian forest and Atlantic forest. Cerrado is Brazilian savanna vegetation of the Brazilian savannas and the Planalto. The vegetation consists of succesional stages of Cerrado, commencing with dry herbaceous fields ("campos limpos") to shrub savanna ("Campo cerrado") to savana forest ("Cerradão") (Por, 1995). Chaco is a vegetation type from Bolivia and Paraguay to the west of the Pantanal and is therefore more prevalant in the western parts. The chaco vegetation is thought to be diminishing. It was once the dominant vegetation during the Pleistocene when conditions were dryer. The Amazonian vegetation is most abundant in the north, nearest to the Amazon forest, but also extends south along the major rivers in gallery forests. The Atlantic forest vegetation originates from the southeastern Atlantic forests in Brazil. This vegetation is most common in the southeastern part of the Pantanal and along the rivers (Por, 1995).

The Pantanal is in a permanent state of succesional changes that ends in semi-deciduous or gallery forests (Por, 1995). The ecological succesion is disturbed by certain stressfactors. In accordance with the Intermediate Disturbance Hypothesis (IDH) this can further explain the great diversity in floral and faunal species (Roxburgh *et al .,* 2004). The main disturbances in the Pantanal are the seasonal flooding and desiccation, the grazing and the fires. The grazing done by the 3 million cattle in this region has a considerable effect on the vegetation, particularly through selective grazing and trampling of the open savanna and the forest understory. This creates an opportunity for the toxic and unpleasant weedy plants that increase in the absence of competitors (Prance and Schaller, 1982). Fires are natural to cerrado lands and the plants are adapted to it. Many woody species have either fire resistant bark or underground organs and often produce flowers and seeds just after a fire (Por, 1995). The *Vochysia divergens* species is less adapted to fires, with high mortalities observed after a fire.

2.3.1. The effects of inundation on the distribution of the vegetation

The terrestrial vegetation of wetlands has to cope with conditions of inundation or high groundwater levels . During inundation vegetation can undergo decreases in growth rate, change in metabolism and changes in morphology of individuals (Damasceno-Junior *et al.,* 2005). Not all species are equally adapted to the stress, however species that are have a considerable advantage. There have been plenty of studies on the relationship between inundation and the distribution of the vegetation in the Pantanal (Zeilhofer and Schessl 1999, Nunes da Cunha et al. 2001, Arieira and Nunes da Cunha 2006, Damasceno-Junior *et al.,* 2005, Arieira *et al.,* 2011). Although many factors influence vegetation establishment, in the Pantanal the length of the inundation and the frequency of inundation are the two main features associated with the abrupt change in vegetation on a small scale (Damasceno-Junior *et al.,* 2005). Based on observations , it is apparent that the semi-deciduous forests and woodlands are manifested on the well drained riverbanks, whereas the open savanna formations dominate the seasonally inundated floodplains (Prance and Schaller, 1982). Zeilhofer and Schessl (1999) found that the water regime influences the forest to grassland, medium-tall grassland to short grassland and seasonal forest to evergreen forest transitions. Short grasslands and marshes dominate stands inundated longer than 6 months. These vegetation types are not found on well drained (paleo) levees, which are seldomly flooded and are instead covered by seasonal forests (Zeilhofer and Schessl, 1999). Between these extremes, the seasonally inundated (less than 6 months) flat areas are dominated by the medium tall grasslands, such as shrubby savanna, low tree and shrub savanna and the vegetated earth mound savanna. Evergreen forests and Cambarazal are more flood resistant than the forest formations on the levees and are found in stands which are seasonally inundated (Nunes da Cunha and Junk, 2004; Zeilhofer and Schessl, 1999).

2.3.2. The effects of drought on the distribution of the vegetation

The Pantanal would have the capacity to host more flood adapted species, however these species prove unable to survive the extreme drought (Nunes da Cunha and Junk, 2001). The drought is another stressfactor which defines the vegetation. Availability of water determines the behavior of the vegetation. In the dry period the only water available in the study area is groundwater. Water deeper than 30 cm below the soil surface is not lost to direct evaporation, but only to transpiration after root absorption (Rawitscher, 1948). The depth and the extent of the roots determines the availability of the water in the dry season. In table 3 the maximum root depth of the different Pantanal vegetation types is shown, based on species investigated by Rawitscher (1948) and Canadell *et al.*, (1996).

Table 3: the vegetation types in the study area and the maximum root depth of a certain species of the vegetation type. In the last column the root depth used in the model is shown. [1]Maximum rooting depth is based on the articles of Rawitscher (1948) and Canadell et al., (1996). [2] Not all vegetation types had a species listed in the before mentioned articles.[3] Vegetated Earth Mound Savanna consists of a few trees, but mostly grasses. Therefore the rootdepth of the grasses is chosen as most influential.

Vegetation type	Maximum rooting depth in m. [1]	Root groundwater depth used in the model in m.
Cambarazal	?[2]	5
Landi/Flooded Forest	18	9
Grassland	1.5	1
Shrubby Savanna	?[2]	3
Vegetated Earth Mound Savanna	1.5[3]	1
Marsh	1.5	1
Dry Forest	10	5
Alluvial Forest	18	9
Savanna Forest	10	5
Carvoal	10	5

In the study area 10 different vegetation types were identified (see appendix C). For each vegetation type a depth was determined to which reasonably the roots could draw down the ground water. This was based on the maximum rooting depth determined by Canadell *et al.,* (1996) and from Rawitscher (1948), but it is not identical to this number as mostly only one species was mentioned to reach this depth. To ensure a more likely depth to which a certain vegetation type is able to reach the groundwater depth the third column of table 3 is used. Using this method the difference in groundwater table due to vegetation cover can be modeled, which is explained in section 2.4.2.

2.4. Hydrologic processes

The hydrologic processes discussed in this paragraph are part of the hydrological cycle and are influential in the wetland environments. It is explained how these processes are used in this thesis.

2.4.1. Precipitation

Precipitation is the process of condensed water falling to the earth. As mentioned above the Pantanal has a very distinct seasonal character, which is due to changes in the major wind patterns (Heckman, 1998). During the wet summer season, from November to April, winds from the north east transport equatorial continental air masses of Amazonian origin (Por, 1995). These air masses contain large quantities of evaporated water almost exclusively from the Atlantic Ocean. In the drier winter months the winds predominantly originate in the Brazilian highlands or sometimes from the colder southern regions (Por, 1995). Precipitation also varies from year to year and in multi-year variations (Nunes da Cunha and Junk, 2001). Extended periods of dryer or wetter climate can result in a change in the distribution of vegetation. An example of this is the expansion of the species *Vochysia divergens* during a multi-year wet period (Nunes da Cunha and Junk, 2001).

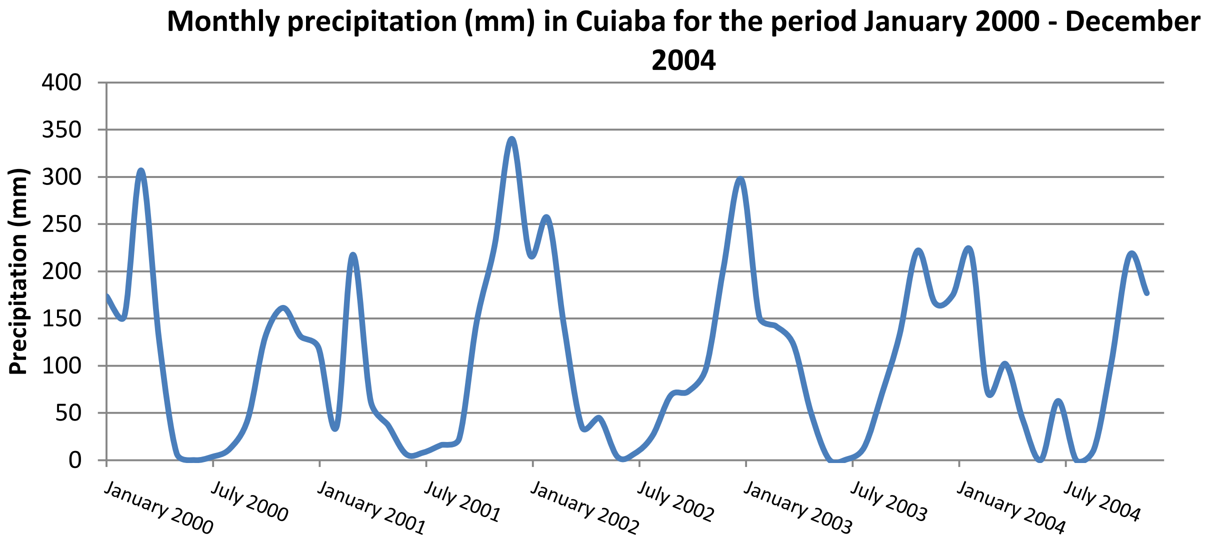


Figure 2: Monthly precipitation data collected at the station in Cuiaba. Data acquired from INMET (Instituto Nacional de Meteorologia).

Precipitation varies spatially, as shown in figure 2. In the Upper Paraguay Basin rainfall is higher in the upland areas (Planalto) than the lower lying Pantanal(1400-1800 mm and 1000-1400 mm, resp.). Therefore, discharge from these upstream areas of the Pantanal has a significant impact on the Pantanal inundation (Heckman, 1998).

The precipitation and data necessary to calculate the evaporation are based on the measurements taken in the year 2002, as this data was fully available and appears to be representative for this region and time. The data used is shown in Appendix A table A2.

2.4.2. Evaporation

Evaporation is the process where water transforms from liquid to gas. Evaporation in the Pantanal exceeds precipitation resulting in a 300 mm hydrological deficit (Heckman, 1998). This is supported by the observations that the total river discharge decreases further downstream (Klammer, 1982).

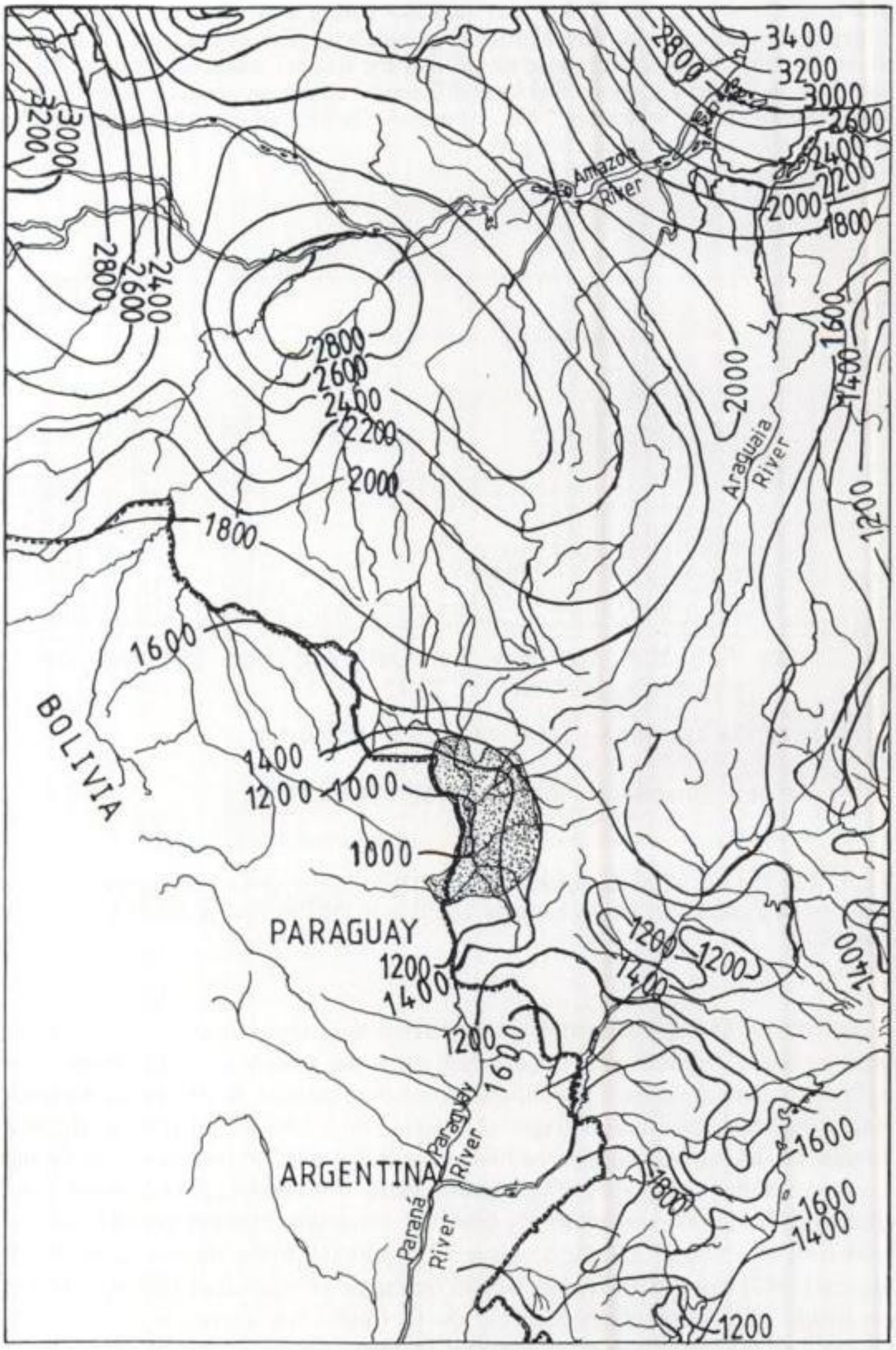


Figure 2. A map of South-eastern Brazil showing the isohyetal lines. The Pantanal is the dotted grey area in the centre, the thin lines are rivers or the isohyetal lines. The numbers correspond to the millimeters annual precipitation. This figure is taken from Heckman (1998)

Evaporation is a difficult process to measure directly without influencing the result. Therefore evaporation is often estimated, based on the available energy necessary to evaporate water and the atmospheric demand. In this study the **potential** evaporation is estimated using the Penman-Monteith equation as described in Hendriks (2010). The

Penman-Monteith equation after setting soil heat transfer to zero and inserting values for (near-)constants is as follows:
Equation 1:

$$E_a = 0.408 * \frac{\Delta\, R_n + \frac{105.028\,(e_s - e_a)}{r_a}}{\Delta + 0.067\left(1 + \frac{r_s}{r_a}\right)}$$

In this equation certain variables are calculated using the following equations:
Equation 2:

$$\Delta = \frac{4098\, e_s}{(237.3 + T)^2}$$

Equation 3:

$$e_s = 0.6108\, e^{\frac{17.27\, T}{237.3 + T}}$$

Equation 4:

$$RH = \frac{e_a}{e_s}$$

Equation 5:

$$R_n = (1 - \alpha)\left(0.25 + 0.50\frac{n}{N}\right) S_0 - 4.903 * 10^{-9}(T + 237.2)^4\left(0.34 - 0.14\sqrt{e_a}\right)(0.25 + 0.75\frac{n}{N})$$

*Table 4: the parameters used in the Penman-Monteith equation and the equation used to determine the variables. * These parameters are based on averaging the data of grassland and forest from Hendriks (2010), because the study area consist of forests and grasslands in a complex mosaic.*

Parameter	Description	Parameter value
E_a	actual evaporation (mm day^{-1})	Equation 1
r_a	aerodynamic resistance (s m^{-1})*	37
r_s	surface resistance (s m^{-1})*	109.5
Δ	gradient of the saturation vapor pressure curve (kPa°C^{-1})	Equation 2
e_s	Saturation vapor pressure (kPa)	Equation 3
e_a	Actual vapor pressure (kPa)	Equation 4
R_n	Net radiation at the earth's surface (MJ m^{-2} day^{-1})	Equation 5
T	Air temperature (°C)	Daily variable (appendix A)
RH	Relative humidity (-)	Daily variable (appendix A)
S_0	Sun's shortwave radiation (MJ m^{-2} day^{-1})	Monthly variable (app A)
N	Total day length (hour)	12.0
n	Number of bright sunshine hours per day (hour)	8.15
α	Albedo (-)*	0.19
e	Base of the natural logarithm (-)	2.71828…

In each scenario the evaporation is modeled differently to indicate the influence of groundwater on the vegetation and the effect of vegetation on groundwater. In scenario 1 the evaporation as calculated by the method described above is used. This creates a uniform evaporation over the entire model area. For scenarios 2 and 3 another equation is used to introduce spatial difference in evaporation. In scenarios 2 and 3 the evaporation (E_a) of a rastercell is a function of the potential evaporation (E_{pot}, calculated using the Penman-

Monteith equation [see chapter 2.3.2]), the root depth (r_d) and the groundwater table depth(w):
Equation 6:

$$E_a = \frac{r_d - w}{r_d} * E_{pot}$$

This equation is used when the water table is below the elevation level and above the root depth. If the water level is above soil surface potential evaporation is used, when the water table is below the root depth there is no evaporation.

In scenario 2 all roots reach 3 m depths. Variation in actual evaporation are introduced due to a difference in groundwater table. In scenario 3 however, each of the 10 different vegetation types that were identified a depth was determined to which the roots could draw down the ground water. This was based on the maximum rooting depth determined by Canadell *et al.,* (1996) and from Rawitscher (1948). Using this method the difference in groundwater table due to vegetation cover can be modeled.

2.4.3. Surface water flow

The surface water is all water at the surface, stagnant such as lakes or flowing such as rivers and brooks (Hendriks, 2010). The Pantanal is strongly influenced by surface water in the wet season. In the dry season the surface water retreats to a few lakes and the larger rivers. Although surface waters are of critical importance in this area, this study is focused on the groundwater. In a personal conversation with Dr. Arieira of UFMT and INAU, who has done research at this study site, the role of surface water at the study site was marginalized. According to Dr. Arieira the study site is mainly subject to precipitation and evaporation. In this modelling study run-on is neglected. Run-off is modeled using the MODFLOW drainage package (see chapter 2.5.4.).

2.4.4. Groundwater flow

Groundwater is the water beneath the land surface that fully saturates the pores in the ground (Hendriks, 2010). In the Pantanal the groundwater is a source of water for the vegetation in the dry season (Nunes da Cunha and Junk, 2001). Groundwater levels drop as the water is evaporated, directly or via plant transpiration. In the wet season rain and surface water replenish the groundwater and all inundated soils become fully saturated (Girard and Nunes da Cunha*,* 1999). Girard *et al.* (2003) encountered the groundwater table in the dry season at 2.0 to 5.6 m below ground, which is consistent with personal observations (Appendix D). Girard *et al.,* (2003) further found that the groundwater was often confined beneath a sequence of layers of silt and clay. When river levels start rising, at the beginning of the wet season, groundwater levels may still decrease. Only close behind the levees of the major rivers does the groundwater table increase with increasing river level, indicating groundwater flow away from the river (Girard *et al.,* 2003).

Water flow is subject to the physical laws, therefore steady groundwater flow can be calculated by solving the partial differential equation based on Darcy's law and the mass balance equation:
Equation 7:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}$$

Where K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes (L/T), *h* is the head (L), *W* volume flux per unit area (T^{-1}), *SS* is the specific storage of the porous material (L^{-1}), and *t* is time (T) (McDonald & Harbaugh, 2000).

The partial differential equation indicates the importance of the hydraulic conductivity in groundwater flow. In this thesis an empirical approach is used to determine the conductivity based on the grain size of the soil. Because the soils in the study area were well mixed, according to the measured data (Appendix D), it is assumed that the soil is homogeneous throughout the entire modeled area. This assumption is incorrect, as the acquired data shows, but it was not feasible to create a representative soil map. The hydraulic conductivity is therefore assumed homogeneous and for modelling purposes the value of loamy sand was used, which is a medial value between sand and clay.

2.5. Modelling

Modelling is the process of representing reality in the simplest possible way that is adequate enough for the purpose of the model. As an abstraction of reality a model can be a useful tool for examining, understanding and predicting the modeled reality (Mulligan and Wainwright, 2004). For environmental sciences modelling is of great importance, because observation of the phenomena involved is either impossible, is very difficult and/or expensive. Models can be physical or mathematical. Physical models are miniature systems in the laboratory, whereas mathematical models are equations that represent processes occurring in reality (Karssenberg, 2003). Mathematical models can provide the possibility to study large-scale, long-term, non-laboratory controlled, multicomponent, multivariate and complex systems which are beyond the capabilities of observation (Mulligan and Wainwright, 2004). With increasing processing power from computers, the mathematical models have grown in complexity (Favis-Mortlock, 2004).

In environmental sciences many mathematical models used are dynamic spatial models, where spatial indicates the space or geographic domain, in two or 3 dimensions, and dynamic indicates the modelling through time (Karssenberg, 2003).

2.5.1. Groundwater modelling

When understanding groundwater systems or predicting its behavior one cannot always rely on engineering or best geologic judgment, in many cases human reasoning is not enough to contrive all factors involved (Anderson and Woessner, 1991). In a mathematical model all the different components can be represented by its own equation, whether based on physical principles or just best describing its nature based on observation, which can be solved numerically almost simultaneously (Mulligan and Wainwright, 2004). For groundwater modelling a choice has to be made between quantitative and qualitative modelling. In quantitative modelling only water flow itself is modeled, as where in qualitative modelling includes simulating solute transport (Oude Essink, 2000). In quantitative modelling fluid flow is based on the equation of motion and continuity, which are Darcy's law and the mass balance equation (Oude Essink, 2000).

Groundwater models are created for three main purposes: prediction, interpretation and generic (Anderson and Woessner, 1991). Most are aimed at predicting, often as a result of human interaction with the environment. Models created for interpretation are generally used to gain insight and formulate ideas on system dynamics, as does this thesis' model. Generic models are build used to study more general systems and therefore being more widely applicable (Anderson and Woessner, 1991).

2.5.2. PCRaster MODFLOW

PCRaster MODFLOW is the combination of the PCRaster and MODFLOW 2000. MODFLOW is one of the most widely used hydrogeological models (Oude Essink, 2000). MODFLOW uses mathematical equations that represent flow and the physical characteristics of the groundwater system to simulate flow through porous media (McDonald & Harbaugh, 2000). MODFLOW is designed to consist of a main structure and independent modules, which simulate a specific hydrologic feature. The modules are grouped together in packages which can simulate stresses such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through riverbeds.

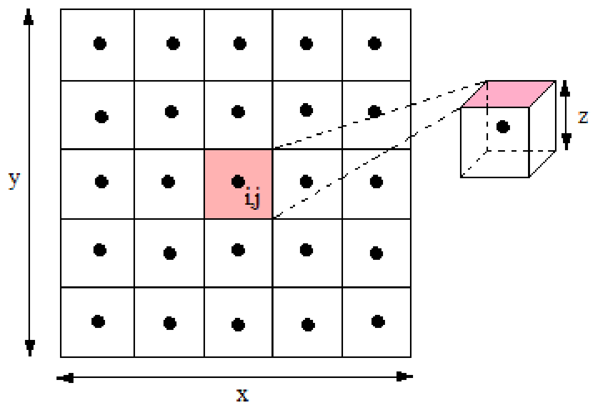


Figure 3: a blockcentered flow finite difference grid. The boundaries are at the edges of the boxes and at each node the head is calculated. The dimensions are x,y,z and the cell is identified as the i^{th},j^{th} cell in which i is the column number and j is the row number.

Ground-water is simulated using a blockcentered finite-difference approach, illustrated in figure 3. The horizontal grid is generated by specifying the grid dimensions in the x and y directions. Flow is modeled by solving the partial differential equation based on Darcy's law and the mass balance equation (see equation 3).

PCRaster is a geographic information system (GIS) modelling environment. This system applies a set of tools for editing the raster based maps. In these maps each cell contains attributes which define its properties. Operations using the PCRaster tools can change these properties in a specific way. The "aguila" tool is a useful visualization tool which can display maps, considering the maps data type. The main application of PCRaster is environmental modelling in disciplines such as geology, hydrology and ecology.

By combining these two systems geospatial information can be quickly edited and viewed using PCRaster and then PCRaster tools write the input files necessary for MODFLOW. This combination results in a well respected ground water modelling system which can easily be viewed, run and edited geospatially.

2.5.3. Data preprocessing

To run the model certain data had to be prepared to be used. For modelling accuracy a buffer zone of 3 km on all sides of the square study area was used. All data was prepared for the study area and this additional buffer zone, which created a modelling area of ca. 11 by 11 km (3+5+3=11 km). These areas will be further named as the study area (the 5 by 5 km area of interest), the buffer zone and the modelling area (the entire 11 by 11 km area). All raster maps used have 30 by 30 m pixels. Figure C1 of appendix C and figure F1 of appendix F are examples of the raster maps used.

For the creation of the digital elevation map (DEM) two techniques were used: inverse distance weighting (IDW) within the measured elevations points of the study area (see figure 4) and a satellite elevation image for the buffer zone, because no elevation measurements with a geodesic GPS were available for that area. IDW was chosen over kriging for the study area, because the kriging technique available made the protruding elevation points less pronounced. These elevation points were measured on paleo levees, which are often not more than 100 m wide and can be several km long. Due to the limited amount of elevation points the IDW and kriging technique could not identify these (often single) points as paleo levees. However, in the map created with the IDW technique these raised points are represented as lumps, whereas the kriging technique smoothes them out. The satellite DEM was a 90 by 90 m pixel image. The vertical accuracy of this DEM was approximately 1 m and therefore it was only used for the buffer zone. The map was then converted to the right size and 30 by 30 m pixels.

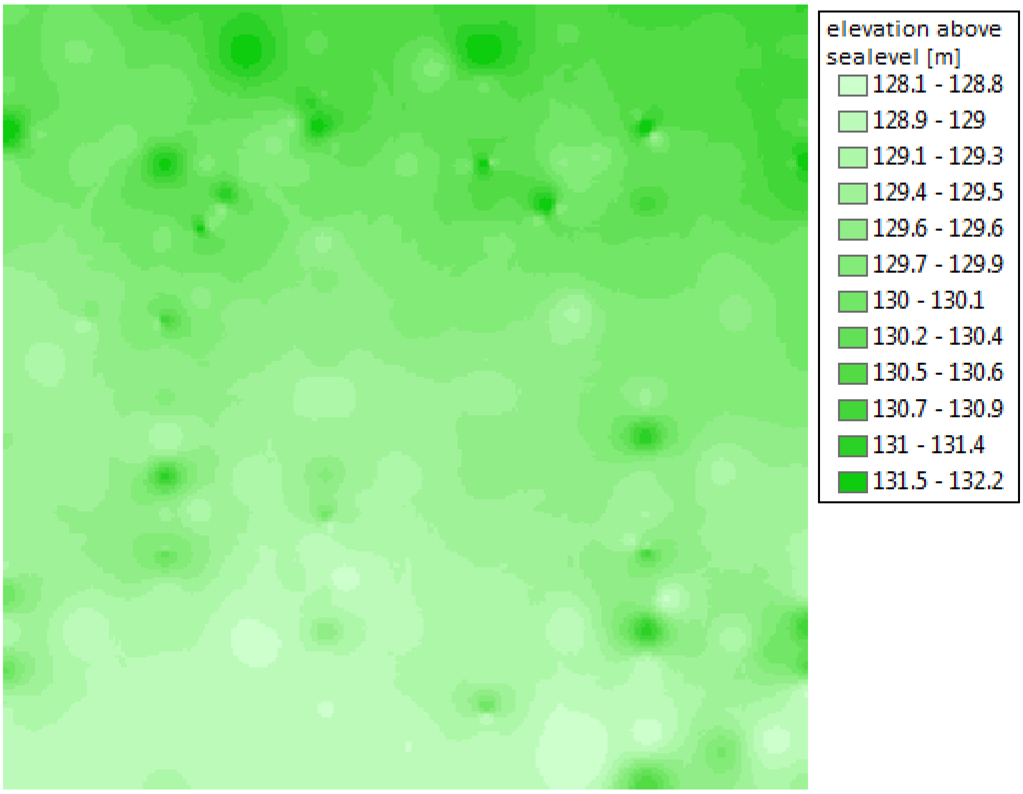


Figure 4: the 5 by 5 km digital elevation map (DEM) of the study area created using the 130 elevation points and an inverse distance weighting technique.

Joining the two DEMs created a unnatural elevation difference at the edge where the two DEMs met. This is also unwanted in modelling as the top layers are not aligned. Using the PCRaster command "*windowaverage*" after overlaying the study area DEM on the satellite DEM, a smoother DEM was created where especially the buffer zone DEM was better suited for the modelling. After that the original IDW DEM for the study area was overlaid. This ensured accuracy of the DEM in the study area and a buffer zone that neatly surround the study area.

The vegetation map provided by dr. Arieira and colleagues at the UFMT and INAU was used to create a map of the root depth. This root depth is necessary for the calculation of the spatial variation in evaporation (see section 2.3.2.).

For the river package of MODFLOW a map with rivers and lakes is needed. In the study area itself there are no permanent lakes. However there is a large permanent lake in the southeastern part of the buffer zone and a few smaller lakes in the southwest. A map is generated where all areas below the elevation of the great lake in the southeast are modeled as rivers/lakes.

The potential evaporation is calculated using the formulae mentioned in section 2.4.2 (equations 1-6). In excel a daily value is calculated (see Appendix A, table A2) which is used as the input to the model in which further calculations provide the actual evaporation. In the model the daily precipitation minus the potential daily evaporation at each cell are calculated and are linked to the groundwater as recharge using the setRecharge module of PCRasterMODFLOW.

2.5.4. Model building

Using the PCRaster MODFLOW software the model was developed (see Appendix G). 3 different scenarios are modeled: one where the potential evaporation is equal to the actual evaporation, one where the root depth is 3 m throughout the entire modeled area and one where the root depth depends on the vegetation and varies between 1 and 9 m. These 3 scenarios are modeled to see what the impact of the vegetation and its corresponding root depth have on the water table during the dry period.

The following states the similarities between the three scenarios. Each scenario is run for 1 year (365 days) with timesteps of 1 day. The elevation of the cell (between 124 m and 140 m above sea level) is the top of the soil in a cell and the bottom is uniform throughout the modeled area and is 75 m above sea level. Thus the entire soil thickness varies per cell and is between 49 and 65 m thick. For the MODFLOW calculations the soil is divided into 5 layers. Each layer is twice as thick as the layer above it: the top layer (layer 5) is 1/31 of the entire soil column thickness, layer 4 is 2/31, layer 3 is 4/31, layer 2 is 8/31 and the bottom layer is 16/31 of the soil column thickness thick. This ensures MODLFOW can be more precise in the upper layers and maintaining a thick enough entire soil column for deeper ground water flow. The hydraulic conductivity of the soil (K_{sat}) is set at 1 m / day, which is a value found in literature for loamy sand (Radcliffe and West, 2009). This value is used for all layers and all cells, because the soil data found by sampling was incoherent.

The cells at the edge of the modelling area are assigned as no flow boundaries. Therefore there is no flow in or out of the model, only drainage, leakage, precipitation and evaporation. The initial head is set at 0.1 m below the ground. Because the first timestep is the January 1st, which is in the wet season, the water level is likely to be near the soil surface. The groundwater table measurements support this assumption.

The river and drain package are used to model drainage and leakage. The drain package is modeled to be everywhere were the river package is not and is 0.1 m below the soil surface. The river package represents the lakes which are still present in the dry summer season. The water level is a fixed at 127.5 m above sea level. In the wet period the surrounding areas drain to the lakes and in the dry periods leakage occurs. This may be opposite to the actual situation, but it has no affect on the study area only the buffer zone. First this data is all used to calculate a steady state model. In the steady state model the recharge is equal to the precipitation minus the potential evaporation, both listed in table A2, in Appendix A. The steady state model gives an indication on the accuracy of the parameters and variables.

The difference between the 3 scenarios is the actual evaporation, which is incorporated in the model as the recharge (the recharge to a cell is the precipitation minus the actual evaporation).

In scenario 1, the actual evaporation is equal to the potential evaporation. This infers that no matter the depth of the groundwater and no matter the vegetation type, evaporation will continue. In scenario 2, the actual evaporation decreases with depth of the groundwater, but is not affected by the vegetation type. The actual evaporation decreases linearly until the water table is 3 m below the soil surface. This is calculated by inserting a 3 m root depth in equation 6. This is done equally over the entire modelling area. Evaporation is thus only spatially different due to spatial differences in the water table. In the third scenario, the actual evaporation decreases with depth of the groundwater and is affected by the vegetation type. Actual evaporation is calculated using equation 6.

Table 5: The 3 modelling scenarios and the differences between them. The evaporation is either the potential evaporation calculated with the Penman-Monteith equation or influenced by the root depth. The vegetation either has no effect on the model or affects the model due to the varying root depth.

Scenario	Evaporation	Vegetation
1	is not limited, evaporation is equal to the potential evaporation	has no effect on the model
2	is limited by the root depth, which is 3 m below the soil surface	has no effect on the model
3	is limited by the root depth, which is determined by the vegetation	affects the model due to the varying root depth of the different vegetation types

3. Results

The output of the model are timeseries, either numerical or maps. The timeseries of maps are displayed as an animation. These animations cannot be displayed on paper therefore the output in this paper is multiple maps of a timeseries at regular intervals. To show the behavior of groundwater over time six maps of the groundwater table for each scenario are shown below (mentioned in table 6). These maps show the contour lines of the groundwater table at days 100, 150, 200, 250, 300, 365. The contour lines differ in color depending on the water table elevation and are in 0.2 m increments (with the exception of figures 6E and 6F with have greater increments). The initial groundwater table is 0.1 m below the elevation and during the first 100 days the water table fluctuates around that level, which is the reason the water table at day 50 is not presented. These maps are shown as contour lines and are lain over the elevation map of the study area. For scenario 3 these contour maps are also draped over the root depth map. An additional contour lines map of the water table depth at day 250 for scenario 3 is shown over lying the root depth. Other output are the timeseries of the recharge in graph 1 and the water table depth at 12 grid points (locations are shown in figure F1 in Appendix F).

Table 6: The different figures and graphs that show the model results. The graphs and figures are sorted in the column for the scenario and the data shown. The graphs and figures are sorted in the row for what timestep the data is relevant.

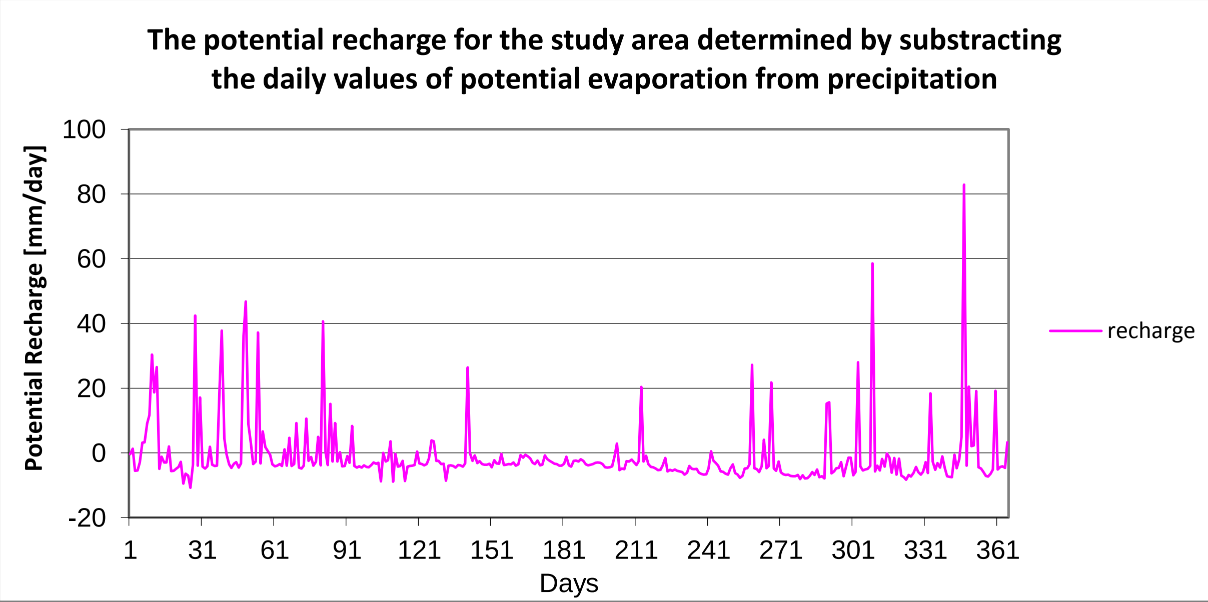
Day	Scenario 1	Scenario 2	Scenario 3		
	Groundwater level and elevation	Groundwater level and elevation	Groundwater level and elevation	Groundwater level and root depth	Groundwater depth and root depth
100	Figure 6A	Figure 7A	Figure 8A1	Figure 8A2	
150	Figure 6B	Figure 7B	Figure 8B1	Figure 8B2	
200	Figure 6C	Figure 7C	Figure 8C1	Figure 8C2	
250	Figure 6D	Figure 7D	Figure 8D1	Figure 8D2	Figure 9
300	Figure 6E	Figure 7E	Figure 8E1	Figure 8E2	
365	Figure 6F	Figure 7F	Figure 8F1	Figure 8F2	

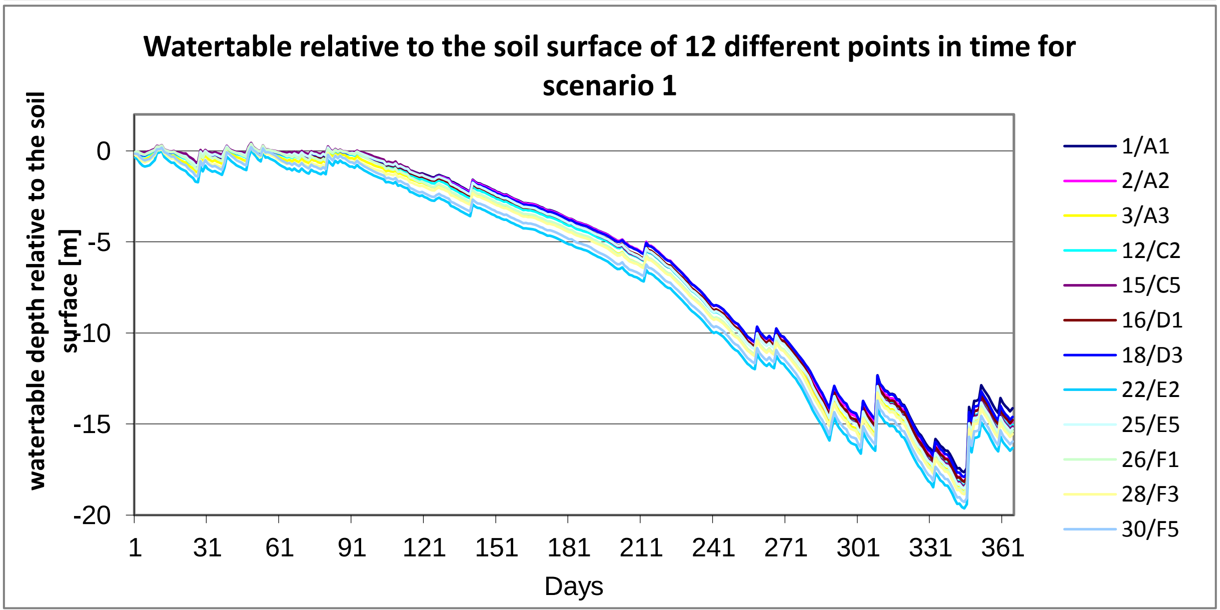
Day	Scenario 1	Scenario 2	Scenario 3
	Groundwater depth	Groundwater depth	Groundwater depth
all	Graph 2	Graph 3	Graph 4

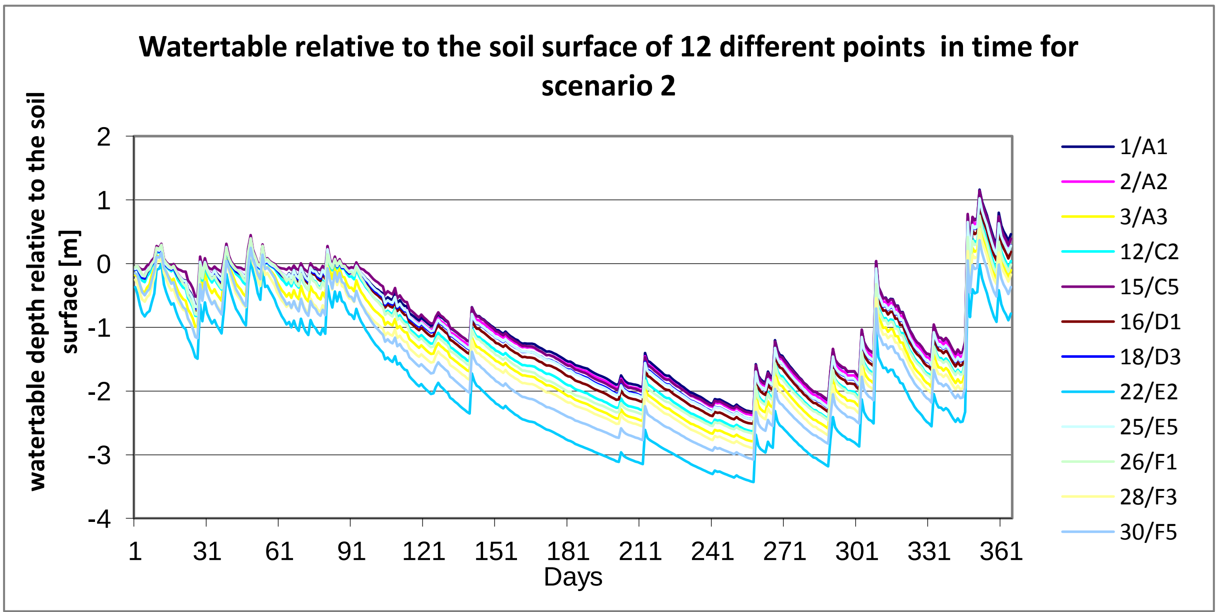
3.1. Model behavior

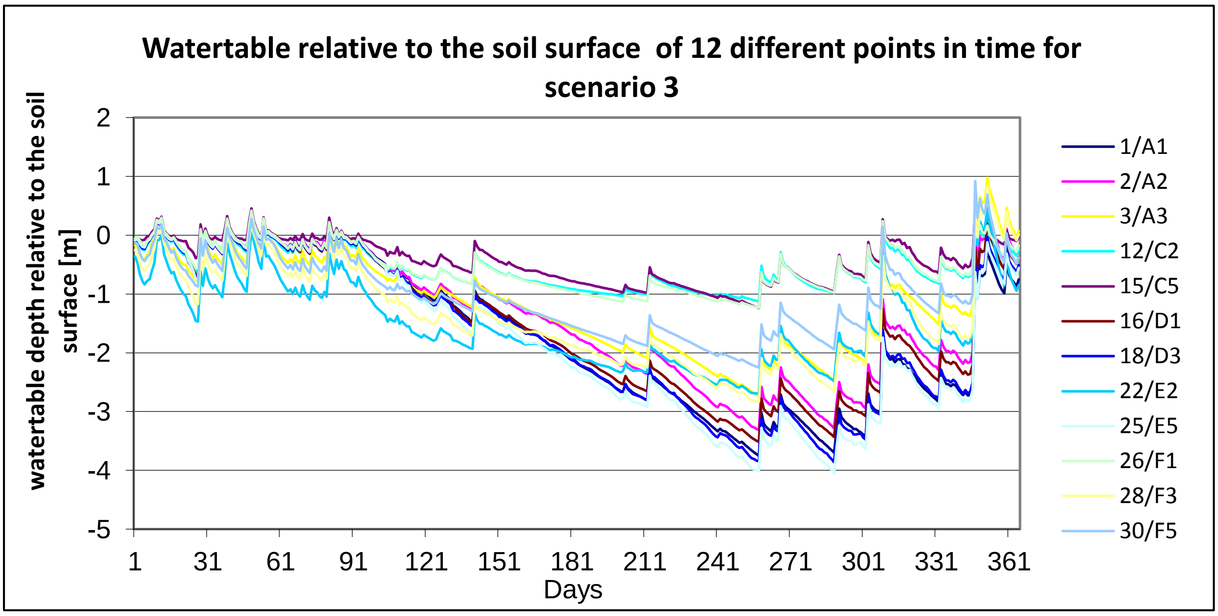
3.1.1. Scenario 1

In Graph 2 the modeled water table depth is shown over time for 12 different points in the study area for scenario 1. Until approximately day 100 the water table stays close to the soil surface, although there are differences between the different points. All points start with the water table at 0.1 m depth and in these first 100 timesteps the difference between the highest and lowest depth has become 1 m. The water tables react in a similar fashion to


The potential recharge for the study area determined by substracting the daily values of potential evaporation from precipitation
Potential Recharge [mm/day]
Days
recharge


Watertable relative to the soil surface of 12 different points in time for scenario 1
watertable depth relative to the soil surface [m]
Days
1/A1
2/A2
3/A3
12/C2
15/C5
16/D1
18/D3
22/E2
25/E5
26/F1
28/F3
30/F5


Watertable relative to the soil surface of 12 different points in time for scenario 2
watertable depth relative to the soil surface [m]
Days
1/A1
2/A2
3/A3
12/C2
15/C5
16/D1
18/D3
22/E2
25/E5
26/F1
28/F3
30/F5



Graphs 1 – 4: Graph 1 (top) shows the recharge over time. The recharge is the precipitation minus the potential evaporation.
Graphs 2 – 4 show the groundwater depth at 12 points over time for the different scenarios. The y –axis shows the depth relative to the soil surface. In these graphs the negative number stands for depth below soil surface.

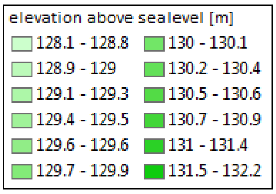
the recharge. After the first 100 days the rainy period has ended and evaporation dominates. In scenario 1 the water tables decrease severely reaching maximum depth of 17.1 to 19.7 m at day 345.

From the figures 6A-F it is clear that the groundwater level decreases everywhere during the final 265 days. In figures 6D-F at the southern end of the study area a circular area of higher groundwater level exists, which is increasingly prominent towards the end of the simulation time. This “bulge” is due to a lake a little south of the study area. This lake has a fixed water table and therefore increases the water level in the surrounding areas.
At day 100 (figure 6A) the water table is still very much influenced by the small scale elevation differences of the soil surface. These small scale elevation differences diminish and cease to exist quite rapidly, smoothing out the water level. Therefore the water level shows only elevation differences over a greater scale matching the greater scale elevation difference of the soil surface, both with a slope of high levels northeast and lower level southwest.

In this scenario the water level would decrease so much that even vegetation with deep roots would likely not reach the groundwater table from timesteps 250 to 365 and the groundwater level does not return to near soil surface levels. This is not similar to observations and groundwater measurements and also very unlikely with a total annual evaporation of 1696.5 mm. Therefore it is probable that this scenario is somewhat erroneous, but may also indicate that incorporating a decreasing factor to evaporation if the groundwater level drops is a necessary factor.

3.1.2. Scenario 2

Graph 3 displays the groundwater table relative to the soil surface at 12 different points for all 365 timesteps. In the first 100 timesteps scenario 2 behaves similar to scenario 1: approximately 1 m difference in groundwater level, the groundwater level fluctuates closely around the soil surface and all points react similarly to the recharge. The change in groundwater levels may appear to be more pronounced than in graph 2, however this is due to a different scale on the Y-axis. After the 100^{th} timestep the dry period starts, which results in a maximum fall of the groundwater level between 2.2 and 3.4 m below soil surface depending on the location. When the wet period starts the water level rises to levels between 1 m above and 1 m below the soil surface. This is more similar to observations in the Pantanal and the study area than the results of scenario 1.



Figures 6: The modelling results for scenario 1. The contour lines indicate the groundwater level at that timestep and the shades of green indicate the elevation (used as input for the model). All maps are 5 by 5 km areas.

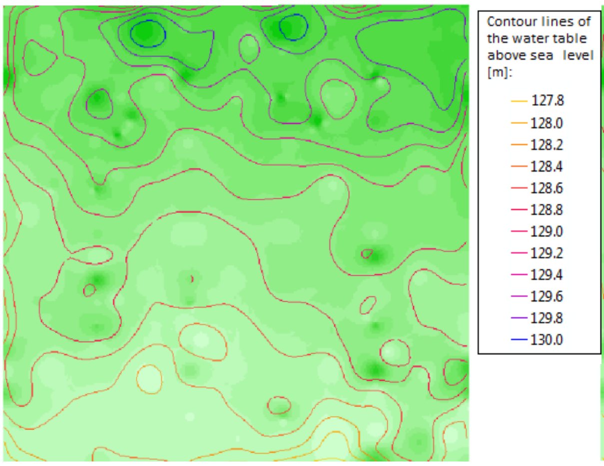


Figure 6 A: The scenario 1 modeled groundwater level at day 100 (the contour lines) compared to the elevation.

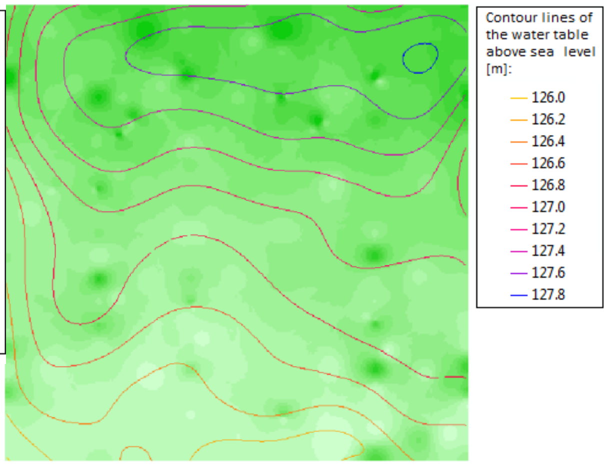


Figure 6 B: The scenario 1 modeled groundwater level at day 150 (the contour lines) compared to the elevation.

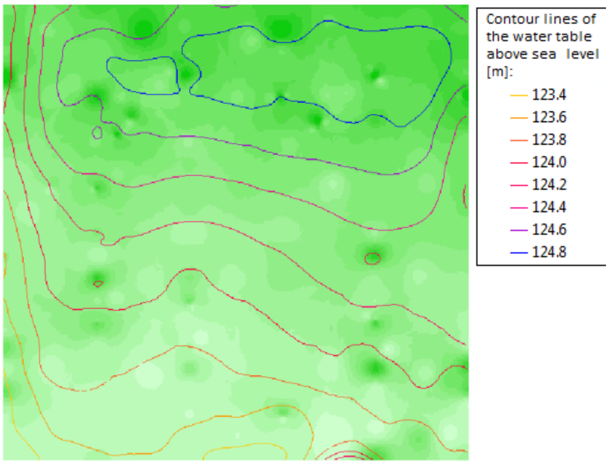


Figure 6 C: The scenario 1 modeled groundwater level at day 200 (the contour lines) compared to the elevation.

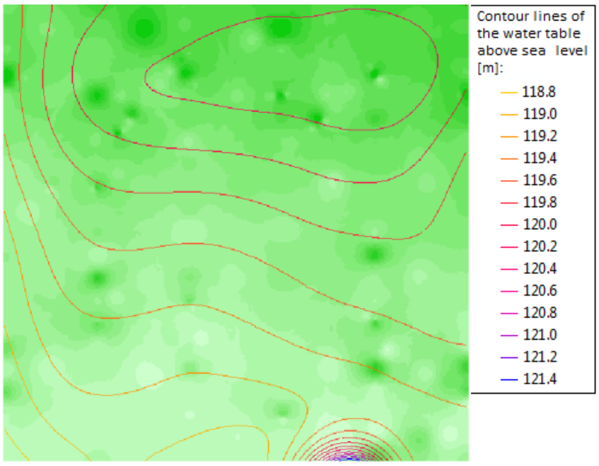


Figure 6 D: The scenario 1 modeled groundwater level at day 250 (the contour lines) compared to the elevation.

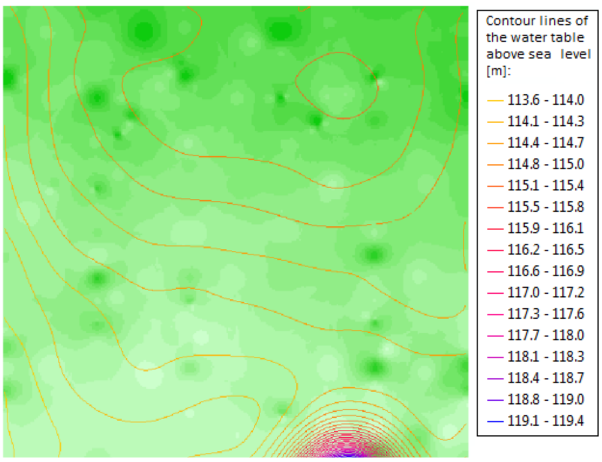


Figure 6 E: The scenario 1 modeled groundwater level at day 300 (the contour lines) compared to the elevation.

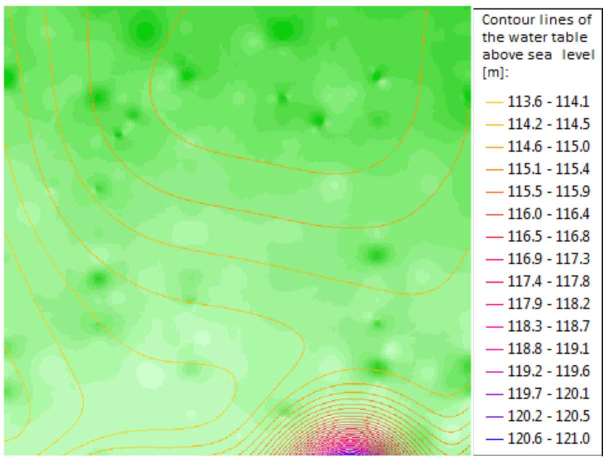
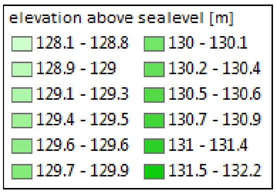


Figure 6 F: The scenario 1 modeled groundwater level at day 365 (the contour lines) compared to the elevation.



Figures 7: The modelling results for scenario 1. The contour lines indicate the groundwater level at that timestep and the shades of green indicate the elevation (used as input for the model). All maps are 5 by 5 km areas.

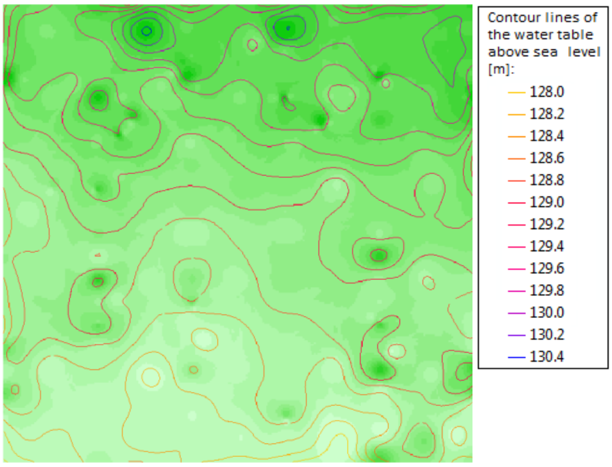


Figure 7 A: The scenario 2 modeled groundwater level at day 100 (the contour lines) compared to the elevation.

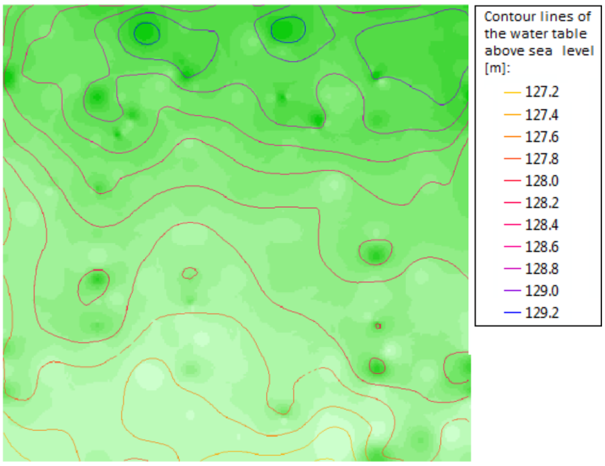


Figure 7 B: The scenario 2 modeled groundwater level at day 150 (the contour lines) compared to the elevation.

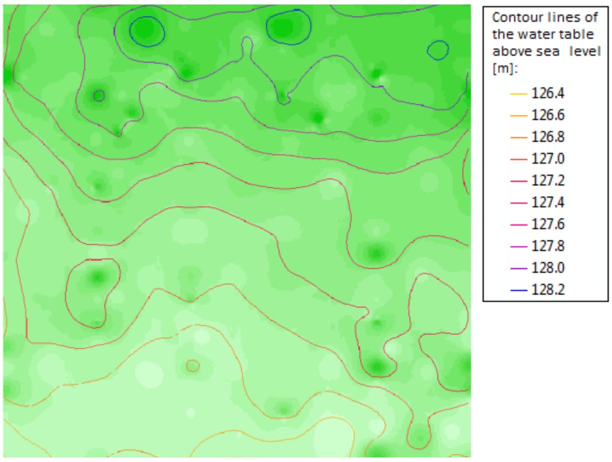


Figure 7 C: The scenario 2 modeled groundwater level at day 200 (the contour lines) compared to the elevation.

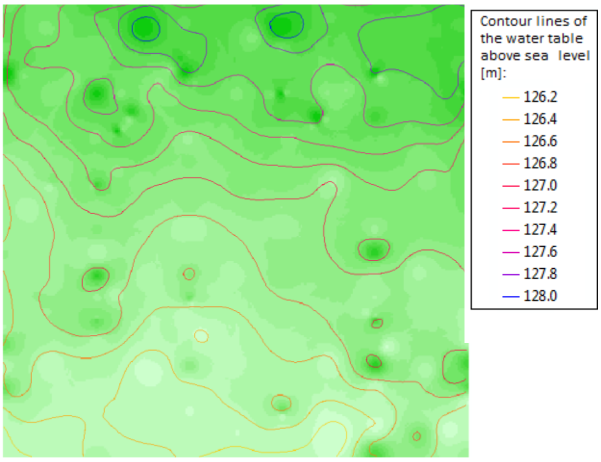


Figure 7 D: The scenario 2 modeled groundwater level at day 250 (the contour lines) compared to the elevation.

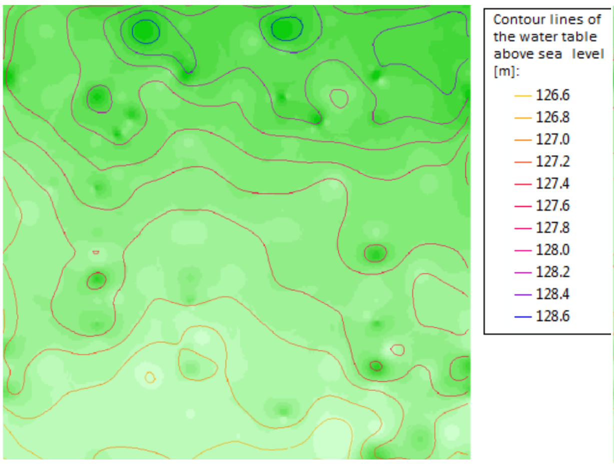


Figure 7 E: The scenario 2 modeled groundwater level at day 300 (the contour lines) compared to the elevation.

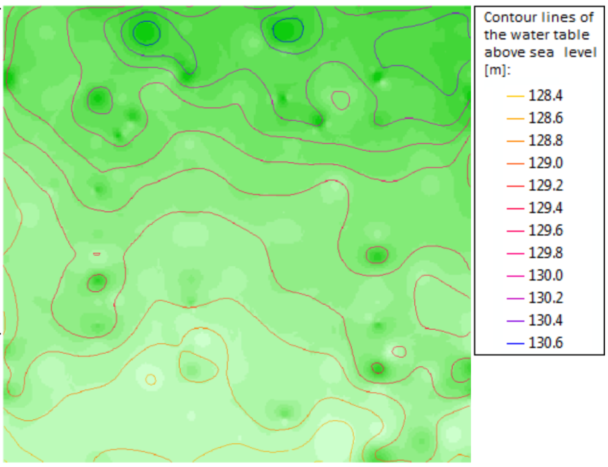
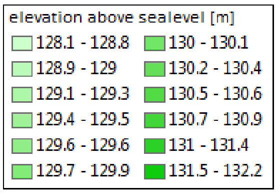
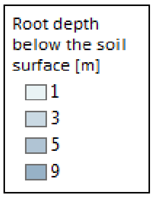


Figure 7 F: The scenario 2 modeled groundwater level at day 365 (the contour lines) compared to the elevation.



Figures 8: The modelling results for scenario 3. The contour lines indicate the groundwater level at that timestep, the shades of green indicate the elevation (used as input for the model) and blue shades indicate the root depth below the soil surface (also used as input. All maps are 5 by 5 km areas.



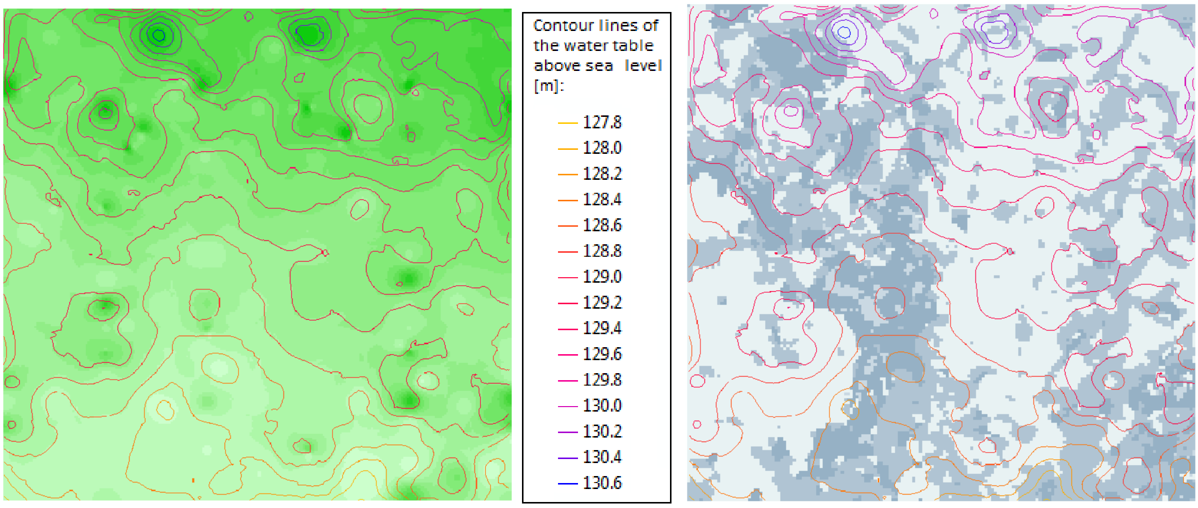


Figure 8 A1 (left) + A2(right): The scenario 3 modeled groundwater level at day 100 (the contour lines) compared to the elevation (A, the green shades) and the root depth (B, the blue shades).

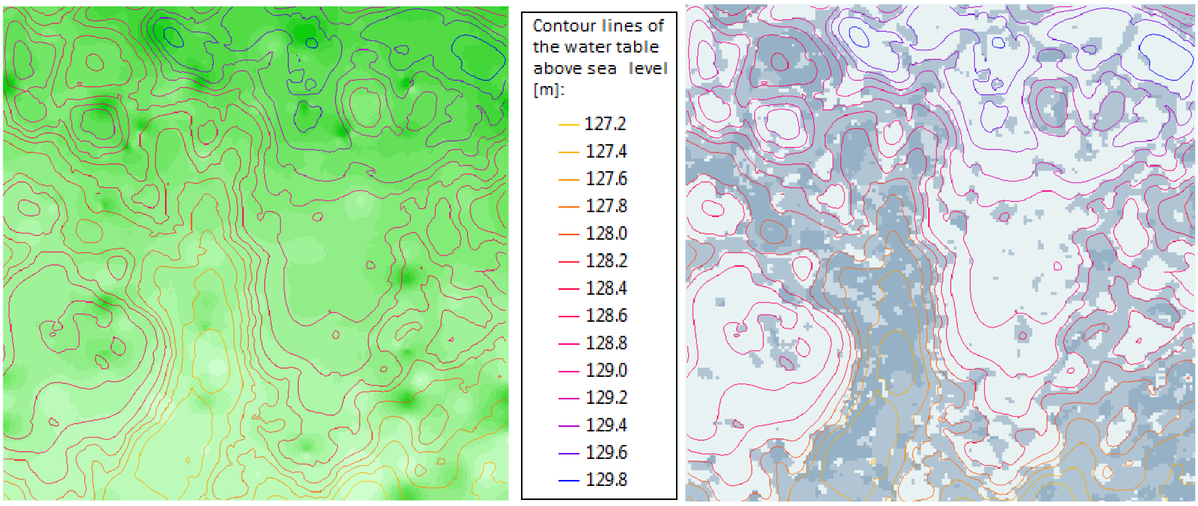


Figure 8 B1 (left) + B2(right): The scenario 3 modeled groundwater level at day 150 (the contour lines) compared to the elevation (A, the green shades) and the root depth (B, the blue shades).

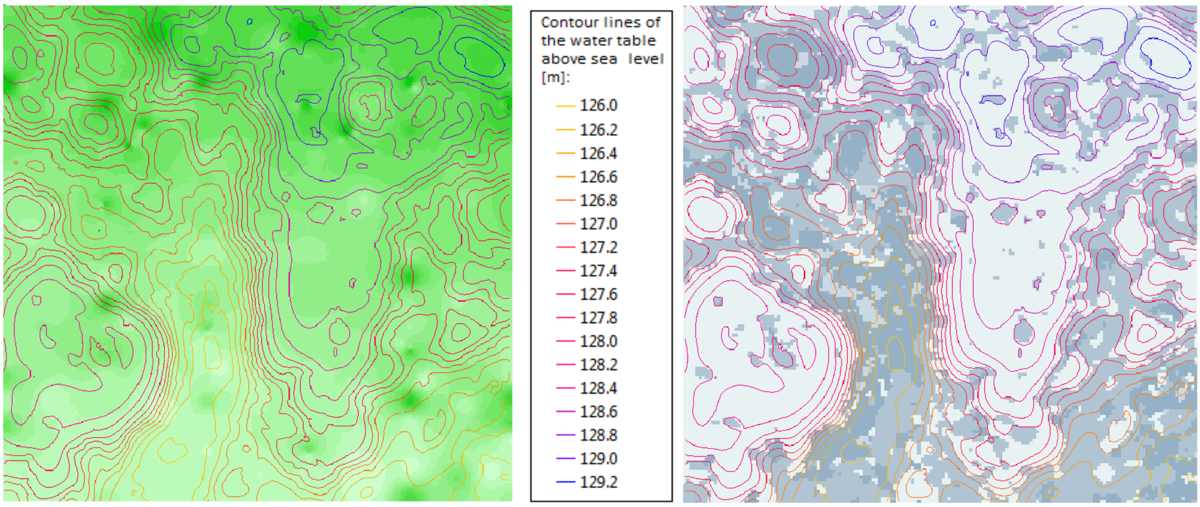
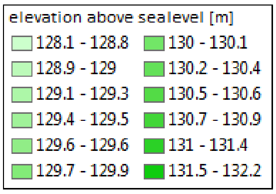
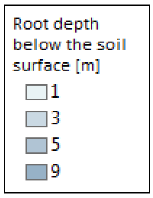


Figure 8 C1 (left) + C2 (right): The scenario 3 modeled groundwater level at day 200 (the contour lines) compared to the elevation (A, the green shades) and the root depth (B, the blue shades).



Figures 8 continued.



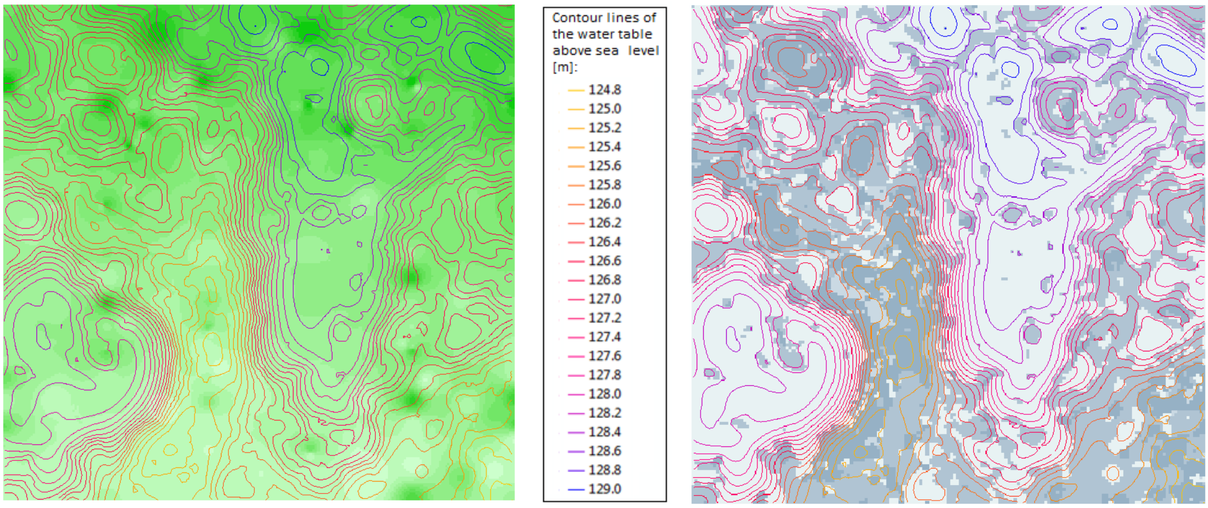


Figure 8 D1 (left) + D2 (right): The scenario 3 modeled groundwater level at day 250 (the contour lines) compared to the elevation (A, the green shades) and the root depth (B, the blue shades).

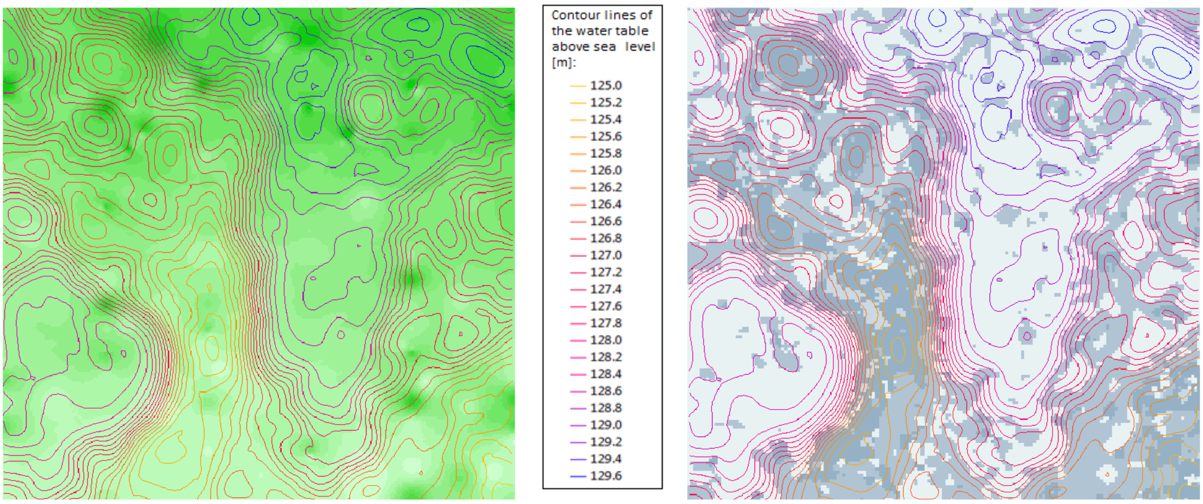


Figure 8 E1 (left) + E2 (right): The scenario 3 modeled groundwater level at day 300 (the contour lines) compared to the elevation (A, the green shades) and the root depth (B, the blue shades).

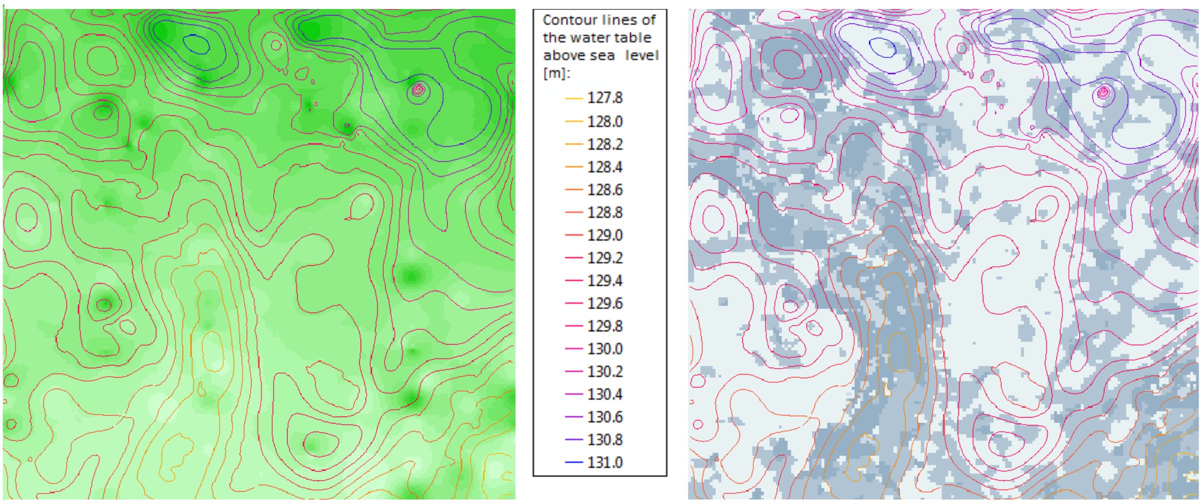


Figure 8 F1 (left) + F2 (right): The scenario 3 modeled groundwater level at day 365 (the contour lines) compared to the elevation (A, the green shades) and the root depth (B, the blue shades).

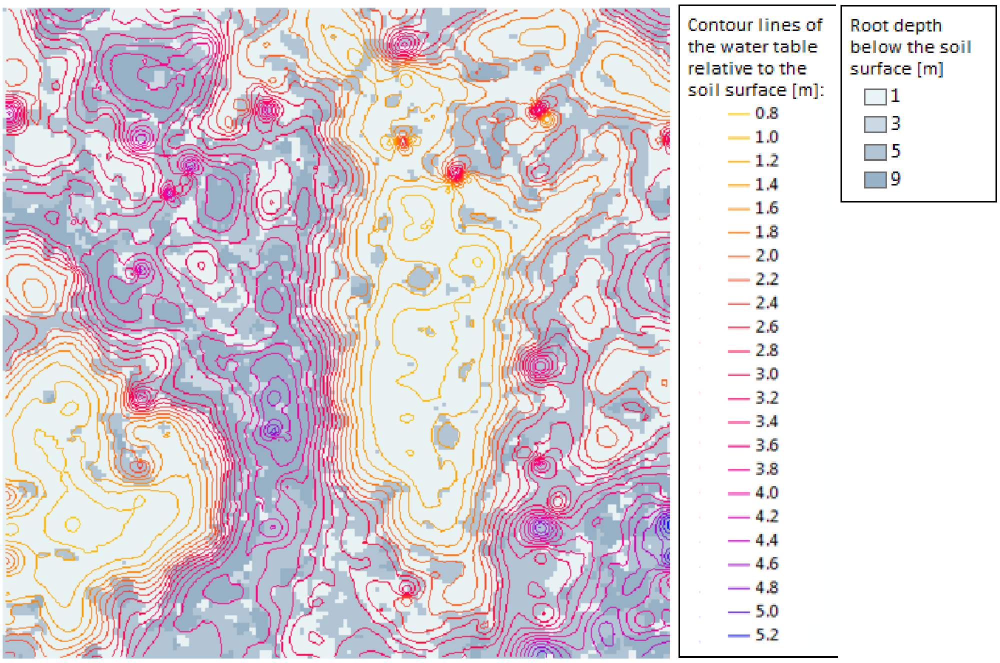


Figure 9: The scenario 3 modeled groundwater depth relative to the soil surface (elevation) at day 250 (the contour lines) compared to the root depth. The map is a 5 by 5 km area.

The figures 7A-7F display the contour lines of groundwater level above sea level and the digital elevation map (DEM) in shades of green. Figure 7A shows that the water level appears to be similar to the DEM. At this timestep small scale differences in the elevation of the water level are visible, but at timestep 150 (figure 7B) the small scale differences have ceased to exist and the water level has become smoother over space. This trend continues to timestep 250 (figure 7D). Although the result is not as smooth as the same timestep in scenario 1, the water level no longer reproduces the small scale elevation differences of the DEM, only the more pronounced general trends in elevation are visible.

From timestep 100 to timestep 250, the water level falls 1.8 to 2.4 m depending on the location. After timestep 250 the groundwater level rises to levels similar to the start of the modelling period. The small scale differences in the elevation of the groundwater level do not appear to return. The cross sections in graphs F1-9 in Appendix F show similar signs validating the analysis of figures 7A-7F.

3.1.1. Scenario 3

Graph 4 appears to be very similar to graph 3, although there are some differences which start after timestep 100. In the dry period the water levels vary more than in scenario 2 (graph 3). Maximum depth of the groundwater level below the soil surfaces varies between 1 and 4 m depending on the location. Another observable difference is that the water level of point 22/E2, which has the deepest groundwater level in the first two scenarios, drops quickly after timestep 80, but after timestep 180 no longer has the deepest groundwater level. The groundwater level for this point does not exceed 3 m during the model period. The reason for this difference compared to the first two scenarios is that point 22/E2 lies on a small scale elevated area, which explains the quick drop in the initial timesteps, but the vegetation at this location has shallow roots which can not draw down the water level as much as in other locations. On other locations deep rooted vegetation can draw down the groundwater level up to 4 m, but this effect is slowly realized between timesteps 80 and 250.

In the figures 8A1-8F2 the scenario 3 water levels are displayed as contour lines, either in combination with the DEM (figures which names end in 1) or with the root depth below soil surface (figures which names end in 2, displaying root depth in shades of blue). At timestep 100 (figures 8A1 and 8A2) the water level is predominantly determined by the soil surface elevation. This changes as is visible at timesteps 150,200 and 250 (figures 8B1-8D2). At timestep 150 the water level is influenced by the root depth of the vegetation. Figure 8B2 shows that the water level contour lines closely follow the transitions between deep and shallow rooted vegetation, with the deep rooted vegetation located on lower lying water levels. In the same timestep it becomes apparent that the influence of the DEM on the water level is decreasing (figure 8B1). This effect increases until timestep 250, when (figure 8D1 and 8D2) the water level is clearly influenced by the root depth and thus vegetation cover. Figure 8D2 shows that deep rooted vegetation decreases the groundwater level up to 3 m more than shallow rooted vegetation. Big patches of deep rooted vegetation adjacent to big patches of shallow rooted vegetation can create a gradient of 2 m water level difference over 500 m horizontal distance. Smaller patches, either deep or shallow rooted, are often encircled by water level contour lines indicating their slight but present influence on the groundwater level.

As the wet period starts, the water level rises to similar levels as in scenario 2. The effect of the soil surface elevation on the water level returns, but the effect of big patches of deep rooted vegetation is still clearly visible at timesteps 300 and 365 (figures 8E1-8F2).

For this scenario additional figures are presented. Figure 9 shows the root depth of the vegetation (in shades of blue) overlain by the contour lines of the groundwater depth relative to the soil surface of timestep 250. In this figure high numbers indicate groundwater levels deeper relative to the soil surface. This shows the influence of the root depth on the groundwater levels. Areas with deep rooted vegetation are accompanied by deeper groundwater levels and vice versa. Transitions between deep and shallow rooted vegetations also show steep gradients in groundwater level as is visible in the increased density of the contour lines in these areas. The influence of soil surface elevation is not entirely gone. In the figure some spots appear to have random groundwater level differences. However, if compared to the surface elevation these spots are accompanied by small scale changes in the elevation. Although not visible in this figure the general trend of the surface elevation (higher in the northeast and lower in the southwest) remains influential on the water levels, albeit it only slightly. The cross sections in Appendix F affirm this. The root depth appears to be the dominant force controlling the groundwater levels at the timesteps in the dry period (timesteps 150-250). In cross section 3 the groundwater level appears to be influenced by the elevation throughout the modelling period. This is less pronounced in the other cross sections.

Figures 10, 11 and 12 present two relationships of the groundwater and the vegetation. Figure 11 shows the root depth to facilitate comparing root depth with the results of figures 10 and 12. In figure 10 it is shown how many days of the modelling period the groundwater was not available to the vegetation at that cell, because the roots where not deep enough to reach the fallen groundwater level in that cell. Comparing figures 10 and 11 it shows that, if a cell indicates the roots are unable to reach the groundwater during certain timesteps, the vegetation was mainly shallow rooted (root depth 1 m). However, the number of days the most shallow rooted vegetation was unable to reach the groundwater varies between 0 and 362 days. This variation predominantly depends on the location of the shallow rooted vegetation in regard to the deeper rooted vegetation. The deep rooted vegetation draws down the groundwater level below the reach of the shallow rooted vegetation, but this affects only approximately 200-300 m in a horizontal direction. Beyond this “reach,” the groundwater is not affected by the deeper rooted vegetation and does not drop below the shallow rooted vegetation. This indicates that shallow rooted vegetation near deeper rooted vegetation can experience increased difficulties in dry periods. Another influence on the number of days the roots cannot reach the groundwater is the small scale differences in surface elevation. At small raised areas the groundwater level quickly falls due to gravitationally induced groundwater flow.

Figure 12 shows the total recharge of a cell over the modeled period. As precipitation does not vary over space, all spatial differences are due to the differences in evaporation. This figure shows that some cells have a total evaporation that exceeds the total precipitation and other cells the opposite. Figures 10 and 12 show similarities, due to the fact that evaporation decreases with falling groundwater levels and is ceased entirely if the groundwater level drops below the reach of the roots. Therefore shallow rooted vegetation show less evaporation than deep rooted vegetation. Figure 12 also presents a difference within the groups of deep rooted vegetation. Within these groups cells that are adjacent to shallow rooted vegetation show increased evaporation. This is due to the groundwater flow from the patches with shallow roots to the patches with deeper rooted vegetation. This groundwater flow first reaches the vegetation adjacent to these patches and also becomes less influential the further it reaches. This indicates that for deep rooted vegetation it can be beneficial to be adjacent to shallow rooted vegetation in dry periods.

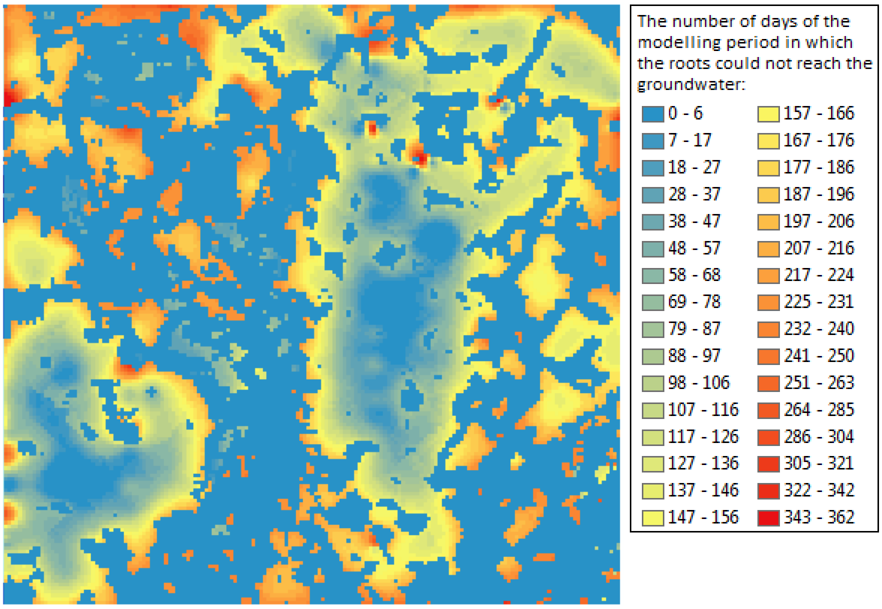


Figure 10: The number of days the vegetation cannot reach the groundwater. Blue colors indicate availability of groundwater year round, whereas red colors indicate that groundwater is out of reach for up to 362 days. This map is 5 by 5 km .

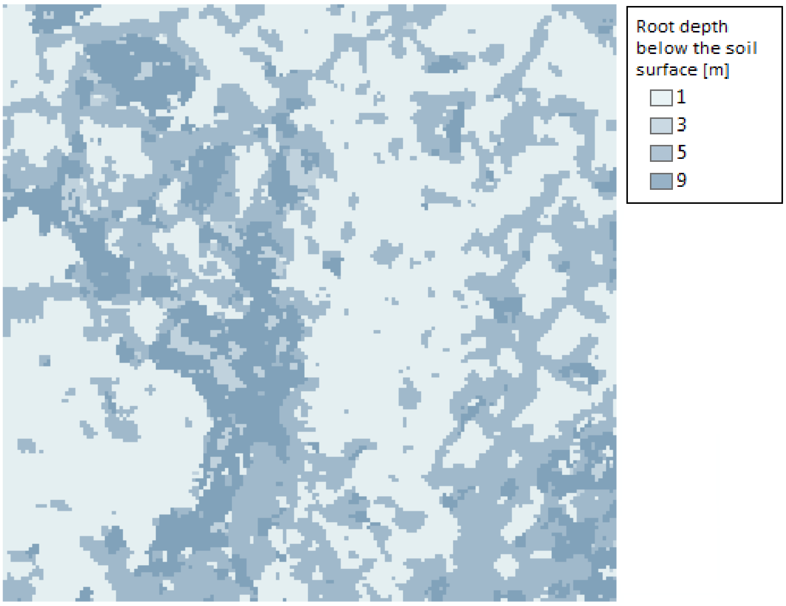


Figure 11: The root depth below the soil surface. This map is 5 by 5 km.

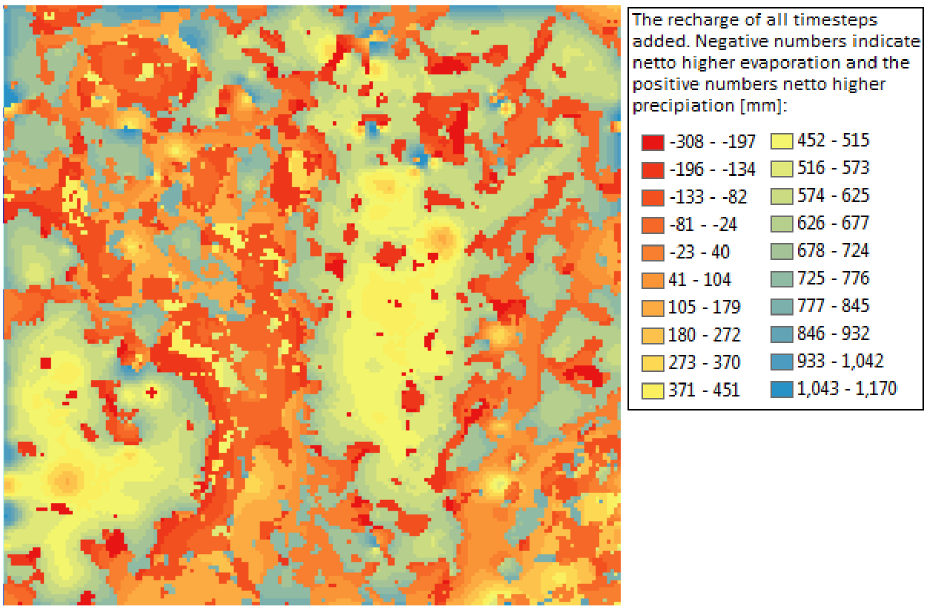


Figure 12: The recharge of all timesteps added. Negative numbers indicate higher evaporation, whereas positive numbers indicate higher precipitation. As precipitation does not vary spatially, all variation in recharge is due to differences in evapotranspiration. This map is 5 by 5 km.

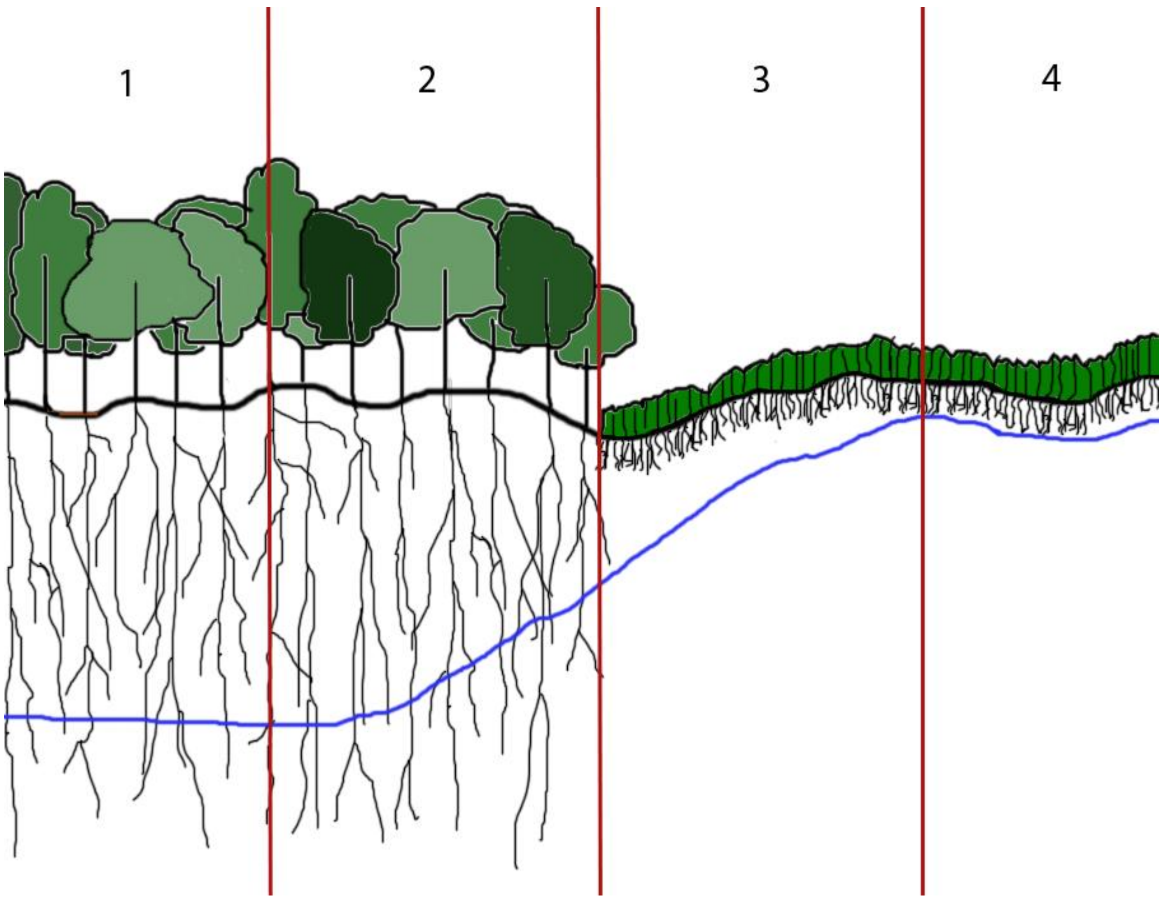
4. Discussion

4.1. Model behavior

The groundwater behavior over time varies between scenarios. Although the reaction to precipitation and evaporation is similar in the scenarios, scenario 1 has a very steep fall of the groundwater table over the entire study area. The decline, a drop of almost 20 m, is not a good representation of reality, where the groundwater table rises to levels around or above the soil surface after the dry season. It is difficult to pinpoint the reason for this exaggerated fall in scenario 1, but it may indicate that it is necessary to implement a limit to evaporation when the groundwater table falls. This makes scenarios 2 and 3 more realistic. The modeled groundwater fluctuates similar to reality as described in the literature, with clearly defined seasonality and groundwater depths which are within the spectrum of depths defined by the measurements.

Water levels similar to the modeled water levels of the wet season were found in a study by Girard & Nuñes da Cunha (1999). In this study the water level were around the soil surface, mostly above in lower elevated areas and mostly beneath in higher elevated areas. Measurements in this study stopped at the end of the wet season so no comparison could be made in the dry season. However a study by Girard *et al.* (2003) encounters similar groundwater levels to the scenarios 2 and 3. Their findings were between 2.0 and 5.6 m below the soil surface. The maximum depth is deeper than the deepest model result in scenarios 2 and 3. A difference in the study by Girard *et al.* (2003) and this modelling study is the influence of the river stage. The groundwater table was critically dependent on the river stage, however in this study that is not modeled, as it was assumed that the study area was too far from a river to be influenced.

In scenario 2 and 3 the water table drops from between 0 and 1 m below the soil surface to between 2.2 and 3.4 m or 1 and 4 m for scenarios 2 and 3 respectively. This also highlights the major difference between these scenarios, as the spatial variation in groundwater depth is greater in scenario 3. In scenario 2 only the surface elevation plays a role in the distribution of the groundwater, but for scenario 3 another influence is the evapotranspiration differences caused by varying root depth of the vegetation. As a result, the scenario 2 groundwater table closely follows the surface elevation. During the dry period it smoothes out, as groundwater has flown from higher to lower hydraulic head. In scenario 3 the distribution of the vegetation has created a difference in evapotranspiration. In the dry period the short rooted vegetation quickly finds difficulty reaching the groundwater. This decreases their ability to transpire. Deep rooted vegetation continues to have access to the groundwater throughout the modelling period and therefore also continue to evapotranspire. From figure 12 it is visible that there are differences in evapotranspiration, not only between deep and shallow rooted vegetation, but also between equally rooted vegetation. This is due to the result that the vegetation influences the groundwater levels and thus groundwater flow. As seen in figure 8D2, at timestep 250 in scenario 3 the deep rooted vegetation has drawn down the groundwater table up to 2 m deeper than the shallow rooted vegetation has. This creates a difference in hydraulic head. The groundwater thus flows from the shallow rooted vegetation to the deep rooted vegetation. The influence is controlled by the horizontal distance. The influence of the flow is therefore strongest for vegetation immediately adjacent to vegetation of other root depth, i.e. shallow next to deep rooted vegetation. At these transition borders groundwater depths are approximately an average of both the deep and shallow rooted groundwater table. This is beneficial for the



1	2	3	4
The deep rooted vegetation draws down the water table, however the roots are deep enough to reach the groundwater the entire year. Too far for groundwater to flow in and compensate for the low groundwater levels.	The deep rooted vegetation draws down the water table, but the groundwater table is replenished by the adjacent area where the shallow rooted vegetation cannot draw down the water level further. Groundwater flow towards this area benefits this vegetation, hence the increased evapotranspiration.	The shallow rooted vegetation can only draw down the groundwater to just below their reach. Because the groundwater is higher elevated than the adjacent deep rooted area, the groundwater also flows to that area. This decreases the groundwater level quicker and more out of reach. This is disadvantageous as this vegetation is therefore longer unable to reach the groundwater.	The shallow rooted vegetation can only draw down the groundwater to just below their reach. The groundwater does not flow away as the distance is to great to influence this area. All the groundwater this vegetation can reach can be evapotranspired by it.

Figure 13: A sketch of the groundwater table (blue line) as situated according to scenario 3 in the dry period. The deep rooted vegetation in areas 1 and 2 draw down the water level more than in the short rooted areas 3 and 4. This results in groundwater flow. Due to the distance groundwater flow is mainly from area 3 to area 2. More extensively described in the accompanying table.

deep rooted vegetation as the groundwater is easier to access, but disadvantageous for the shallow rooted vegetation as the groundwater is deeper and harder to reach. This is highlighted by figure 12. In this figure maximum evapotranspiration occurs where deep rooted vegetation is immediately adjacent to minimum evapotranspiration rates, which is where shallow rooted vegetation grows.

This modelling study shows that vegetation influences groundwater distribution, but it is difficult to indicate the influence of groundwater on vegetation. From scenario 1 and 2 no relationship between vegetation and groundwater is visible. Only in scenario 3 a relationship is visible, however, as explained above, this arises through the variation in evaporation and thus driven by the vegetation.

It was mentioned earlier that the drought stress might increase species diversity along the mechanisms of the Intermediate Disturbance Hypothesis (IDH)(Roxburgh *et al .,* 2004). However, contrary to the IDH, where stress decreases succession, this model shows that the groundwater availability favors the deep rooted vegetation. These deep rooted vegetation types are successors to the shallow rooted vegetation types. Thus the transition to the final successional stages is promoted by the groundwater. For the vegetation of part 2 in figure 13 to not colonize part 3 in figure 13, an other environmental disturbance must take place to halt this. Without another stress the patchiness in the Pantanal would likely not exist.

Self organization of vegetation as mentioned by Rietkerk *et al.* (2002) and Rietkerk *et al.* (2004) is a process that is based on a limiting factor, i.e. water shortage or nutrient limitation. These studies show that these limiting factors assure that the area does not become covered by a single vegetation type, in a mono-dominancy, because the limiting factor only supports partial coverage of this vegetation. It is unlikely that the groundwater is limiting enough to force self organization upon the deep rooted vegetation in the study area. To prove this however, a modelling study is necessary which models plant growth as a function of water availability over multiple years. This study is limited to one year and it is therefore is not possible to formulate conclusions on self organization.

4.2. Model uncertainties and improvement possibilities

Although a model is always a simplification of reality and much input data are estimates and do not consider spatial variation, there are some ways in which the model performance can be improved. First the surface elevation of the study area has proven to be important for groundwater in this study as can be seen in scenarios 1 and 2. The digital elevation map (DEM) of this study was created using inverse distance weighting (IDW) of approximately 230 elevation data points. These points were highly accurate, however the IDW technique was not capable of recreating the exact surface elevation due to lack of data. The difference between the personal observation of the study area and the DEM used for modelling is that small scale variations in elevation were often paleo-levees, which are long and narrow. Due to the lack of points these paleo levees were modeled as individuals mounds. Besides these levees, other inaccuracies ensured that the DEM was not a perfect model of reality. Therefore, vegetation that mainly grows at a certain landscape unit and thus preferred elevation may be modeled to grow at alternating elevations. Increasing the accuracy of the DEM would greatly increase the accuracy of the surface and groundwater modelling.

Second, soil texture is modeled as homogeneous. It is known that in the study area the soil texture varies greatly in both horizontal as vertical directions. Girard *et al.,* (2003) found that groundwater could be confined to highly conductive sand layers beneath clay layers. This is a result that is impossible to model without spatial variation in soil texture. The soil texture may greatly influence groundwater flow and for increased accuracy it is advisable to incorporate soil texture variation into a model.

In this modelling study it was assumed that runon and runoff were negligible. This may be unlikely as the Pantanal, including this study area, is a alluvial depression and consists mainly of alluvial deposits, which are only deposited during inundation. Furthermore, Heckman (1998) states that evaporation exceeds precipitation by 300 mm in the Pantanal. This is only possible if the excess evaporation is equaled by either surface runon or groundwater flow and in the Pantanal the former is more likely.

5. Conclusion

In this modelling study a groundwater model was created using PCRasterMODFLOW. For the model, the vegetation distribution map was used and a digital elevation map created from 230 elevation points. Additionally, precipitation and evaporation, calculated with the Penman-Monteith equation, were used to simulate spatio-temporal changes in the groundwater. 3 different scenarios were modeled, the first with no limit to evaporation with falling groundwater level, the second and third scenario with decreasing evaporation as groundwater drops depending on the root depth. In the second scenario root depth was uniform and was 3 m below the soil surface, whereas in the third scenario root depth depended on the vegetation distribution and varied 1 to 9 m below the soil surface.

The behavior of the groundwater varied per scenario. In scenario 1 the groundwater fell to almost 20 m below soil surface. This is not observed in or measured in the Pantanal and would also have a strong impact on the vegetation as it would not be able to reach the groundwater during at least 100 days of the year. In scenario 2 and 3 the groundwater behaved more realistic. The groundwater table was just above or just below soil surface during the wet season, both in the beginning of the modeled year as at the end, and in between in the dry season the groundwater table was 2 to 4 m below the soil surface. In scenario 2 the groundwater table varied little over space and it was only influenced by the variation in surface elevation. In scenario 3 however, the variation of the water table varied over space, up to 2 m over 1 km horizontal distance. The groundwater was deepest at locations with deep rooted vegetation and least deep at locations with shallow rooted vegetation.

From this modelling study it became apparent that the evaporation at locations with deep rooted vegetation was higher than at shallow rooted vegetation. There was also observable difference in evaporation between locations with equal rooting depth. Deep rooted vegetation immediately adjacent to shallow rooted vegetation had increased levels of evaporation in comparison to deep rooted vegetation surrounded by other deep rooted vegetation. This is due to groundwater flow from shallow rooted vegetation in the direction of the deep rooted vegetation. This benefits the closest deep rooted vegetation most. The opposite happens for the shallow rooted vegetation adjacent to the deep rooted vegetation. Here the groundwater flows away to the deep rooted vegetation decreasing the available groundwater for evaporation. This effect is weaker the further away from the deep rooted vegetation the location is.

According to this study the behavior of the groundwater as is modeled in this study has no effect on the distribution of the different vegetation types. The groundwater is accessible to deep rooted vegetation throughout the modeled year. The groundwater behavior benefits deep rooted vegetation, therefore there must be an other environmental factor that halts the colonization of the entire model area by this vegetation and keeps this equilibrium of patched vegetation.

The vegetation does affect the groundwater distribution. The deep rooted vegetation is able to draw down the groundwater level up to 2 m more than the shallow rooted vegetation. This creates a gradient along which groundwater flows in the direction of the deep rooted vegetation. In scenario 3 the groundwater contour lines were lay parallel to the borders of shallow to deep rooted vegetation. It is clear that the vegetation was the main factor controlling the groundwater level.

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Appendices

I. Appendix A: Meteorological data

Table A1: Sun's short wave radiation per month, S_0 (MJ m^{-2} day^{-1}) for the latitude 20° South.

Sun's short wave radiation per month, S_0 (MJ m^{-2} day^{-1}) for the latitude 20° South	
January	41.9
February	40.0
March	36.6
April	31.3
May	26.6
June	24.1
July	25.0
August	28.9
September	34.2
October	38.6
November	41.2
December	42.1

Table A2: In this table the meteorological data is shown used in the model. Precipitation, relative humidity and temperature were measured by Instituto Nacional De Meteorologia (INMET) in the year 2002.

day of the year	Precipitation (mm)	Potential Evaporation (mm)	Relative humidity (-)	Temperature (°C)
1	3	3.36	0.94	25.6
2	6	4.70	0.80	27.6
3	0	5.52	0.71	28.2
4	0	5.46	0.73	28.7
5	2	4.99	0.77	27.6
6	7	3.81	0.89	26.3
7	7	3.72	0.90	26.1
8	13	3.91	0.88	26.5
9	14.6	2.91	0.80	26.3
10	33.6	3.18	0.95	24.9
11	22	3.26	0.92	24.3
12	31	4.48	0.81	26.6
13	0	4.90	0.76	27.0
14	0	1.21	0.81	27.8
15	0	2.91	0.80	27.0
16	0	2.91	0.80	27.0
17	7	5.04	0.76	27.5
18	0	5.60	0.70	28.0
19	0	5.55	0.68	27.0
20	0	4.90	0.76	27.0

21	0	4.30	0.83	26.7
22	2	4.79	0.80	27.8
23	1	10.44	0.80	28.8
24	0	6.43	0.66	30.2
25	0	6.99	0.60	30.7
26	0	10.73	0.80	29.7
27	1	4.68	0.80	27.4
28	47	4.53	0.82	27.4
29	0.4	4.32	0.84	26.9
30	20	2.91	0.80	26.9
31	0	4.29	0.86	27.6
32	0	4.87	0.76	27.8
33	0	4.12	0.83	26.6
34	6	4.15	0.84	26.9
35	0	3.68	0.88	26.0
36	0	4.07	0.85	26.9
37	0	3.90	0.86	26.6
38	23	3.16	0.93	25.2
39	41	3.22	0.93	25.6
40	8	3.58	0.90	26.2
41	4	4.53	0.82	28.3
42	0	3.50	0.88	24.8
43	0	4.61	0.79	27.4
44	1	4.37	0.82	27.3
45	0	2.86	0.80	26.3
46	0.1	4.66	0.80	28.1
47	0.2	3.50	0.88	24.9
48	40	3.77	0.87	26.3
49	50	3.20	0.93	25.2
50	12	3.10	0.95	25.7
51	7	4.14	0.83	26.7
52	0.2	3.67	0.89	26.3
53	1	3.69	0.88	26.1
54	41	3.76	0.89	26.9
55	0	3.22	0.94	26.0
56	11	4.37	0.83	27.9
57	5	3.21	0.92	25.1
58	5	4.25	0.82	26.8
59	0.5	1.03	0.87	26.3
60	0	3.59	0.84	25.5
61	0	4.15	0.80	27.1
62	0	3.91	0.84	27.6
63	0.8	4.23	0.80	27.4
64	0	4.03	0.80	26.3
65	6	4.86	0.73	27.8
66	0	3.95	0.79	25.5
67	9	4.31	0.78	27.0
68	0	4.07	0.83	27.8
69	0	3.48	0.88	26.4
70	13	3.80	0.84	26.9
71	0	4.57	0.76	27.7
72	0	4.82	0.75	28.5
73	0	3.98	0.83	27.5
74	16	5.37	0.70	29.4

75	2	4.51	0.80	29.0
76	0	1.24	0.73	29.0
77	0	3.99	0.82	27.1
78	1	3.78	0.85	26.9
79	6	1.05	0.82	26.9
80	0	3.85	0.83	26.7
81	44	3.33	0.87	25.2
82	3	2.76	0.80	25.2
83	0	3.77	0.83	26.2
84	18	2.87	0.94	25.4
85	0.7	3.38	0.90	26.8
86	18	8.75	0.80	24.8
87	1	3.71	0.85	26.5
88	3	2.76	0.80	26.3
89	0	4.18	0.83	28.4
90	0	4.06	0.83	27.9
91	4	5.00	0.68	29.0
92	0	3.08	0.86	25.8
93	12	3.66	0.81	27.0
94	0	4.03	0.78	27.9
95	0	4.59	0.72	28.6
96	0	4.18	0.75	27.6
97	0	4.55	0.73	28.7
98	0	3.86	0.80	27.8
99	0	4.38	0.72	27.4
100	0	4.41	0.72	27.8
101	0	3.74	0.81	27.7
102	0	2.97	0.89	26.8
103	0	3.33	0.85	26.9
104	0	3.08	0.87	26.5
105	0	8.75	0.80	26.3
106	3	3.04	0.87	26.2
107	0	2.62	0.80	26.3
108	0.8	3.03	0.87	25.8
109	7	3.41	0.82	25.9
110	0	8.92	0.80	26.9
111	3	3.24	0.87	27.3
112	0	4.21	0.74	27.4
113	0	4.05	0.75	27.0
114	2	4.45	0.71	27.6
115	0	8.68	0.80	26.0
116	0	4.22	0.73	26.8
117	0	4.08	0.74	26.7
118	0	3.91	0.78	27.4
119	0	3.75	0.78	26.5
120	3	2.62	0.80	26.3
121	0	3.22	0.81	27.2
122	0	3.46	0.79	27.8
123	0	3.89	0.76	28.6
124	0	3.46	0.79	27.6
125	2	3.67	0.76	27.4
126	6	2.13	0.93	25.3
127	6	2.39	0.88	24.4
128	0.6	3.07	0.79	25.1

129	0	2.48	0.80	26.3
130	0	3.49	0.77	26.8
131	0	3.33	0.80	27.1
132	0	8.64	0.80	27.3
133	0	3.95	0.72	27.3
134	0	3.87	0.76	28.5
135	0	4.04	0.74	28.8
136	0	4.50	0.69	29.1
137	0	3.78	0.75	27.6
138	0	3.86	0.74	27.6
139	0	4.21	0.71	28.3
140	0	3.21	0.77	24.9
141	28	1.61	0.95	21.3
142	2	2.08	0.86	20.3
143	0	2.50	0.82	22.3
144	0	0.81	0.80	26.3
145	0	3.15	0.75	23.7
146	0	2.58	0.85	24.5
147	0	3.48	0.75	25.9
148	0	3.67	0.69	24.1
149	0	3.69	0.68	23.8
150	0	3.36	0.73	24.1
151	0	4.43	0.59	24.5
152	0	2.27	0.85	23.6
153	0	3.30	0.75	25.7
154	0	3.35	0.72	24.8
155	3	3.27	0.72	24.2
156	0	3.75	0.65	24.2
157	0	3.64	0.66	24.1
158	0	3.50	0.68	23.9
159	0	3.51	0.68	24.0
160	0	2.91	0.77	24.3
161	0	3.93	0.65	25.3
162	0	3.52	0.69	24.5
163	0	0.70	0.82	26.3
164	0	1.47	0.90	18.0
165	0	0.59	0.87	26.3
166	0.3	1.43	0.90	17.6
167	0.2	1.87	0.87	20.6
168	0	3.03	0.74	23.5
169	0	3.44	0.70	24.3
170	0	2.34	0.82	22.2
171	0	3.80	0.69	26.5
172	0	3.66	0.66	23.9
173	0	0.78	0.79	26.3
174	0	1.85	0.83	18.4
175	0	2.51	0.75	19.9
176	0	2.85	0.73	21.8
177	0	3.38	0.69	23.8
178	0	3.44	0.69	23.8
179	0	3.95	0.66	25.9
180	0	3.98	0.66	26.1
181	0	3.33	0.73	25.0
182	0	1.20	0.60	26.3

183	0	3.87	0.66	25.0
184	0	4.24	0.61	24.9
185	0	2.44	0.80	26.3
186	0	2.32	0.80	20.5
187	0	2.63	0.78	21.9
188	0	1.99	0.81	18.1
189	0	2.45	0.73	18.1
190	0	3.58	0.63	21.8
191	0	3.80	0.64	23.6
192	0	3.67	0.66	23.7
193	0	3.45	0.69	23.5
194	0	3.01	0.71	21.6
195	0	2.94	0.74	22.4
196	0	3.07	0.74	23.1
197	0	3.46	0.73	25.7
198	0	4.43	0.61	26.1
199	0	4.53	0.61	26.7
200	0	4.41	0.61	25.9
201	0	4.19	0.67	27.2
202	0	0.92	0.73	26.3
203	7	4.11	0.68	27.2
204	0	5.33	0.53	27.5
205	0	4.80	0.63	29.0
206	0	5.01	0.59	28.3
207	0	2.55	0.81	22.9
208	0	2.62	0.80	22.7
209	0	2.06	0.86	21.2
210	0	2.81	0.80	24.4
211	0	3.74	0.72	26.7
212	0	2.56	0.82	23.5
213	23	2.61	0.87	24.1
214	0	2.63	0.79	20.3
215	0	0.88	0.80	26.3
216	0	3.49	0.76	25.3
217	0	4.29	0.69	26.8
218	0	4.44	0.68	27.4
219	0	4.87	0.66	28.8
220	0	5.30	0.58	27.9
221	0	5.20	0.56	26.4
222	0	3.86	0.71	25.2
223	0	1.57	0.48	26.3
224	0	5.68	0.52	27.5
225	0	5.20	0.58	27.1
226	0	5.57	0.53	27.2
227	0	5.14	0.56	26.3
228	0	5.50	0.54	27.1
229	0	5.70	0.55	28.4
230	0	5.89	0.54	28.9
231	0	6.69	0.46	29.8
232	0	6.09	0.50	28.6
233	0	4.03	0.72	26.4
234	0	4.92	0.63	27.7
235	0	5.06	0.62	28.0
236	0	4.92	0.61	27.1

237	0	6.14	0.53	29.8
238	0	6.54	0.49	30.0
239	0	6.75	0.44	29.2
240	0	6.60	0.49	30.3
241	0	4.81	0.63	27.1
242	3	2.50	0.86	23.1
243	0.2	2.55	0.80	26.3
244	1	4.17	0.58	19.8
245	0	3.99	0.55	18.0
246	0	5.72	0.42	22.6
247	0	5.87	0.51	25.7
248	0	6.41	0.52	28.4
249	0	6.73	0.55	30.9
250	0	4.83	0.69	27.1
251	2	5.53	0.58	26.6
252	0	6.22	0.56	29.0
253	0	6.75	0.52	30.0
254	0	7.69	0.41	30.1
255	0	7.09	0.45	29.0
256	0	4.84	0.69	27.3
257	0	4.75	0.72	28.0
258	0	3.52	0.84	26.3
259	32	4.76	0.73	28.4
260	0	4.71	0.74	28.5
261	0	5.06	0.69	28.5
262	0	5.88	0.61	29.4
263	0	4.13	0.78	27.2
264	8	3.89	0.72	23.3
265	0	4.71	0.65	25.1
266	0	4.06	0.72	24.0
267	25.4	3.66	0.77	23.9
268	0	4.80	0.63	25.0
269	0	5.56	0.57	26.6
270	0	2.70	0.80	26.3
271	0	6.01	0.56	28.3
272	0	6.62	0.55	30.4
273	0	6.85	0.53	30.8
274	0	6.73	0.58	30.2
275	0	7.10	0.56	31.0
276	0	7.19	0.53	30.3
277	0	7.21	0.54	30.8
278	0	6.83	0.60	31.2
279	0	8.12	0.48	32.3
280	0	6.94	0.54	29.7
281	0	7.91	0.47	31.2
282	0	7.85	0.48	31.3
283	0	7.15	0.53	30.3
284	0.8	6.77	0.54	29.0
285	0	6.79	0.56	29.8
286	0	5.11	0.70	27.1
287	0	7.55	0.48	30.2
288	0	7.19	0.53	30.3
289	0	7.89	0.46	31.0
290	18.4	3.19	0.91	25.2

291	20	4.41	0.79	27.2
292	0	6.34	0.59	28.8
293	0	5.69	0.69	29.6
294	0	4.73	0.77	27.8
295	0	4.66	0.74	26.2
296	0	2.82	0.80	26.3
297	0	7.20	0.56	31.3
298	1.4	5.81	0.65	28.6
299	0	1.50	0.64	26.3
300	0	1.52	0.63	26.3
301	0	6.95	0.56	30.4
302	0	5.94	0.66	29.5
303	32	3.99	0.82	25.9
304	0	4.16	0.78	25.2
305	0	5.48	0.70	27.8
306	0	5.15	0.75	28.0
307	1	5.92	0.67	28.9
308	0	4.09	0.87	27.7
309	61.4	2.81	0.94	22.0
310	0	5.72	0.69	28.4
311	1.6	5.54	0.71	28.4
312	0	5.45	0.74	29.2
313	3	4.90	0.78	28.1
314	0	4.22	0.85	27.3
315	4	4.19	0.84	26.9
316	3	4.46	0.80	26.7
317	0	6.17	0.64	28.9
318	0	1.53	0.66	26.3
319	0	6.67	0.58	29.0
320	0	1.73	0.57	26.3
321	0	7.02	0.57	30.0
322	0	7.46	0.56	31.4
323	0	8.25	0.49	32.0
324	0	6.83	0.64	31.5
325	0	7.33	0.58	31.5
326	0	6.19	0.65	29.4
327	0	4.31	0.84	27.6
328	0.4	6.29	0.63	28.9
329	0	6.75	0.61	30.2
330	0	5.78	0.69	29.0
331	0	2.89	0.80	26.3
332	0	6.25	0.66	29.8
333	22.8	4.43	0.81	26.6
334	0.2	2.89	0.80	26.3
335	0	5.27	0.71	26.8
336	1.8	4.97	0.79	28.2
337	0.6	5.14	0.74	27.3
338	3.3	4.37	0.84	27.3
339	1.8	6.49	0.64	29.7
340	0	7.24	0.58	31.0
341	0	7.39	0.57	31.1
342	0	7.46	0.54	30.3
343	3.6	4.18	0.86	27.2
344	0	4.79	0.79	27.4

345	1.8	3.80	0.89	26.3
346	8	3.06	0.97	24.9
347	87	4.15	0.85	26.3
348	0	3.90	0.88	26.2
349	24	3.55	0.90	25.2
350	6	3.94	0.87	26.0
351	7	4.72	0.81	27.9
352	24	4.92	0.78	27.7
353	0.6	5.01	0.75	27.1
354	0.6	5.47	0.71	27.9
355	0	5.79	0.70	28.8
356	0	7.10	0.57	30.0
357	0	7.35	0.57	31.1
358	0	6.42	0.64	29.7
359	0	5.13	0.75	27.6
360	24.8	5.63	0.70	28.2
361	0	5.16	0.76	28.0
362	0	4.34	0.84	27.2
363	1	5.11	0.77	28.2
364	0	4.64	0.82	28.0
365	7	3.68	0.91	26.4

II. Appendix B: Map of the sudy area

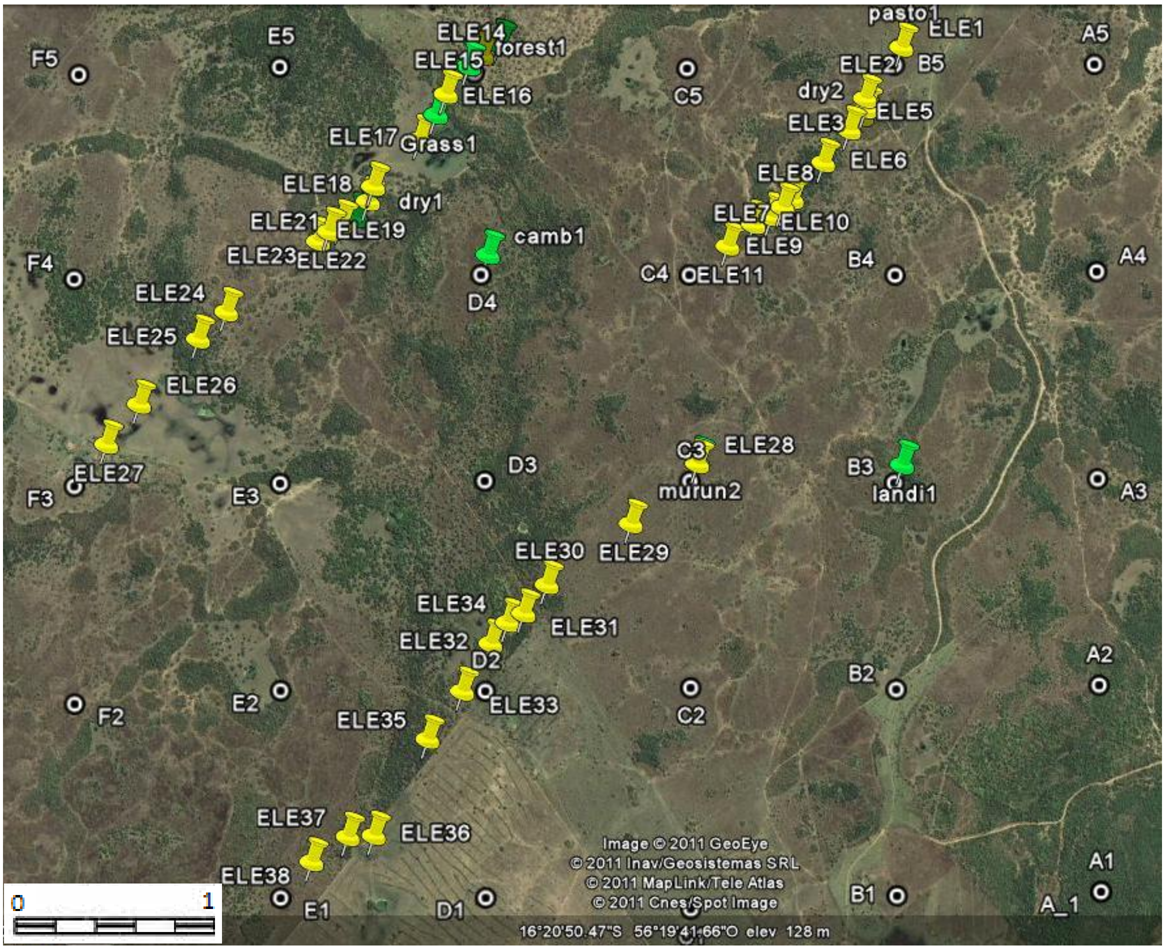


Figure B1: The study site in the Pantanal of Pirizal. The 30 groundwater and surface water measurement points are the round black and white dots with the letters(A-F) and numbers (1-5). The yellow pins with the description ELE and a number (1-38) are the proposed additional elevation points measured along three different transects. The green pins (not all visible) are the 9 proposed drilling sites.

III. Appendix C: Map of the vegetation

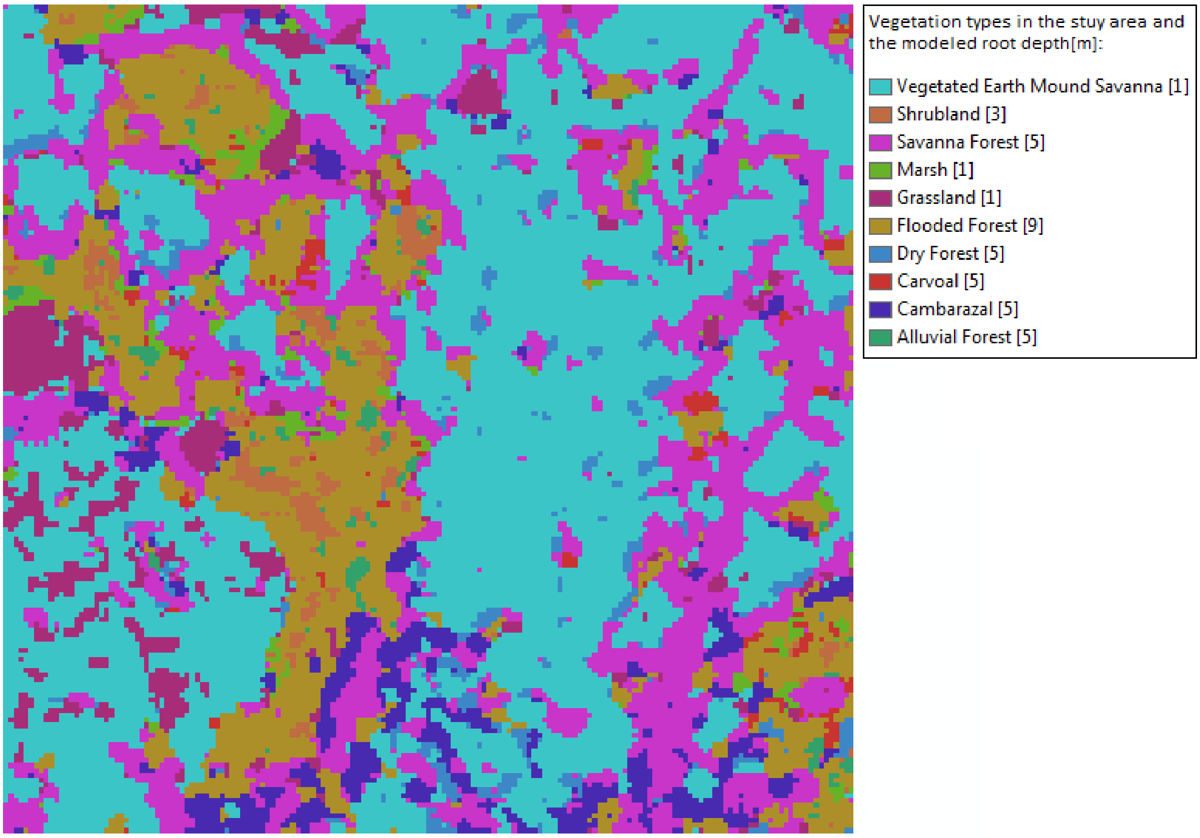


Figure C1: the 5 by 5 km vegetation map of the study area, adapted from Arieira et al. (2011).

IV. Appendix D: Drilling results

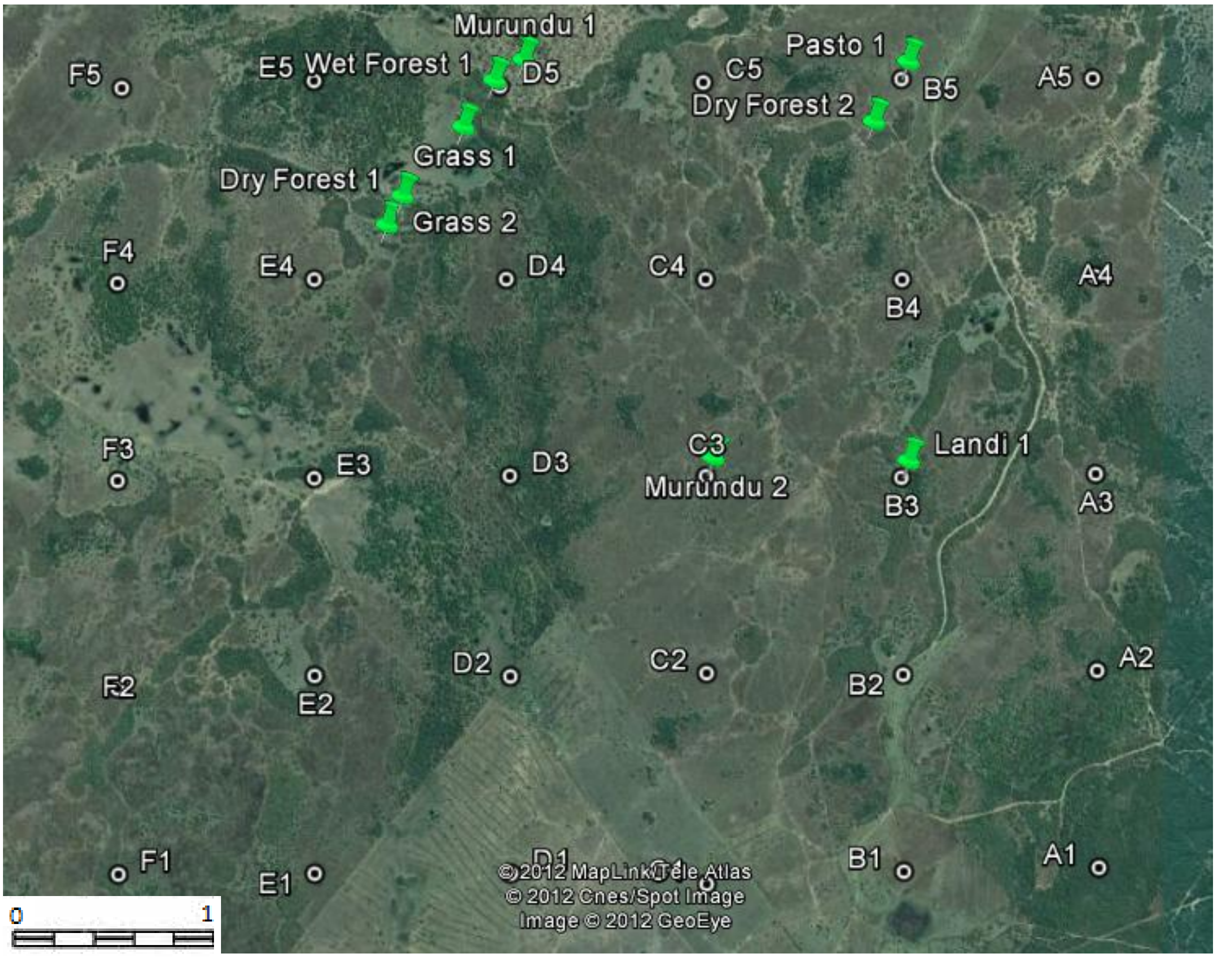


Figure D1: Location of the drilling sites in the study area. The names correspond to the names in table D1.

Table D1: Results of drilling in the study area. Every 20 cm the soil texture was measured by hand and rated on a scale of 1-7, where 1 was all sand and 7 all clay. Blue means the groundwater was encountered there and Rock! indicates a rock halted any further drilling at that site.

depth (cm)	Pasto1	dry forest 2	Landi 1	Murundu 2	Wet forest 1a	Wet forest 1b	Wet forest 1c	Wet Forest 1d
20	1	3	1	1	1	1	1	4
40	1	3	1	1	1	Rock!	1	4
60	5	3	1	1	Rock!		Rock!	4
80	5	4	1	4				5
100	5	4	1	5				4
120	6	5	1	5				3
140	6	5	5	5				4
160	7	4	5	5				4
180	7	5	5	3				1
200	7	5	5	5				1
220	7	7	5	5				1
240	7	7	1	3				1
260	7	5	1	3				1
280	1	5	1	1				1
300	4	5	1	1				1
320	6	5	1	1				1
340	7	5	1	1				1
360	7	6	1	1				1
380	7	6	1	1				1
400	7	6	1	1				1
420	7	6	1	1				
440	7	7	1					
460	7	1	1					
480	7	1	1					
500	7	1	1					

1 = Sand
2 = Sand with a little bit clay
3 = Sand with a bit clay
4 = Sand/Clay mixture
5= Clay with a bit sand
6 = Clay with a little bit sand
7 = Clay
Blue = Groundwater

Table D1 continued

depth (cm)	Grass 1	Murundu 1	Dry Forest 1a	Dry Forest 1b	Grass 2
20	1	5	1	1	4
40	4	5	1	1	5
60	4	5	1	1	5
80	3	5	1	1	6
100	3	5	1	1	6
120	3	5	1	1	6
140	3	5	1	1	6
160	3	4	1	1	5
180	3	6	Rock!	1	7
200	3	6		1	4
220	3	6		1	4
240	3	6		Rock!	5
260	3	6			5
280	3	6			5
300	3	4			4
320		5			4
340		5			4
360		5			1
380		5			4
400		5			1
420		5			
440		1			
460		1			
480		3			
500		4			

1 = Sand
2 = Sand with a little bit clay
3 = Sand with a bit clay
4 = Sand/Clay mixture
5= Clay with a bit sand
6 = Clay with a little bit sand
7 = Clay
Blue = Groundwater

V. Appendix E: Groundwater Depth Boxplots

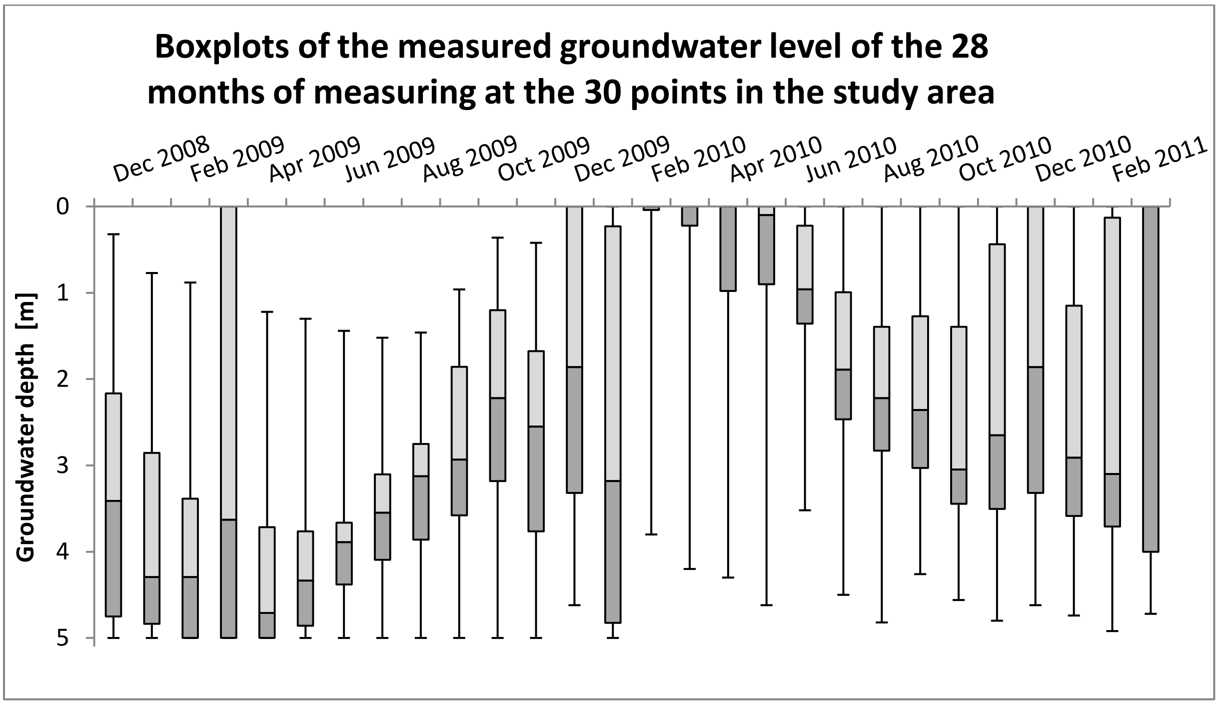


Figure E1: Boxplots of the measured groundwater depth for 28 months of measuring 30 points (the points seen in figure B1) in the study area. Maximum measured depth is 5 m.

VI. Appendix F: Cross sections and grid points and cross section results

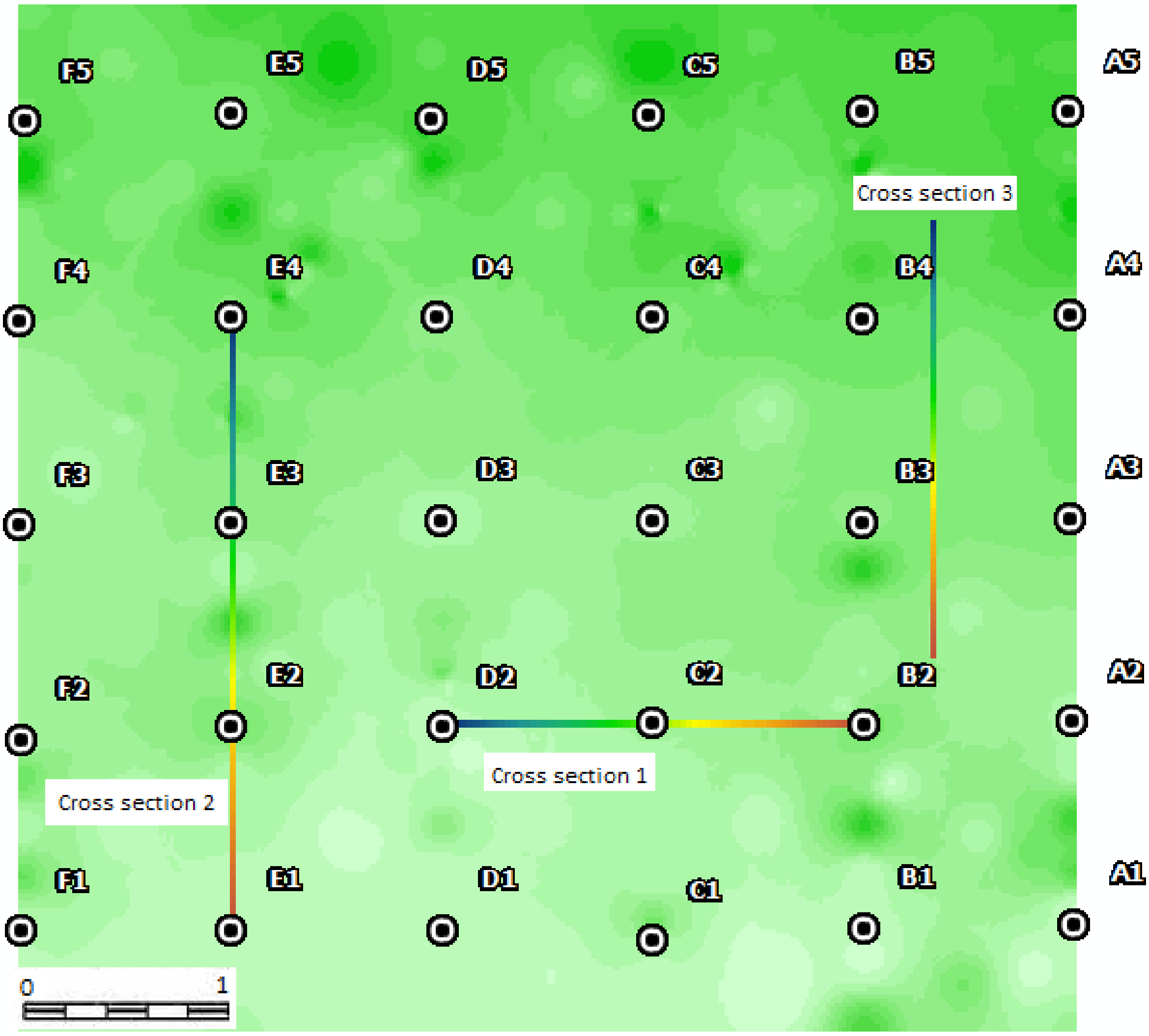
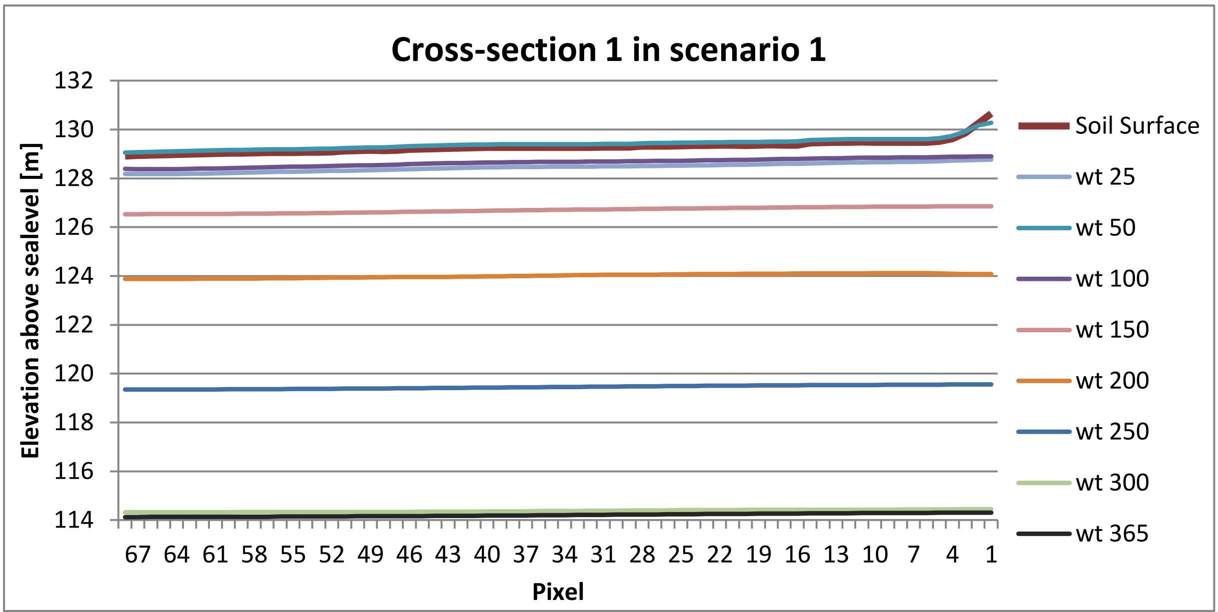
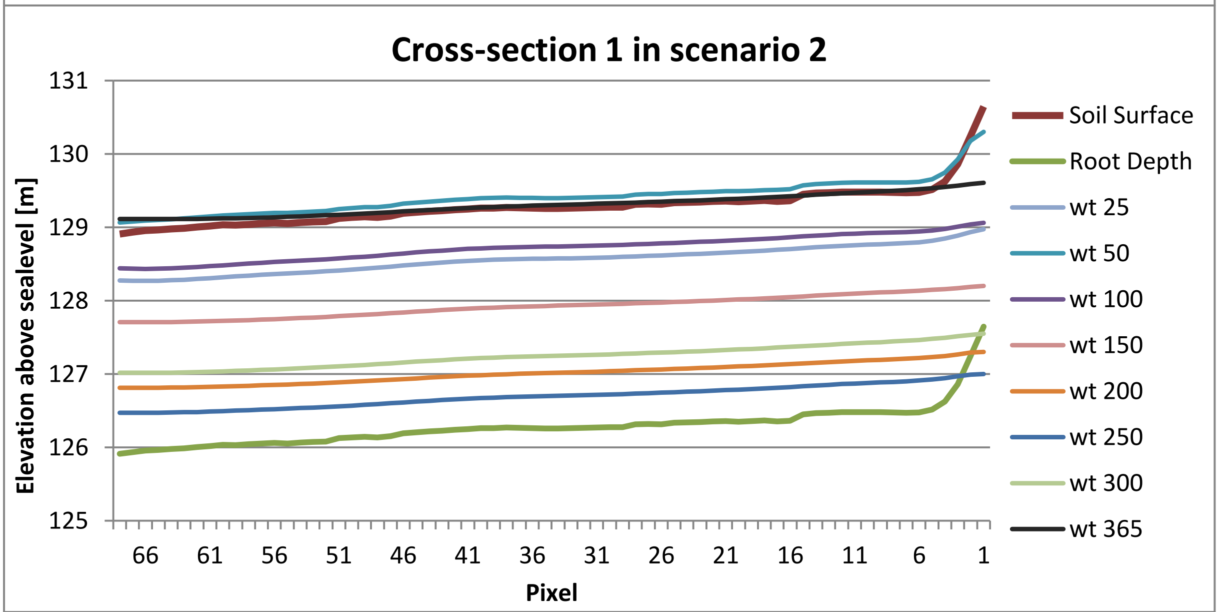


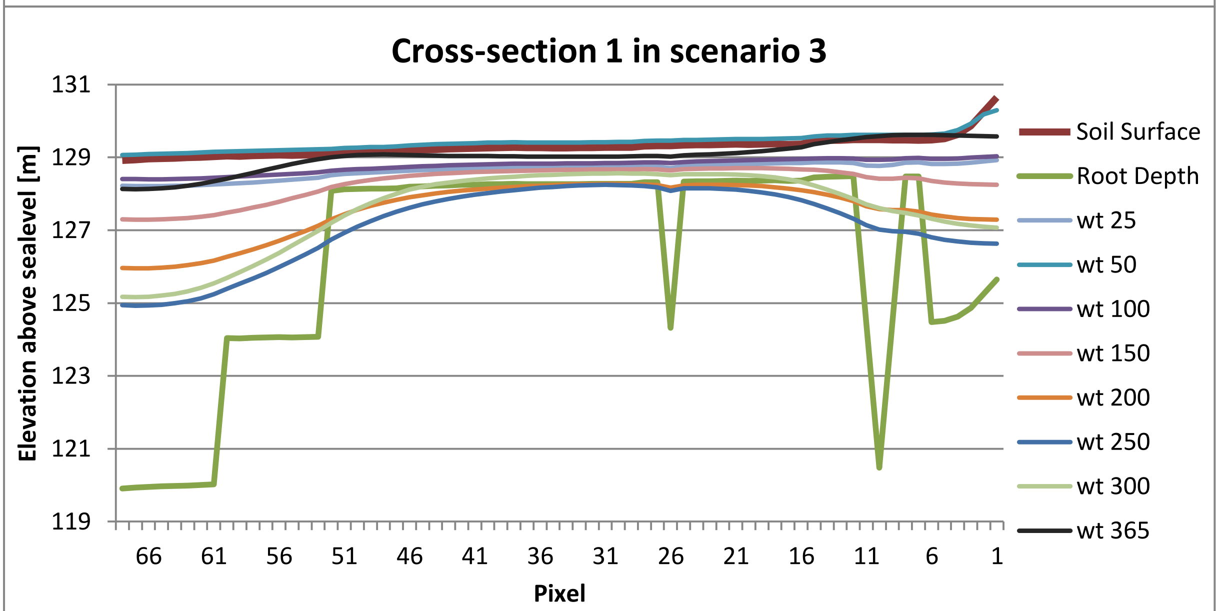
Figure F1: The study site in the Pantanal of Pirizal. The 30 groundwater and surface water measurement points are the round black and white dots with the letters(A-F) and numbers (1-5). The location of the cross sections 1 – 3 are shown and the colors correspond to the pixel numbers of the graphs F1-9: the first pixel is red and the last pixel is blue.

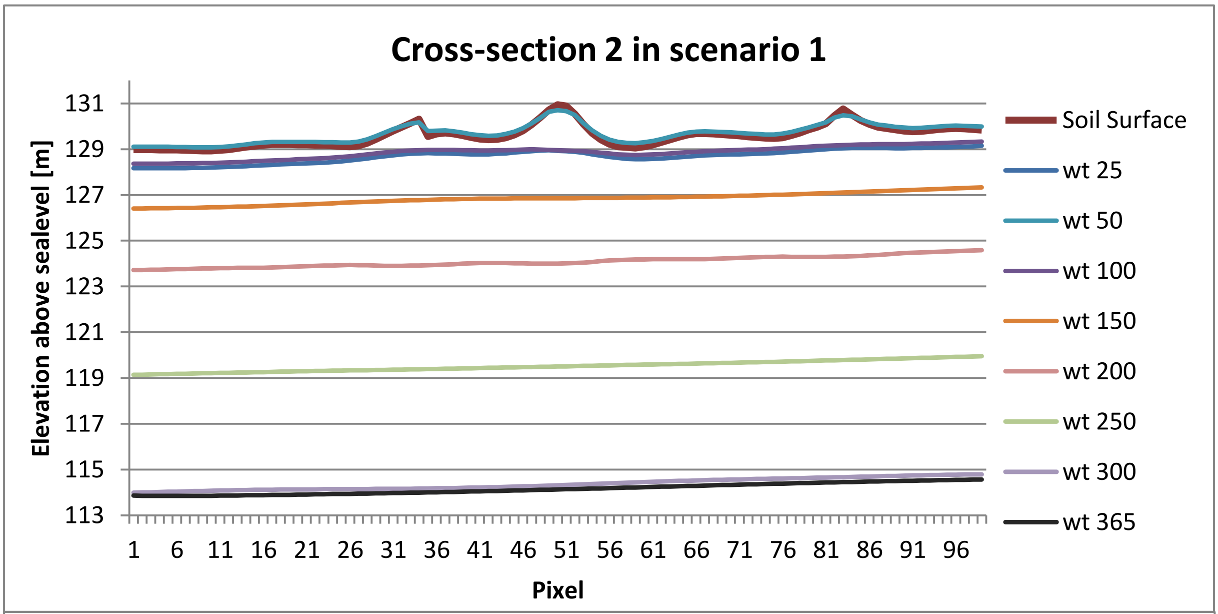
.

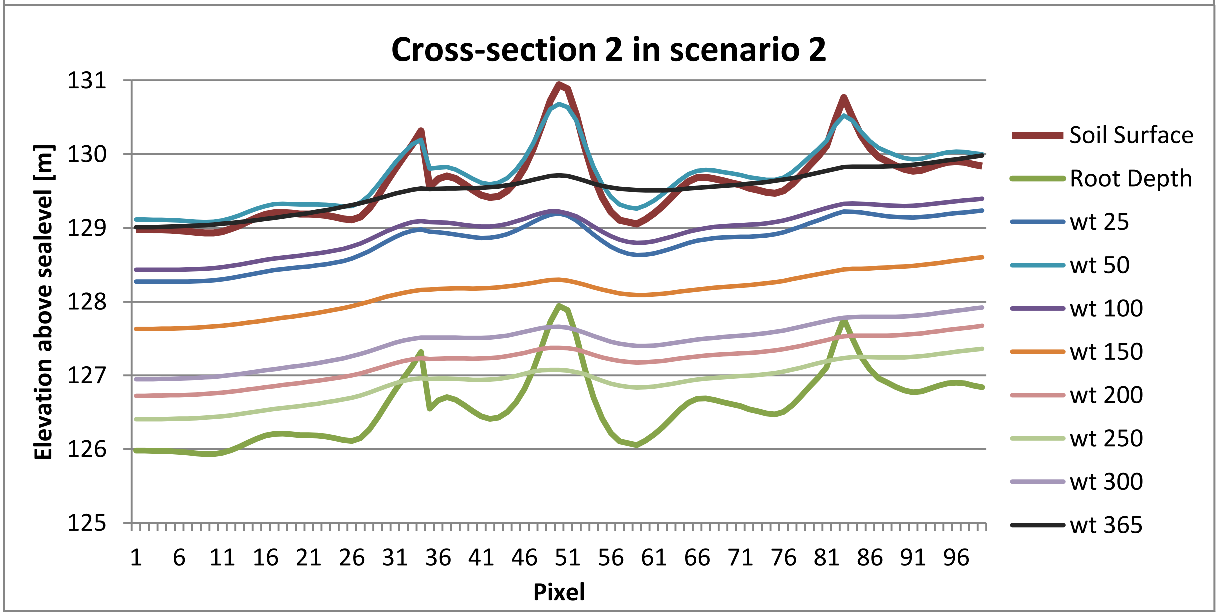
On the next 3 pages are figures F1-9: Surface elevation (soil surface), root depth elevation (root depth) and the water table at timesteps 25,50,100,150,200,250,300,365 for the cross sections from figure F1. On each X-axis the pixel number is shown. Each pixel is 30 by 30 m and the numbers correspond to the colors in figure F1: pixel 1 is red and the last pixel is blue.

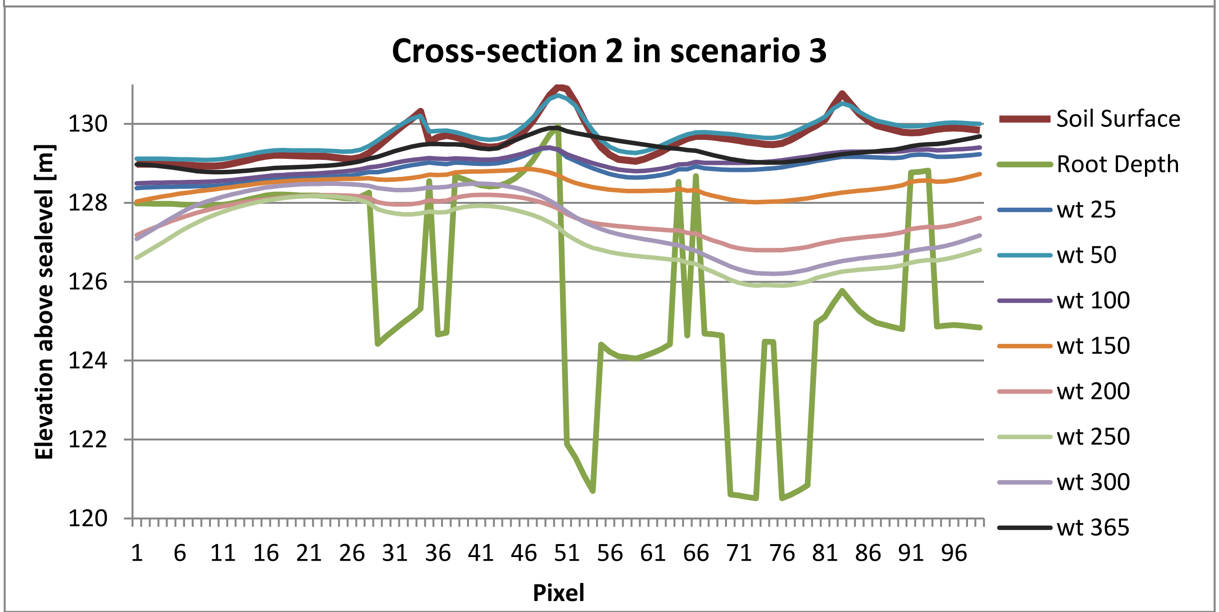

Cross-section 1 in scenario 1
Elevation above sealevel [m]
132
130
128
126
124
122
120
118
116
114
67 64 61 58 55 52 49 46 43 40 37 34 31 28 25 22 19 16 13 10 7 4 1
Pixel
Soil Surface
wt 25
wt 50
wt 100
wt 150
wt 200
wt 250
wt 300
wt 365

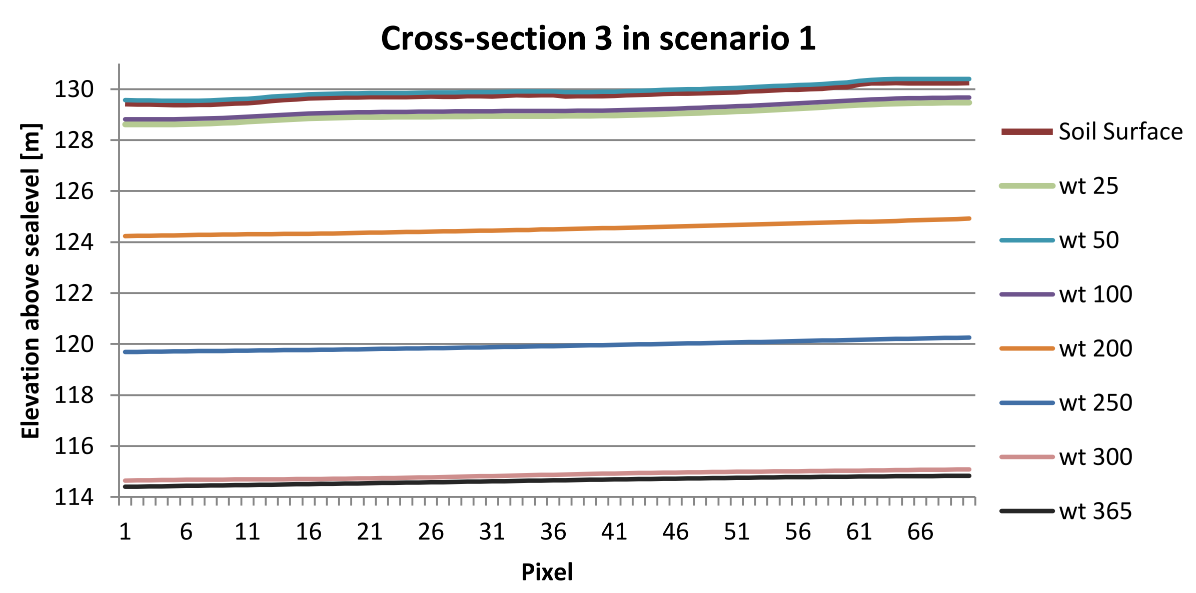

Cross-section 1 in scenario 2
Elevation above sealevel [m]
131
130
129
128
127
126
125
66 61 56 51 46 41 36 31 26 21 16 11 6 1
Pixel
Soil Surface
Root Depth
wt 25
wt 50
wt 100
wt 150
wt 200
wt 250
wt 300
wt 365

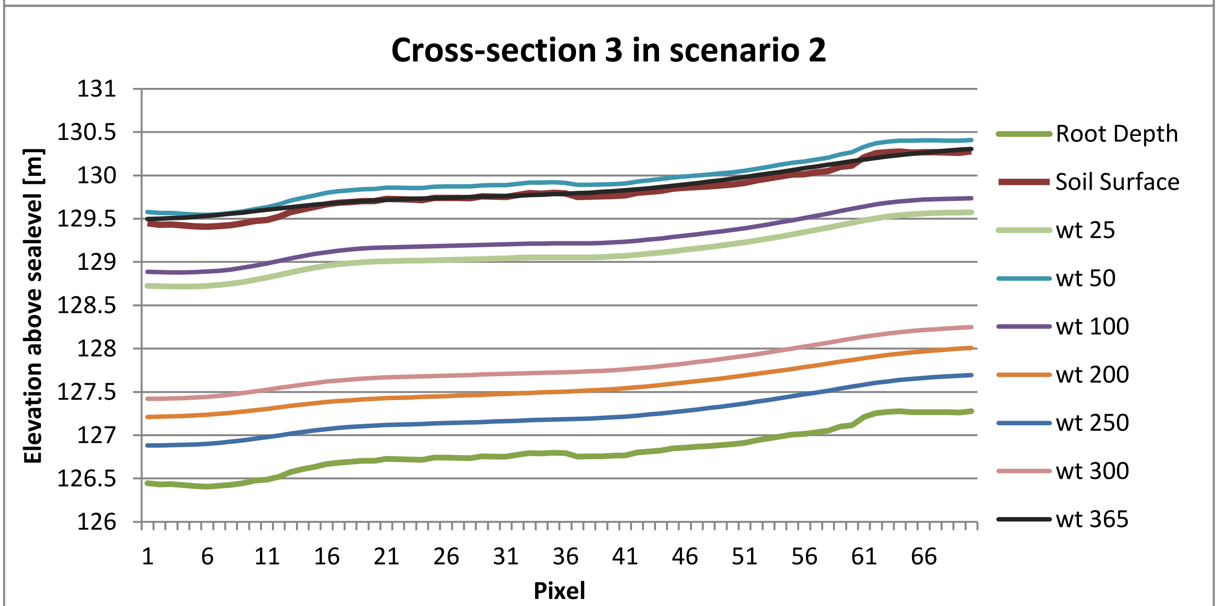

Cross-section 1 in scenario 3
Elevation above sealevel [m]
131
129
127
125
123
121
119
66 61 56 51 46 41 36 31 26 21 16 11 6 1
Pixel
Soil Surface
Root Depth
wt 25
wt 50
wt 100
wt 150
wt 200
wt 250
wt 300
wt 365

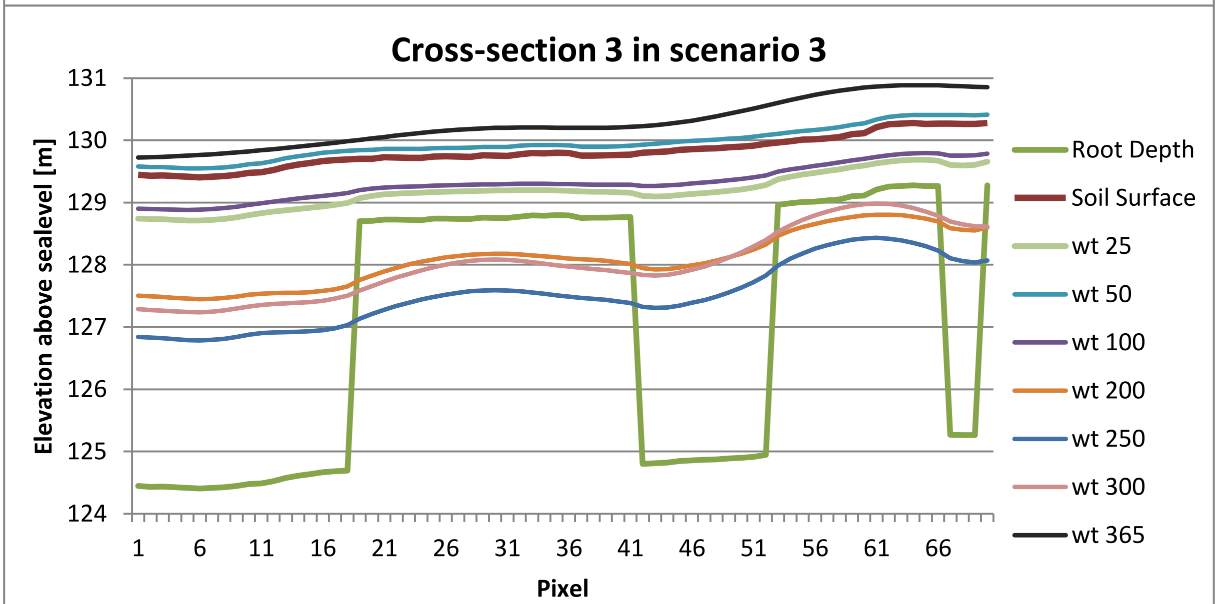

Cross-section 2 in scenario 1
Elevation above sealevel [m]
131
129
127
125
123
121
119
117
115
113
1 6 11 16 21 26 31 36 41 46 51 56 61 66 71 76 81 86 91 96
Pixel
Soil Surface
wt 25
wt 50
wt 100
wt 150
wt 200
wt 250
wt 300
wt 365


Cross-section 2 in scenario 2
Elevation above sealevel [m]
131
130
129
128
127
126
125
1 6 11 16 21 26 31 36 41 46 51 56 61 66 71 76 81 86 91 96
Pixel
Soil Surface
Root Depth
wt 25
wt 50
wt 100
wt 150
wt 200
wt 250
wt 300
wt 365


Cross-section 2 in scenario 3
Elevation above sealevel [m]
130
128
126
124
122
120
1 6 11 16 21 26 31 36 41 46 51 56 61 66 71 76 81 86 91 96
Pixel
Soil Surface
Root Depth
wt 25
wt 50
wt 100
wt 150
wt 200
wt 250
wt 300
wt 365


Cross-section 3 in scenario 1
Elevation above sealevel [m]
130
128
126
124
122
120
118
116
114
1 6 11 16 21 26 31 36 41 46 51 56 61 66
Pixel
Soil Surface
wt 25
wt 50
wt 100
wt 200
wt 250
wt 300
wt 365


Cross-section 3 in scenario 2
Elevation above sealevel [m]
131
130.5
130
129.5
129
128.5
128
127.5
127
126.5
126
1 6 11 16 21 26 31 36 41 46 51 56 61 66
Pixel
Root Depth
Soil Surface
wt 25
wt 50
wt 100
wt 200
wt 250
wt 300
wt 365


Cross-section 3 in scenario 3
Elevation above sealevel [m]
131
130
129
128
127
126
125
124
1 6 11 16 21 26 31 36 41 46 51 56 61 66
Pixel
Root Depth
Soil Surface
wt 25
wt 50
wt 100
wt 200
wt 250
wt 300
wt 365

VII. Appendix G: PCRaster model code

```
binding


areamap
 clone.map;

timer
 1 365 1;


initial
object mf = PCRasterModflow::initialise();

#creating boolean clone map
report clone_boo.map = boolean(clone.map);

# creating usable elev.map

report dem_average.map = dem.map/2 + 64.5;
report predem.map = if (centre.map eq 1, dem_centre.map, dem_average.map);
report predem_wa.map = windowaverage( predem.map, 180);
report elev.map = if (centre.map eq 1, dem_centre.map, predem_wa.map);
report slope.map = slope(elev.map);


# creating the layer information

report bottom.map = clone.map * 75;
report l12345_tt.map = elev.map - bottom.map;
report l4_top.map = elev.map - ((1/31)* l12345_tt.map);
report l3_top.map = l4_top.map - ((2/31)* l12345_tt.map);
report l2_top.map = l3_top.map - ((4/31)* l12345_tt.map);
report l1_top.map = l2_top.map - ((8/31)* l12345_tt.map);

# adding the layers to the MODFLOW model
res = mf::createBottomLayer(bottom.map, l1_top.map);
res = mf::addLayer(l2_top.map);
res = mf::addLayer(l3_top.map);
res = mf::addLayer(l4_top.map);
res = mf::addLayer(elev.map);

# creating the conductivity informations
report ksat.map = clone.map * 1.0;

# adding the conductivities to the MODFLOW model
res = mf::setConductivity(0, ksat.map, ksat.map, 1);
res = mf::setConductivity(0, ksat.map, ksat.map, 2);
res = mf::setConductivity(3, ksat.map, ksat.map, 3);
```

```
res = mf::setConductivity(3, ksat.map, ksat.map, 4);
res = mf::setConductivity(1, ksat.map, ksat.map, 5);

# creating the boundary conditions / initial values
report b_x.map = xcoordinate(clone_boo.map);
report b_y.map = ycoordinate(clone_boo.map);
report vert.map = if(b_x.map gt -6270630,b_y.map);
report vert_line.map = if(vert.map lt -6270000 ,b_y.map);
b_left.map = mapminimum(b_x.map) eq b_x.map;
b_bottom.map = mapminimum(b_y.map) eq b_y.map;
b_right.map = mapmaximum(b_x.map) eq b_x.map;
b_top.map = mapmaximum(b_y.map) eq b_y.map;
b_edges.map = b_left.map or b_top.map or b_right.map or b_bottom.map;
report bound.map = nominal(not b_edges.map);

# adding the boundary conditions to the MODFLOW model
res = mf::setBoundary(bound.map, 1);
res = mf::setBoundary(bound.map, 2);
res = mf::setBoundary(bound.map, 3);
res = mf::setBoundary(bound.map, 4);
res = mf::setBoundary(bound.map, 5);


# adding the initial values to the MODFLOW model
res = mf::setInitialHead((elev.map - .1 ), 1);
res = mf::setInitialHead((elev.map - .1), 2);
res = mf::setInitialHead((elev.map - .1), 3);
res = mf::setInitialHead((elev.map - .1), 4);
res = mf::setInitialHead((elev.map - .1), 5);

# recharge steady state
#report p.map = clone.map * (0.17/365);
#report e.map = clone.map * (1.596/365);
#report r.map = p.map - e.map;
#res = mf::setRecharge(p.map, 3);

# river Package
report watertbl.map = elev.map lt 127.5;
report riv_bottom.map = if(watertbl.map, elev.map, 0);
report riv_head.map = if(watertbl.map, scalar(127.5),scalar(0));
report r_cond.map = if(watertbl.map, scalar(2*30*30),0);
report riv_cond.map = cover(r_cond.map, 0);
res = mf::setRiver(riv_head.map,riv_bottom.map,riv_cond.map,5);

# drain, drains 0.1m below elev
report drain_loc.map = if(watertbl.map, boolean(0), boolean(1));
report drain_cond.map = if(drain_loc.map, scalar(60),scalar(0));
report drain_elev.map = (elev.map - 0.1);
res = mf::setDrain(drain_elev.map, drain_cond.map, 5);

#creating storage maps
report sec_storage.map = clone.map * 4.1;
```

```
report prim_storage.map = clone.map * 4;
report prim_storage_L1.map = clone.map * 4.1;

# adding storage values
res = mf::setStorage(prim_storage_L1.map,sec_storage.map,1);
res = mf::setStorage(prim_storage.map,sec_storage.map,2);
res = mf::setStorage(prim_storage.map,sec_storage.map,3);
res = mf::setStorage(prim_storage.map,sec_storage.map,4);
res = mf::setStorage(prim_storage.map,sec_storage.map,5);

#defining rootDepth
report rootDepth.map = lookupscalar(rootdepth.tbl, veget.map);

# simulation parameters

res = mf::setDISParameter(4,2,365,1,1,0);
res = mf::setPCG(40,70,1,0.001,0.001,1.0,2,1);
res = mf::setNoFlowHead(-55);


dynamic

#recharge
report precip = timeinputscalar(precip.tss, clone_boo.map) *0.001; # mm to m
report pot_evap = timeinputscalar(evap.tss, clone_boo.map) *0.001; # mm to m
report aboveGroundEvap = if(wtDepth.map le 0, pot_evap, scalar(0));
report belowGroundEvap = if(wtDepth.map gt 0, (((rootDepth.map-
wtDepth.map)/rootDepth.map)*pot_evap), scalar(0));
report evap = max(aboveGroundEvap, belowGroundEvap);
report testevap = if(precip > 0.003,pot_evap,evap);
report recharge = precip - evap;
res = mf::setRecharge(recharge, 3);

# execute Modflow modelling engine
res = mf::run();

#retrieve head values
report h5 = mf::getHeads(5);
report h4 = mf::getHeads(4);
report h3 = mf::getHeads(3);
report h2 = mf::getHeads(2);
report h1 = mf::getHeads(1);

# retrieving watertable
h5Ad = if(h5>0,h5);
h4Ad = if(h4>0,h4);
h3Ad = if(h3>0,h3);
report wt = cover(h5Ad,h4Ad,h3Ad,h2,h1);
report wtDepth = elev.map - wt;
report wtDepth.map = wtDepth;
report wtElev = wt gt elev.map;
```

```
# drain leakage
report d5 = mf::getDrain(5);

#river leakage
report riv_leak = mf::getRiverLeakage(5);

#punten
report out.tss = timeoutput(punt_n.map, wtDepth);

#lijnen
report wt1.tss = timeoutput(lijn1.map, wt);
report recharge1.tss = timeoutput(lijn1.map, recharge);
report wt2.tss = timeoutput(lijn2.map, wt);
report recharge2.tss = timeoutput(lijn2.map, recharge);
report wt3.tss = timeoutput(lijn3.map, wt);
report recharge3.tss = timeoutput(lijn3.map, recharge);
```