# Analyses of impacts of a sand storage dam on groundwater flow and storage

**Groundwater flow modelling in Kitui District, Kenya**

Supervisors:
Dr. J. Groen
Dr. M.J. Waterloo

Merel Hoogmoed
July 2007

Master Thesis Hydrogeology (code 450122, 27 ECTS)
Faculty of Earth and Life Sciences
VU University, Amsterdam

vrije Universiteit amsterdam

aqua for all

Acacia Institute
Solutions in Groundwater

GASOL

# Analyses of impacts of a sand storage dam on groundwater flow and storage

**Groundwater flow modelling in Kitui District, Kenya**

*'A river without sand, doesn't hold the water'*

*Kenyan proverb - SASOL calendar 2006*

Photo on the cover is made by:
Merel Hoogmoed
December 2006

Supervisors:
Dr. J. Groen
Dr. M.J. Waterloo

Merel Hoogmoed, student number 1277448
Master Thesis Hydrogeology (code 450122, 27 ECTS)
Faculty of Earth and Life Sciences
VU University, Amsterdam

**Note**: Some figures require a colour view to be interpreted

# Summary


### Introduction

Large parts of the world cope with problems of water supply during periods of low rainfall and consequent low or no river discharge. Kitui District is a semi arid region in Kenya where, during the dry season, communities in rural areas almost completely rely on water abstraction through hand-dug wells (scoop holes) in the dry sand riverbeds. To increase water availability during the dry season, SASOL (a local NGO) builds sand storage dams. The construction of sand dams has turned out to be very successful in increasing groundwater storage capacity, prolonging the period of groundwater availability (bridging dry seasons) and improving water quality.

### Research

To use the experiences in Kitui District to successfully construct sand storage dams in other parts of Kenya and other countries, the Acacia Institute and SASOL started the ‘Recharge Techniques and Water Conservation in East Africa - Up-scaling and Dissemination of the good practices with the Kitui sand storage dams’ project in 2005. The project is funded by Aqua for All (A4A), a Dutch NGO, and the VU University Amsterdam (VUA). In October 2005, the Acacia Institute started with a measuring programme around the Kwa Ndunda sand dam in the Kiindu catchment (Kitui District, Kenya; UTM WGS 37S 389200 m East, 9838380 m North) to understand processes regarding functioning of these dams in terms of groundwater storage. The results formed the base of this study performed in October and November 2006, concentrating on the same sand dam and focusing on local groundwater dynamics.

### Groundwater model

To determine the physical parameters accountable for successful implementation of sand storage dams and to study the impacts on groundwater flow and storage, a groundwater modeling effort is performed. The model is set up in the Triwaco modeling environment (calculations performed by Flairs) on the Kwa Ndunda sand dam. The above-mentioned field visits in 2005 and 2006 provided data forming the input for the set up and calibration of the groundwater model. The model is used to run several scenarios, through which the effects of the sand storage dam on groundwater levels and storage are tested (using the scenario without sand dam), as well as influences of increasing dam height and riverbank infiltration on functionality of the sand dam. Additionally, effects of groundwater abstraction are studied.

### Fieldwork

During the field visits, piezometers are installed around the Kwa Ndunda sand dam, arranged in cross sections perpendicular to the riverbed, both upstream (50 meter) and downstream (100 m)

of the sand dam and next to the sand dam. From October 2005 forward, groundwater levels are measured manually on a daily interval and twice a day during wet seasons. Precipitation is measured manually on a daily interval from the fieldwork 2005 onward.
Through augering and geophysical techniques, thicknesses of subsurface layers as well as depth of the basement are determined. Hydraulic properties (e.g. hydraulic conductivity and porosity) of the subsurface layers are determined through several techniques. Hydrochemistry is used to determine evaporation of soil water. In combination with the results of Jansen (2007), discussing the fraction of precipitation infiltration the subsoil, groundwater recharge is determined.

**Function and influence of sand dams on groundwater flow and storage**
Sand dams are small concrete check dams build in the riverbed perpendicular to the flow direction. Behind the dam fast sedimentation occurs, causing an enlargement of the natural sand aquifer present in the riverbed. Groundwater flow through the permeable riverbed is obstructed, creating a groundwater reservoir upstream of the sand dam. During the dry season, the reservoir is replenished through groundwater flow through the riverbed and by flow from the riverbanks towards the bed outside the zone of influence of the sand dam. Within the zone of influence, elevated heads in the riverbed upstream of the sand dam result in groundwater flow from the riverbed into the banks and through the banks around the sand dam. Downstream of the sand dam groundwater flow is oriented towards the riverbed.

Sand dams effectively increase the volume of groundwater available for abstraction as well as prolonging the period in which groundwater is available for abstraction. From model results, it follows that in absence of the sand dam the riverbed dries up within 1.5 months from the start of the dry season, while in presence of a sand dam the riverbed still contains approximately 580 $m^3$ groundwater in the riverbed over a length of 200 meter upstream of the sand dam. Continuous replenishment from the riverbanks ensures the volume to be sufficient to bridge the period of drought until the next rain season.

The coarse sand enables the fast response of the groundwater table on precipitation and protects groundwater from excessive evaporation because of low capillary forces and increased thickness of the sand layer in the riverbed. After the first heavy rainfall event, the riverbed aquifer is recharged completely and the river starts to flow, leading to the conclusion that downstream areas are not significantly influenced by refilling of the larger aquifer.

**Parameters of importance to successful functioning of sand dams**
Thickness of the sand layer in the riverbed and hydraulic conductivity and thickness of the sediment layer in the riverbanks significantly influence the reaction of groundwater levels on

precipitation, groundwater recession curves and the volume of groundwater stored in the riverbed. Higher hydraulic conductivity leads to a less pronounced response of groundwater levels to precipitation. Additionally, groundwater flow velocity is higher, together resulting in a faster leveling out of heads and a faster decline in the volume of water stored in the riverbed. Hydraulic conductivity and thickness of the weathered rock layer and flood depth have less influence on model results.

**Improving functionality sand dams**

Increasing riverbed thickness by enhancing the height of the sand dam has the most direct positive effect on groundwater availability. An increase of 0.75 meter results in an increase of groundwater storage in the riverbed from 500 $m^3$ to 1590 $m^3$ while having a negligible effect on the downstream area. The effect is largest during the dry season, which is the most crucial period. It can however not be established with certainty what happens if this measure is applied to a cascade of dams. Increasing dam height with more than 0.75 meter causes lower groundwater levels in downstream areas because rainfall events are not large enough to fill the aquifer in the riverbed in one wet season.

It is however not necessary to increase the height of the sand dam, since groundwater abstraction as performed momentarily (approximately eight $m^3$/day) influences groundwater levels only very locally. This is caused by the fact that abstraction is compensated by groundwater flow from the banks towards the riverbed. Potential groundwater harvest from an aquifer upstream of a sand storage dam is thus larger than the volume of water present at a certain moment in time in riverbed.

Applying land husbandry techniques will, besides other positive effects on for example erosion, further increase the volume of groundwater available for abstraction. This might be necessary when groundwater will be used for irrigational purposes on larger scale.

**Application of the model in other areas**

The groundwater model can be used as an indication of the effect of building a sand storage dam in the riverbed in terms of the volume of water stored in the riverbed, potential storage in riverbanks and the period in which groundwater is available for abstraction. To this aim, generic data, such as a SRTM DEM, VESses, approximate precipitation data and literature values of hydraulic parameters, can be used as input to the model.

## Table of content

## List of Figures

## List of Tables

# 1 Introduction

This chapter points out the functionality of sand storage dams to provide water to communities in semi arid regions, explains the significance of this study through objectives and a justification, and gives an outline of the report.

## 1.1 Sand storage dams

Large parts of the world cope with the problem of water supply during periods of low rainfall and consequent low or no river discharge. Climate change further decreases the reliability of rainfall, both spatially and temporally. In addition, populations are increasing, thereby enlarging the water demand. The answer to this problem lies in increasing water storage to bridge periods of drought and thereby securing water supply to communities.

One of the successful examples of a rural water conservation program is the construction of sand storage dams in Kitui District in Kenya (Figure 1.1a and cover picture). This program is initiated by SASOL (Sahelian Solution Foundation), a NGO founded in 1992. The main objective was shortening the distance of communities to water sources to less than two kilometers whilst making water available for productive use. To this aim, SASOL assists communities to address water scarcity in rural areas by constructing sand storage dams. The program is funded by the Kenyan Ministry of Water and foreign agencies. To date, almost 500 dams have been constructed, serving about 100 000 people with water during the dry season (Munyao et al., 2004).

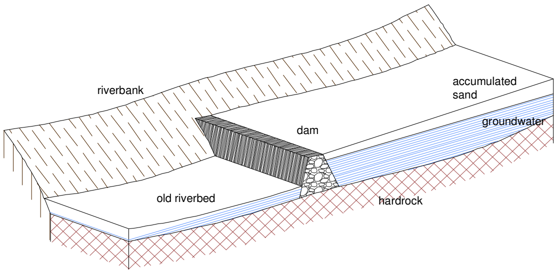



Figure 1.1a Typical sand storage dam during the dry season (Borst et al., 2006)
Figure 1.1b Schematic cross section of a typical sand storage dam (Borst et al., 2006)

### 1.1.1 Principle of sand storage dams

Sand storage dams are small concrete check dams built in the riverbed of ephemeral rivers perpendicular to the flow direction. Upstream of the sand dam fast sedimentation occurs, which is regarded a problem considering surface water dams. However, sand accumulating behind these dams has a large grain size diameter, thereby enlarging the natural aquifer. An enlargement of groundwater storage capacity compared to a situation without a sand dam is the result (Figure 1.1b). In addition, the dam obstructs groundwater flow through the riverbed, creating a groundwater reservoir upstream of the sand dam. During the dry season, groundwater is abstracted manually by means of scoop holes (hand dug wells in the riverbed) as has been done traditionally for thousands of years in semi arid and arid areas (Nissen-Petersen, 1997; Figure 1.2). Increasingly, wells are built. During the short wet seasons, the river floods and surface water instead of groundwater is used for domestic purposes.

Figure 1.2 Groundwater abstraction from the riverbed by means of a scoop hole (10-10-2006)

Tuinhoff et al. (2002) acknowledge the importance of groundwater storage as water resource through comparing subsurface storage dams with surface water reservoirs. As concluded by Borst et al. (2006), the advantages of subsurface water storage over open water storage are evident and mainly related to increased water availability (larger yield, longer availability) and higher water quality caused by protection against evaporation and contamination and by filtration through groundwater flow (Borst et al., 2006). Additionally, malaria mosquitoes are limited in their propagation due to the absence of open water.

The effectiveness of subsurface storage is underscored by Wheater (unknown publication date), who argues it minimizes evaporation loss and can provide long-term yields from infrequent recharge events. Furthermore, he states recharge of alluvial groundwater systems interacting with ephemeral rivers can provide appropriate water resources, although quantification of the sustainable yield of such systems is necessary to enable appropriate resource development.

The concept of constructing sand dams in large numbers has turned out to be very successful in increasing groundwater storage and improving water quality. Water is now available within short distances from the homesteads, and people have improved their livelihoods significantly by engaging in small-scale irrigation for growing food- and cash crops (De Bruijn, et al., 2006). Additionally, the natural vegetation in the Kitui region is regenerating.

## 1.2 Research

In 2005, the Acacia Institute and SASOL started the ‘Recharge Techniques and Water Conservation in East Africa – Upscaling and Dissemination of the good practices with the Kitui sand storage dams’ project. The goal is to use experiences in Kitui District for successful construction of sand storage dams in other parts of Kenya and in other countries. The project is funded by Aqua for All (A4A), a Dutch NGO, and the VU University Amsterdam (VUA).

To understand the processes regarding the functioning of sand storage dams in terms of groundwater storage, the Acacia Institute started with a measuring programme around the Kwa Ndunda sand dam in the Kiindu catchment (Kenya) in October 2005. The results are described in Borst et al. (2006), providing insight in the principle of sand storage dams and giving an estimation of the effects of these dams on the water balance. The results formed the base of the field study performed in October and November 2006, concentrating on the same sand dam. Currently the Acacia Institute is, in cooperation with the Dutch RAIN (Rainwater Harvesting Implementation Network) Foundation, SASOL and Ethiopian NGO’s, in the process of identifying suitable catchments in southern Ethiopia to construct a cascade of several dams. The initiative is recently awarded the Swiss Re International ReSource Award for Sustainable Watershed Management, proving the relevance of the hydrological research.

### 1.2.1 Objectives

The second phase of the ‘Recharge Techniques and Water Conservation in East Africa – Up-scaling and Dissemination of the good practices with the Kitui sand storage dams’ project aims to provide more information on the following subjects.

- Determining parameters of importance for successful functioning of a sand dam and providing a GIS model which can be used to identify potential sand dam areas, described by Gijsbertsen (2007),
- Measuring and modeling the influence of sand dams on the rainfall-runoff relation in a semi-arid catchment, described by Jansen (2007),
- Improving understanding of hydrological processes, analysing relative importance of physical parameters in the successful functioning of sand dams and studying the impacts of a sand dam on the hydrology of the area (this report).

To the aim of the last objective, this research focuses on local groundwater dynamics in and around a sand dam through field study and a modeling effort. The following questions need to be answered through the model effort.

- Which physical parameters determine the successful implementation of the sand storage dam technology?
- How does the presence of a sand storage dam influence groundwater flow?
- What is the net effect of the sand storage dam on groundwater availability?
- How large is the loss of water through presumed groundwater flow around a sand storage dam?

### 1.2.2 Justification

Results of the water balance study presented by Borst et al. (2006) are based on data including one wet season, which was regarded exceptionally dry, and the beginning of the following dry season. Insight in spatial and temporal patterns in groundwater flow was therefore limited. Hut et al. (2005) has set up a mathematical model to provide insight in groundwater flow around a single dam in a Matlab environment. Orient Quilis (2007) designed a Modflow model to study interaction between several sand dams and long-term effects on groundwater levels. Both models are theoretically based. The model presented in this report is a physically based numerical groundwater model, based on and calibrated with data collected during field visits in 2005 and 2006 (Chapter 6).

De Hamer (2007) has set up a finite difference groundwater model in MODFLOW to perform a water balance study of an alluvial aquifer in southern Zimbabwe based on 2 months of groundwater level measurements. However, the riverbanks, which are suspected to play an important role in groundwater storage, are not incorporated in the model (Borst et al., 2006).

The model, set up in the Triwaco modeling environment (Royal Haskoning, 2004; Triwaco), calculates groundwater dynamics in and around a sand dam and is applied to answer the questions mentioned above.

The research is performed as part of the Master program Hydrogeology at the VU University Amsterdam, covering the Master Thesis Hydrogeology (code 450122, 27 ECTS), coordinated by Dr. J. Groen and Dr. M. J. Waterloo.

## 1.3 Outline of the report

To meet the objectives described above, the presentation and discussion of results of the field study in 2006 is spread over three reports. Jansen (2007) discusses the methodology and results (precipitation, runoff plots and discharge) related to the set up, calibration and application of the surface water model. Gijsbertsen (2007) gives a description of activities to gather data forming the basis of the GIS model which is set up to indicate areas with particular potential to apply the sand storage dam technology. Furthermore, he discusses collecting and processing sediment samples as well as the visits to other catchments.

This report will discuss the hydrological processes related to sand dams and reveal the hydrological impacts of a sand dam on groundwater flow and storage. Furthermore, it will provide insight in the parameters influencing the functioning of these dams. The report has the following outline.

Chapter 2 will introduce the field area and discusses a literature study on groundwater flow models. Chapter 3 deals with the field methodology. Chapter 4 describes results of the field study, which are discussed in Chapter 5. Based on the field results and literature study, Chapter 6 describes the set up of the conceptual model. Chapter 7 deals with the calibration of the model, containing the sensitivity analysis, optimal parameter values, calibration results and a reliability analysis. Chapter 8 discusses the model results of the calibrated model. Chapter 9 discusses model application through four scenarios of which the set up and model results are described and discussed. Chapter 10 gives an overall conclusion of the model effort. The last chapter, Chapter 11, gives recommendations for further research.

# 2 Background

This chapter will give a brief overview of the study area, focusing on location, topography, geology and hydrogeology of the region. A more detailed description of these subjects on a regional scale can be found in the report of Borst et al. (2006).

## 2.1 Geography

Kitui District is part of Kenya's Eastern Province and is located between UTM coordinates 510000 m East, 10000000 m North and 344000 m East and 9662000 m North (zone WGS84 37S). The capital of the district is Kitui town, located about 150 km East of Nairobi (Figure 2.1a).
The case study focuses around the Kwa Ndunda sand dam located in the river Kiindu (Figure 2.1b; UTM 389200 m East, 9838380 m North), a seasonal river about 10 km South of Kitui town. The catchment area is located between the towns Wikililye in the North (UTM 390230 m East, 9845760 m North), Mulango and Kyangunga in the East (UTM 390000 m East, 9837850 m North) and Yakalia and Kangalu in the West (UTM 386000 m East, 9838000 m North). The Kiindu river has a total length of 16 km and drains into the Nzeeu river in the South. The Kiindu catchment has a surface area of about 37 km$^2$. The elevation varies between 950 and 1140 m above sea level sloping southward (Figure 2.1).

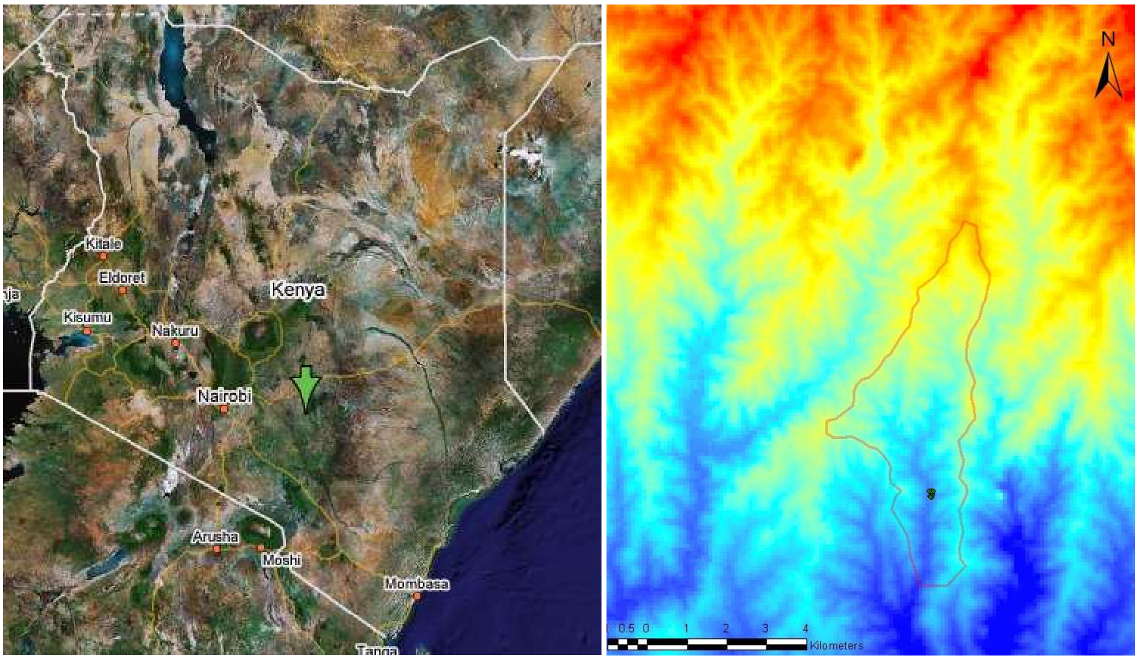



Figure 2.1a Location of the Kiindu Catchment, Kitui District, Kenya (googlemaps.com)
Figure 2.1b Location of the Kwa Ndunda sand dam in the Kiindu Catchment

## 2.2 Climate

The climate is semi arid (Louis Berger International Inc., 1983). Rainfall in Kitui District is seasonal with two wet seasons; October to February and March to May, respectively the short rains and long rains. The short rains are more reliable compared to the long rains. Approximately 90% of the expected annual rainfall occurs during the rain seasons (Biamah et al., 2004). The topography of the landscape influences the amount of rainfall received (ALRMP). The area around Kitui town receives between 760 and 1270 mm precipitation per year, but shows large fluctuations between years (Borst et al., 2006).

In the light of this project, precipitation is measured continuously since October 2005 (Paragraph 4.2.1).

Kitui District experiences high temperatures throughout the year, ranging from 16 °C to 34 °C. The highest temperatures occur during June to September and January to February. The minimum mean annual temperature is 25 °C, the maximum mean annual temperature is 30 °C (ALRMP). According to Opere et al. (2002), average daily evaporation is approximately 6 mm.

## 2.3 Vegetation

Around Kitui Town, vegetation is sparse and predominantly drought resistant, consisting mainly of dry woodlands and bush lands. The area has medium to low potential for plant growth (Kigomo, unknown publication date). Natural vegetation consists mainly of Acacia's and other thorny bushes, e.g. *Acacia clavigera, Acacia nilotica, Acacia seyal, Terminalia combretum* and *Commiphora* sp. (Katumo, 2001). However, along the riverbed less drought resistant species can exist (Figure 2.2).

Figure 2.2 Overview of the zone next to the riverbed at the Kwa Ndunda sand dam during the dry season

The patches of natural vegetation are scattered and cut by agricultural fields. Agricultural plots are located on the riverbanks. During the dry season, agricultural fields are bare (Figure 2.3). During the wet season, crops are cultivated (e.g. maize, cow pies and sukuma wiki). Papaya and mango trees are planted locally at the wetter sites in the field (e.g. along the base of terrace walls). However, these are not very abundant in the study area.

Figure 2.3a Riverbank at the end of the dry season (12-10-2006)
Figure 2.3b Riverbank at the beginning of the wet season (25-10-2006)

Vegetation responds rapidly on precipitation (Borst et al., 2006). At the end of the dry season, vegetation cover is very sparse. As soon as the first rains fall, vegetation starts to grow (Figure 2.4).

Figure 2.4a Runoff plot on an agricultural field on the silty bank at the end of the dry season (10-10-2006)
Figure 2.4b The same runoff plot during the wet season (02-11-2006)

Soils are medium-textured ferrasols, predominantly consisting of moderately deep chromic luvisols (Kigomo, unknown publication date). Paragraph 4.3 presents the results of the augerings performed in the riverbed and banks during the field visits. Gijsbertsen (2007) discusses grain size analysis of the soils in the Kiindu catchment in further detail.

During the dry season, a soil crust forms covering the riverbanks. In addition, drought cracks develop, although predominantly in clayey soils (Figure 2.5). After a few rainfall events, the soil crust softens and disappears and drought cracks close.

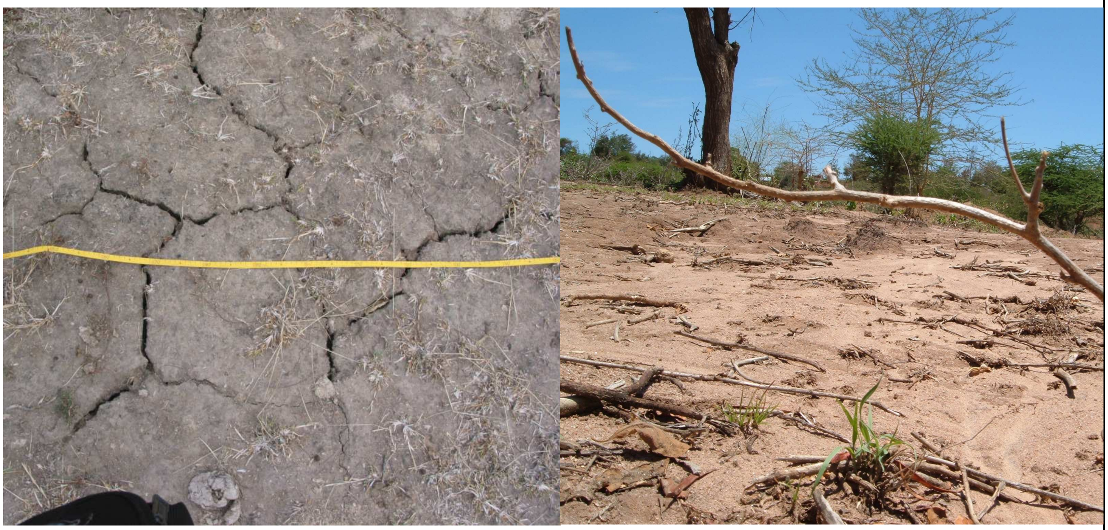


Figure 2.5a Cracks in clayey soil at the western riverbank at the end of the dry season (10-10-2006)
Figure 2.5b Crusting of silty soil at the end of the dry season (10-10-2006)

## 2.5 Hydrogeology

### 2.5.1 Regional setting

The basement system is formed by Precambrian crystalline metamorphic rocks (gneisses and schissts) of are at least 540 Ma, showing a regional North-South trend in foliation. This corresponds to the geology of the Mozambique belt, which is of Proterozoic age (2,500 Ma – 540 Ma BP) and is found in large parts of East Africa.

The basin outlining the present morphological features is formed during Paleozoic tectonic activity, influencing erosion during the Tertiary (65 Ma – 2 Ma BP) and erosion and deposition during the Quaternary (2 Ma BP until present). Quaternary sediments exist primarily of alluvium, limestone, sand, clay and silt and are present on hill slopes and in riverbeds (Table 2.).

A geological map is enclosed in Appendix 1.

Table 2.1 Overview of geological events in Kitui District (after Borst et al., 2006).

| Period | Process | Products |
|---|---|---|
| Precambrium<br>(Achaean, Proterozoic) | Tectonics and metamorphism | gneisses and schissts |
| | Erosion, peneplanation | |
| Paleozoic<br>(Carboniferous – Permian) | Forming of basin by tectonic activity and faulting. | Shales and sandstones |
| Tertiary (Miocene) | Tectonic activity | Intrusives and dikes |
| Quaternary | Erosion, local sedimentation | Soils, sands, alluvium, limestone, clays, silts |

### 2.5.2 Case study area

In the Kiindu catchment, hardrock mainly consists of granitoid and biotite gneisses intersected by pegmatite veins. Granitoid gneiss is a little more resistant to erosion as compared to biotite gneiss. Layers vary in width between half a meter to tens of meters. Locally some quartzites as well as layers of saline rock and limestone (Kunkar Limestone, precipitation after the weathering of other rock) appear between the gneisses. The dip of the hard rock varies between 0° and 35°. The gneisses form the basement of the area, underlying weathered rock formed through erosion during the Quaternary. Thickness of the layer and degree of weathering differ throughout the area. On top of the weathered rock, a layer consisting primarily of clay and silt on the riverbanks and sand or silt in the riverbeds is present. At the location of the Kwa Ndunda sand dam, the riverbed is filled with coarse sand, which is an erosion product of different lithological units, especially gneisses. Thickness of this layer varies between a few centimeters and more than 2 meters, caused by the irregular shape of the basement. Properties of the sediment and weathered rock layers (e.g. thickness and hydraulic properties) in the area around the Kwa Ndunda sand dam are determined during the fieldworks. The results are presented in Paragraph 4.3.

## 2.6 Hydrology and hydrogeology

### 2.6.1 Surface water

Due to limited rainfall, surface water sources are very scarce. Most rivers, such as the Kiindu river, are ephemeral. These rivers flow during the wet season and generally dry up within one month after the end of the wet season.

Most seasonal rivers in Kitui District drain to the river Tana, a perennial river draining into the Indian Ocean. The river Athi, the second perennial river in Kitui District forms the western and southern borders of Kitui District (Figure 2.6).

Surface water hydrology of the study area will be discussed in more detail in Jansen (2007).

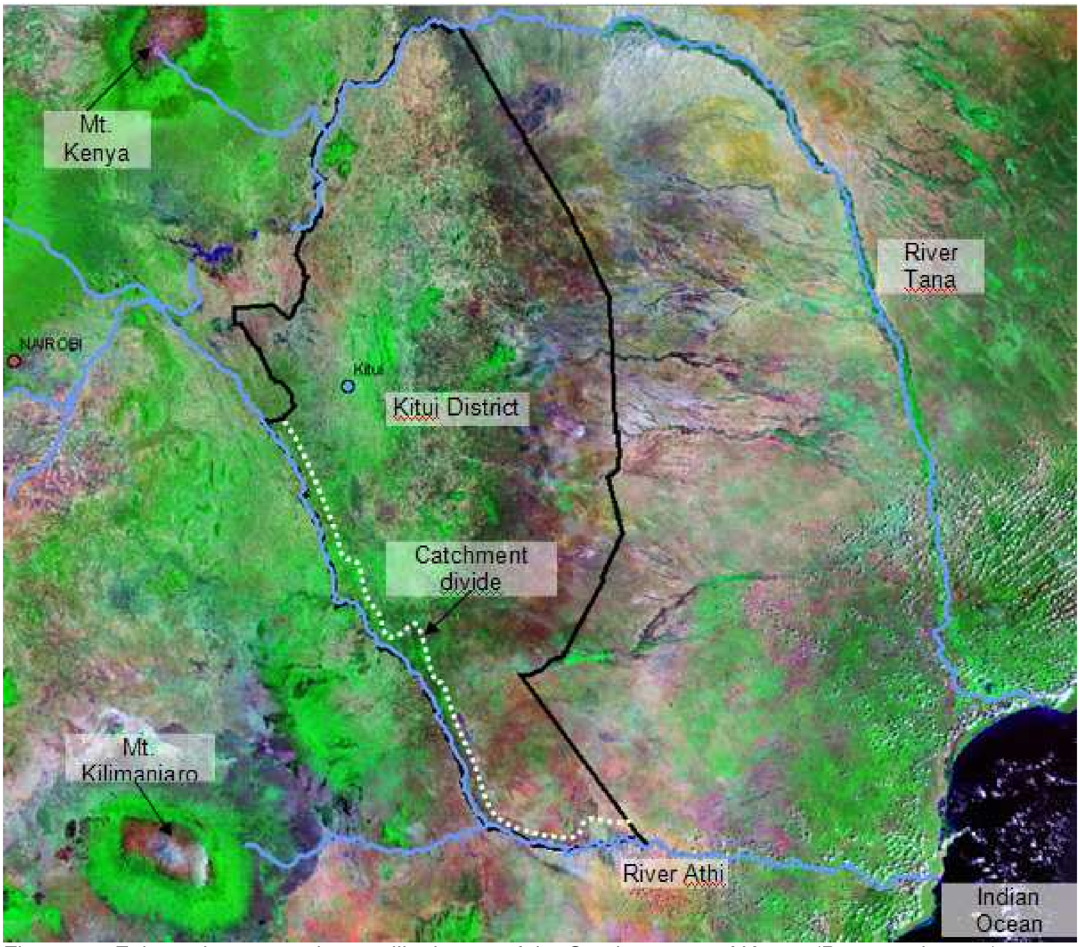


Figure 2.6 False color composite satellite image of the Southern part of Kenya (Borst et al. 2006)

### 2.6.2 Groundwater

In Kitui District three main groups of aquifers are recognised (Louis Berger International Inc., 1983); Quaternary superficial deposits, Tertiary rocks, Paleozoic sedimentary rocks and Precambrium crystalline rocks.

Tertiary volcanic rocks, forming poor aquifers, and sandstones of Paleozoic age, forming good aquifers, are not present in the Kiindu catchment (Borst et al., 2006). However, metamorphosed crystalline Precambrian rocks (schissts and gneisses) underlie most of Kitui District, including the study area. Schissts and gneisses are poor aquifers, although locally water can be stored in fractures, faults, joints and weathered zones. Gneisses are intersected by quartzite veins, forming good aquifers, which can provide water for cities such as Kitui Town. Important recharge zones are located in the hills of Northern and Central Kitui, in the Miambani and Migwani Ridges.

The Precambrian aquifer is not accessible for manual groundwater abstraction as performed by small communities throughout Kitui District. For these communities, Quaternary sediments and the weathered zone of the Precambrian rocks are the primary water supply. Therefore, these aquifers are incorporated in the modeling effort, as described in Paragraph 6.5.
The alluvial aquifers of Quaternary age from good shallow aquifers. At locations where basement is at shallow depth, natural barriers against groundwater flow through the riverbed are formed. Upstream of these barriers, shallow groundwater reservoirs are formed from which water is extracted through scoop holes. Sand dams are preferably built at these locations (Nissen-Petersen, 2006).
Unconsolidated deposits on the riverbanks are less good aquifers, consisting predominantly of silt and clay. However, the importance of riverbanks for groundwater flow and storage will become clear in Paragraph 8.1.

### 2.6.3 Groundwater quality

Water quality is barely influenced by the metamorphous rocks forming the basement in the Kiindu catchment because of limited chemical weathering. Locally, groundwater quality might be influenced significantly by occurrence of layers of saline rock and limestone. Although water quality is not of main concern during this study, water chemistry is used to determine evaporation from the subsoil.

## 2.7 Literature

The publication of Borst et al. (2006) is used to outline the field visit which focused on enlarging insight in groundwater level fluctuations further in the riverbanks, gathering more insight in groundwater recharge and collecting more information on the subsurface (both stratification and hydrological properties). Although a water balance study was performed, insight in spatial and temporal patterns in groundwater flow was limited. This groundwater modeling effort focuses on groundwater dynamics around sand dams, determining which physical parameters are essential in the successful functioning of sand dams and quantification of the increase in storage capacity. To this aim, the conceptual model of Borst et al. (2006) is modified based on the data gathered during the fieldwork in 2006.

Orient Quilis (2007) has set up a groundwater model using Modflow to analyze behavior of a cascade of sand storage dams and to determine water loss to the deeper groundwater as well as effects on a longer time scale. Hut (2006) has set up a groundwater model to study groundwater flow around a single sand dam in the Matlab environment, based on the Bousinesq equation. Both models are theory based, which is in contradiction to the groundwater model presented in this report of which the conceptual model is based on data gathered during fieldwork around the

Kwa Ndunda sand dam and which is calibrated with 1.5 years of groundwater level measurements.

Results of the model effort of Orient Quilis (2007) together with the preliminary results of this modeling effort were presented as a poster presentation on the General Assembly of the European Geosciences Union, Vienna, April 2007 (Appendix 2). Furthermore, a paper entitled '*Determining the reputation of a thousand years by the conduit of one hour – Modeling hydrological processes of sand-storage dams on different temporal scales'* (Orient Quilis et al., 2007) is published in this light.

De Hamer (2007) performed a study in a small river catchment in the arid southern part of Zimbabwe. Three coupled models are used to simulate the hydrological processes; a rainfall-runoff model, a spreadsheet-based water balance model of the dam reservoir and a finite difference groundwater model in Modflow to simulate the water balance of the alluvial aquifer. The riverbanks are not incorporated in the model. However, these are suspected to play an important role in groundwater storage based on the fieldwork in the Kiindu catchment.

In Paragraph 6.1, field results are combined with a literature study on hydrological processes in small-scale semi arid catchments, together resulting in the conceptual model.

# 3 Field methodology

This chapter discusses measurement techniques applied during the fieldwork in 2006 and of which the results form the input for the set up and calibration of the groundwater model. Data were gathered on groundwater levels, precipitation, water chemistry and properties of the subsurface (thicknesses of layers and hydraulic properties, e.g. porosity and hydraulic conductivity).

## 3.1 Groundwater levels

To provide information concerning groundwater flow patterns and changes in them as a consequence of wet and dry seasons, piezometers were installed around the Kwa Ndunda sand dam (UTM 389200 m East, 9838380 m North). Groundwater level fluctuations will be used to evaluate and adapt the conceptual model of Borst et al. (2006). Furthermore, calibration of the groundwater model is based on the measured groundwater levels (Chapter 7).

During the fieldwork in October 2005, 21 piezometers were installed around the Kwa Ndunda sand dam by Borst et al. (2006). The piezometers were arranged in cross sections perpendicular to the riverbed, both upstream (50 meter) and downstream (100 m) of the sand dam and in the eastern riverbank next to the sand dam. During the field study, diver data loggers (Van Essen Instruments, The Netherlands) were installed in piezometers p02, p04, p06, p14 and p15, measuring pressure and temperature (Figure 3.1, Appendix 3). To correct for barometric conditions a barometric data logger (Van Essen Instruments, The Netherlands) was installed at the home of Mrs. Christina Paul on the eastern bank of the Kiindu catchment (UTM 38939 m East, 9838422 m North). The setup provided measurements of groundwater levels on a half hour time interval from October 2005 to the end of November 2005. Additionally, a community member was employed to measure groundwater levels manually using a sounding device with measuring tape (Eijkelkamp Agrisearch Equipment, The Netherlands) on a daily interval (and twice a day during the rain season). The piezometers were not removed after the fieldwork in 2005, thereby enabling continuation of the daily groundwater level measurements. However, one piezometer got clogged (p03) and four were destroyed during floods (p05, p06, p16 and p17). To compensate for the losses and to study the groundwater level fluctuations of the riverbanks in more detail, seven piezometers (p22 to p28) were installed during the fieldtrip in 2006. Divers (Van Essen Instruments, The Netherlands) were placed in piezometers p04, p22, p25, p27 (groundwater) and in p28 (surface water), hereby providing continuous measurement of groundwater levels in a profile perpendicular to the riverbed. The measurement interval was set to 2 minutes to measure the quick response of groundwater levels on precipitation (especially in the riverbed) at the start of the wet season in detail. Unfortunately, two divers (from p27 and p28) were not accessible at the end of the field trip because of high surface water levels. Possibly, these divers can be retrieved later during the dry season. Divers were left behind in piezometers p04, p25 and p28, performing measurements at 5 minute intervals.

Manual measurements are still performed at publication of this report; Mr. Munyoki is collecting the groundwater level measurements (both manual and automatic) at regular base and sends it to the Acacia Institute.

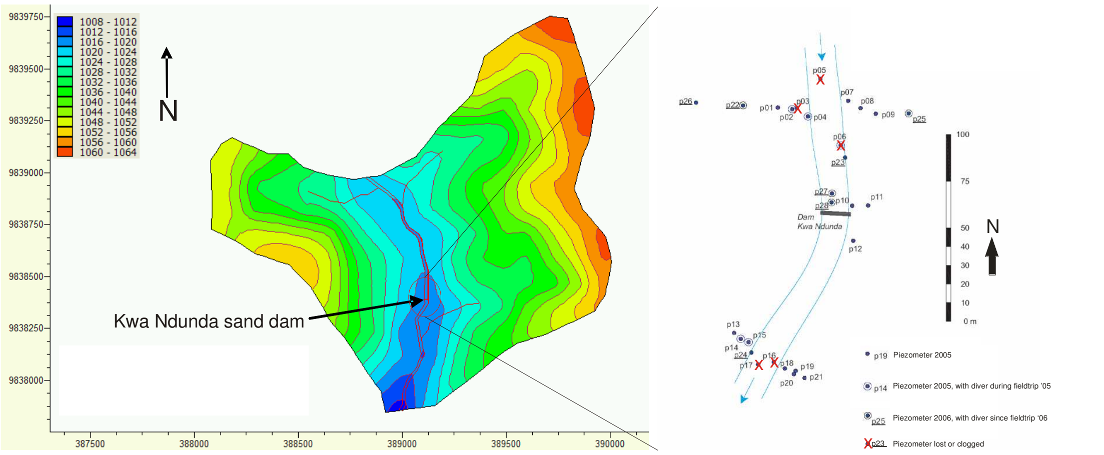



Figure 3.1 Locations of piezometers around the Kwa Ndunda sand dam in December 2006 (Appendix 3)

Data are referenced with respect to the lowest part of the Kwa Ndunda sand dam as described in Appendix 4.

A description of the methodology on creating and installing piezometers is given in Borst et al. (2006). Specifications on location, depth of the piezometers and length of the screen are attached in Appendix 5.

## 3.2 Subsurface

### 3.2.1 Augering

Depth of the basement and thicknesses of subsurface layers form the foundation of the groundwater model. Borst et al. (2006) mapped two soil profiles at the locations of the piezometers based on soil sampling during borehole construction. These profiles provide information on the stratigraphy and depth of the basement. Auger cores were interpreted primarily based on grain size and color, as described by Borst et al. (2006). During the field visit in 2006, more boreholes were made on the upstream array at the locations of piezometers p22, p25, p26, in the riverbed (p23, p24, p27 and p28) and near runoff plots on the eastern riverbank (Figure 3.5, Appendix 3).

### 3.2.2 Vertical Electrical Soundings

In addition to the augerings, 16 Vertical Electrical Soundings were preformed using the ABEM terrameter on the eastern and western riverbanks, both upstream and downstream of the Kwa Ndunda sand dam. The electrodes were arranged according to the Schlumberger configuration. Reynolds (2003) discusses details on Vertical Electrical Sounding according to the Schlumberger configuration.

The results were interpreted using SchlumBG (VU University, Amsterdam). Variation of actual resistivity and layer thickness has to result in a fit between measured and modeled apparent resistivity. However, the solution is not unique (several combinations of layer thickness and actual resistivity can result in the same apparent resistivity). Thereto, borehole data were used on a number of locations to verify the subsurface models.

### 3.2.3 Hydraulic properties

Data collected by Borst et al. (2006) resulted in the distinction of two layers; a sediment layer consisting of clay, silt or sand, overlying weathered rock which is underlain by crystalline basement (Figure 3.2).

Soil characteristics, porosity, specific yield and hydraulic conductivity are layer specific properties, which were taken from literature by Borst et al. (2006). To estimate the properties more accurately, porosity and hydraulic conductivity were determined of silt (eastern riverbank, at runoff plot 1 and 3), clay (western riverbank, at runoff plot 4), and coarse sand (riverbed).

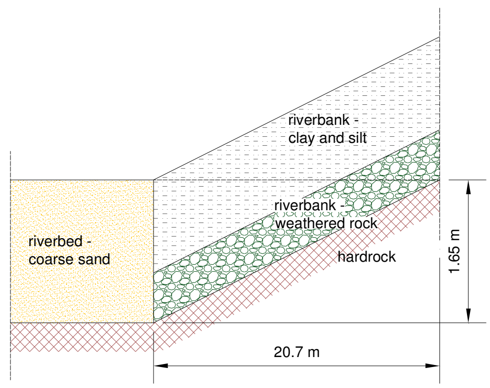



Figure 3.2 Schematic representation of subsurface (after Borst et al. (2006))

**Saturated hydraulic conductivity**

Two methods were applied to measure saturated hydraulic conductivity in unsaturated soil: the inverse auger hole method and double ring infiltrometer.

***Inverse auger hole method (or Porchet test)***

The inverse auger hole method was applied to determine saturated hydraulic conductivity of the subsurface. To this aim, a diver data logger (Van Essen Instruments, The Netherlands) with a preset measuring interval of 2 seconds was placed in the piezometer. The piezometer was filled with water, which subsequently drains. The velocity with which the water level drops is dependent of soil properties. To minimize the influence of errors on the result, the test was repeated several times.

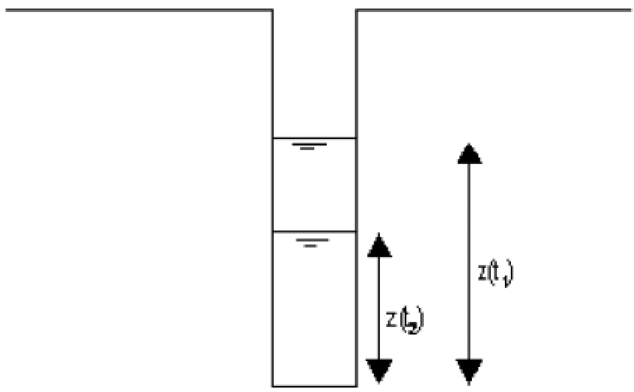



Figure 3.3 Schematic representation of the inverse auger hole method (Waterloo 2005)

According to Borst et al. (2006), the results of the tests performed during the fieldwork in 2005 were unreliable. However, using the methodology described in Van Beers (1983), it was possible to determine saturated hydraulic conductivity from their data (Figure 3.3). Saturated hydraulic conductivity (Ks [cm $s^{-1}$] )is calculated using Equation 3.1, where r is the radius of the borehole [cm], $h_0$ equals the water level at time $t_1$ [s] and $h_t$ is the water level at time $t_2$ [s]. Only the steep part of the recession curve is taken into account to perform the calculation.

$$K_s = 1.15r \frac{\log(h_0 + \frac{r}{2}) - \log(h_t + \frac{r}{2})}{t} \qquad \textbf{[3.1]}$$

In addition to the measurements conducted by Borst et al. (2006), new tests were preformed in piezometers 22 and 25.

***Double ring infiltrometer***

The double ring infiltrometer (VU University Amsterdam, The Netherlands) was used to measure the saturated hydraulic conductivity of the surface layer. The double ring infiltrometer consists of an inner and outer stainless steel ring with diameters of 30 and 60 centimeter, which were partly inserted into the soil. The inner ring was supplied with water through a mariotte bottle to maintain a constant water level. Water infiltrating the soil will cause the water level in the inner ring to fall below the base of the tube, resulting in water flow. The volume of water needed to keep the water level at constant height per unit of time was recorded. Once steady-state flow is reached (*i.e.* dz/dh = 1 in Equation 3.2), the saturated hydraulic conductivity can be calculated from the flux through the inner ring using Equation 3.3, in which V equals the volume depleted from the Marriotte bottle [$m^3$], t is the time between readings [s] and A is the surface area of the inner ring [$m^2$].

$$K_s = -v\frac{dz}{dh} \quad \textbf{[3.2]}$$

$$K_s = \frac{V}{tA} \quad \textbf{[3.3]}$$

The outer ring eliminates the problem of overestimating the hydraulic conductivity due to non-vertical, three-dimensional flow by contributing water to lateral flow. To this aim, the water level in the outer ring was held manually at the same level as the water level in the inner ring (Figure 3.4).

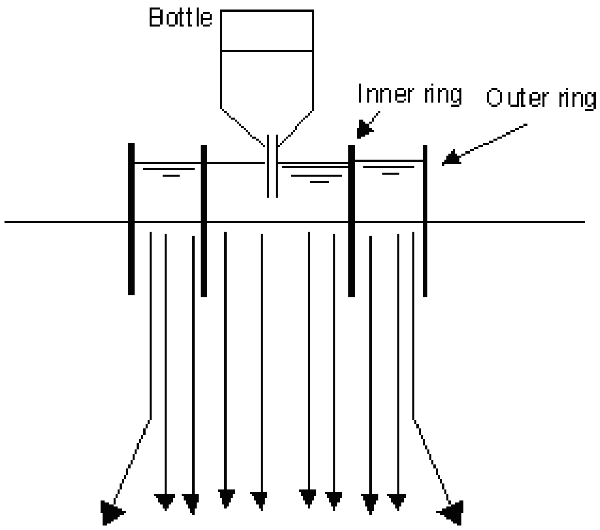



Figure 3.4 Schematic cross-section view of the double-ring infiltrometer installation used in the instruction fieldwork (Waterloo, 2005)

**Porosity**

Bulk density, porosity and volumetric soil water content were determined in one procedure. Soil samples were taken using sample cylinders with a volume of 100 $cm^3$. A balance with an accuracy of 0.1 g was used to determine the weight of the sample and ring, after which the sample was saturated bottom up. The sample was re-weighted to determine saturated weight (X [g]). The sample was dried using an oven (24 hrs at 105 $^0$C). The sample was re-weight to determine the dry weight of the soil (Y [g]), and of the rings (Z [g]). Porosity (n [-]) was determined using Equation 3.4.

$$n = \frac{X - Z - Y}{100} \qquad \textbf{[3.4]}$$

## 3.3 Meteorology

### 3.3.1 Groundwater recharge

The model will simulate the response of groundwater levels on groundwater replenishment, which is dependent of the potential groundwater recharge and evaporation from subsoil. Potential groundwater recharge $(R_{gw,pot})$ [m] is determined by precipitation $(P)$ [m] and the fraction of precipitation infiltrating the subsoil $(1 - f_{SRO,gem})$ [-], in which $f_{SRO,gem}$ [-] equals the mean surface runoff (Equation 3.5). The actual groundwater recharge $(R_{gw,act})$ [m] is calculated using the potential groundwater recharge and the evaporation factor $(f_e)$ [-], as described by Equation 3.6.

$$R_{gw,pot} = P * (1 - f_{SRO,gem}) \qquad \textbf{[3.5]}$$

$$R_{gw,act} = R_{gw,pot} / f_e \qquad \textbf{[3.6]}$$

**Precipitation**

Precipitation is measured on the western water divide of the catchment dam (UTM 38939 m East, 9838422 m North, Figure 3.5). The intensity measured at this location is assumed to be representative of the whole model area.

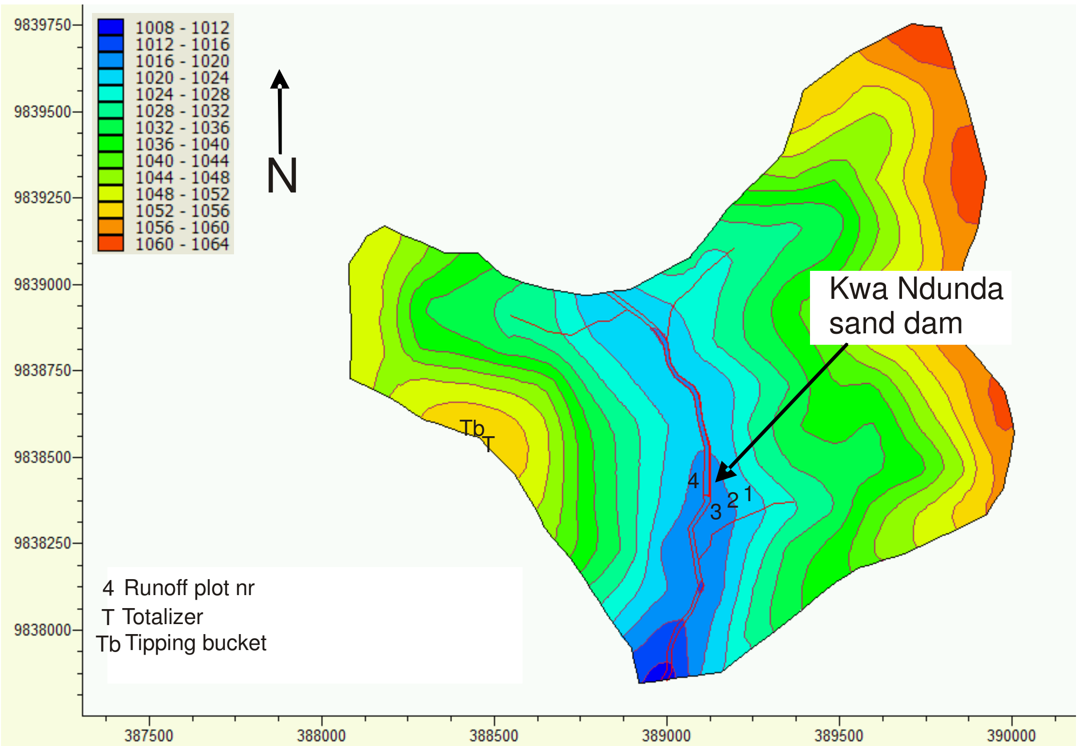


Figure 3.5 Location of equipment during the field visit 2006

Precipitation was measured using two methods, an automated tipping bucket rain gauge system (VU TBL1) and manual measurements using a totalizer (locally produced). Automated measurements were conducted during the field visits. The manual measurements are performed continuously on a daily interval from October 2005 onward.

**Infiltration**

The fraction of precipitation infiltrating the subsoil was determined using runoff plots, located on the eastern riverbank (Figure 3.5). The methodology is described by Jansen (2007), who also discusses the results.

**Evaporation**

The evaporation factor is used to determine evaporation from the subsoil. To this aim, water samples were collected of groundwater at the end of the dry season and during the wet season (p09) in addition to samples of rain and river water. The samples were analyzed using titration on different ions using the chemical field kit developed at the Faculty of Earth and Life Sciences of the VU University Amsterdam as described by Beenke et al. (2005). Additionally, samples were analysed in the hydrochemistry laboratory of the VU University Amsterdam.

Using chloride to determine recharge of the saturated zone is an accepted technique (Mazor et al., 1992) based on the principle of the chloride mass balance in which chloride is assumed to be acting as a conservative tracer. Rainwater contains low concentrations of chloride and concentrations in groundwater are proportional to the fraction of water evaporated prior to groundwater recharge. Although Borst et al. (2006) found halite rock (NaCl) in the study area, rock dissolution, except locally, is not expected to influence water chemistry significantly. The evaporation factor is calculated using Equation 3.7, in which $(Cl_P^-)$ is the chloride concentration in precipitation [mmol $l^{-1}$], and $(Cl_{gw}^-)$ equals the concentration of chloride in the groundwater sample [mmol $l^{-1}$].

$$f_e = \frac{Cl_{gw}^-}{Cl_P^-} \qquad \textbf{[3.7]}$$

# 4 Results of field campaign

This chapter describes results of the fieldwork regarding precipitation, water chemistry, soil sampling, VESses, hydraulic properties and groundwater level measurements.

## 4.1 Groundwater

Figure 4.1 until Figure 4.5 show the rise of groundwater in response of precipitation and the lowering of the groundwater table during the dry season in piezometers placed around the Kwa Ndunda sand dam (Figure 3.1, Appendix 3). The graphs represent groundwater level fluctuations in several cross sections upstream and downstream of the sand dam.

Figure 4.1 and Figure 4.2 show groundwater levels at the eastern and western riverbanks upstream of the Kwa Ndunda sand dam. During the dry season, heads in the riverbed are constantly higher compared to the banks. Furthermore, groundwater levels measured in piezometers next to the riverbank (p04 and p07) are constantly higher as compared to levels measured in piezometers located further from the riverbed (p03 and p02 at the western riverbank and p07 and p09 at the eastern riverbank). To the contrary, groundwater levels observed in p25 and p26 are constantly higher as compared to piezometers located closer to the riverbed (p02 to p04 and p07 to p09).

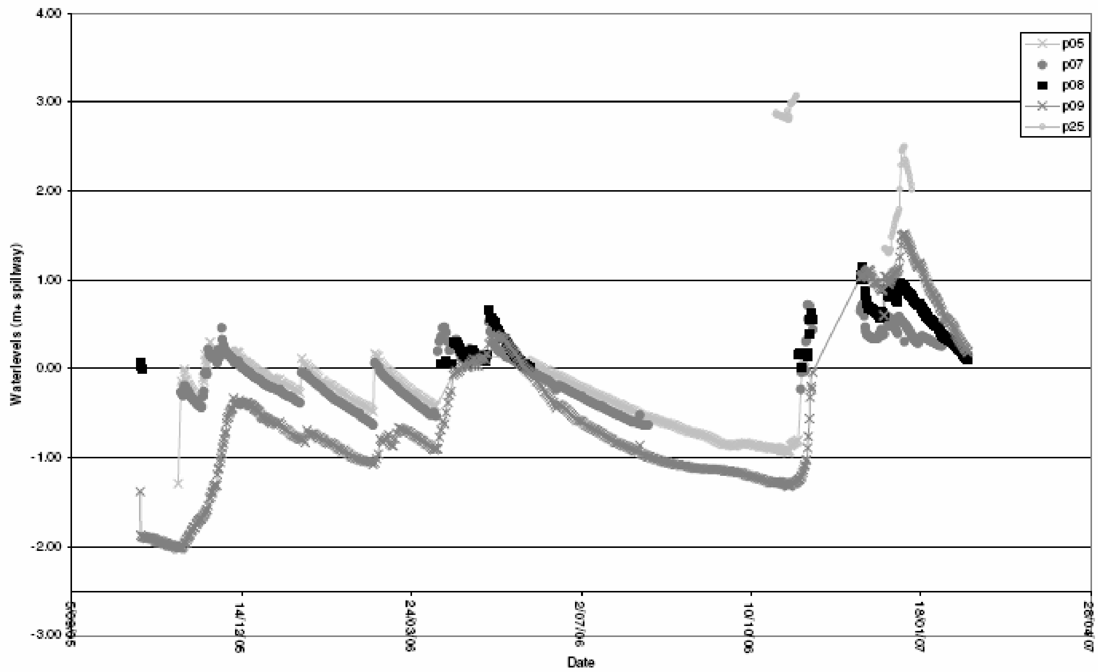



Figure 4.1 Groundwater levels as measured manually 50 meters upstream of the sand dam in the riverbed and eastern riverbank

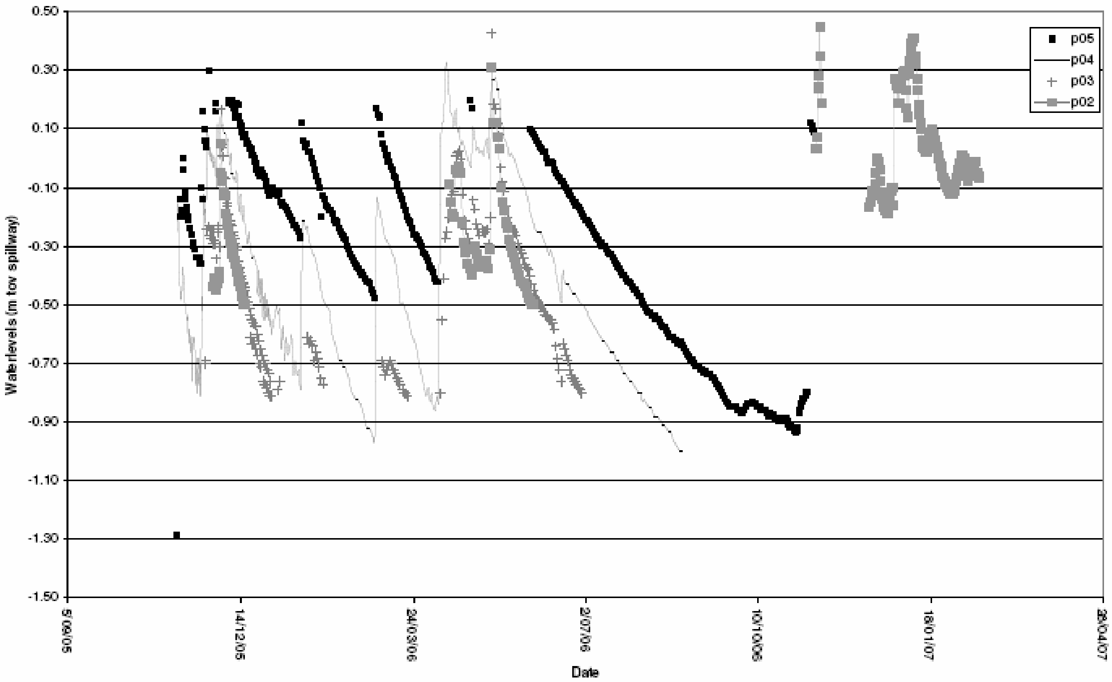



Figure 4.2 Groundwater levels as measured manually 50 meters upstream of the sand dam in the riverbed and western riverbank

Figure 4.3 displays groundwater levels measured in piezometers near the sand dam. Groundwater levels in the riverbed (p06) are consistently higher as compared to p10 and p11. During the wet season, no measurements are available from piezometer p06. Comparing p10 and p11 with p12 shows a difference in groundwater level of more than one meter on average.

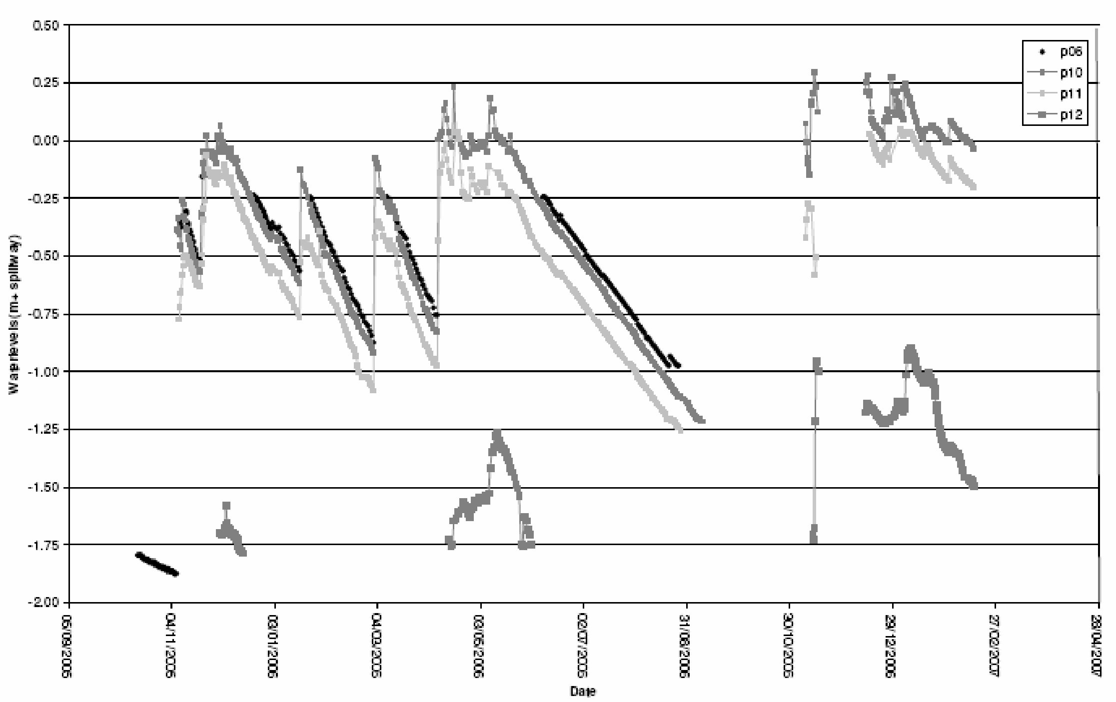



Figure 4.3 Groundwater levels as measured manually in the riverbed at the sand dam and in the eastern riverbank

Figure 4.4 and Figure 4.5 show groundwater levels measured in piezometers located on the eastern and western riverbanks 100 meter downstream of the Kwa Ndunda sand dam. Groundwater levels in p18 are consistently higher as compared to the riverbed (p17). Piezometer p21, located further from the riverbed, registers heads higher than p18 (except for a short period in April 2006, in which the heads were temporarily lower). Heads in the western bank show small differences; p15 registering slightly higher levels than p14 and p13, respectively. Nevertheless, heads in all piezometers located in the riverbed are higher as compared to the riverbed, except during the wet season when the river is flowing.

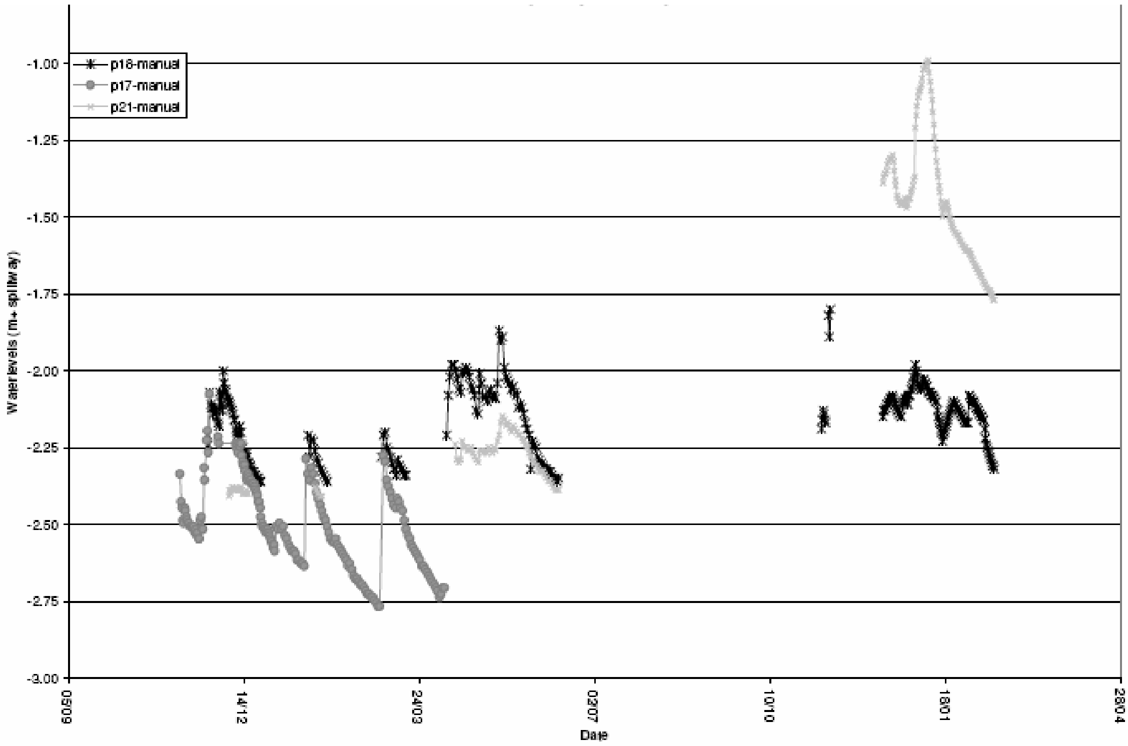



Figure 4.4 Groundwater levels as measured manually 100 downstream of the sand dam in the riverbed and eastern riverbank

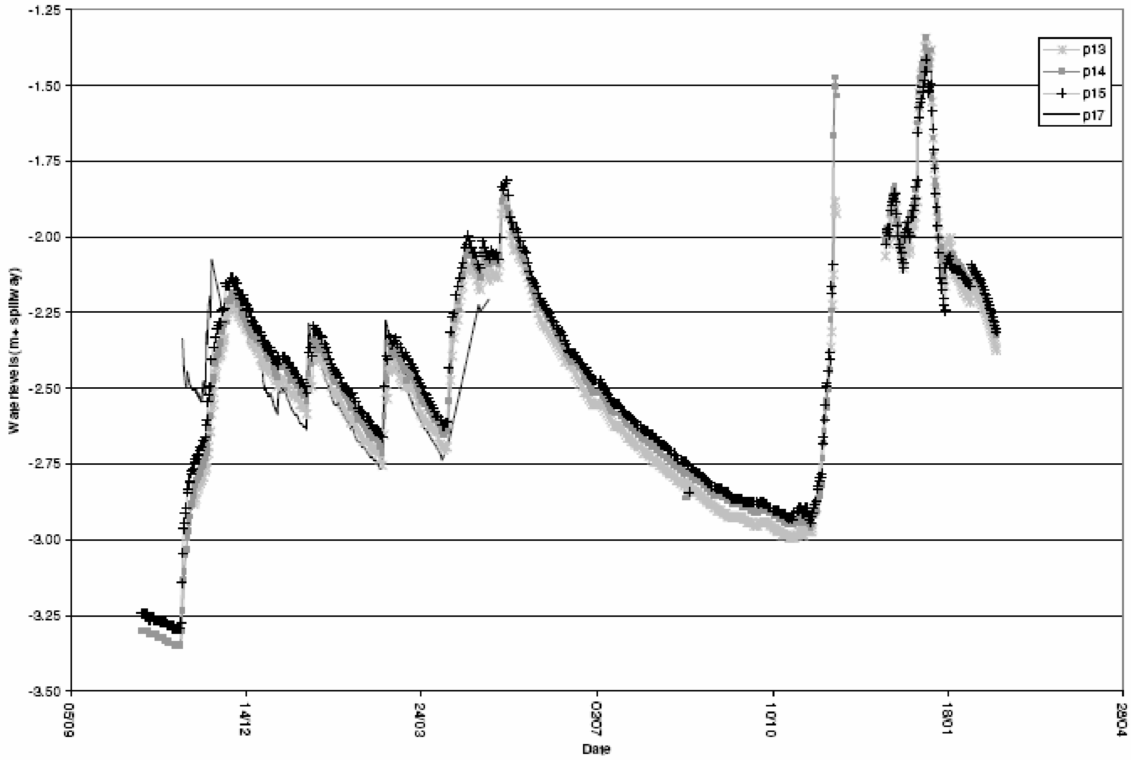



Figure 4.5 Groundwater levels as measured manually 100 meters downstream of the sand dam in the riverbed and western riverbank

Figure 4.6 shows the response of groundwater levels upstream of the Kwa Ndunda sand dam on precipitation and successive dry seasons. Three components can be distinguished. First, the reaction of groundwater levels to precipitation, also shown in Figure 4.7 in detail. Evidently, groundwater levels respond rapid to precipitation; groundwater level in the riverbed (p05 and p17) shows the quickest and largest amplitude of response, followed by piezometers close to the riverbed (p04 and p15). Amplitude of response decreases and response time increases with increasing distance from the riverbed.

Secondly, the constant shape of the recession curves during the short dry seasons (e.g. 18-01-2006 to 01-03-2006) which are dependent of soil type. Sand has a more gradual recession curve compared to clayey soils on the riverbanks. The last component is observed during the prolonged dry season (24-05-2006 to 20-10-2006) showing an evident decrease in gradient of the recession curve when the groundwater levels fall below a certain groundwater level (-0.60 m + spillway for p05, Figure 4.6).

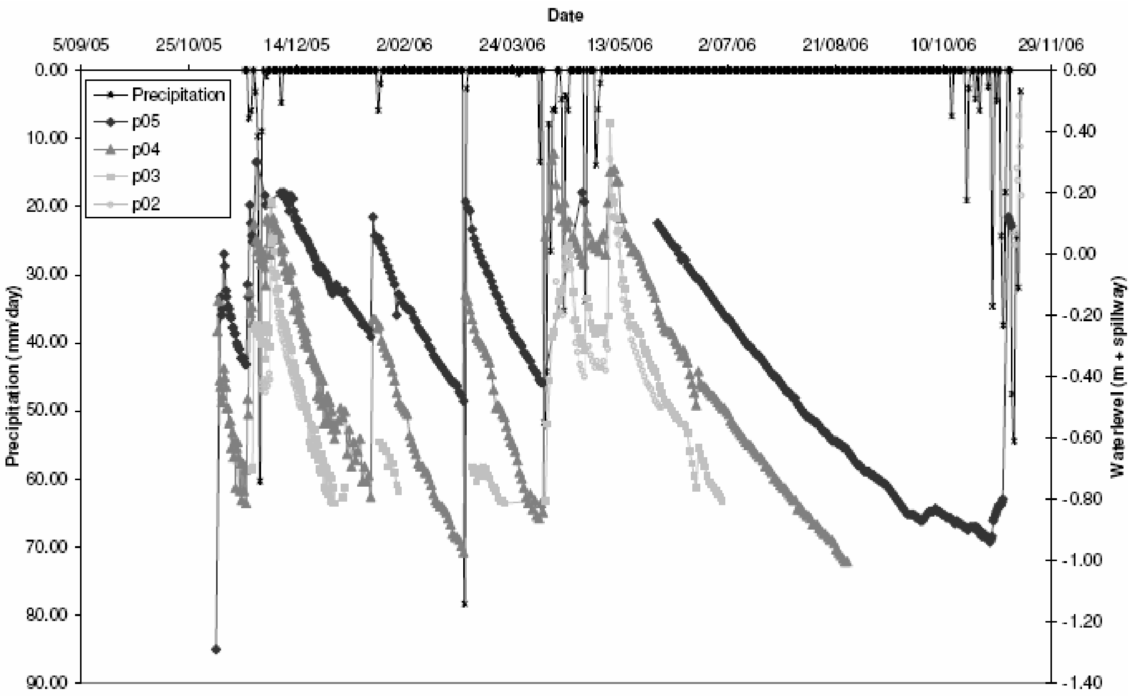



Figure 4.6 Reaction of groundwater levels on precipitation as measured in the piezometers in the riverbed and western riverbank 50 meter upstream of the Kwa Ndunda sand dam

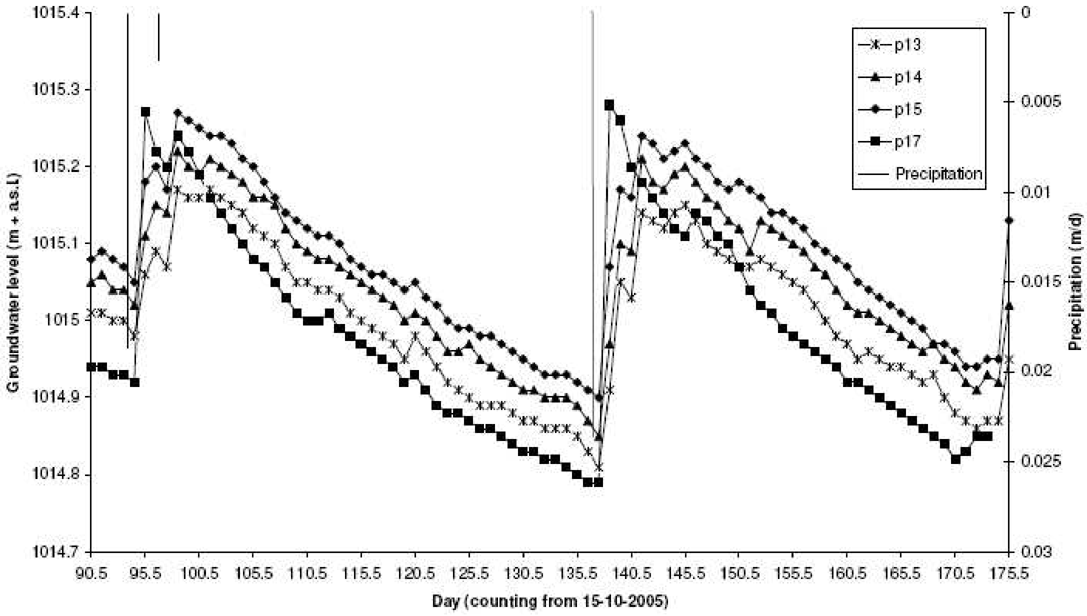



Figure 4.7 Detail of measured groundwater levels as measured manually 100 meters downstream of the sand dam in the riverbed and western riverbank in combination with precipitation

## 4.2 Meteorology

### 4.2.1 Precipitation

Results of the manual daily precipitation measurements are presented in Figure 4.8. The occurrence of precipitation is focused in three main wet seasons; 21-11-2005 to 19-11-2005, 08-04-2006 to 03-05-2006 and 15-10-2006 to the end of the field visit (15-11-2006). Two rainfall events occurred during the dry period from 19-11-2005 to 08-04-2006; on 20-01-2006 and 29-02-2006.

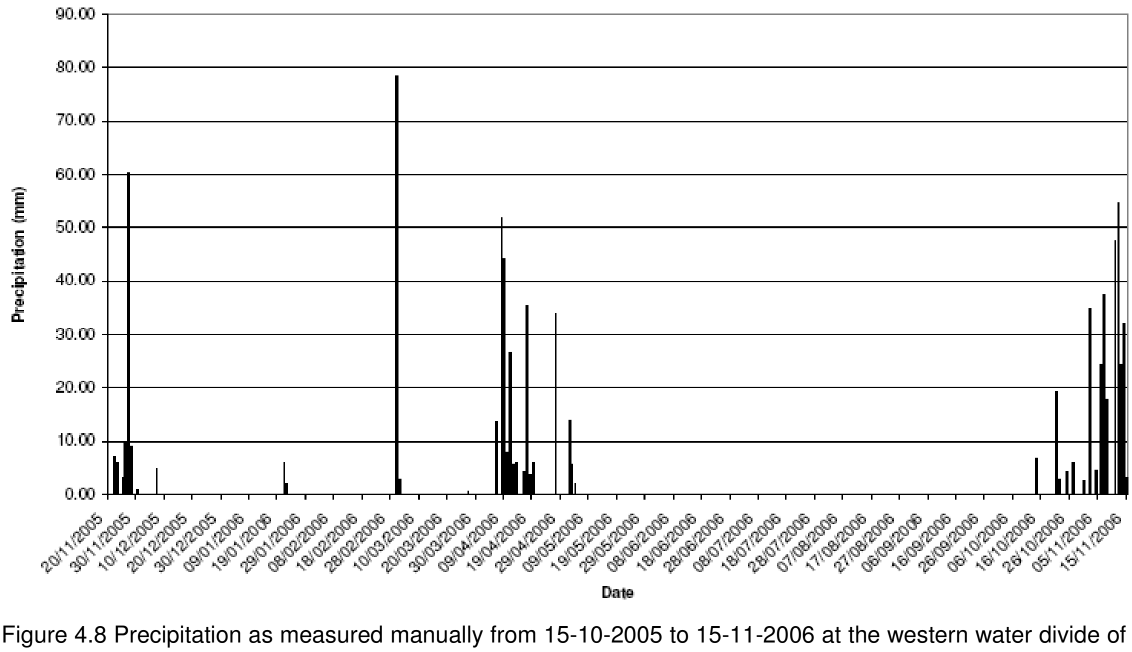



Figure 4.8 Precipitation as measured manually from 15-10-2005 to 15-11-2006 at the western water divide of the model area

### 4.2.2 Groundwater recharge

Unfortunately, water samples were damaged and lost during transportation. Therefore, results of the manual titrations performed in Kenya are considered most reliable.

Application of Equation 3.7 results in an average evaporation factor of 114.5 (Table 4.1).

Table 4.1 Average evaporation factor determined using chemical analysis

| Water sample | Date | $Cl^-$ [mmol/l] | Evaporation factor |
|---|---|---|---|
| Rain | 07-11-2006 | 0.8 | |
| p09 | 07-10-2006 | 93.2 | 116.5 |
| p09 | 24-10-2006 | 90 | 112.5 |
| | | **Average** | 114.5 |

Jansen (2007) discusses the results from the runoff plots. The average runoff coefficient is 0.15; 85 percent of the precipitation thus infiltrates. Combining potential groundwater recharge with the evaporation factor according to Equation 3.5 leads to an actual groundwater recharge of 0.74 percent of the precipitation on average.

## 4.3 Subsurface

Based on borehole descriptions, the subsurface is schematized as consisting of clay, silt, sand, weathered rock and hard rock.
Figure 4.9 and Figure 4.10 show the subsurface upstream and downstream of the Kwa Ndunda sand dam as reconstructed from borehole data. Depth of the hard rock (e.g. rock which the auger could not penetrate) and occurrence and thicknesses of sediment and weathered rock layers is very irregular.

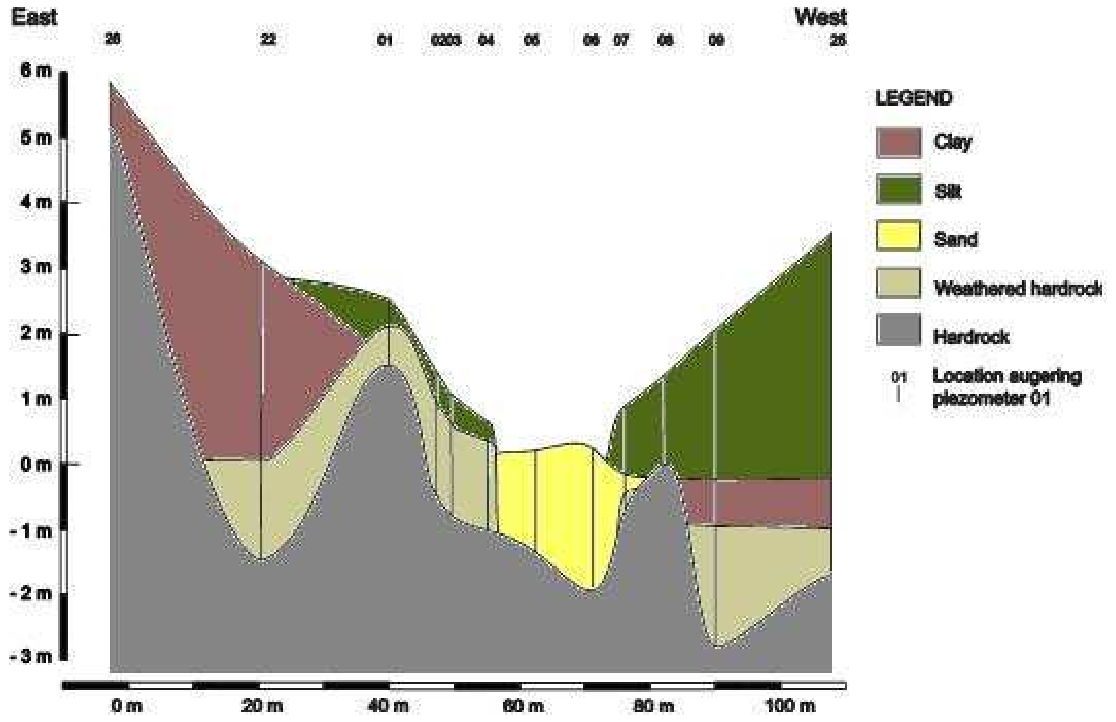



Figure 4.9 Cross section 50 meter upstream of the Kwa Ndunda sand dam (after Borst et al. (2006))

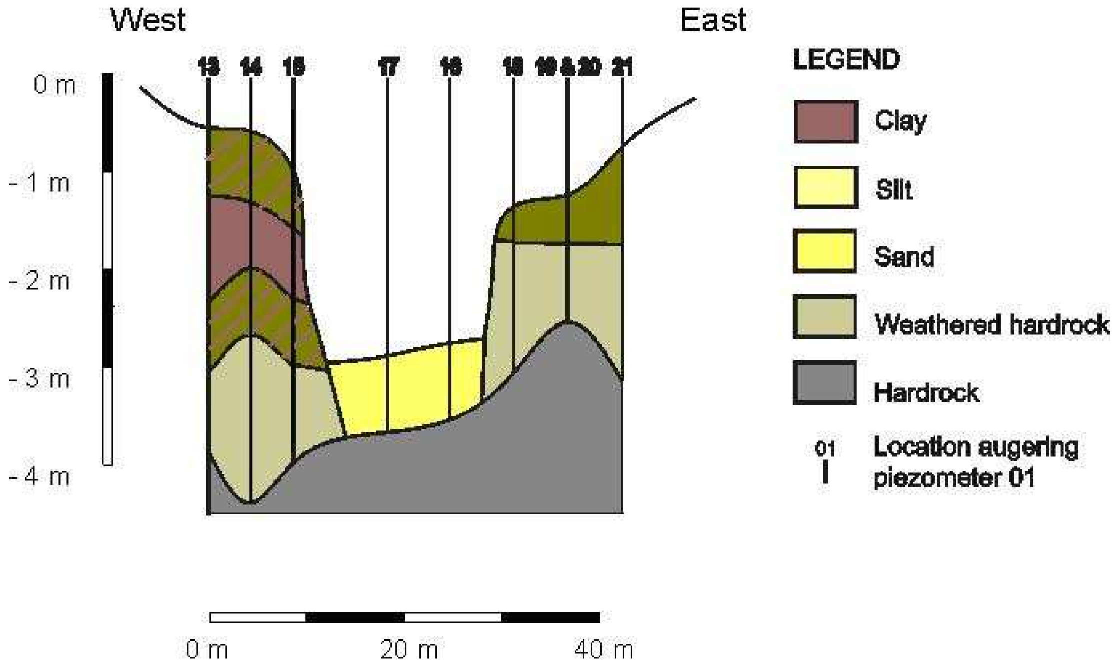



Figure 4.10 Cross section 100 meter downstream of the Kwa Ndunda sand dam (after Borst et al. (2006))

Geo-electrical measurements are used to determine thickness of the weathered rock layer beyond the depth that the manual auger could penetrate and to extent spatial coverage of geological data. Resistivities of the different subsoils are presented in Table 4.2.

Results from Vertical Electrical Soundings indicate a relative small increase in thickness of the sediment layer from the riverbed further into the riverbanks. The thickness of the weathered rock layer increases more evident; from a meter near the riverbed to approximately 16 meter towards the hillcrest. The degree of weathering is highly variable, varying from slightly to highly weathered. VES results also indicate the presence of groundwater in the weathered rock layer of the riverbanks.

Table 4.2 Resistivity of different subsoils as interpreted with SchlumBG (VU University, Amsterdam)

| **Soil type** | | **Resistivity (Ωm)** |
|---|---|---|
| Silt | Dry | 100 – 170 |
| | Wet | 60 – 80 |
| Clay | Dry | 20 – 40 |
| | Wet | 4 – 10 |
| Weathered rock | | 80 – 180 |
| Basement | | 200 – >800 |

The hydraulic properties of the soil layers are discussed in the following sections.

### 4.3.1 Hydraulic conductivity

Inverse auger hole tests were functional in several piezometers; p06, p10, p13, p17, p20, p21, p22 and p25. Resulting curves (Figure 4.11) are used to determine saturated hydraulic conductivity.

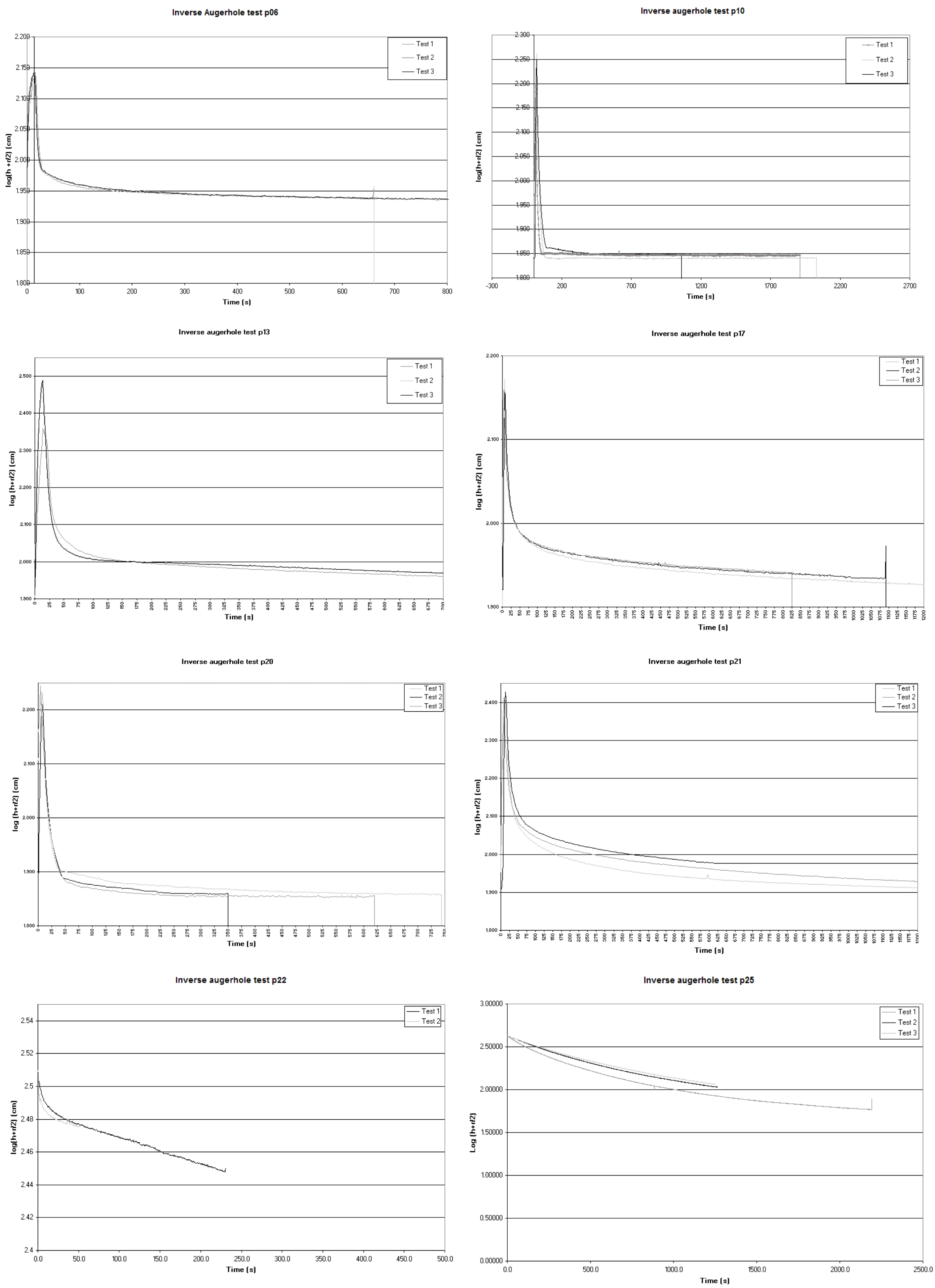



Figure 4.11 Results of inverse auger hole tests in piezometer p06, p10, p13, p17, p20, p21, p22 and p25

Calculated saturated hydraulic conductivity is presented in Table 4.3, in which IAT means Inverse Auger hole Test and DR means double ring infiltrometer.

Table 4.3 Saturated hydraulic conductivity (m/d) per sediment type

| **Sediment** | **Location** | **Method** | **Ksat (m/d)** |
|---|---|---|---|
| Silt | p10 | IAT | 11.8 |
| | p13 | IAT | 14.6 |
| | RP3 | DR | 10.1 |
| Clay | p22 | IAT | 1.2 |
| | p26 | DR | 3.2 |
| Sand | p6 | IAT | 35.9 |
| | p17 | IAT | 35.7 |
| | Riverbed | DR | 56.7 |
| Weathered rock | p25 | IAT | 7.2 |
| | p21 | IAT | 11.0 |
| | p20 | IAT | 12.0 |

Saturated hydraulic conductivity of silty soil varies between 10.1 and 14.6 m/d. Hydraulic conductivity in clay is measured twice and shows a variation between 1.2 and 3.2 m/d. The hydraulic conductivity in the riverbed shows a large variation, between 35.7 and 56.7 m/d. Weathered rock has a hydraulic conductivity varying between 7.2 and 12.0 m/d.

### 4.3.2 Porosity

Results of different subsoils are displayed in Table 4.4.

Table 4.4 Porosity as determined for coarse sand (riverbed) and silt (RP3)

| **Location** | **Porosity** |
|---|---|
| Riverbed | 0.42 |
| Runoff plot 3 | 0.34 |
| Runoff plot 3 | 0.30 |

Coarse riverbed sand has a porosity of 0.42. Silty soils (Runoff plot 3) have a porosity varying between 0.34 and 0.30. Porosity in clayey soils and of weathered rock could not be determined.

# 5 Discussion of field results

This chapter discusses dynamics in groundwater flow patterns and, from a modelling effort point of view, the accuracy of input parameters (groundwater recharge, hydrogeology).

## 5.1 Groundwater

Groundwater flow through the riverbed and a small part of the riverbanks is obstructed through the presence of the sand storage dam. This results in a groundwater reservoir with raised piezometric heads. During the dry season, heads measured by piezometers in the riverbed upstream of the sand dam are higher in comparison to those in the banks. Consequently, groundwater flows from the riverbed into the riverbanks. However, piezometers located at the largest distance from the riverbed show the contrary; these continuously register higher groundwater levels as compared to piezometers located closer to the riverbed. This results in the conclusion that groundwater flow is oriented towards the riverbed outside the zone of influence of the sand dam.

In addition to the previous mentioned observations, heads measured in piezometers upstream of the sand dam are higher than those measured in downstream piezometers are. This indicates groundwater flow around the sand dam. Downstream of the sand dam, groundwater levels in the riverbanks are higher as compared to those in the riverbed. Groundwater flow downstream of the sand dam is thus oriented towards the riverbed.

In response to precipitation, a change in direction of groundwater flow is observed. Due to groundwater recharge, groundwater levels in the riverbanks decrease towards the riverbed in both the upstream and downstream cross sections. Groundwater flow is thus oriented towards the riverbed both up- and downstream of the sand dam. Nevertheless, groundwater is still flowing around the sand dam.

The aquifer behind the sand dam fills up rapidly in response to precipitation; after one large rainfall event the sand aquifer in the river is filled and the river starts to flow. The time lag and decrease in amplitude of the reaction of groundwater on precipitation in the riverbanks is caused by lower hydraulic conductivity of the soils in the riverbanks compared to the riverbed and the depth of the groundwater table with respect to the surface level.

It should be noted that the piezometers were installed using hand augering equipment. The ability to penetrate the weathered rock layer is dependent on the degree of weathering of this layer. Vertical Electrical Soundings indicate groundwater present in the weathered rock layer, leading to the conclusion that groundwater levels might drop below the bottom of piezometers during the dry period.

Piezometers are concentrated around the sand dam, groundwater levels are thus only known with acceptable precision in a radius of 50 meter from the sand dam. The addition of piezometers located further on the riverbanks includes the zone outside the direct influence area of the sand dam. However, groundwater level data of these piezometers are available over a relative short period at the moment of publication of this report. The reaction of groundwater levels during the dry season are not known with certainty. Nevertheless, the piezometers registered groundwater levels after the long dry period from 03/05/2006 to 15/10/2006, which are evidently higher compared to levels in piezometers located closely to the riverbed.

## 5.2 Groundwater recharge

Precipitation is measured manually from 15-10-2005 onwards at the western riverbank. Although precipitation is measured on a daily interval, and is thus known with acceptable accuracy, the actual groundwater recharge is subject of discussion.

Firstly, the ratio between precipitation and infiltration, which is obtained from data collected during the wet season from 15-10-2006 to 20-11-2006 (Jansen, 2007). The ratio varies due to different land use and soil characteristics. Since the runoff plots were located on different types of land use, the obtained ratios could be compared. According to Butterworth et al. (1999a), rainfall intensity is of importance to the percentage of precipitation leading to groundwater recharge. However, during the field study rainfall events of different intensity and duration occurred enhancing the precision of the estimation.

After infiltration, soil water evaporates from the unsaturated zone before recharging the groundwater. An estimation of evaporation is made based on the chloride content of groundwater water and precipitation samples. Accuracy can be increased by analysis of oxygen isotopes in precipitation and groundwater samples.

## 5.3 Hydrogeology

Layer thicknesses of the sediment and weathered rock layers are varying throughout the area. Boreholes are located in a radius of 100 meter from the sand dam. Especially the thickness of the weathered rock layer is difficult to estimate because of variation in degree of weathering. Using VES, the extent of information is increased to a distance of 300 meter at both sides of the riverbed. Additionally, using VES the thickness of the weathered rock layer could be determined with more accuracy.

Hydraulic conductivity is determined in several piezometers, which resulted in consistent data between the applied methodologies for one layer. Porosity is determined at only two locations although variation can be large. Uncertainty in the values is large. Furthermore, porosity of the weathered rock layer could not be determined.

# 6 Groundwater model

The groundwater model is designed to study local groundwater dynamics in and around a sand dam as well as the actual influence on groundwater flow and storage. In addition, the model will provide insight in physical parameters fundamental for successful functioning of sand dams. The model effort is performed according to the scheme presented in Figure 6.1, and will be discussed accordingly.

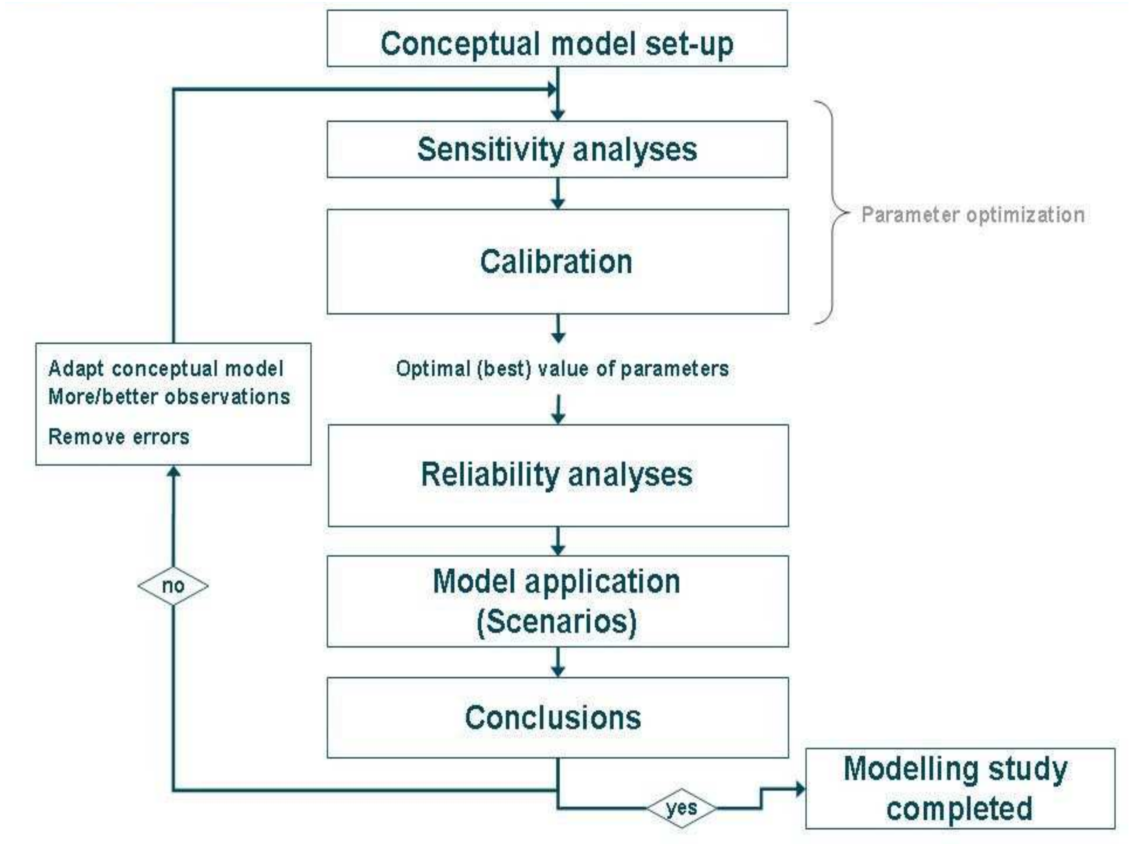



Figure 6.1 Scheme of the model effort (after TAIEX, 2007)

This chapter describes the conceptual model. Furthermore, the model specifications, such as location and dimensions of the model area, spatial discretization, hydrogeological schematization, initial conditions, time discretization and boundary conditions are discussed. The parameter values are based on field data and are accounted for in Chapter 4.

## 6.1 Conceptual model

The conceptual model is based on the results obtained during the field studies in 2005 and 2006 which are discussed in Chapter 5, as well as a literature study on hydrological processes in semi arid catchments. It should be noted that little has been published on groundwater dynamics in small semi arid catchments.

**Precipitation**

Groundwater levels measured from October 2005 onward show rapid responses to precipitation. The same observation was made during a study on catchment hydrology in Romwe (a small catchment in Tanzania) by Butterworth et al. (1999b), showing rainfall to be the most important groundwater supplier. Studies of Andersen et al. (1998) and Wheater et al. (2002) on sand rivers of Botswana showed a single major rainfall event after a long dry period being sufficient to recharge the alluvial riverbed aquifer completely. As compared to the Kiindu catchment, significant resource potential remained throughout the dry season, supplying local communities with water.

**Evaporation**

The field study indicated a small percentage of the infiltrated precipitation leading to groundwater recharge. Wheater et al. (2002) shows most of the rainfall is lost through evaporation during soil moisture studies in semi arid areas in Saudi Arabia and Arizona. However, several studies indicate evaporation being small once infiltration has taken place and the water table drops below the surface (Andersen et al., 1998). Parrisopoulos et al. (1991) shows evaporation losses generally not significantly affecting the water balance or water table responses in short-term simulations at (sub)catchment scale. According to Wheater et al. (2002), evaporation from the riverbed is not significant once infiltration has taken place; alluvium underlying wadi bed is effective in minimizing evaporation loss through capillary rise because of its coarse structure. Hellwig (1973) found that when the water table drops 60 cm below the surface level, evaporation losses are insignificant. Biamah et al. (2004) state that high evapotranspiration rates are experienced in the soil water zone but evapo(trans)piration from the groundwater table in the riverbanks is expected to be negligible. As described in Paragraph 2.3, little vegetation is present on the riverbanks during the dry season; natural vegetation is scattered and disrupted by bare crop fields. Soil water is protected against evaporation through a crust because of higher reflectance and retardation of capillary movement of water (USDA, 1996). The exception to this situation is the area next to the riverbed where less drought persistent vegetation exists.

During the wet season, crops are grown on the riverbanks. This vegetation presumably has a limited root depth, enhanced by the fine textured soils which usually result in a more superficial root zone development compared to coarser subsoil (WWD, 2000).

**Groundwater flow**

Groundwater level measurements performed from October 2005 onward in piezometers up- and downstream of the Kwa Ndunda sand storage dam lead to the following conclusion. Sand storage dams cause enlargement of the natural aquifer and obstruct groundwater flow through the

permeable riverbed. A groundwater reservoir is formed upstream of the sand storage dam. Raised heads in this zone of influence results in groundwater flow from the riverbed into the riverbanks and through the riverbanks around the dam. Upstream of the sand dam outside the zone of influence and ddownstream of the dam, groundwater flow is directed towards the riverbed.
In correspondence with Jothiyangkoon et al. (2001), subsurface runoff is identified as the key process. Uhlenbrook et al. (2005) describes subsurface groundwater flow in the aquifer situated in the soil cover above the bedrock as topography driven. Accordingly, groundwater flow in the Kiindu catchment would be directed towards the riverbed and south, following the general topography of the region. Therefore, potential groundwater storage of the sand body in the riverbed should increase downstream since the catchment area and thus groundwater flow towards the riverbed increases downstream. This corresponds with observations during visits to downstream parts of the Kiindu river described by Gijsbertsen (2007); river width and depth of the sand aquifer increase downstream. Also, from communication with local communities it became clear that in the natural situation groundwater was available for longer periods of time during dry seasons in more downstream parts of the Kiindu catchment. This assents the hypothesis.

## 6.2 Model

The model is developed in the Triwaco modeling environment (Royal Haskoning, 2004; Triwaco).

Groundwater flow is computed by finite element simulation in calculation module Flairs. A major advantage of the finite element method is grid flexibility, allowing a close spatial approximation of irregular boundaries of the aquifer, internal structures, point sources and parameter zones within the aquifer (Konikow, 2004; Viaene et al., 1998). This feature is important to enable incorporation of sand dams and scoop holes in the model.

Flairs solves the partial differential equation for water level $h$ in different aquifers by using the Galerikin finite element method (Solomatine et al., 1999). Flairs uses an integrated combination of the preconditioned conjugate gradient (PCG) method complemented with the over relaxation method (SOR) to ameliorate the solution for changes in head due to source terms and phreatic calculations (Viaene et al., 1998).

The upper aquifer has phreatic conditions. However, based on numerical considerations, the aquifer is schematized as confined. The primary reason is the steep gradient of the slope, resulting in large parts of the aquifers theoretically being dry for most of the model run. Consequently, the saturated thickness and thus calculated transmissivity of the aquifers are zero. Groundwater flow is thus not occurring in theory while it does in reality. During the wet season, groundwater levels rise rapidly in response to precipitation, leading to an extreme increase in transmissivity. This results in an almost immediate emptying of the aquifers and thus an extremely low transmissivity. The rapid changes lead to convergence problems. To avoid this problem, a constant transmissivity is used which approximates the saturated thickness of the aquifer multiplied by its hydraulic conductivity. To this aim, the calculations are performed in a confined setting.

## 6.3 Model area and boundary conditions

The model area is located between the up- and downstream dams of the Kwa Ndunda sand dam and between water divides on both sides of the river. Both riverbanks are included in the model because the eastern riverbank primarily consists of silty soils while the western riverbank is comprised of clay. This is observed throughout the Kiindu catchment as well as in other catchments (Gijsbertsen, 2007). The hydraulic properties of the riverbanks differ substantially (Paragraph 4.3), resulting in significantly dissimilar hydrological behavior (Paragraph 4.1) supporting the choice to incorporate both riverbanks in the groundwater model.

The model area covers approximately 1.9 $km^2$, and has a length of approximately 1900 meter and a width of approximately 1950 meter (Figure 6.2).

The largest part of the model boundary is defined at hill ridges and is considered a no flow boundary. However, in depressed areas around the up- and downstream sand dams, groundwater flow is expected to occur. A constant head boundary is assigned to these parts of the boundary (Figure 6.2). The distance of the boundary is large enough to ensure the boundary condition to have a negligible effect on simulated groundwater levels in the area of attention. The head is based on observations at the Kwa Ndunda sand dam of approximately 0.5 meter below surface level on average. To ascertain the boundary conditions don’t influence modeled groundwater levels in the area of interest, the model is run with heads of +0.3 m, +0.1 m, -0.1 m and -0.3 m with respect to this boundary condition (Appendix 8).

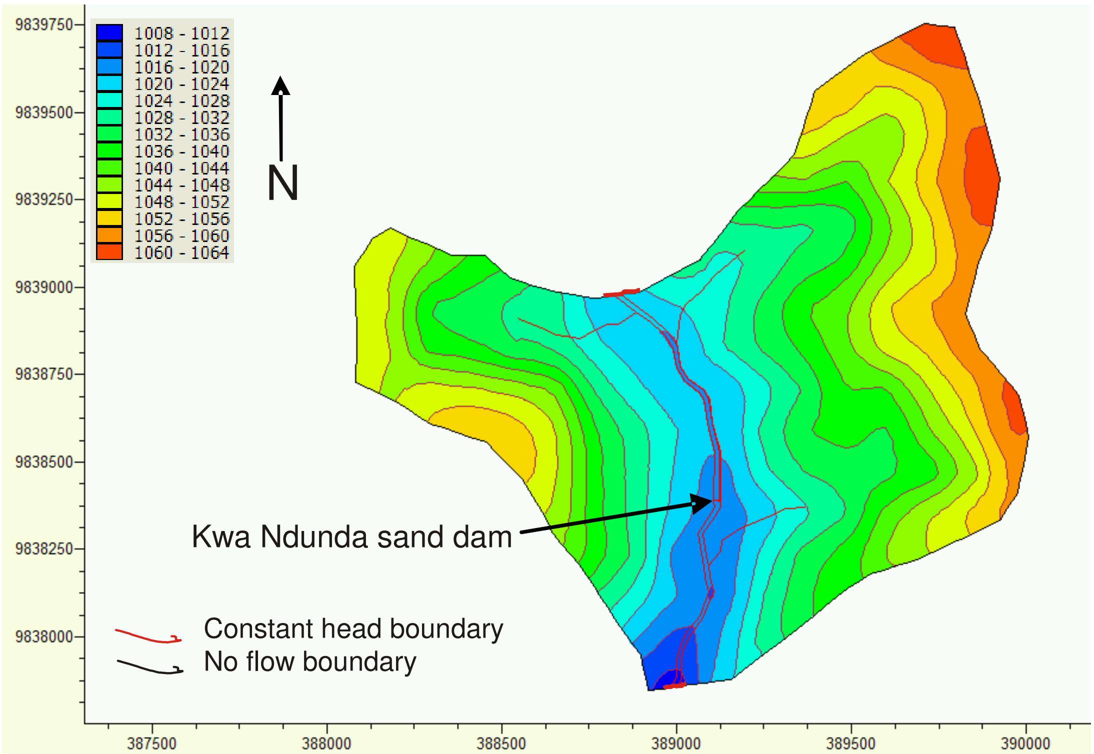



Figure 6.2 Model boundary and boundary conditions with surface elevation level contoured (m+ M.S.L.)

## 6.4 Spatial discretization

Grid resolution determines the detail with which parameters can be represented and thus allots the detail of model results. However, it also determines calculation time. The balance is found by creating a dense network in the area of interest (the area around the Kwa Ndunda sand dam) and decreasing grid density towards the model boundaries. To represent resistance between riverbed and bank (as will be explained in Paragraph 6.7.2), it is necessary to extent the dense network along the riverbed upstream of the sand dam. This allows a close spatial approximation of irregular boundaries between riverbed and –banks.

A rule of thumb states differences between levels of discretization should increase by a factor 3 at most, thereby preventing irregularities in the model grid. The smallest nodal distance is 1 meter, increasing to 5, 10, 20 and 40 meter at the model boundary. The model is run in Flairs using a finite element grid created in grid generator program Tesnet, resulting in the network shown in Figure 6.3, consisting of

- 36274 nodes;
- 181 boundary nodes;
- 72365 elements

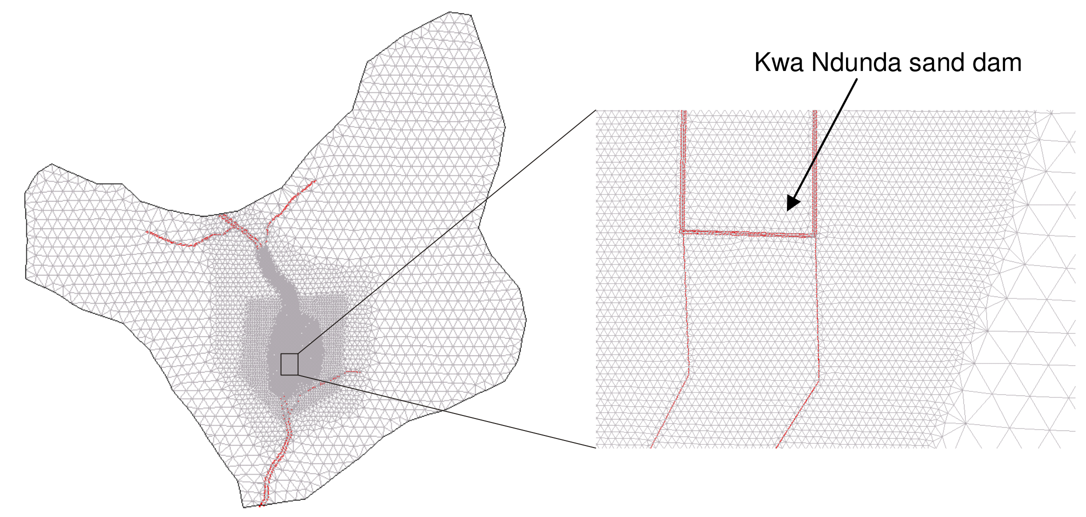



Figure 6.3 Visualization of the used discretization in the groundwater model, with a special focus to the area around the Kwa Ndunda sand dam

### 6.4.1 Schematization of ephemeral river

Upstream of the sand dam, the river is schematized as three lines incorporated in the modeling grid. These lines enable precise allotment of parameters. The pairs of lines are 15 meter apart, corresponding to the actual width of the Kiindu river. Downstream of the Kwa Nunda sand dam, the Kiindu river is schematized as two lines being 15 meters apart. Tributaries of the Kiindu river are simulated as single lines (Figure 6.4).

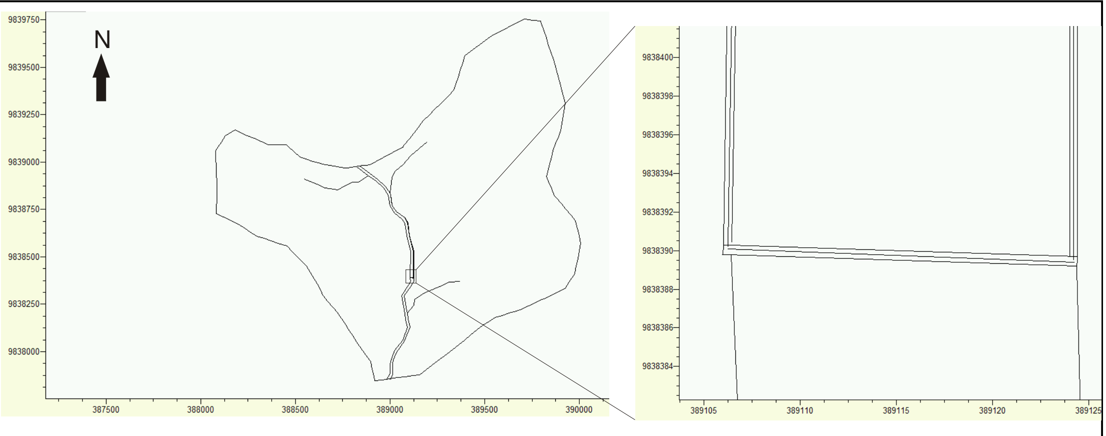



Figure 6.4 Representation of the Kiindu river and Kwa Ndunda sand dam

### 6.4.2 Schematization of the storage dam

Flairs determines transmissivity as a mathematical average of the values of transmissivity at the nodes of an element (Viaene et al., 1998). A barrier, e.g. a sand dam, should thus be presented as a narrow zone of nodes with a very low conductivity; the sand dam is incorporated as three lines with a polygon with very low conductivity (0.00001 m/d) around the inner line. The resistivity between riverbed and banks is incorporated likewise, having a hydraulic conductivity of 0.1 m/d.

## 6.5 Hydrogeological schematization

### 6.5.1 Surface elevation

Surface elevation is defined by a SRTM 90 m DEM with a horizontal resolution of 90 meters and a vertical resolution of 5 meter available through the CGIAR Consortium for Spatial Information (CIS). The SRTM 90 m DEM covers half of Kenya. The image was cropped to fit the topographical map of the field area (Figure 6.5). Also, the coordinate system was converted from UTM WGS84 74S in decimal degrees to UTM WGS84 in meters.

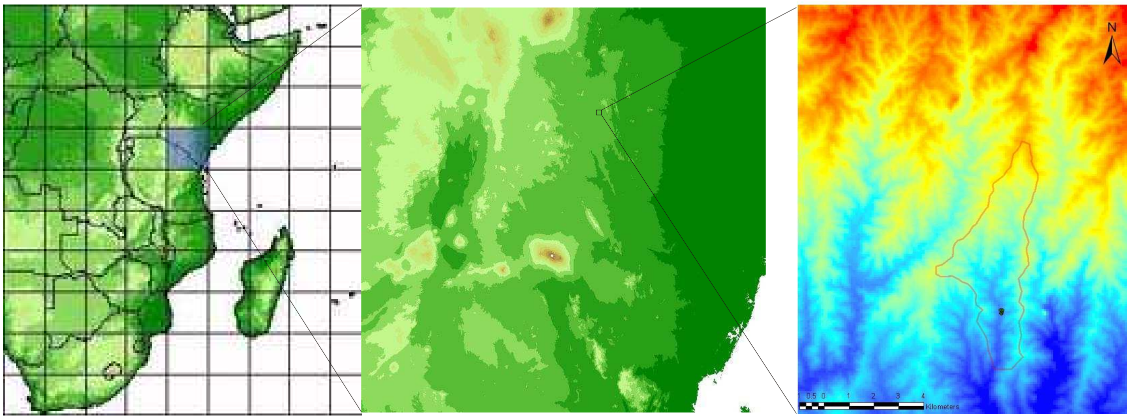



Figure 6.5 Arial coverage of the SRTM 90 m DEM focussing on the catchment of the Kiindu river

### 6.5.2 Model layers

The model consists of 2 aquifers; sediment and weathered rock on top of impervious basement (Figure 6.6). At the location of the river, the sediment layer consists of coarse sand. On the riverbanks the sediment consists of clay on the western riverbank and silt on the eastern riverbank. The weathered rock layer is present throughout the model area.

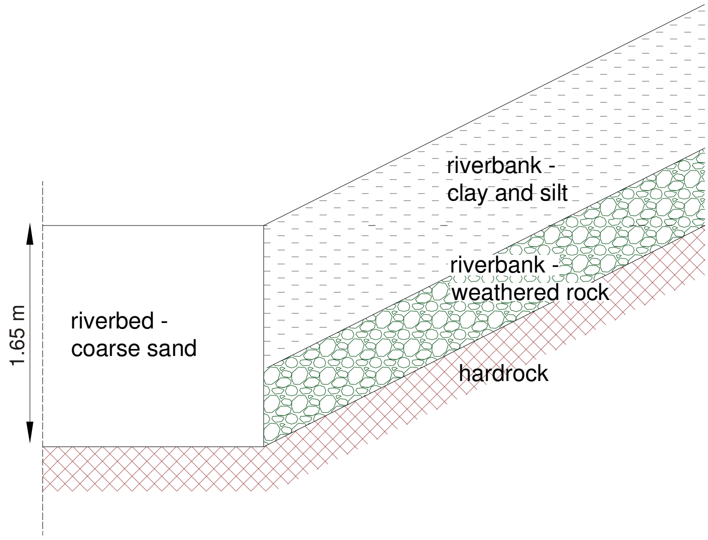



Figure 6.6 Schematic representation of the subsurface (after Borst et al. (2006))

## 6.6 Temporal discretization

The simulated period is from 15-10-2006 to 15-11-2006, starting at the end of a dry period and including several wet and dry seasons. The model runs on a five day interval. Data regarding precipitation and groundwater levels are available from October 15$^{th}$ 2005.

### 6.6.1 Initial condition

A semi arid system is very dynamic, consisting of wet and dry seasons. Since the measurements of groundwater level and precipitation started at the end of the dry season (15-10-2005), the initial conditions is representative of the situation at the end of a dry period. To this aim and to account for irregularities due to model instabilities in the initial period, a year in advance of the groundwater simulation is added to the model run. The model run thus starts at 15-10-2004. Figure 6.7 shows that one year in advance of the actual model run is sufficient to obtain a stable initial condition; elevated groundwater levels due to recharge in the first time step decrease to a constant groundwater level within ten time steps, after which the drop of groundwater level is almost negligible.

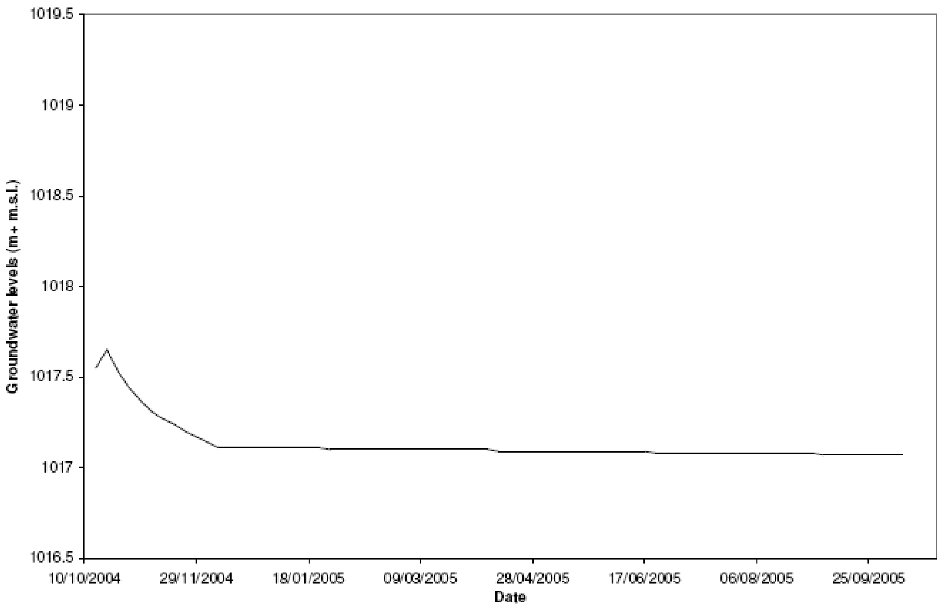



Figure 6.7 Representative drawdown curve during the first year after a large recharge event

## 6.7 Upper boundary conditions

### 6.7.1 Groundwater recharge

Groundwater recharge is a time dependent parameter assumed to be uniform throughout the model area although varying in intensity and duration. As argued in Paragraph 5.1, 'Conceptual model', evaporation can be assumed to be negligible after groundwater recharge. However, evaporation from the soil prior to groundwater recharge can be extensive. Although subsoil evaporation is not incorporated in the model, it is accounted for indirectly through the evaporation factor.

### 6.7.2 River floods

River stages are modelled using a controlled water level; if the controlled water level rises above the base elevation of the primary drainage system, the system is active and drainage will occur. These moments correspond to the actual occurrence of river discharge derived from the groundwater level measurements. The height of river stages is based on the experiences of the local community and field observations.

### 6.7.3 Groundwater abstraction from the riverbed

Groundwater is abstracted from the riverbed using scoop holes (Paragraph 2.6.2). Manual abstraction of groundwater is not incorporated in the initial model since the aim of the calibrated model is studying the effect of the presence of a sand dam on groundwater flow. Groundwater abstraction would result in undesirable influences on groundwater flow. However, a well is incorporated in model scenario 4 (Paragraph 9.4) to study the effect of groundwater abstraction on groundwater flow and storage during dry seasons.

# 7 Calibration

This chapter deals with the calibration of the model describing model sensitivity, optimal values of model parameters leading to the best fit with measured groundwater levels (e.g. the calibrated model), model results regarding groundwater flow and storage and model reliability.

## 7.1 Sensitivity analysis

To determine the influence of parameters on groundwater levels (timing and amplitude of peaks in head and gradients of recession curves) and the relative importance of parameters, a sensitivity analysis is performed. To this aim, several simulations are performed with parameter values based on field values using multiplication factors of 0.5, 0.8, 0.9, 1.1, 1.2 and 1.5.

### 7.1.1 Results

Results of the sensitivity analysis are described and illustrated per parameter (e.g. hydraulic conductivity and thickness of both aquifers, thickness of the sand layer in the riverbed, groundwater recharge, and flood depth) in Appendix 6. This paragraph gives a summary.

Model results are most sensitive to thickness and hydraulic conductivity of the sediment layer on the riverbanks. These parameters influence the reaction of groundwater levels on precipitation as well as the gradient of simulated drawdown curves. Decreasing these parameter values influences the model result most pronounced, leading to higher peak groundwater levels and smaller gradients of recession curves.

Hydraulic conductivity and thickness of the weathered rock layer influence model results to a lesser extent as compared to varying these properties of the sediment layer. Decreasing these parameters mainly results in a smaller gradient of simulated drawdown curves.

Varying thickness of the sand layer in the riverbed has a large influence on calculated groundwater levels in the riverbed. Decreasing the thickness influences groundwater levels most pronounced, resulting in lower peak groundwater levels.

Model results are relatively insensitive to changes in groundwater recharge of less than 20 percent. However, a decrease of 50 percent causes instable model results while doubling groundwater recharge leads to significant elevation of groundwater levels in the riverbanks.

Increasing flood depth influences calculated groundwater levels negligible. However, decreasing flood depth with more than 20 percent leads to lower groundwater levels in the riverbed.

## 7.2 Parameters of the calibrated model

Based on the sensitivity analysis, calibration of the groundwater model is primarily focused on layer thickness and hydraulic properties of the sediment layer, as well as thickness of the sand layer in the riverbed. However, also layer thickness and hydraulic properties of the weathered rock layer and groundwater recharge are regarded important to the calibration. Flood depth has least effect on model results and is thus only used to fine tune model results with measured groundwater levels. Simulated groundwater levels fit measured groundwater levels best using parameter input as described below.

### 7.2.1 Layer thickness

Thickness of the sediment layer is known through augerings and VESses within approximately 300 meter from the riverbed at both riverbanks within 100 meter up- and downstream of the Kwa Ndunda sand dam (Paragraph 4.3). In addition, layer thicknesses are irregular. Because of this, layer thickness is subject to parameter optimalisation.

Model results fit observed groundwater levels best when the thickness of the sediment layer increases from 1.6 meter at the riverbed to 4 meter on the eastern riverbank and from 1.5 meter to 5 meter on the western riverbank. At the location of the riverbed, the sediment layer consists of coarse sand. Thickness of the sand layer is largest directly upstream of the sand dam (1.6 m), decreasing to 10 centimeter at the location of the upstream sand dam. The same schematization is used for the sand layer at the location of the river downstream of the Kwa Ndunda sand dam.

Borehole data indicate weathered rock not being present in the riverbed. However, to guarantee continuality of the layer while ensuring an accurate physical representation of the subsurface, the weathered rock layer is present in the schematization, decreasing to 0.1 meter at the location of the riverbed. The weathered rock layer reaches a maximal thickness of 15 meter at the eastern and western catchment boundaries (Figure 7.1).
Underneath the weathered rock, basement is present. Groundwater flow is regarded negligible in the basement (Paragraph 2.6).

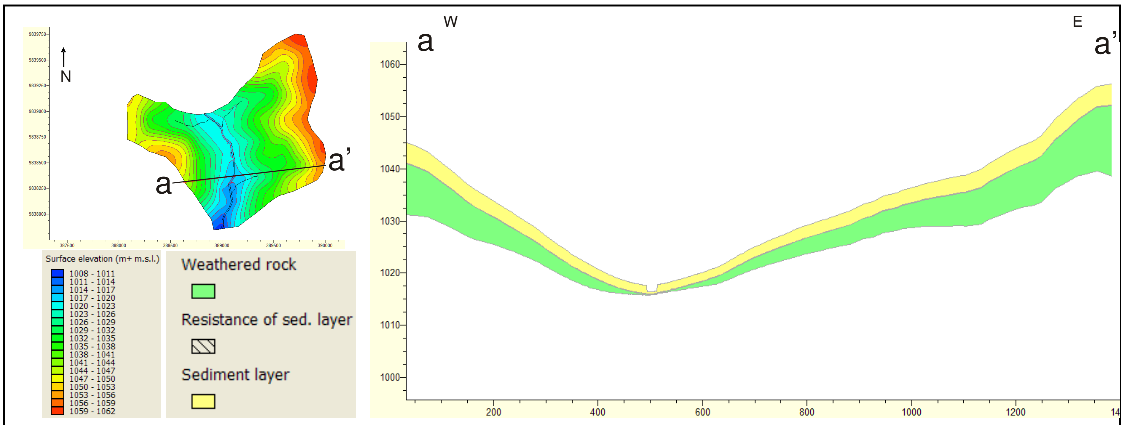



Figure 7.1 Schematized subsurface in Triwaco

### 7.2.2 Layer properties

Hydraulic properties leading to the best model result are presented in Table 7.1.

Table 7.1 Hydrogeological parameters leading to the optimal model result

| Soil type | Ksat (m/d) | Storage coefficient (Andersen et al., 2002) |
|---|---|---|
| Silt | 10 | $1 \times 10^{-3}$ |
| Clay | 2 | $1 \times 10^{-3}$ |
| Weathered rock | 4 | $1 \times 10^{-3}$ |
| Sand | 60 | $5 \times 10^{-4}$ |

### 7.2.3 Groundwater recharge

Although groundwater recharge is determined to be 0.74 percent (Section 4.2.2), optimal fit between simulated and measured groundwater levels is achieved when 2 percent of the precipitation leads to groundwater recharge, which is regarded acceptable. The occurrence, intensity and length of groundwater recharge is shown in Figure 7.2.

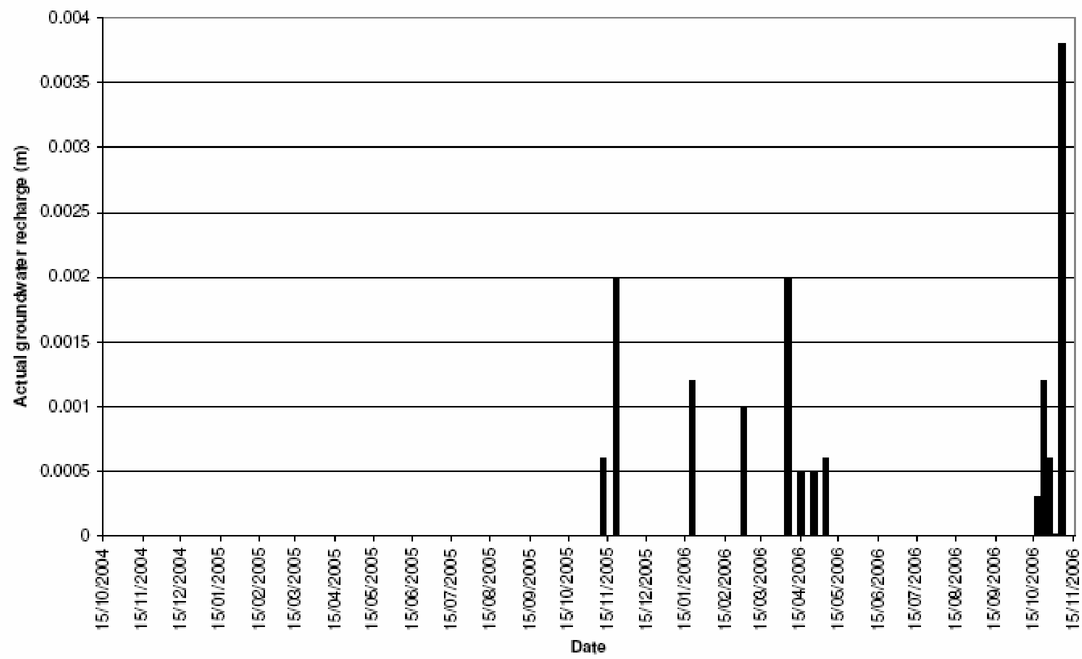



Figure 7.2 Occurrence, intensity and duration of groundwater recharge forming the input to the Triwaco model

### 7.2.4 Flood depth

From the sensitivity analysis flood depth is concluded to have a minimal influence on groundwater levels. However, input leading to the optimal result is shown in Figure 7.3.

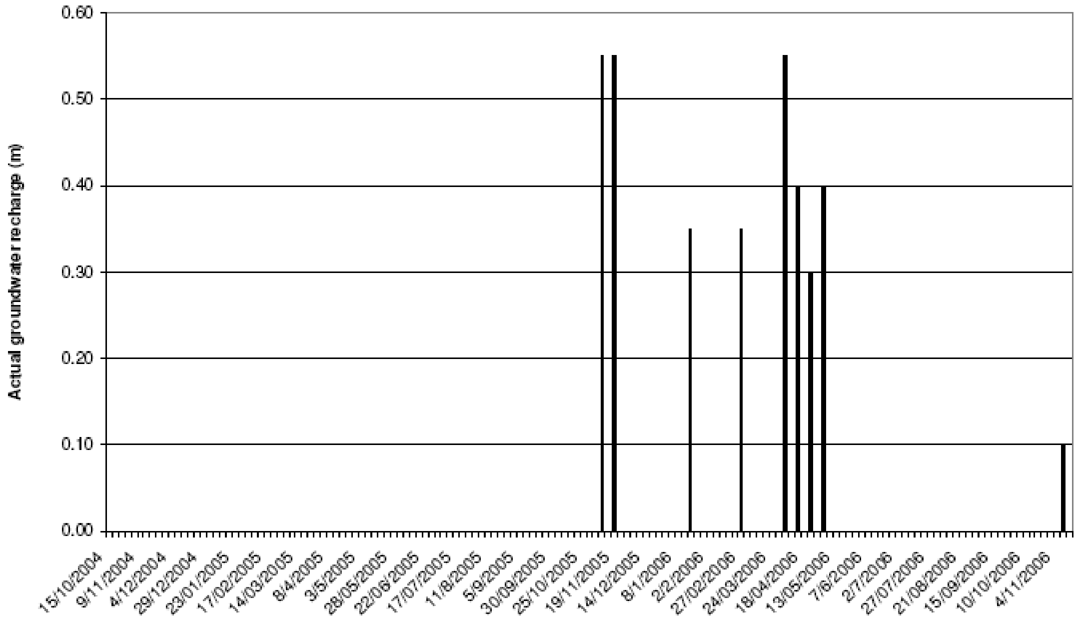



Figure 7.3 Occurrence and duration of the controlled water level in the riverbed, forming the input to the Triwaco model to simulate the occurrence of river discharge

## 7.3 Calibration results

### 7.3.1 Groundwater levels

The calibrated model aimed at reconstructing manual measurements of groundwater levels. Assessment of the fit with the measurements is performed by approaching the features describing the groundwater graphs, such as shapes of recession curves, moments of raised groundwater levels and relative height of groundwater levels (determining the direction of groundwater flow).

Figure 7.4 to Figure 7.8 represent simulated and actual groundwater levels per piezometer (Figure 3.1, Appendix 3). Figure 7.9 to Figure 7.11 visualize the accuracy with which the model reproduces measured groundwater levels through the distribution of differences between simulated and measured groundwater levels. A differentiation is made between simulations during dry seasons (light gray) and during wet seasons (black). A positive deviation represents an underestimation by the model. It should be noted that the manual measurements did not result in continuous records.

Deviation analysis shows model results primarily being in a range of 0.10 meter in all piezometers. Exceptions are generally due to a less accurate approximation of peak events or overestimation of groundwater levels during the dry period from 03-05-2006 to 15-10-2006. The last mentioned imperfection is observed in piezometer p04, p05, p09 to p11, p13 to p15 and p17 (Figure 7.4 and Figure 7.5). Although the angle of recession curves determined by the model corresponds to actual drawdown curves, the model reaches a more or less stable groundwater level while the actual groundwater level continues to drop. However, the gradient of the actual recession curves also decrease while groundwater declines (p05, p09 and p13 to p15).

The model underestimates groundwater levels as well as the angle of the recession curves in p05. Piezometer p06, also located in the riverbed upstream of the Kwa Ndunda sand dam, underestimates peak groundwater levels as well. However, the angle of the recession curves corresponds quite accurately with manual measurements. The major part of the groundwater simulation has a deviation of 0.10 meter.

Groundwater levels in the eastern riverbank upstream of the sand dam (p07 and p08) are underestimated on average. However, angles of recession curves are approximated well and the simulation is generally accurate within 0.10 meter. Fluctuations in groundwater levels observed in piezometer p09 differ from nearby piezometers; reaction of groundwater levels to precipitation is less rapid and pronounced. The model overestimates heads in several cases. The gradient of drawdown curves is however reasonably matched. During the dry season from 03-05-2006 to 15-10-2006, groundwater levels are underestimated.

Peaks in groundwater level during the wet seasons of 18-01-2006 and 27-02-2006 are overestimated in piezometer p10 and p11. Because simulated recession curves have a smaller angle, the overestimation increases as the dry season proceeds. However, groundwater levels are generally approached within 0.10 meter, except for the period between 03-05-2006 and 15-10-2006 in which simulated groundwater levels reach a more or less stationary level while actual heads continue to decline (Figure 7.5). From both Figure 7.5 and Figure 7.10 it is evident that the model overestimates groundwater levels in piezometer p12 with 0.75 meter on average.
Groundwater levels in piezometer p13 and p14 are overestimated. However, shapes of recession curves and moments of raised groundwater levels are represented reasonably well (Figure 7.6). Simulation of heads in piezometer p15 resulted in a more accurate result; the major part of the deviation lies within 10 centimeter, except for the last part of the recession period between 03-05-2006 to 15-10-2006.
Piezometer p17, located in the riverbed, shows an accurate simulation of the measured heads; the maximum deviation is less than 20 centimeter and is primarily caused by the recession during the long dry period. Replication of heads in piezometers located on the eastern riverbank (piezometer p18 and p21) show a small deviation from actual groundwater levels.
Piezometer p25 and p26 are located upstream of the sand dam furthest from the riverbed on respectively the eastern and western riverbanks. At these locations, a relative short period of data is available. However, simulations reach the groundwater stage fairly well although the zone in

which these piezometers are located respond different from those located near the riverbed (Paragraph 5.1).

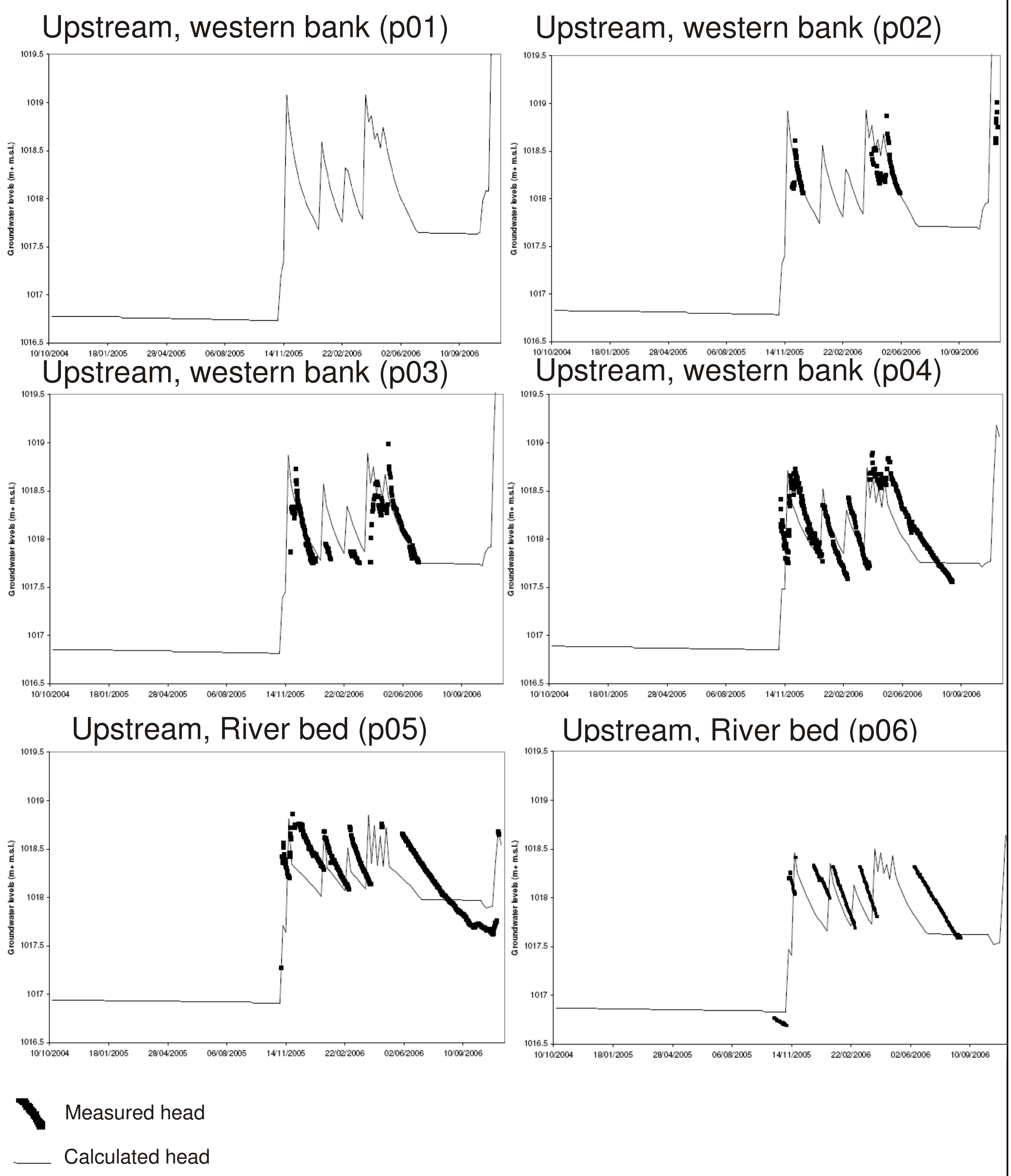



Figure 7.4 Measured and calculated groundwater levels using the calibrated model in piezometer p01 to p06

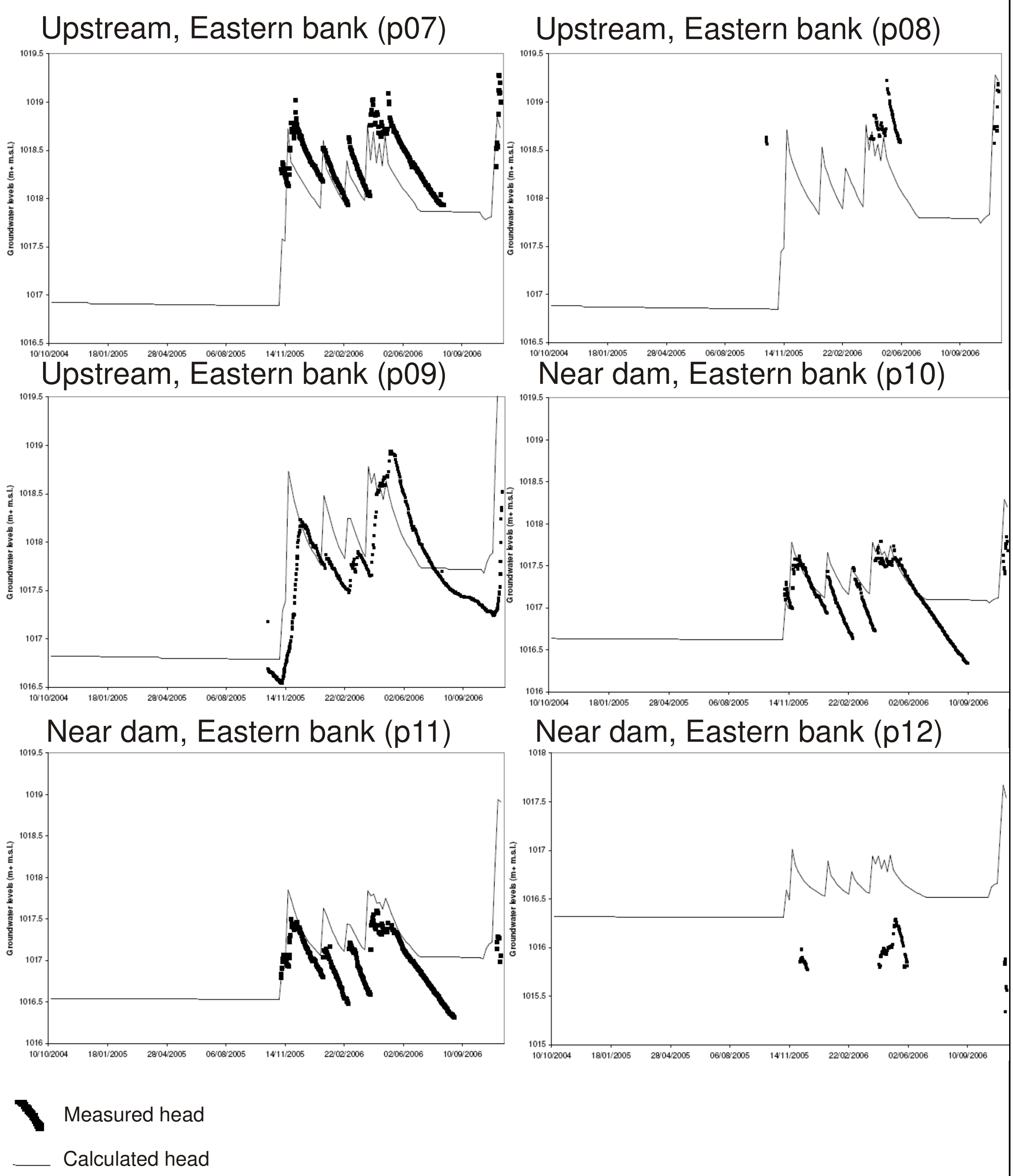



Figure 7.5 Measured and calculated groundwater levels using the calibrated model in piezometer p07 to p12

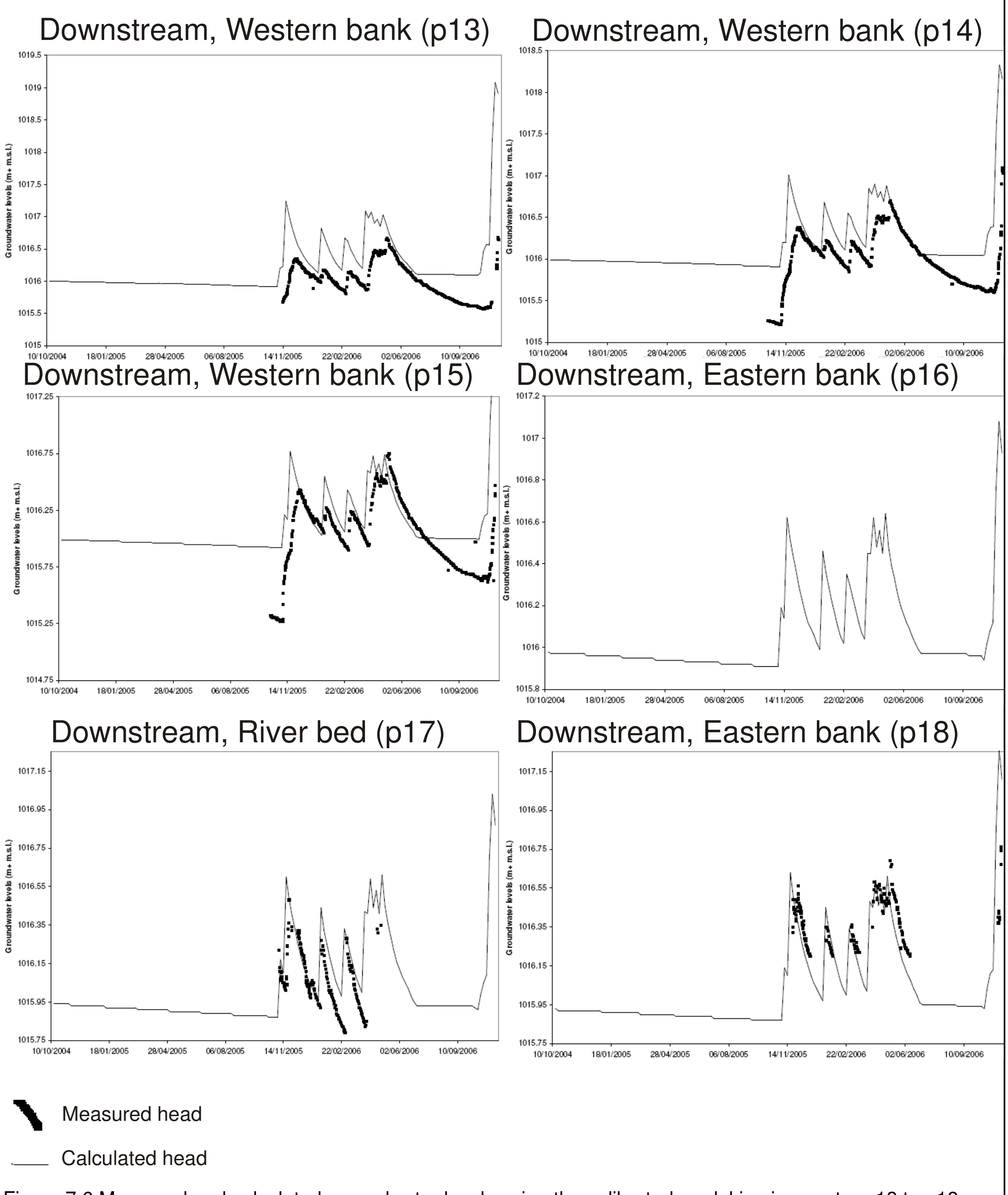



Figure 7.6 Measured and calculated groundwater levels using the calibrated model in piezometer p13 to p18

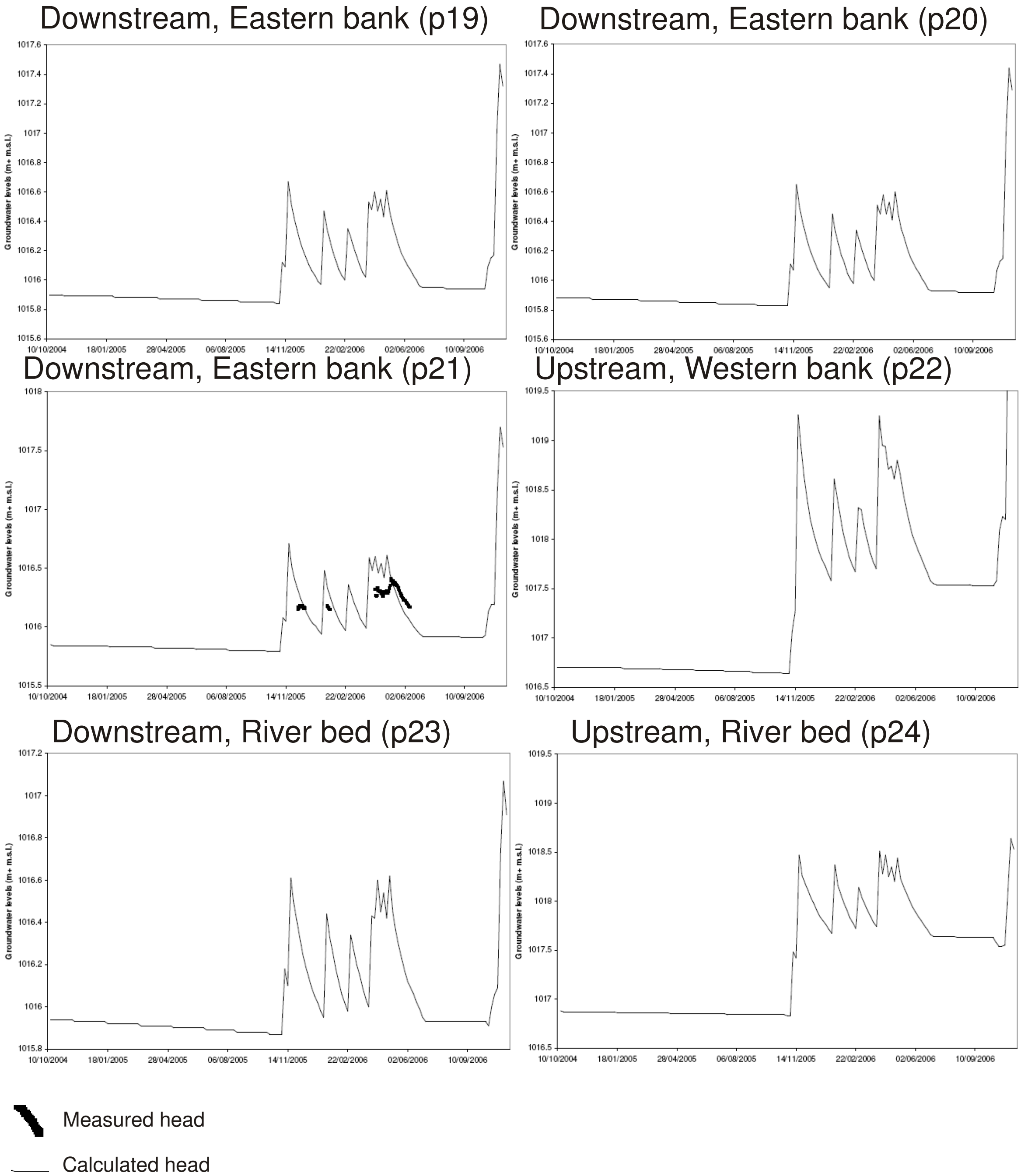



Figure 7.7 Measured and calculated groundwater levels using the calibrated model in piezometer p19 to p24

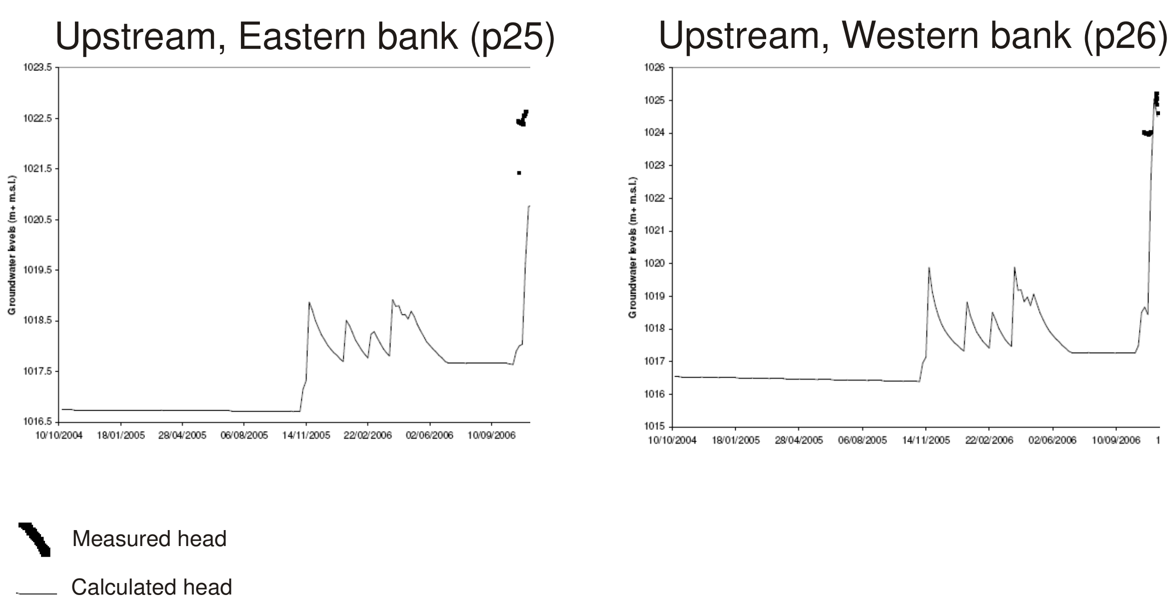



Figure 7.8 Measured and calculated groundwater levels using the calibrated model in piezometer p25 and p26

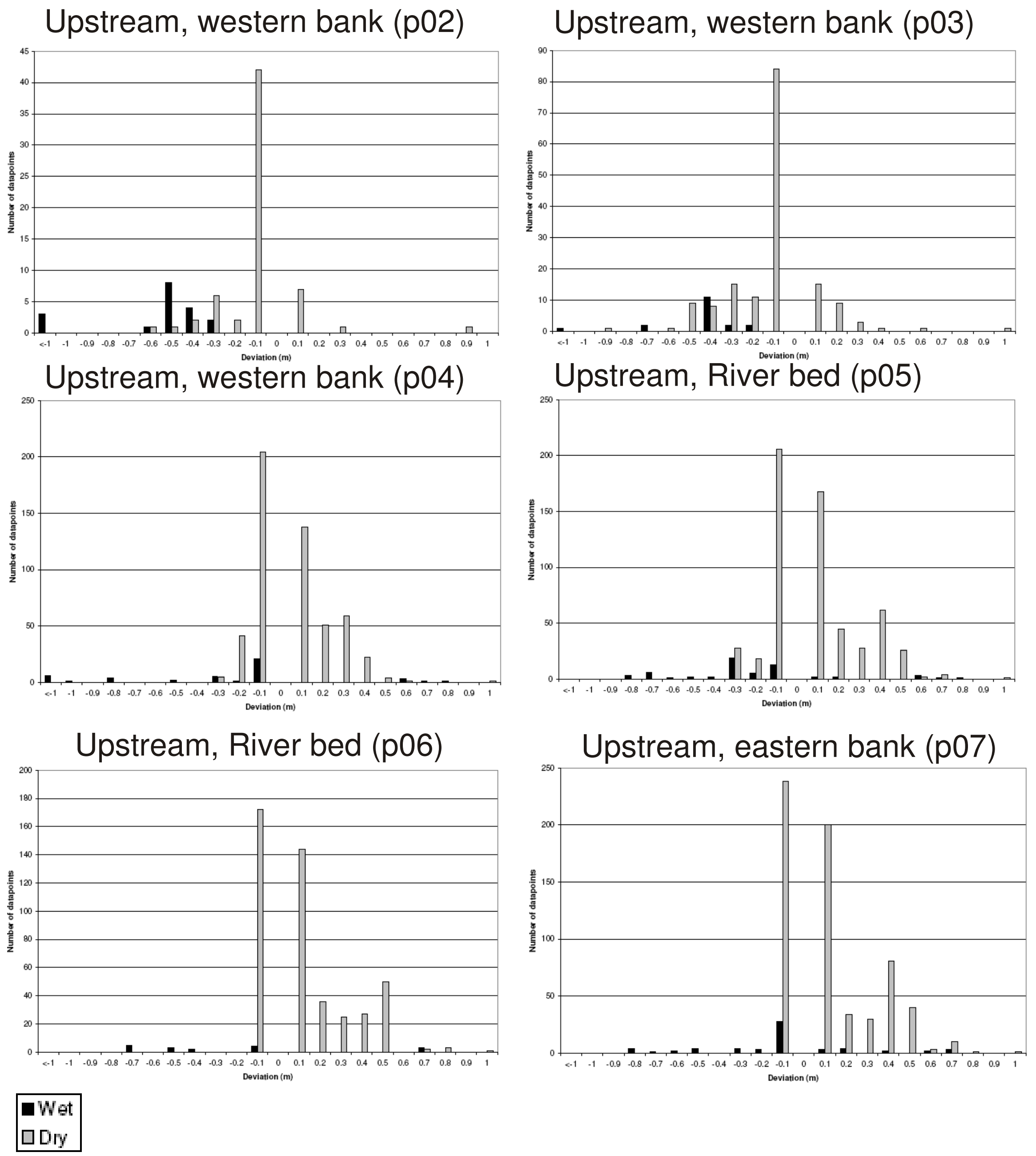



Figure 7.9 Difference in groundwater levels calculated by the model and measured in p02 to p07

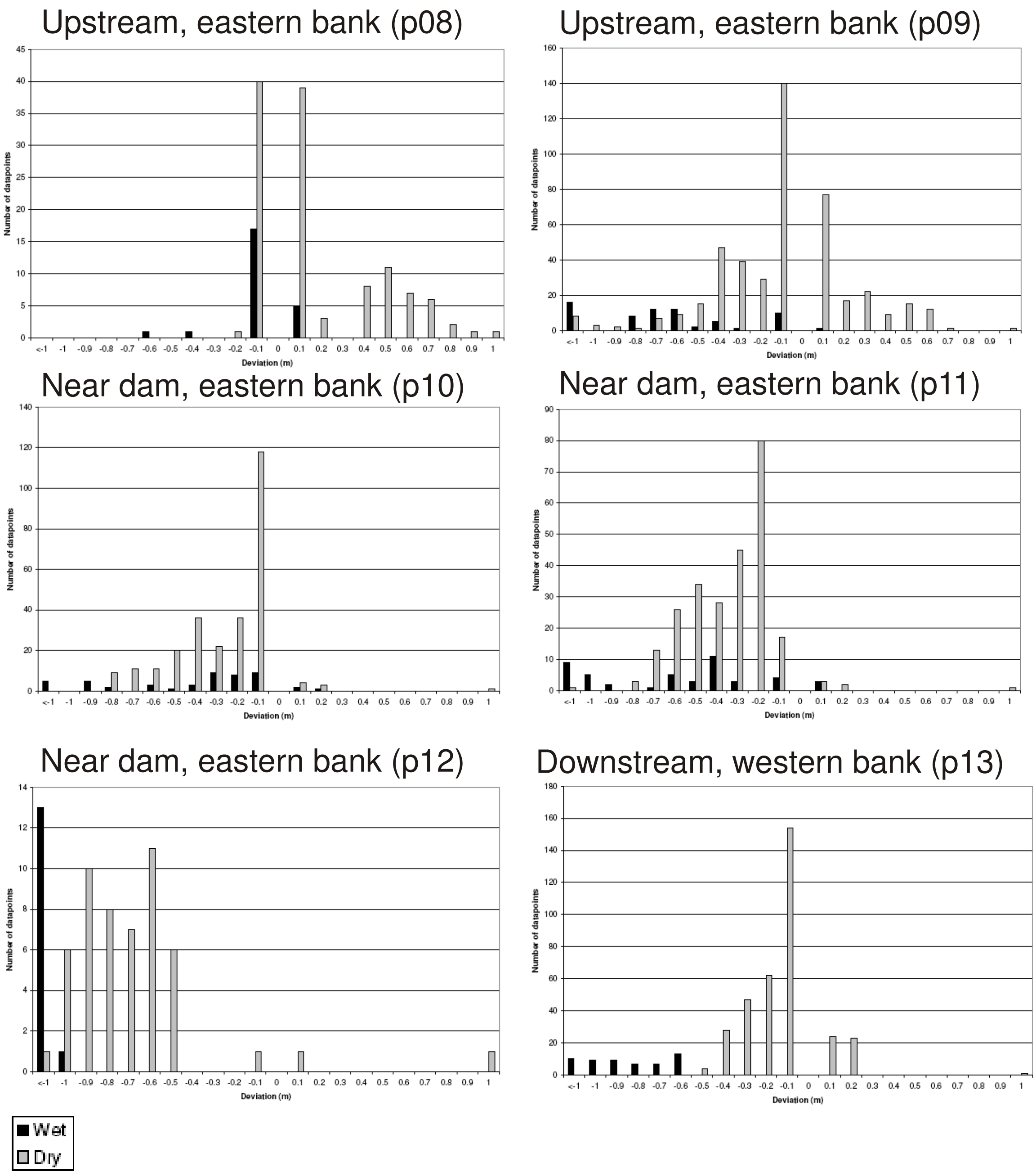



Figure 7.10 Difference in groundwater levels calculated by the model and measured in p08 to p13

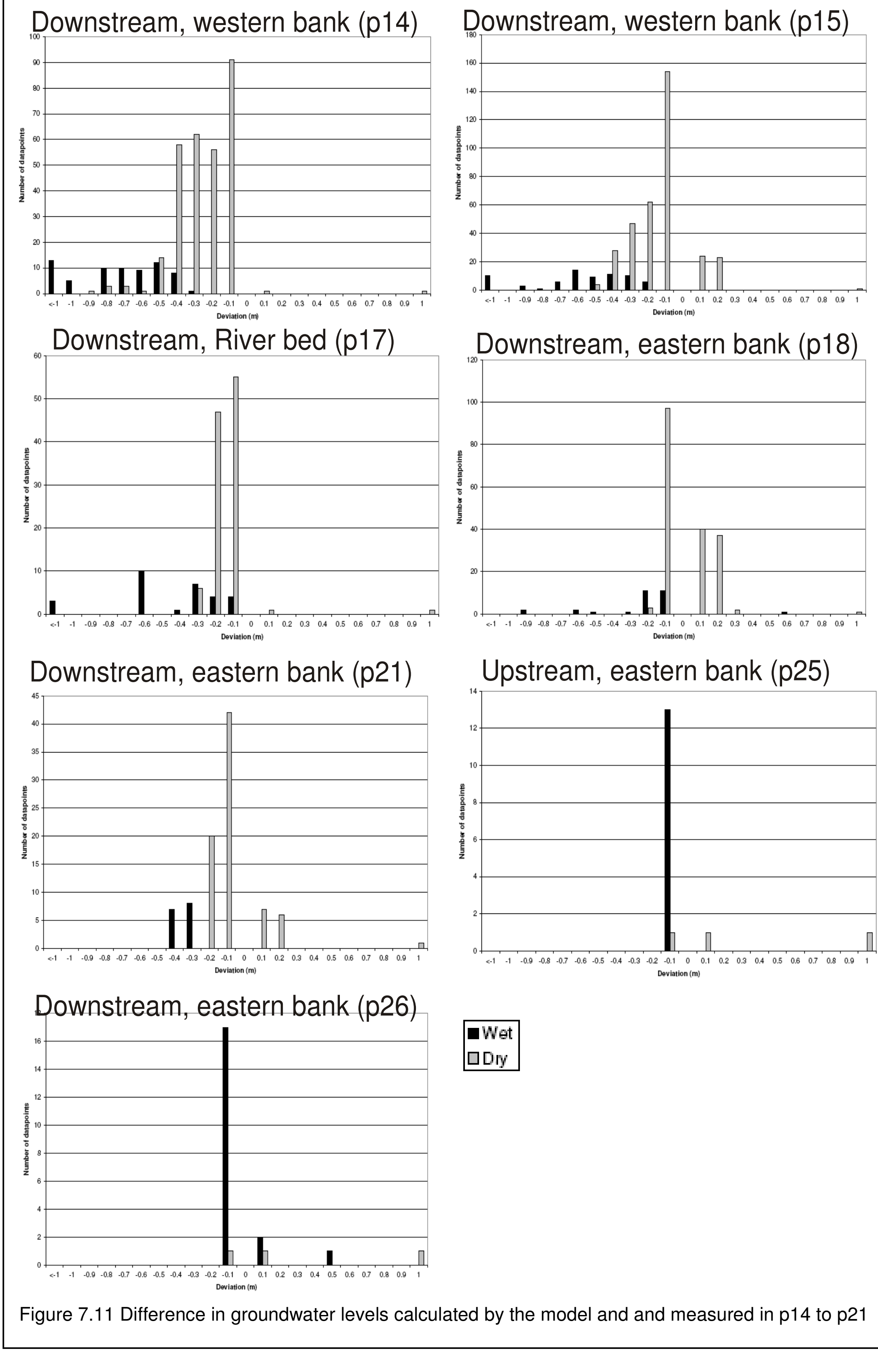



Figure 7.11 Difference in groundwater levels calculated by the model and and measured in p14 to p21

### 7.3.2 Groundwater storage

To determine the volume of groundwater available for abstraction and to resolve the loss of groundwater from the sand aquifer in the riverbed by flow around the sand dam, a water balance study is performed on the riverbed upstream of the sand dam in the area of influence. However, after careful study of the fluxes, it had to be concluded that the program used to perform the water balance calculation could not determine horizontal fluxes over the boundaries with sufficient accuracy. This is a known problem, which normally results in small errors. Due to the large horizontal fluxes in this area, running the water balance program leads to large inconsistencies. Solving this problem is beyond the scope of this research.

However, groundwater storage in the riverbed is determined for two polygons upstream of the Kwa Ndunda sand dam (Figure 7.12). In polygon 1, directly upstream of the sand dam, the thickness of the sand layer is largest, decreasing from 1.60 meter directly upstream of the sand dam to 1 meter at the upstream end of the polygon. The sand layer in polygon thus has an average thickness of 1.22 meter. The size of the polygon is 2620 m$^2$. Since the porosity of the sand is 0.42, the maximum groundwater storage is 1340 m$^3$. The riverbed in polygon 2 has an average thickness of 0.73 meter, decreasing from 1 meter to 0.50 meter at the upstream boundary. The surface of Polygon 2 equals 2860 m$^2$, leading to a maximum groundwater storage of 876 m$^3$.

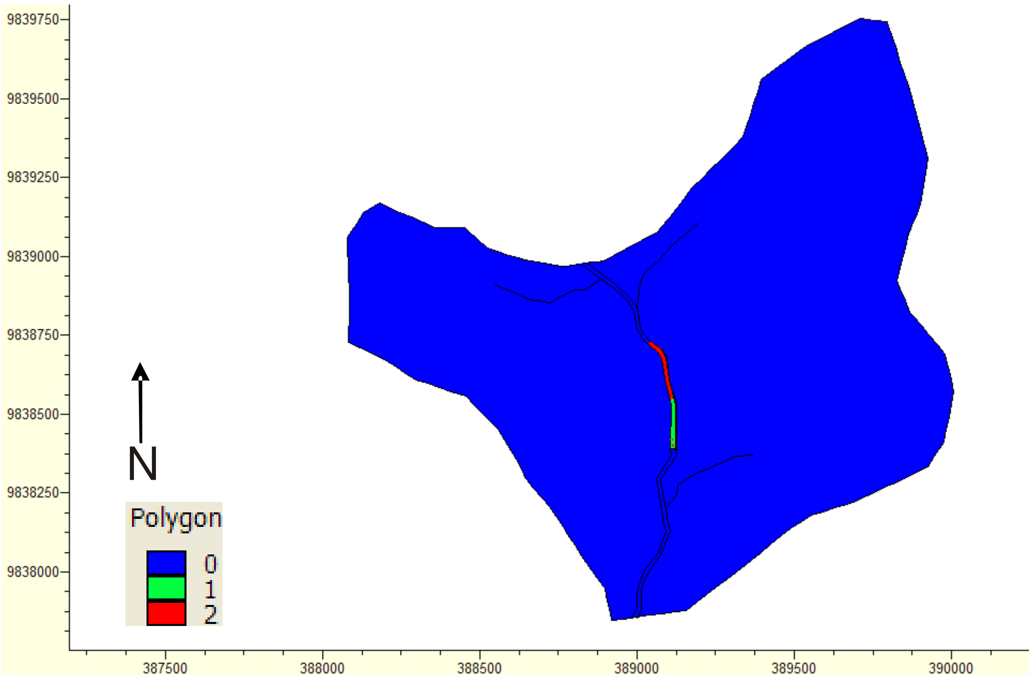



Figure 7.12 Location of polygons in the riverbed

During the wet season, water levels are above the surface level. At these moments, maximum storage is reached, which is thus 1340 $m^3$ in Polygon 1, and 876 $m^3$ in Polygon 2. The minimum calculated groundwater storage in polygon 1 equals 1280 $m^3$, reached during the prolonged dry season from 03-05-2006 until 15-10-2006. The stable volume in Polygon 2 is approximately 380 $m^3$.

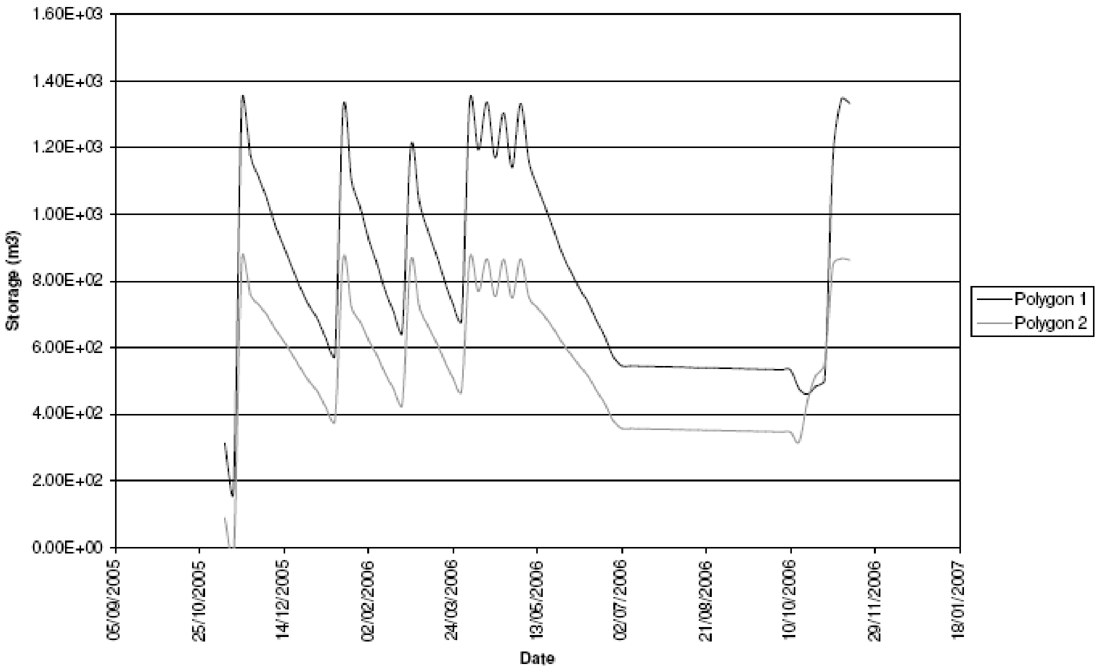



Figure 7.13 Fluctuation in storage of groundwater in the polygons located in riverbed upstream of the Kwa Ndunda sand dam

## 7.4 Reliability analysis

Field data forms the basis of the groundwater model. However, not all parameters are known with certainty while others needed extrapolation to cover the whole model area. To assess the reliability of the model, the impacts of a certain change in value of a parameter is quantified. To this aim, parameters under consideration (e.g. hydraulic conductivity and thickness of both aquifers, thickness of the sand layer in the riverbed, groundwater recharge, and flood depth) are varied from the calibrated values using multiplication factors of 0.5, 0.8, 0.9, 1.1, 1.2 and 1.5. Differences in calculated groundwater levels between the calibrated model and scenarios are quantified for piezometers p02, p08, p06, p14, p17 and p19 (Figure 3.1, Appendix 3). A positive difference means elevation of groundwater levels in comparison to the calibrated model. Also, influence on groundwater storage and availability in the riverbed in two polygons upstream of the sand dam is analyzed (Figure 7.12).

The results of the reliability analysis are discussed and illustrated per calibration parameter in Appendix 7. Combining the summary of the reliability analysis with the discussion on the accuracy of field results (Chapter 5) leads to the following conclusions.

Simulated groundwater levels, especially in the riverbed, as well as groundwater storage are primarily influenced by the thickness of the sand layer in the riverbed. An increase in thickness of the riverbed leads to higher groundwater levels and an increase in groundwater storage. The effect on calculated heads in the riverbed of increasing the thickness is larger than of decreasing with the same factor.
Within 100 meter upstream of the sand dam, the thickness of the sand layer is known with satisfactory precision through borehole data. Change in thickness of the sand layer in the river towards the dam upstream of the Kwa Ndunda sand dam is estimated based on field experiences. Since the riverbed aquifer is largest directly upstream of the sand dam and will thus influence groundwater storage to the largest extent, the data is considered satisfactionary accurate.

Thickness of the sediment layer on the riverbanks influences groundwater levels in the riverbed more than in the banks. Variation of this parameter with 20 percent leads to a significant change in head. Additionally, from the reliability analysis it is concluded that increasing the parameter with 50 percent leads to an instable model result. Decreasing by the same factor leads to a significant increase in groundwater storage; average groundwater storage leads to an increase in groundwater storage in the riverbed of approximately 20 percent.
Thickness of the weathered rock layer influences model results less pronounced. Although groundwater levels are influenced by changes of less than 20 percent, variation is within 10 centimeter on the riverbanks. Heads computed in the riverbed are somewhat more sensitive to variation of this parameter. However, changes of as much as 50 percent lead to a change in average riverbed storage of only 10 percent.
In a zone of approximately 300 meter from the riverbed, the thicknesses of these layers are known with acceptable certainty. Trends in layer thicknesses are used to extrapolate towards the catchment boundary. However, layer thicknesses can fluctuate significantly. Although model results will primarily be influenced by layer thicknesses in the zone close to the sand dam, model accuracy can be improved by conducting additional VES measurements further towards the catchment boundaries.

Hydraulic conductivity of the sediment layer influence calculated heads in the riverbed more compared to the riverbanks. Small variations (equal to or less than 20 percent) have however little effect on groundwater levels. Changing hydraulic conductivity of the sediment layer with 50

percent leads to instabilities of the model (when increasing the $K_{sat}$), and influences the reaction of groundwater levels on precipitation as well as lowering the gradient of simulated drawdown curves. Additionally, the volume of water stored in the riverbed increases with 20 percent.
Hydraulic conductivity is determined through the inverse auger hole test at the locations of the piezometers (Figure 3.1, Appendix 3). Values resulting form this method are a volumetric integrated result of the hydraulic properties of the soil layer in which the piezometer is located (Waterloo, 2005). The results are regarded sufficiently accurate.

The properties of the weathered rock are known with less certainty because the degree of weathering varies throughout the catchment, as can be concluded from the VES data. Saturated hydraulic conductivity is to a large extent dependent on the degree of weathering. However, from the sensitivity analysis, it became clear that variation of this property has little effect on model results as compared to the sediment layer.

Model results seem relatively insensitive to changes in groundwater recharge of less than or equal to 20 percent. Decreasing groundwater recharge with 50 percent causes instabilities in model results, while increasing with the same value leads to significant elevations of groundwater levels and storage in the riverbed.
Although precipitation is known with satisfactionary accuracy for the timescale at which the model is running, and spatial coverage of the model area is of such limited extent that the assumption of uniform precipitation seems legitimate, this parameter is known with lowest accuracy. Variation in the ratio between infiltration and surface runoff throughout the model area due to differences in land use (Jansen, 2007) and soil characteristics are the cause. Due to the fact ratios of runoff plots with different land uses, an average can be used, decreasing inaccuracies. Furthermore, because rainfall events of varying intensity and duration are encountered during the field visit, these are averaged as well, further increasing reliability.
However, another uncertainty is the fraction of water evaporating from the unsaturated zone before recharging the groundwater. Although a reasonably accurate estimation of the evaporation factor is made based on the chloride content of the water samples, reliability can be increased by determining the fractions of oxygen isotopes in several samples.

Flood depth only significantly influences groundwater levels and storage when decreasing it with more than 20 percent. However, values are based on field experiences and are not expected to differ with as much as 20 percent.

# 8 Discussion of model results

This chapter discusses model accuracy and results of the calibrated model, focusing on groundwater flow and storage.

## 8.1 Calibrated model

This paragraph discusses the results following from the application of the calibrated model regarding groundwater flow and storage in the riverbed.

### 8.1.1 Groundwater flow

Figure 8.1 shows groundwater flow directions at typical moments during a dry and wet season as calculated by the groundwater model. To visualize quick groundwater dynamics, a simulation of the calibrated model is added in Appendix 9.

During the dry season, groundwater flow is oriented predominantly south and towards the riverbed. Due to the presence of the Kwa Ndunda sand dam, the preferent path of groundwater flow through the permeable riverbed is obstructed, creating a subsurface water basin. From the shape of contour lines in the zone upstream of the sand dam, heads are evidently raised, resulting in groundwater flow from the riverbed into the riverbanks. Upstream of this zone of influence, groundwater flow is still oriented towards the riverbed in the riverbanks and downstream through the riverbed. Groundwater is flowing through the riverbanks around the sand dam. Downstream of the sand dam, contour lines curve towards the riverbed, indicating groundwater flow from the riverbanks towards the riverbed.

At the start of the wet season, orientation of contours changes direction abruptly in response to groundwater recharge. Groundwater flow is directed predominantly towards the river throughout the model area. After the wet season, contour lines in the area upstream of the sand dam change orientation in one time step and groundwater flow is oriented from the riverbed towards the riverbanks again in a zone upstream of the sand dam. Considering groundwater level dynamics through the simulation in Appendix 8, head differences between riverbed and banks are evidently leveling out during the dry season. The zone of influence of the sand dam is largest at the end of the dry season, stretching approximately 350 meter upstream of the sand dam.

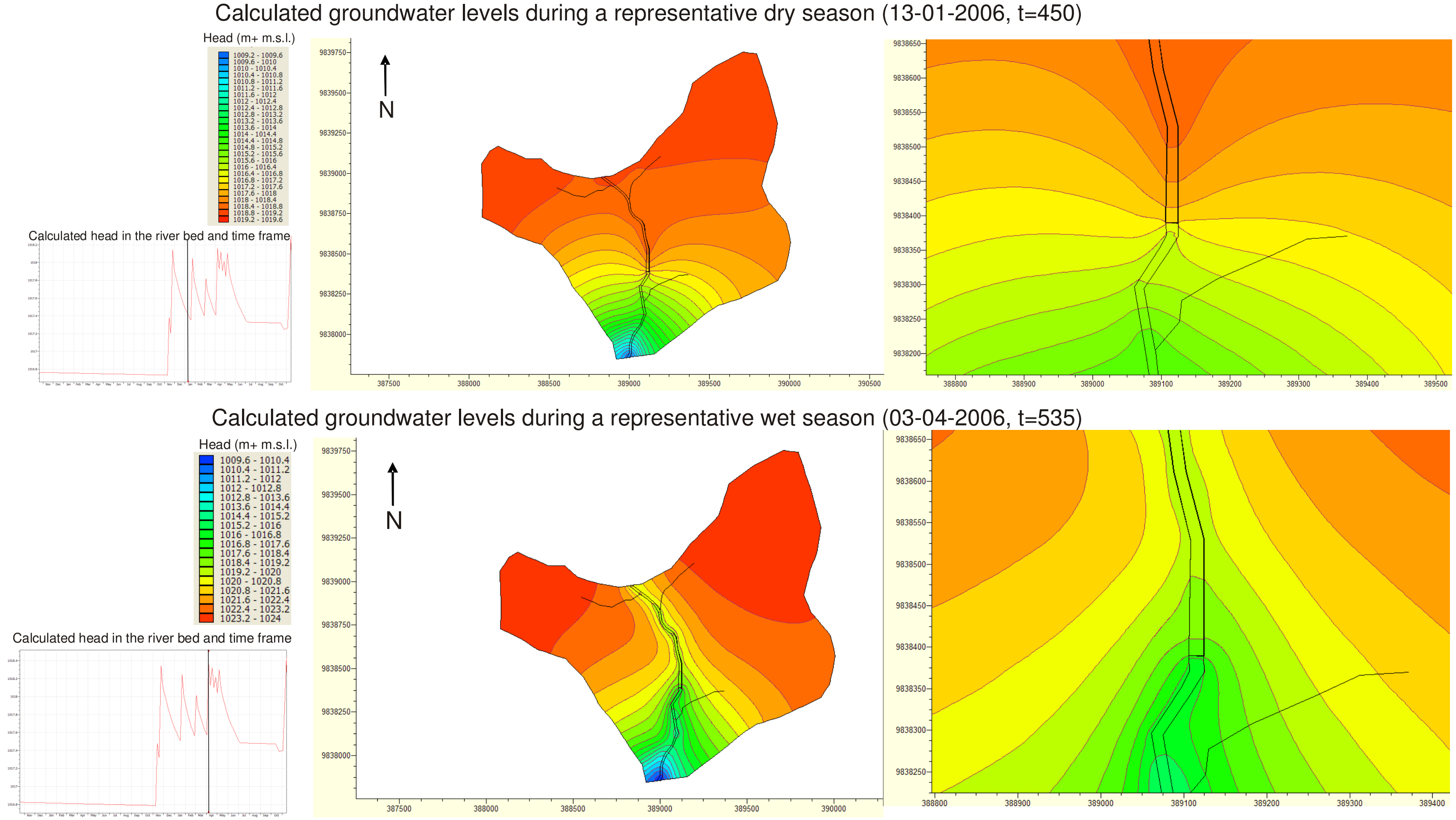



Figure 8.1 Model results during moments representative of dry and wet seasons

### 8.1.2 Groundwater storage

Groundwater storage is directly linked to groundwater levels in the riverbed and thus shows the same fluctuations. The volume of groundwater storage in the riverbed increases in direct response to precipitation to the maximum volume of the polygon, after which the river starts flowing. During the dry season, groundwater levels decline in response to groundwater flow from the riverbed into the riverbanks within the zone of influence of the sand dam (Paragraph 8.1.1) and flow of groundwater downstream through the riverbed (in Polygon 2). Groundwater in the riverbed is continuously replenished by groundwater flow from the riverbanks into the riverbed and by groundwater flow through the riverbed upstream of the zone of influence.

Groundwater levels in Polygon 1 are decreasing faster as compared to Polygon 2, caused by groundwater flow from the riverbed into the banks in Polygon 1, which is larger than replenishment by groundwater flow through the riverbed. However, as the dry season proceeds, groundwater levels level out, resulting in a balance between in- and outflow. During the prolonged dry season (from 03-05-2006 to 15-10-2006) groundwater levels thus reach a continuous level and storage in the riverbed reaches a constant volume.

# 9 Application of the model

Using the calibrated model, four scenario calculations are performed to determine the influence the sand dam (scenario without a sand dam) and of measures to optimize the effect of a sand dam, such as increasing infiltration in the riverbanks and increasing the height of the sand dam itself. Also, the effect of groundwater abstraction from the riverbed is studied, also focusing on the effect of variation of abstraction rates. The effect on groundwater levels is quantified through differences in calculated groundwater levels between the calibrated model and the scenarios for piezometers p02, p08, p06, p14, p17 and p19. A positive difference means an increase in head at a certain moment in time due to the scenario. Furthermore, the influence on groundwater storage in the riverbed is analysed for the polygons shown in Figure 7.12.

## 9.1 Scenario 1 – Removal of the Kwa Ndunda sand dam

### 9.1.1 Description

To determine the effect of the Kwa Ndunda sand dam on groundwater levels, a scenario without a sand dam is run. To this aim, the low conductivity zone at the location of the sand dam is removed and the thickness of the sand layer in the riverbed is decreased. The effect of removal on thickness of the sand layer is most evident directly upstream of the sand dam since it will have a more uniform thickness. In the calibrated model, the presence of the sand dam influences layer thickness to a distance of approximately 350 meter upstream of the dam. Removal of the sand dam leads to a decrease from 1.6 meter to 0.25 meter directly upstream of the sand dam, from 1 meter to 0.20 meter 150 meter upstream of the dam and from 0.5 to 0.20 meter at the edge of the former influence area (Figure 9.1). The sand layer directly downstream of the sand dam will encounter a slight increase in thickness since sand is no longer flushed away by water flowing over dam crest. At this location, an increase from 0.05 meter to 0.25 meter is experienced, matching the thickness of the sand layer directly upstream of the former sand dam.

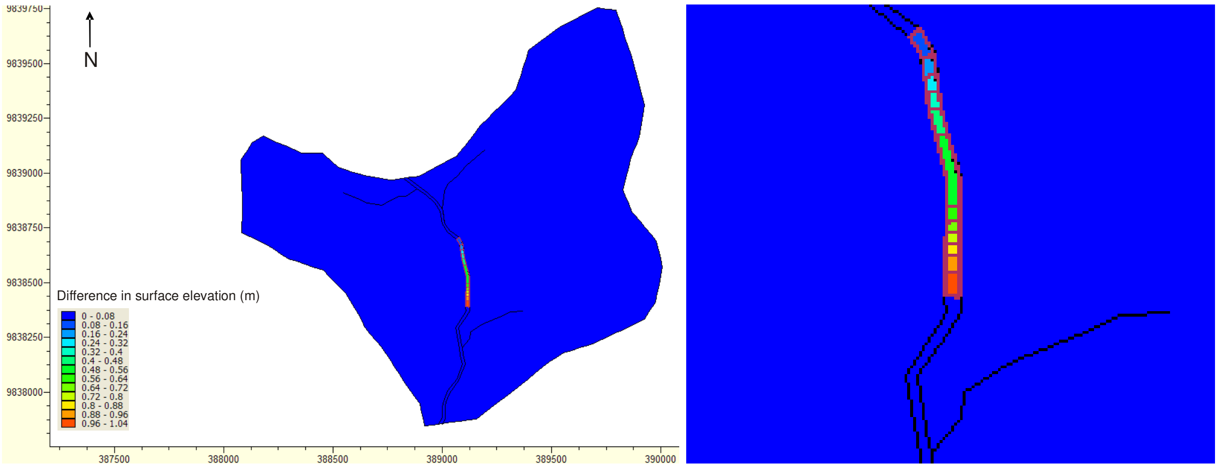



Figure 9.1 Effect on surface elevation (and thus thickness of the sand layer in the riverbed) resulting from the removal of the Kwa Ndunda sand dam

### 9.1.2 Model results

Figure 9.2, Figure 9.3 and Figure 9.4 show the impacts of removal of the Kwa Ndunda sand dam. Figure 9.3 represents calculated heads at representative moments during dry and wet seasons. The main difference between groundwater levels calculated by this scenario as compared to those computed by the calibrated model occurs during the dry season. As in the calibrated model, groundwater flow is mainly directed south and towards the riverbed. However, in contradiction to the calibrated model, groundwater flow is oriented uniformly throughout the model area. During the wet season, groundwater levels react similar to the calibrated model.

Differences in calculated groundwater level are largest in the zone direct upstream of the sand dam (
Figure 9.2a, Figure 9.4). Groundwater levels are lower almost throughout the model area. Upstream of the former sand dam average difference in calculated groundwater levels varies between 0.40 and 0.50 meter in the riverbed (p06). Groundwater levels in the riverbanks show a larger drop in head; between 0.60 and 0.70 meter as compared to the original situation (
Figure 9.2a).

Figure 9.2b shows changes in groundwater storage in the riverbed. The presence of the sand dam increases groundwater availability with approximately 300 percent on average. During the dry season from 03-5-2006 to 15-10-2006, storage in the riverbed as calculated in the scenario would have decreased to negligible volumes within two months. This conclusion is in correspondence with the actual recession of groundwater levels during the dry season. Groundwater levels calculated by the calibrated model are still 0.5 meter above the bottom of the piezometers in the riverbed at the end of the prolonged dry season (Figure 4.2). However, an extra drop in head of 0.5 meter on average and up to 0.79 meter will lead to a situation in which heads are decreased beyond abstractable levels (e.g. in the weathered rock) at a certain moment in the dry season. The riverbed would thus have dried up within 1.5 months, around the being of July. Normally, the next wet season begins half of October, meaning a period of drought for 3.5 months until the next rain season while in the original situation the riverbed would still contain approximately 580 $m^3$ groundwater, enough to bridge the period of drought until the next rain season.

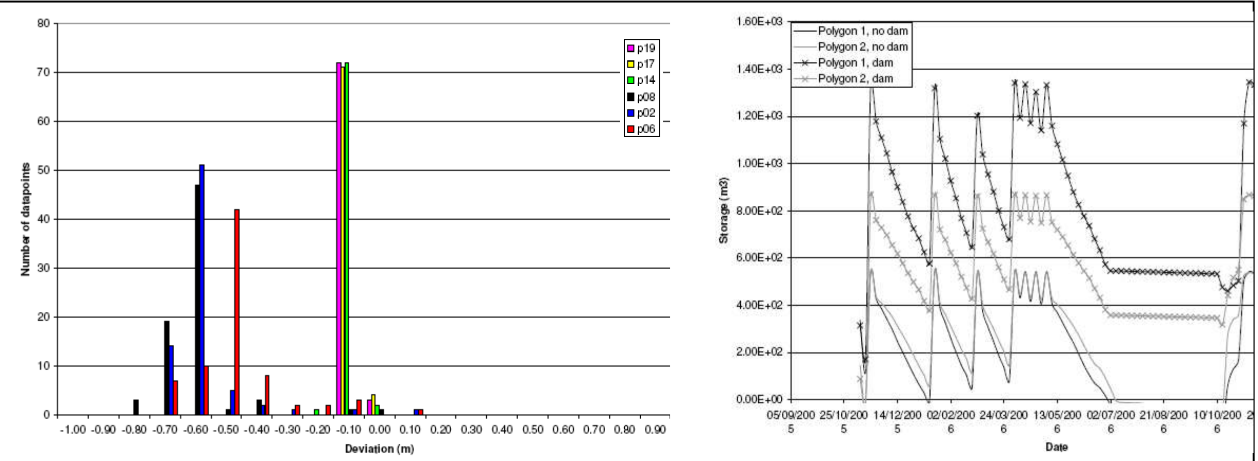



Figure 9.2 Difference between the calculated groundwater levels and storage in the riverbed as a consequence of scenario 1

### 9.1.3 Discussion

In absence of a sand storage dam, groundwater levels are lower almost throughout the model area because groundwater flow through the riverbed (and part of the banks) is not obstructed by the presence of a sand dam as it was in the calibrated model. Consequently, no groundwater reservoir is created and groundwater flow is oriented from the banks towards the riverbed throughout the model area.

The positive influence of the presence of a sand storage dam on the volume and period of groundwater availability is evident when comparing the results of the scenario calculation to those of the calibrated model. A sand dam increases the thickness of the sand layer in the riverbed (e.g. larger storage capacity) and obstructs groundwater flow through the riverbed, resulting in prolonged groundwater availability throughout dry seasons and larger volumes of groundwater present in the riverbed. In absence of the sand dam, groundwater would only be present in the riverbed during the first 1.5 months of the dry season, while in a situation with sand dam the riverbed would still contain enough groundwater to bridge the period of drought until the next rain season.

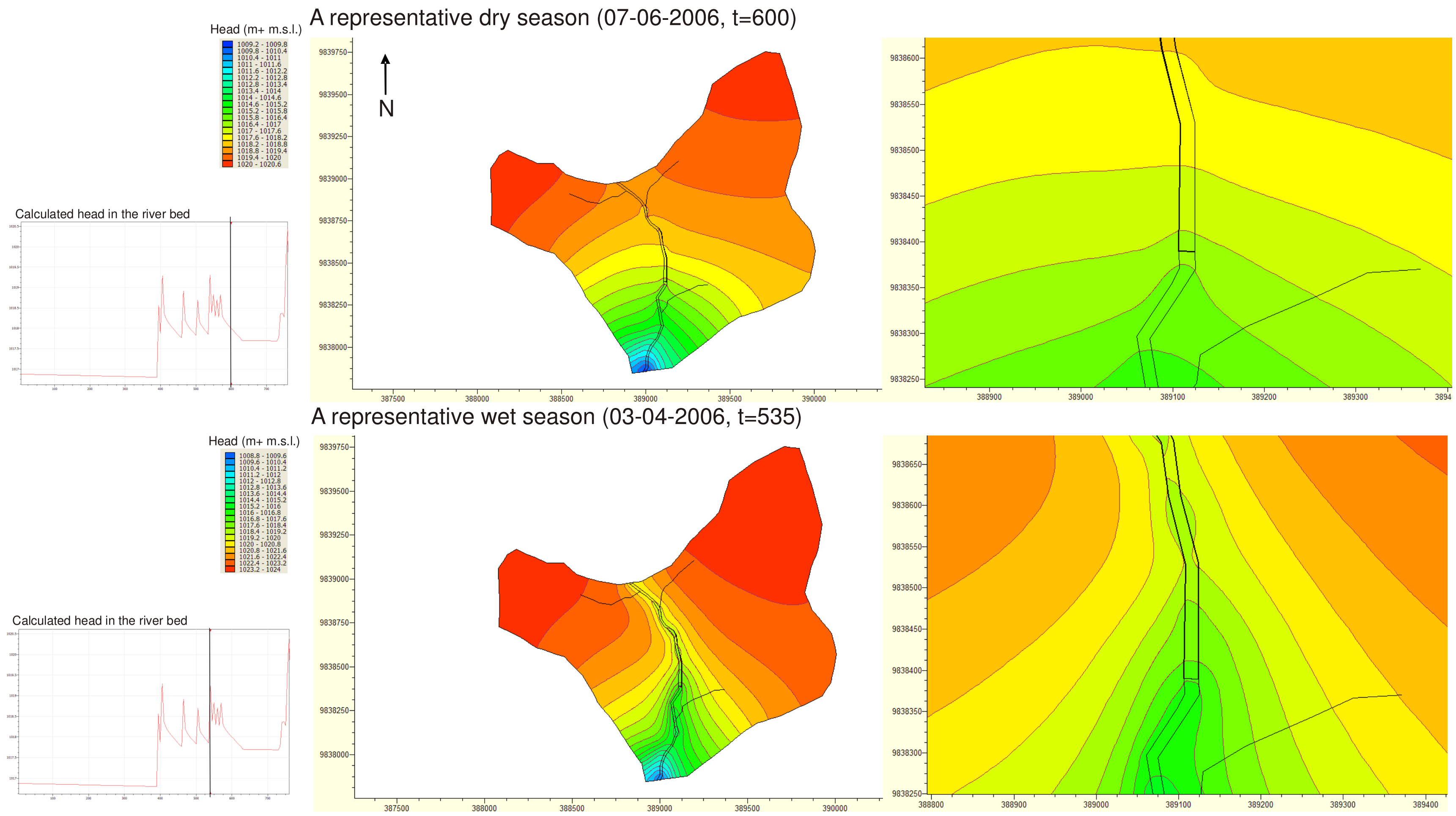



Figure 9.3 Results of 'Scenario 1 – Dam removal' during moments representative for the dry and wet seasons

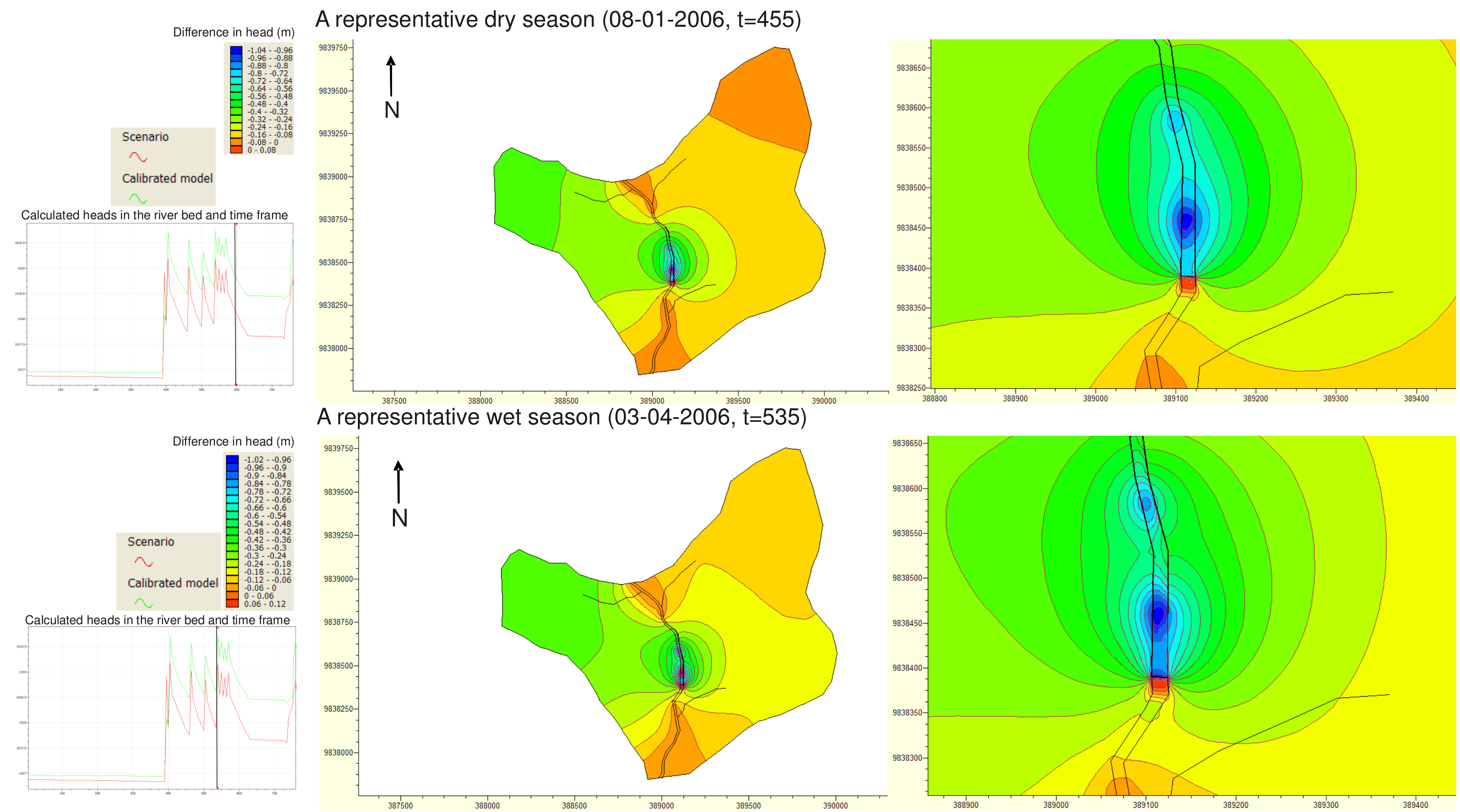



Figure 9.4 Difference in calculated groundwater levels comparing the calibrated model results with the results of ‘Scenario 1 – Dam removal’ during moments representative for the dry and wet seasons

## 9.2 Scenario 2 – Increasing groundwater recharge

### 9.2.1 Description

Because approximately 90% of expected annual rainfall occurs during the two rain seasons, it is imperative that as much rainwater as possible should be conserved (Biamah et al., 1999). Jansen (2007) analysed precipitation – infiltration ratios. Runoff plots on identical soil types and slope but with different land use (natural vs. agricultural) result in remarkably different runoff percentages; natural land use results in consistently higher surface runoff percentages as compared to the agricultural plot, up to 50 percent. The main cause is crust formation of bare soil, resulting in a barrier to infiltration of rainwater. In agreement with Schechambo et al. (1999), increasing groundwater recharge is concluded to be primarily dependent on enlarging infiltration of precipitation and minimizing runoff. The objective is to prevent surface flow of excess rainwater and prolong time available for infiltration. It is suspected that the percentage of precipitation infiltrating the soil can be improved with as much as 70 percent when the soil is subjected to cultivation and land husbandry measures such as regenerating natural vegetation, ploughing, bench terracing and contour bunds and retention ditches (Biamah et al., 1999). These measures also limit erosion and nutrient loss, which can be severe in sloping semi arid catchments (Rockstrom, 2000).

The groundwater recharge used to run 'Scenario 2 – Increasing the infiltration rate of the riverbanks' is shown in Figure 9.5. In this scenario, groundwater recharge is expected to increase with 50 percent.

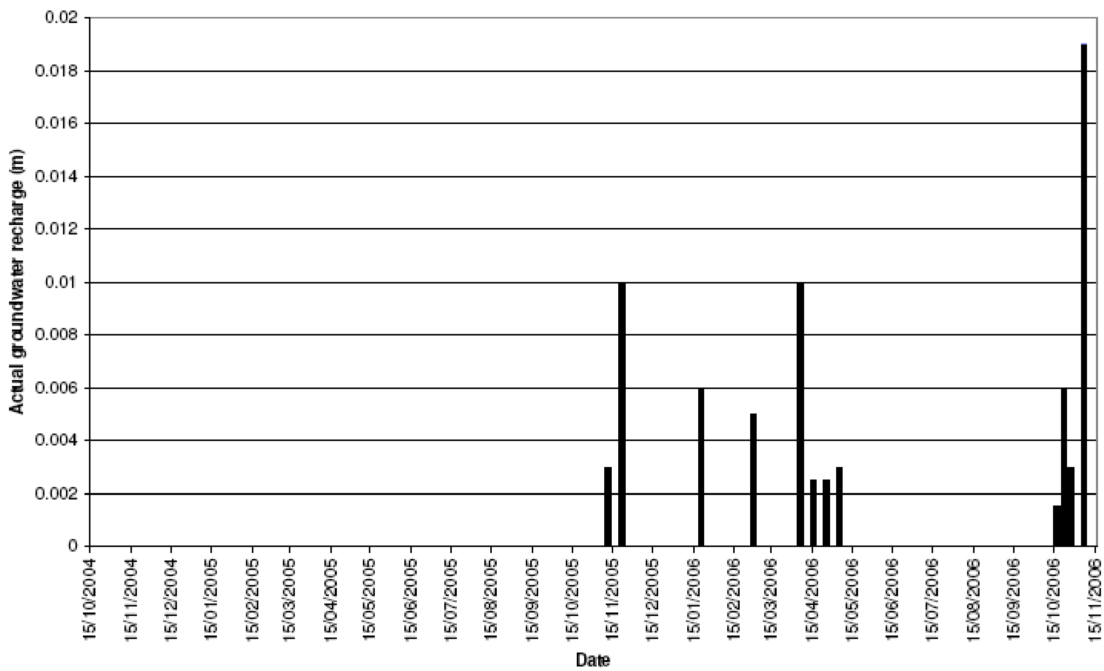



Figure 9.5 Groundwater recharge to the Triwaco model when running 'Scenario 2 – Increasing the infiltration rate of the riverbanks'

### 9.2.2 Model results

Figure 9.6, Figure 9.7 and Figure 9.8 show the effect of increased riverbank infiltration on groundwater levels and storage. Figure 9.7 represents calculated heads during representative dry and wet seasons. Comparable to groundwater flow calculated by the calibrated model, groundwater flow is directed south and towards the riverbed during the dry season. Analogue to the calibrated model, the Kwa Ndunda sand dam obstructs groundwater flow through the river, resulting in a subsurface reservoir behind the sand dam. The elevated heads initiate flow around the sand dam. Downstream of the sand dam, groundwater flow in the banks is oriented towards the riverbed.

At the start of the wet season, direction of groundwater flow changes in immediate response to groundwater recharge and is oriented mainly towards the river. Groundwater flow is redirected south and flow velocity decreases as the dry season proceeds. Groundwater level contours show leveling out of head differences between riverbed and banks.

Largest differences in calculated groundwater level between the calibrated model and the scenario occur in the riverbanks during the wet season; groundwater levels increase with 3.75 meter in the northwestern corner of the model area during the dry season. The average head difference during the wet season is 0.50 meter and 0.30 meter in the dry season. During the wet season, the largest gradient in head difference is experienced almost perpendicular to the riverbed; a minimal effect on calculated groundwater levels occurs in the riverbed due to the fact that these are almost continuously at surface level already (e.g. the river is flowing). Nevertheless, groundwater levels in the riverbed (p06) have increased with 0.20 meter at the end of the dry season, which is the crucial period.

The effect on groundwater storage is most prominent during the dry season (Figure 9.6b). Groundwater levels in the river upstream of the sand dam increase more than downstream, leading to an increase in groundwater flow around the sand dam.

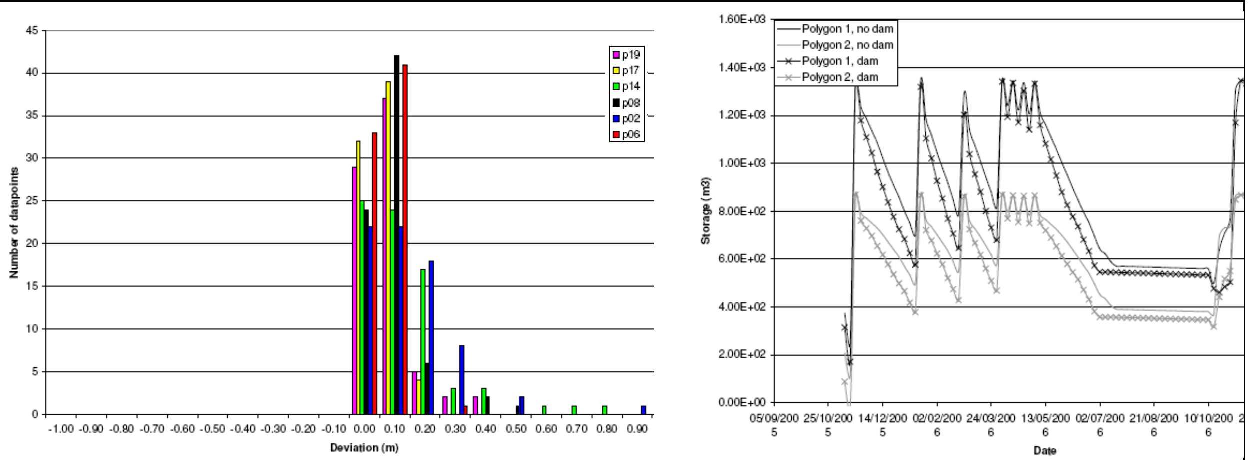



Figure 9.6 Difference between the calculated groundwater levels and storage in the riverbed as a result of increasing groundwater recharge

### 9.2.3 Discussion

Functionality of sand dams is for an important part explained by replenishment of the riverbed aquifer by groundwater flow from the riverbanks towards the bed. Only a small percentage of precipitation actually leads to groundwater recharge. This can be increased significantly by performing land husbandry measures, such as terracing and ploughing of bare soil and agricultural plots (Schechambo, 1999).

Impact of increased groundwater recharge is largest farest from the riverbed, resulting in a larger gradient in head. The effect is an increased groundwater flow velocity from the banks towards the riverbed, leading to an increase in total volume of water supplied from the banks to the riverbed. This is in agreement with calculated storage of groundwater in the polygons in the riverbed.

In correspondence with Rama Mohan Rao (1996), increased groundwater recharge in the riverbanks is thus concluded to result in a larger volume and prolonged period of groundwater availability. The effect of increased groundwater recharge on groundwater storage is most evident in the area upstream of the sand dam during dry seasons, which could be fundamental in years of drought.

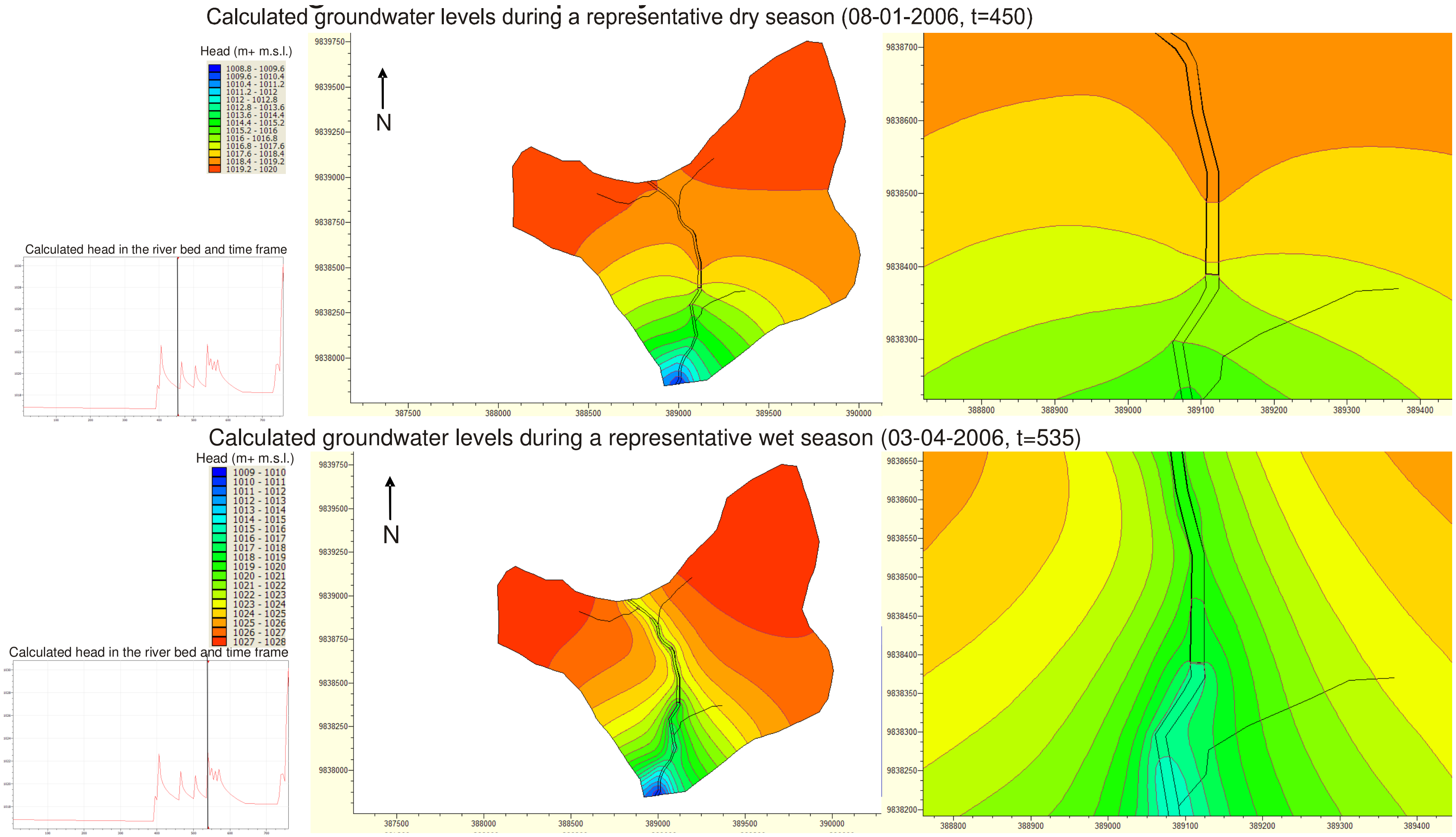



Figure 9.7 Results of ‘Scenario 2 – Increasing riverbank infiltration’ during moments representative for the dry and wet seasons

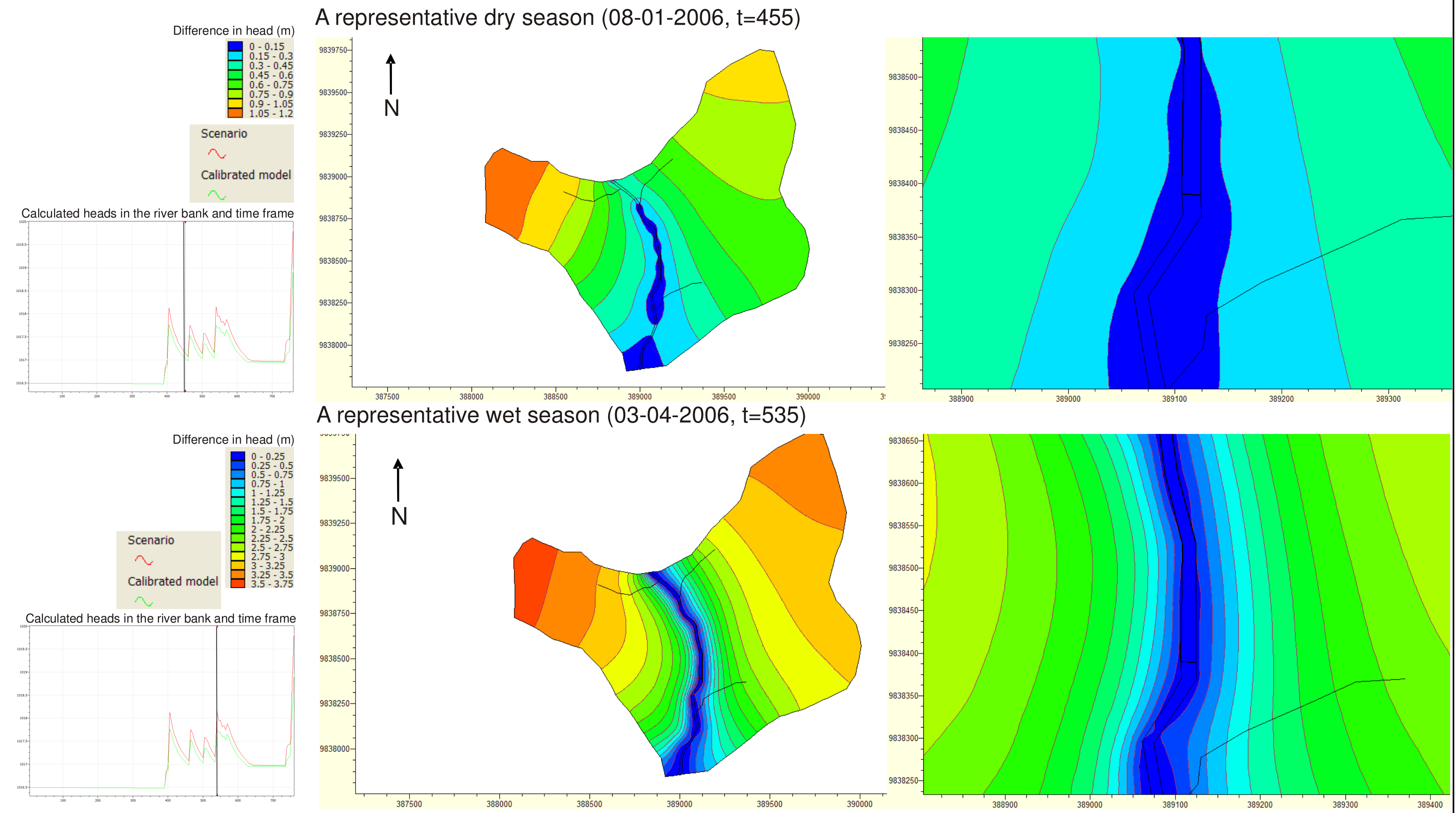



Figure 9.8 Results of 'Scenario 2 – Increasing riverbank infiltration' during moments representative for the dry and wet seasons

## 9.3 Scenario 3 – Increasing the height of the sand dam

### 9.3.1 Description

The effect of increasing the height of the Kwa Ndunda sand dam on groundwater flow is studied in this scenario. The height of the original dam is 1.60 meter. In this scenario, dam height increases to 3.00 meter and the width increases from 18 meter to 60 meter, which is dependent on the slope of the riverbanks (Figure 9.9 and Figure 9.10). It is assumed that the extra volume of sand sedimented behind the higher dam has the same hydraulic properties as the sand already present in the riverbed (hydraulic conductivity = 60 m/d). Spatial coverage and variation in thickness of the extra sand layer is shown in Figure 9.9. The scenario also results in a new surface elevation model.

The extra sand is integrated in the sediment layer (aquifer 1). To compromise for the fact that the riverbanks actually consist of two layers with quite distinct hydraulic properties, an integrated value for hydraulic conductivity is assigned at these locations; the eastern riverbank is given a value of 35 m/d and the western riverbank a value of 15 m/d.

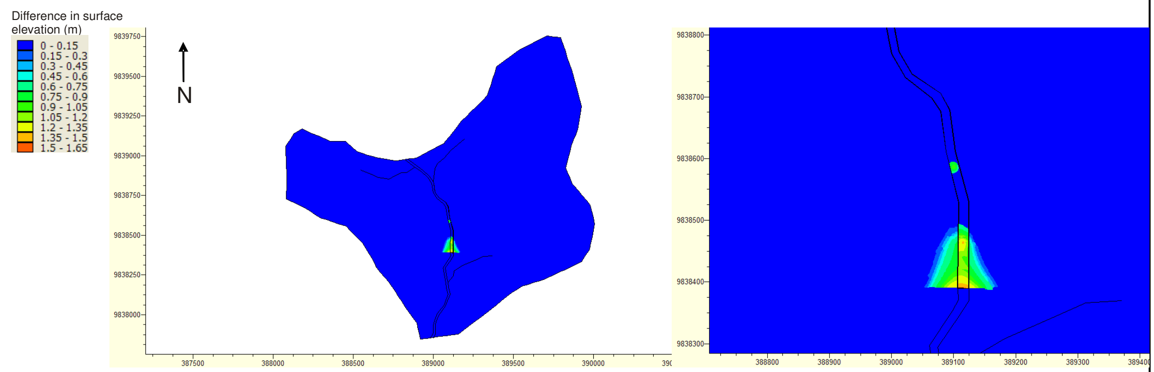



Figure 9.9 Difference in surface elevation (equal to the increase of thickness of the sand layer) as a result of increasing the height of the Kwa Ndunda sand dam to 3 meter

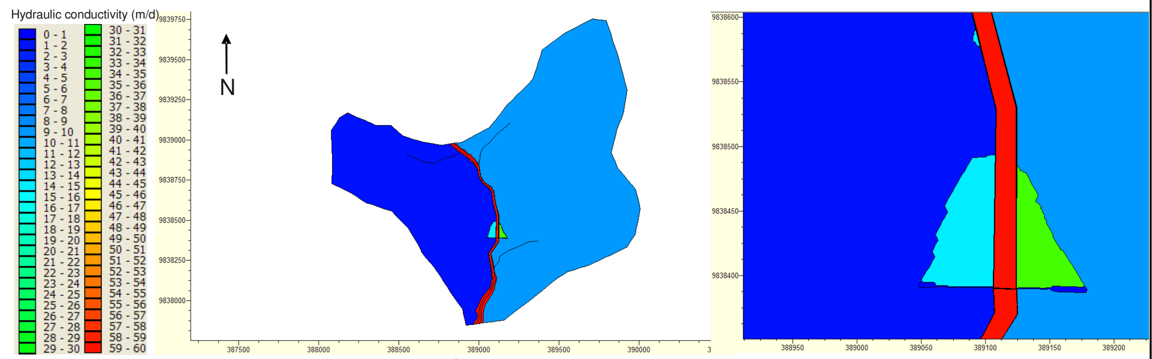



Figure 9.10 Hydraulic conductivity used in 'Scenario 3 – Increasing the height of the Kwa Ndunda sand dam'

### 9.3.2 Model results

Figure 9.11, Figure 9.12, Figure 9.13 and Figure 9.14 show the effect of increasing the height of the Kwa Ndunda sand dam on model results. As compared to the calibrated model, groundwater flow is directed south and towards the riverbed during the dry season and groundwater flow is oriented around the sand dam. Downstream of the sand dam, orientation of the contour lines change to more parallel to the riverbed, indicating flow towards the river. At the end of the long dry season, the zone stretches 400 meter upstream of the sand dam.

At the start of the wet season, groundwater flow direction changes in immediate response of groundwater recharge on the riverbanks and is oriented mainly towards the river. Like during the dry season, groundwater flow is directed around the sand dam. Downstream of the sand dam groundwater contours are closely spaced. Head differences between riverbed and banks level out during the dry season, resulting in a larger zone of influence. The direction of groundwater flow is redirected to the south and flow velocity decreases while the dry season proceeds.

Figure 9.14 shows differences in head calculated by the calibrated model and scenario 3. During the long dry period (07-06-2006), the zone in which heads are elevated with 0.10 meter stretches approximately 300 meter upstream of the sand dam. Within 130 meter upstream of the sand dam, groundwater levels are elevated 0.24 to 0.36 meter. Figure 9.11 visualizes groundwater levels calculated by the calibrated model and the scenario in the riverbed upstream of Kwa Ndunda sand dam as an illustration of fluctuations in time. Responses of head calculated by the scenario are less pronounced than those computed by the calibrated model. This leads to lower groundwater levels during the wet seasons and the first part of the dry season. However, groundwater levels decline slower resulting in elevated groundwater levels from certain moments during the dry season. As the model runs, deviations between calibrated model and scenario become smaller during the wet seasons (negative) and increase during the dry seasons (positive). In general, heads in the riverbed keep levitating in time; the aquifer in the riverbed fills up. Figure 9.12b is evidently in agreement with this conclusion. The volume of water stored in the riverbed continues to increase on average. At the end of the simulation period, the groundwater storage in polygon 1 has increased with 350 percent on average compared to the calibrated model and with 50 percent in polygon 2. The polygon lies for the foremost part outside the area in which the thickness of the sand layer in the riverbed is increased, leading to a smaller enhancement of the groundwater storage possibility.

From Figure 9.12a it becomes clear that increasing the height of the Kwa Ndunda sand dam with 1.5 meter does affect the groundwater levels in the downstream area; peaks in head are 10 centimeter on average and approximately 7 centimeter during the dry season.

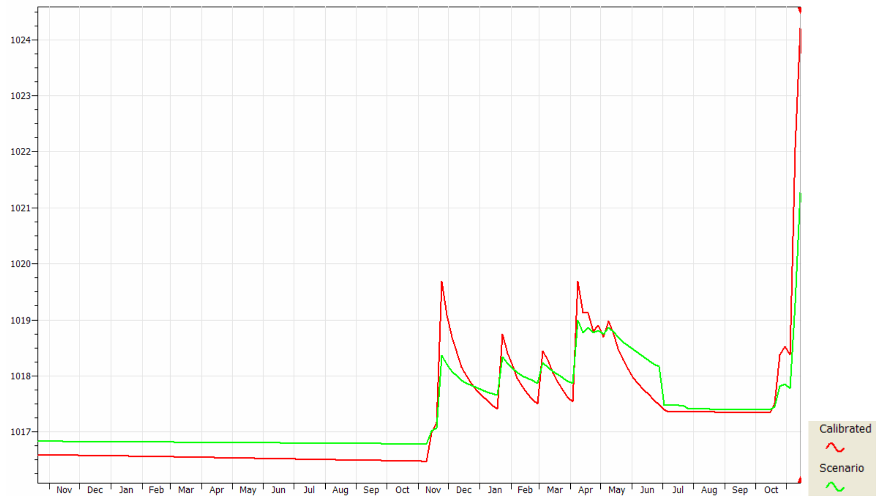



Figure 9.11 Groundwater level calculated by the calibrated model and the scenario as calculated in the western riverbank

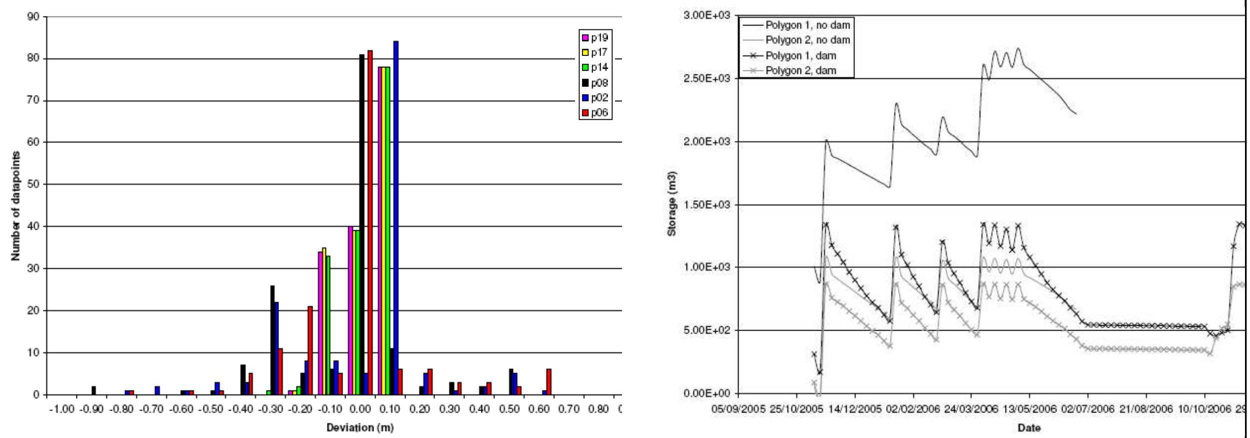



Figure 9.12 Difference between the calculated groundwater levels and storage in the riverbed as a result of increasing the height of the Kwa Ndunda sand dam (Scenario 3)

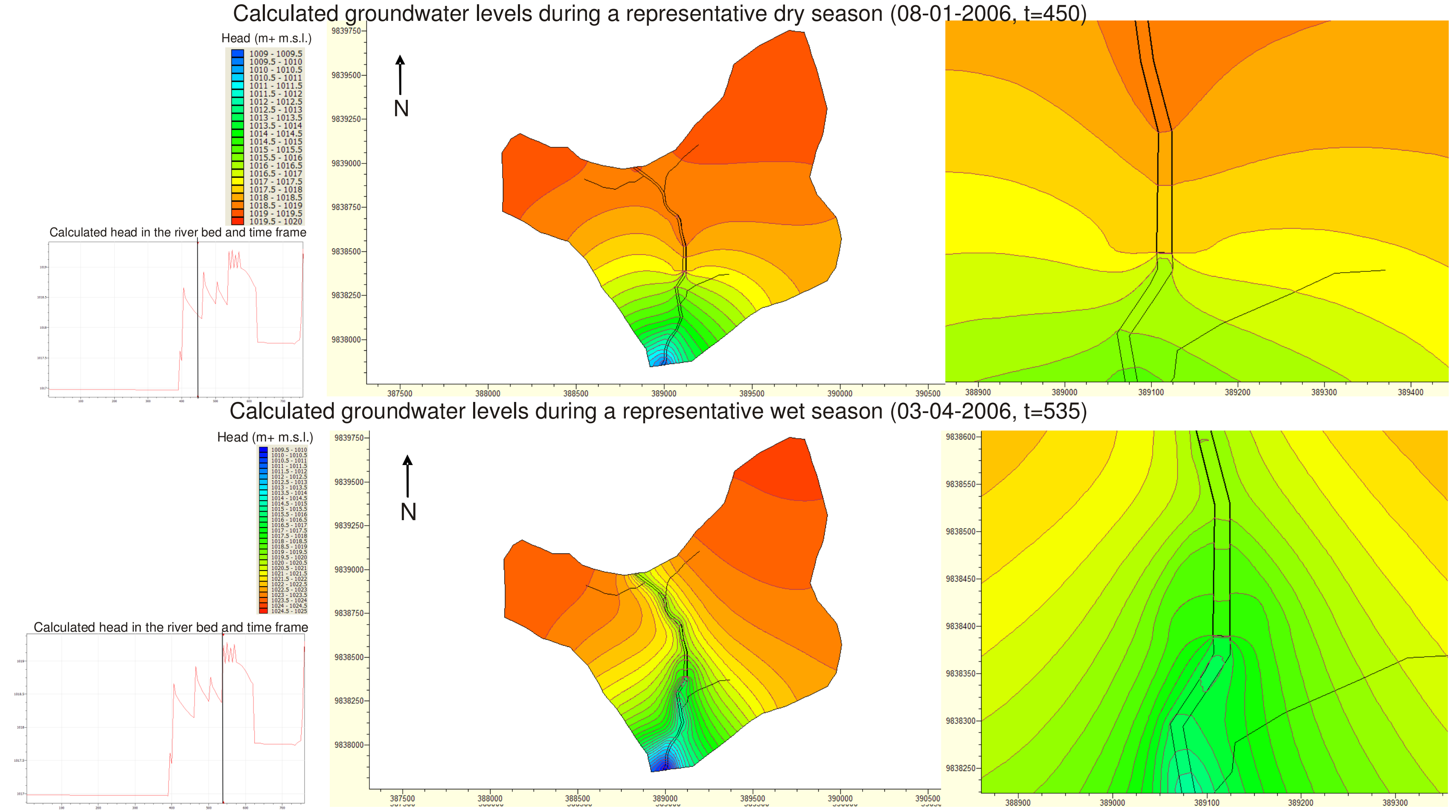



Figure 9.13 Results of ‘Scenario 3 – Increasing the height of the Kwa Ndunda sand dam’ during moments representative for the dry and wet seasons

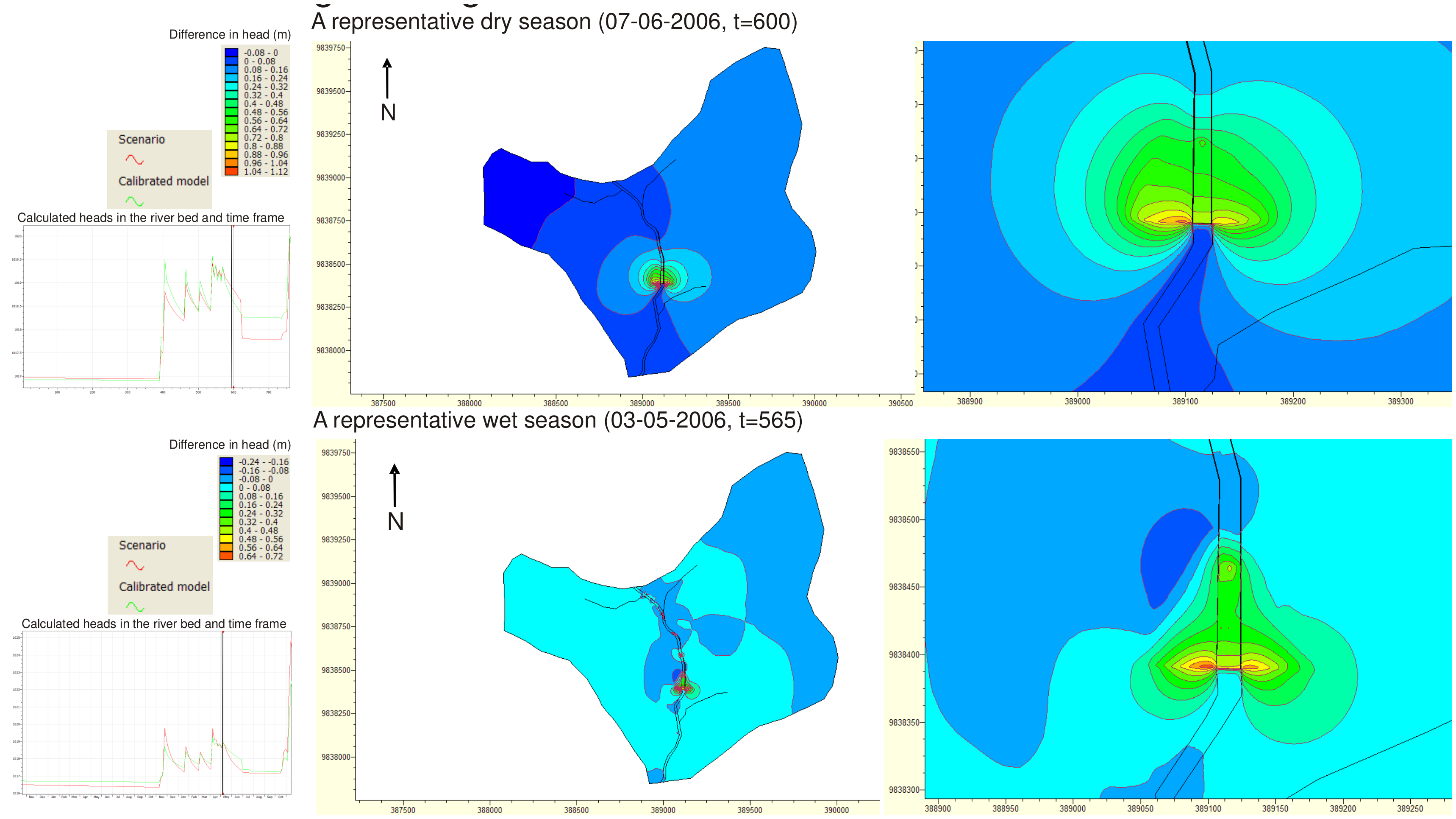



Figure 9.14 Results of ‘Scenario 3 – Increasing the height of the Kwa Ndunda sand dam’ during moments representative for the dry and wet seasons

### 9.3.3 Discussion

The higher and wider dam obstructs groundwater flow through the riverbed and part of the riverbanks, resulting in a groundwater basin comprising a larger part of the riverbed and –banks as compared to the calibrated model. Comparable to the calibrated model, raised heads directed around the sand dam. The closely spaced contour lines indicate an increase in flow velocity towards the riverbed downstream of the sand storage dam.
The close

Increasing the dam height with 1.5 meter leads to a situation in which the riverbed aquifer is not recharged completely within one wet season. Several wet seasons are required to fill up the aquifer, resulting in lower groundwater levels in downstream areas.

### 9.3.4 Scenario 4b – Increasing the dam height with 0.75 meter

To test the above mentioned hypothesis, a variation on scenario 4 is made (Scenario 4b) in which the dam height is increased with 0.75 meter instead of 1.50 meter. The result of running the model under these settings is shown in Figure 9.15.

Groundwater levels calculated by the model run of scenario 4b are elevated with respect to those calculated by the calibrated model but show normal trends; fluctuations of groundwater storage in the riverbed corresponds to those of the calibrated model, although the volumes are enlarged by the enhanced storage capacity. However, recession curves show a smaller gradient (Figure 9.16).
Groundwater flow is not affected by the increased height of the sand dam as compared to the calibrated model.
Groundwater levels upstream of the sand storage dam are influenced most; 0.24 meter on average, increasing to 35 centimeter during the dry season. Increasing dam height leads to an average increase in storage of more than 200 percent during the dry season, equal to 1590 $m^3$.
The effect on downstream piezometers is negligible; 4 centimeters on average and maximal 7 centimeters.

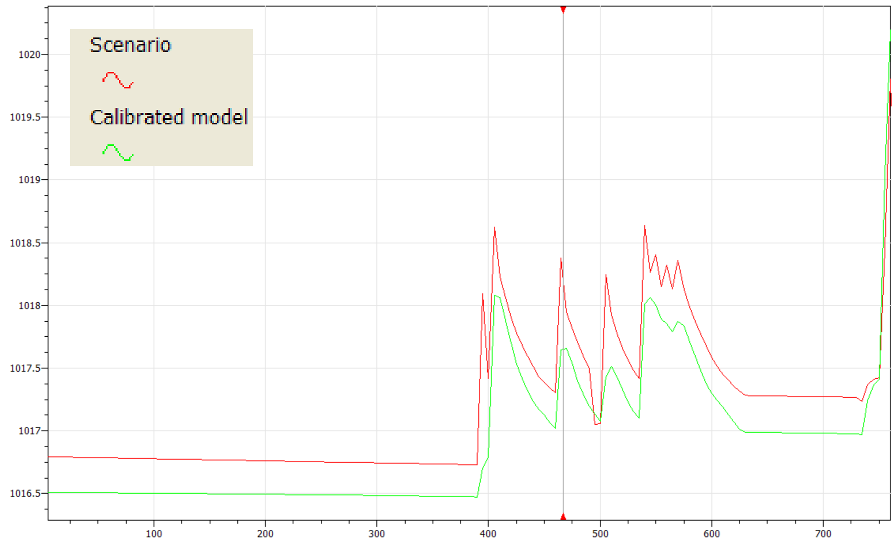


Figure 9.15 Groundwater level calculated by the calibrated model and the scenario with an increase in dam height of 0.75 meter as calculated in the riverbed upstream of the Kwa Ndunda sand dam

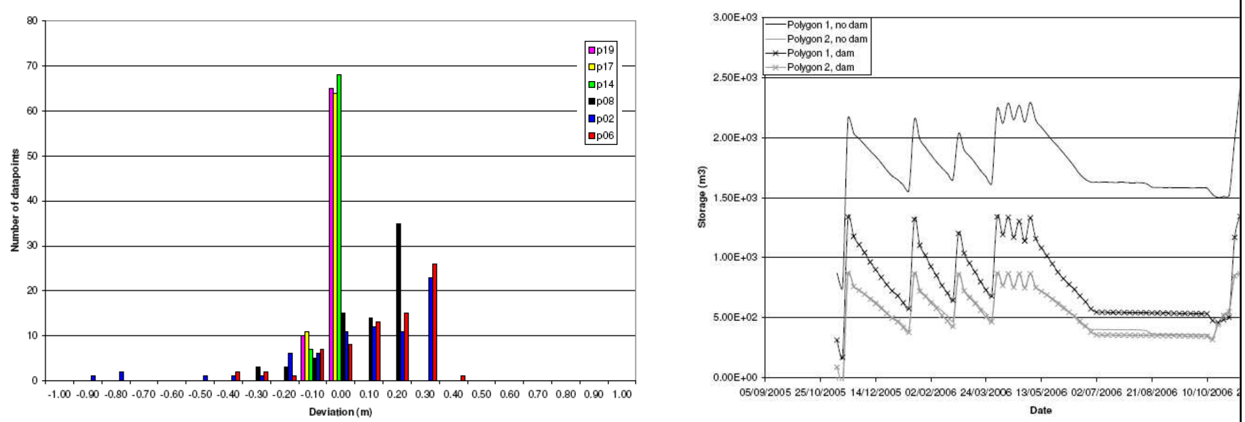


Figure 9.16 Fluctuations in the volume of groundwater stored in the river bed upstream of the Kwa Ndunda sand dam as calculated by the calibrated model (crossed) and Scenario 4b (plain

### 9.3.5 Discussion

Increasing crest height with 0.75 meter influences groundwater storage in the riverbed positively, especially during the dry season, due to an increase in storage capacity. The aquifer is still recharged completely within one or two rainfall events and thus influences downstream areas to a limited extent. It can however not be established with certainty what happens if this measure is applied to a cascade of dams.

## 9.4 Scenario 4 – Groundwater abstraction from the riverbed

### 9.4.1 Description

Groundwater abstraction from the riverbed is included in this scenario to study the effects on groundwater flow, storage and period of availability. As explained in Paragraph 2.6.2, during the dry season groundwater is primarily abstracted from the riverbed through hand-dug wells. Figure 9.17 shows the location at which the most important scoop hole is located. Borst et al. (2006) estimated the total current water demand of the community to be 8 $m^3$/day. Groundwater is only abstracted during the dry season, since surface water is available during the wet season. The input to the model is shown in Figure 9.18.

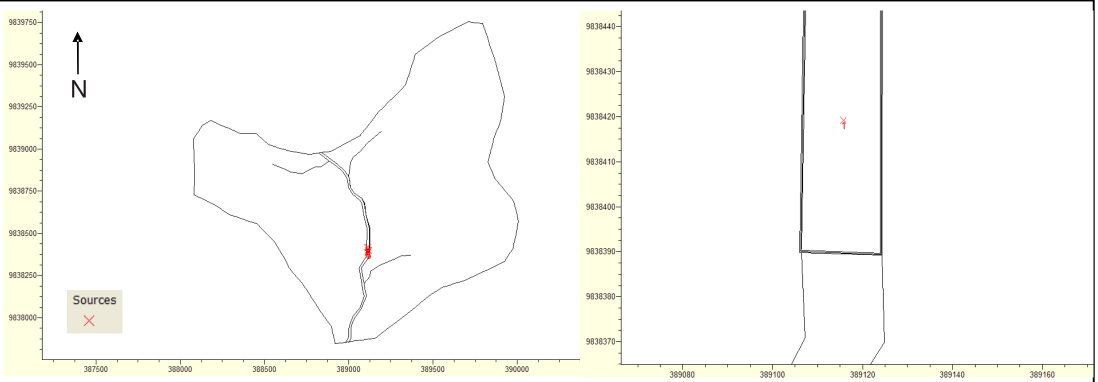



Figure 9.17 Locations of abstraction point in the riverbed upstream of the Kwa Ndunda sand dam

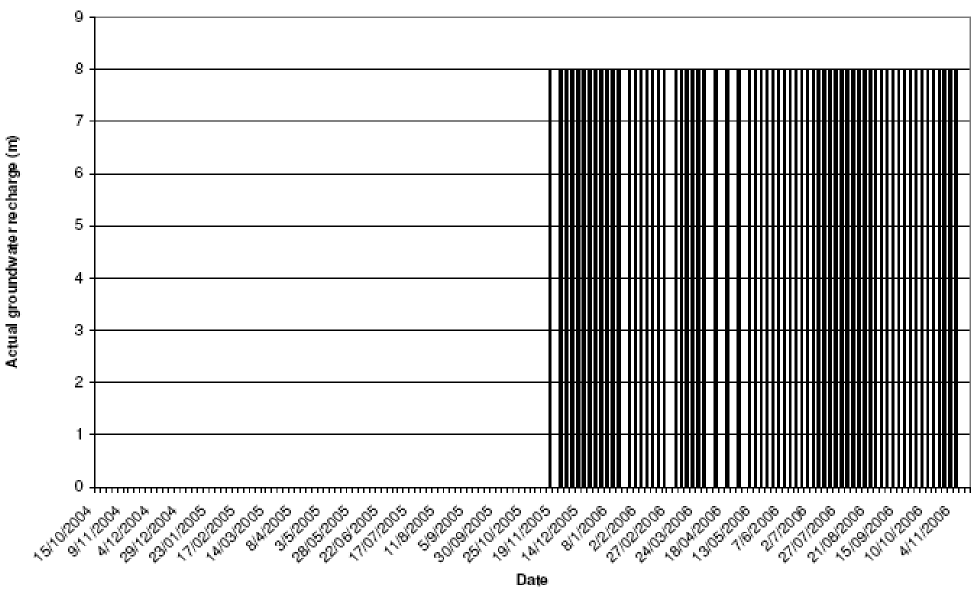



Figure 9.18 Time frame of groundwater abstractions from the river bed upstream of the Kwa Ndunda sand dam as used in Scenario 4 – Groundwater abstraction

### 9.4.2 Model results

Figure 9.19, Figure 9.20 and Figure 9.21 show the effect of groundwater abstraction from the riverbed on model results.

As compared to the results of the calibrated model, groundwater flow is directed south through the banks and riverbed. Upstream of the sand dam, groundwater flows from the riverbed towards the banks and around the sand dam through the banks. However, groundwater levels decrease faster during the dry period in the zone behind the sand dam.
Orientation of contours changes direction abruptly in response to groundwater recharge; groundwater flow is directed towards the river. After the last rainfall event, head differences between the riverbed and -banks level out and groundwater flow is oriented to the south and towards the riverbed again.

Figure 9.21 visualizes spatial differences between groundwater levels calculated by the calibrated model and the ones computed in this scenario. Groundwater levels decrease circular towards the scoop hole. Deviation from the calibrated model is biggest during the dry season. Groundwater levels decrease with 10 centimeter in a zone of approximately 20 meter from the location of the scoop hole. Heads in piezometer p06 lowered 17 centimeter due to abstraction during the long dry period, representing a volume of 150 $m^3$ (Polygon 1). The influence on groundwater storage in Polygon 2 is 50 $m^3$. The riverbanks are also influenced by the abstraction of water from the riverbed; a lowering of 10 centimeter is experienced at 25 meters from the scoop hole. Piezometer p02 and p08 experience a maximum drawdown of 13 centimeter (Figure 9.19a). Downstream of the sand dam groundwater levels are influenced negligible by abstraction of groundwater from the riverbed. Differences between computed groundwater levels diminish completely as soon as the wet season starts (Figure 9.21); the aquifer recovers fully from abstraction within the first rainfall event. This conclusion is in correspondence with the recovery of groundwater storage visualized in Figure 9.19b.

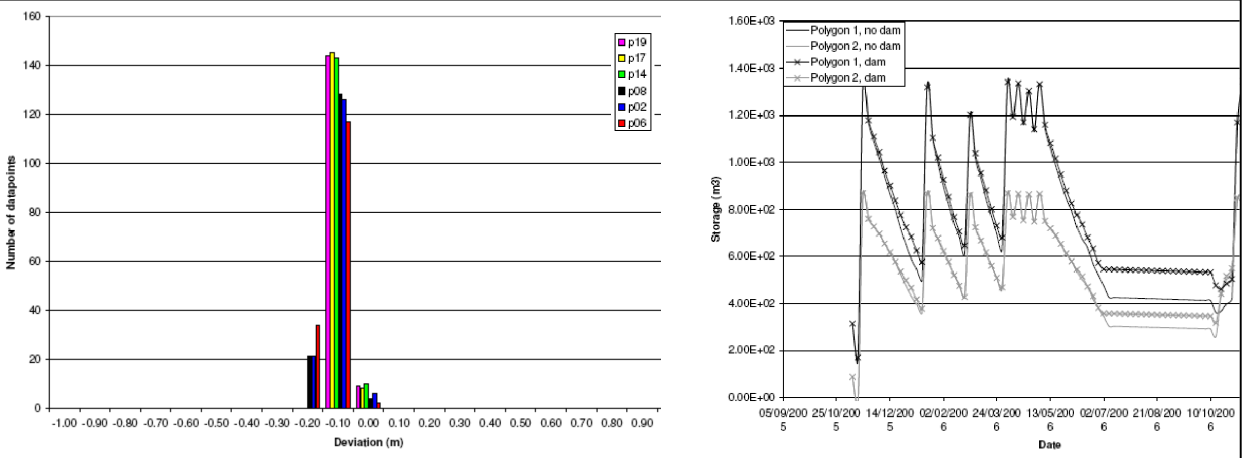



Figure 9.19 Difference between the calculated groundwater levels of scenario 4 and the calibrated model

### 9.4.3 Discussion

Abstraction of water from the riverbed results in a faster decrease in head compared to the situation of the calibrated model. Groundwater levels decrease circular towards the location of the scoop hole. However, at the rate of groundwater abstraction as performed momentarily, groundwater levels upstream of the sand dam are influenced to some extent but very locally. However, increased groundwater flow from riverbanks and through the riverbed will compensate the groundwater abstraction for an important part. This points out the importance of the riverbanks in groundwater storage. Furthermore, the abstraction rate can be enlarged, for example to extent the aerial of irrigated crops.

Declined groundwater levels due to abstraction of water diminish completely at the start of the wet season; the aquifer recovers fully within the first rainfall event.

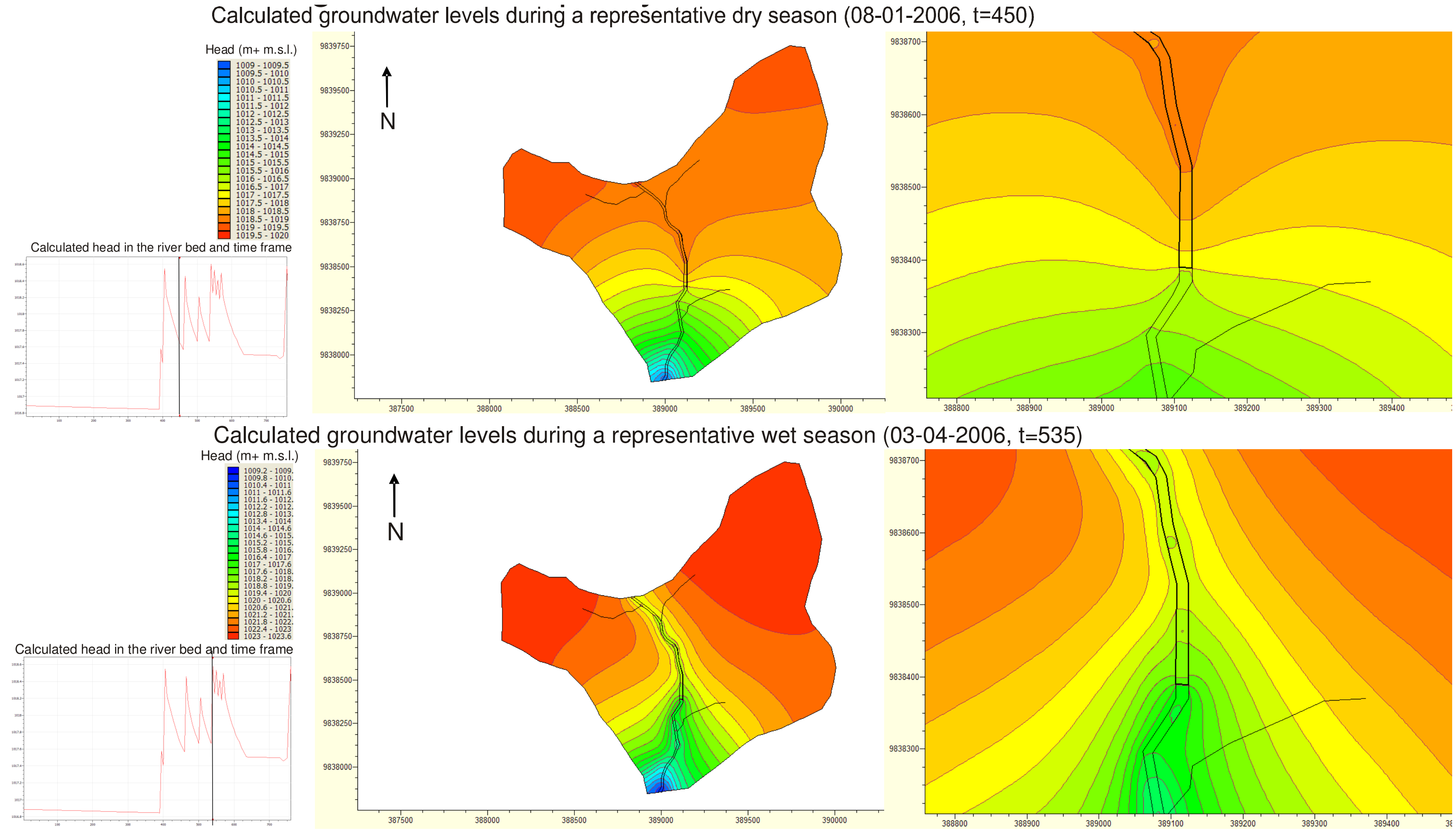


Figure 9.20 Results of ‘Scenario 4 – Groundwater abstraction from the riverbed’ during moments representative for the dry and wet seasons

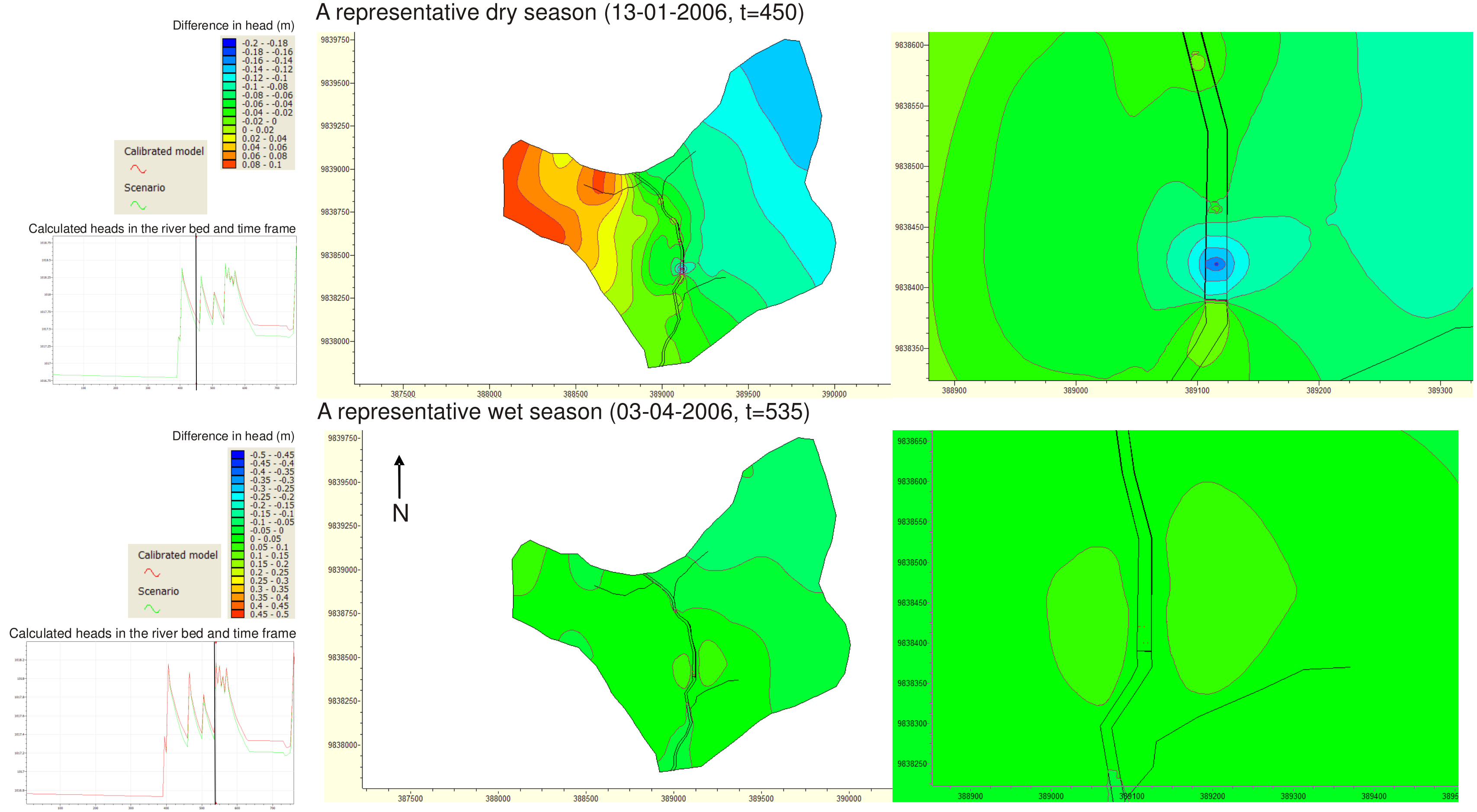



Figure 9.21 Results of ‘Scenario 4 – Groundwater abstraction from the riverbed’ during moments representative for the dry and wet seasons

# 10 Conclusions

**Importance of sand dams**

Communities in rural areas have always relied almost completely on water abstraction through hand-dug wells (scoop holes) from dry sand riverbeds. However, the riverbed would often desiccate before the start of the next rain season, because of which water would need to be fetched in other catchments. The socio-economic impacts of this situation are discussed more elaborately in De Bruijn et al. (2006). Since centuries, sand storage dams are constructed in sandy riverbeds in (semi) arid areas (Nissen-Petersen, 2006) to increase the natural groundwater storage capacity through sedimentation of sand upstream of the dam during wet seasons. This method has proven to be very successful in addressing water scarcity in semi-arid Kitui District, Kenya.

To study the impacts of sand storage dams on groundwater flow and availability, a quasi-3D groundwater model was set up around the Kwa Ndunda sand dam (Kiindu river, Kenya) in model environment Triwaco, using calculation module Flairs.

**Impacts of sand dams on groundwater flow and storage**

The presence of a sand storage dam increases the natural storage capacity of the riverbed, while obstructing groundwater flow through the riverbed as well. Groundwater flow is predominantly topography driven, resulting in groundwater flow oriented south and towards the riverbed during the dry season. The obstruction of groundwater flow through the riverbed results in a subsurface water reservoir. The consequential elevated heads upstream of the sand dam in the zone of influence (stretching to a maximum of 350 meter upstream of the sand dam at the end of the dry season) result in groundwater flow from the riverbed into the banks and through the riverbanks around the sand dam. Downstream of the sand dam groundwater flow is oriented towards the riverbed. The riverbed aquifer is replenished by groundwater flow downstream through the riverbed. The presence of the sand dam bridges periods of drought until the next rain season. At the end of the dry season the sand body within 200 meter upstream of the sand storage dam contains a volume of approximately 580 $m^3$, while in a model scenario in which the sand dam is absent the riverbed dries up within 1.5 months after the start of the dry period.

From a hydrogeological point of view, the functionality of sand storage dams in semi arid areas with unreliable and scarce precipitation can be explained partly by the coarse riverbed sand. The coarse sand enables rapid responses of the groundwater table on precipitation and protects groundwater from excessive evaporation due to low capillary forces and increased thickness of the sand layer in the riverbed. After the first heavy rainfall event, the riverbed aquifer is recharged completely and the river starts to flow. This leads to the conclusion that downstream areas are not significantly influenced by refilling of the enhanced riverbed aquifer.

**Parameters of importance to successful functioning of sand dams**

Besides thickness of the sand layer in the riverbed, hydraulic conductivity and thickness of the sediment layer in the riverbanks are important parameters, influencing the reaction of groundwater levels on precipitation on the riverbanks, recession of groundwater levels and the volume of groundwater storage in the riverbed. Higher hydraulic conductivity leads to a less pronounced response of groundwater levels to precipitation and a larger gradient of the recession curve, as well as a faster decline in the volume of water stored in the riverbed. Hydraulic conductivity and thickness of the weathered rock layer and flood depth have less influence on model results.

**Improving functionality sand dams**

Increasing riverbed thickness by enhancing the height of the sand dam increases groundwater availability effectively. An increase of 0.75 meter results in an enhancement of groundwater storage in the riverbed from 500 $m^3$ to 1590 $m^3$ while having a negligible effect on the downstream area. It can however not be established with certainty what happens if this measure is applied to a cascade of dams. Increasing the dam height with more than 0.75 meter causes lower groundwater levels in downstream areas. Rainfall events are not large enough to fill the riverbed aquifer in one wet season, leading to a decrease in groundwater flow towards the downstream area.

It is however not necessary to increase the height of the Kwa Ndunda sand dam, since groundwater abstraction as performed momentarily (approximately 8 $m^3$/day) influences groundwater levels in the riverbed and -banks upstream of the sand dam to some extent but very locally. Increasing the abstraction rate with 50 percent still only leads to a decrease in groundwater levels of 25 percent of the average groundwater volume present in the riverbed. However, a volume of approximately 400 $m^3$/day is still present in the riverbed, pointing out the potential of increasing groundwater abstraction for irrigation of crops. Larger groundwater abstraction from the riverbed is compensated for an important part by increased groundwater flow from the riverbanks towards the riverbed, which would otherwise simply be emptied. The riverbanks are the main source of groundwater replenishment during the dry season; the potential groundwater harvest from an aquifer upstream of a sand storage dam is thus larger than the volume of water present at a certain moment in time in riverbed.

Declines in groundwater level caused by the abstraction of water diminish completely as soon as the wet season starts; the aquifer recovers fully within the first rainfall event.

Improved groundwater recharge is concluded to lead to a larger volume and prolonged period of groundwater availability. Increasing groundwater recharge with 20 to 50 percent (through performing land husbandry measures such as regenerating natural vegetation, terracing and ploughing of agricultural plots) leads to significantly higher groundwater levels and thus in riverbed storage.

**Loss of groundwater**

The program used to perform the water balance calculation had difficulties determining the horizontal fluxes over the boundaries of the water balance area with sufficient accuracy. It was thus not possible to quantify the volume of groundwater lost through flow around the sand dam. On the other hand, loss of groundwater through groundwater flow around a sand dam is not relevant when considering a cascade of sand dams (Orient Quilis, 2007).

The risk of increased groundwater flow through the riverbanks around the sand dam due to above discussed measures is related to larger chance on failure of the sand dam due to potential erosion of the riverbanks caused by larger groundwater fluxes. Failure of sand dams because of erosion of the riverbanks is described in Gijsbertsen (2007). To decrease the risk, sand dams should be attached to the basement in the riverbanks. Otherwise, erosion of the riverbanks will lead to failure of the sand dam (Nissen-Petersen, 2006).

**Application of the model in other potential sand dam areas**

The groundwater model can be used as an indication of the effect of building a sand storage dam in the riverbed in terms of the volume of water stored in the riverbed, potential storage in riverbanks and the period in which groundwater is available for abstraction. To this aim, generic data, such as a SRTM DEM, VESses, approximate precipitation data and literature values of hydraulic parameters, can be used as input to the model.

# 11 Recommendations

**Water balance**

Although fluctuations in storage in the riverbed are determined, performing a water balance study to quantify the groundwater flux around the sand dam and the influxes of water from the banks would be a great improvement of the present state of knowledge.

**Groundwater flow model**

Several additions to the groundwater model can be made to include more processes. Firstly, an unsaturated zone model could be integrated. In this way, the delay between precipitation and actual groundwater recharge can be incorporated. Furthermore, it might increase certainties regarding the percentage of precipitation leading to groundwater recharge by incorporating evaporation from the upper part of the soil. However, additional data will be needed (e.g. thickness of the sediment layer throughout the model area).

From a scientific point of view, improving the conceptual model might also include integration of the groundwater model with the precipitation-discharge model set up by Jansen (2007), which would lead to an integration of the reaction of groundwater levels in the riverbed to precipitation. However, for the aim the groundwater model is designed, integration of these models will probably have limited effect.

**Fieldwork**

Thickness of the riverbed affects model results most extensively. Although the parameter is known with acceptable certainty in the area of interest, it might be interesting to apply geophysics to study the degree of weathering of the granite underneath the riverbed. A remaining question is whether a significant volume of water is lost by infiltration into and flow through the granite basement, which is assumed to be impermeable underneath the weathered zone.

Another way to enhance model reliability efficiently is by extending groundwater level measurements further into the riverbanks and to more upstream parts of the riverbed. This will also provide more data on hydrogeology (on which more data could be collected through performing VESses more towards the catchment boundaries).

Uncertainty on model input is largest of groundwater recharge. From a practical point of view, accuracy regarding this parameter could be enhanced by performing oxygen isotope analysis of groundwater and precipitation samples.

When applying the sand dam technology in other areas, it would be advisable to install piezometers in advance of building the sand storage dam, to study fluctuations in groundwater levels and the effect of constructing a sand dam on heads and thus groundwater flow.

# Acknowledgements

Dear Koos, I appreciate your extensive knowledge on diverse (groundwater related) subjects and the willingness to share it very much.

Dear Maarten, I am grateful for you support during my Master Thesis project and throughout my study period in general. I am still wondering how you always seem to find time to listen to the troubles of your students and to provide them with cups of fresh liquorice tea.

Dear Jouke, thank you for introducing me to the magic world of groundwater flow modeling. Your extensive experience with groundwater modeling, combined with patience and willingness to assist made the experience worthwhile. I must admit I became accustomed to the ‘Tips van de Dag’ and hope you will continue sharing these with me.

The sponsors of the project, Aqua4All, the Acacia Institute and the VU University of Amsterdam, are thanked for the opportunity to perform this research. I hope the results will contribute to the successful implementation of the sand storage dam methodology in other semi-arid and arid environments.

I am very grateful for the extraordinary experiences when residing in Kitui Town, Kenya. Sam, Julius, Mutinda and Mary of the Sahelian Solutions foundation (SASOL), thank you for your support during our field visit. Muinde, I really enjoyed your company in the field and especially appreciated your skill to find the most comfortable lunch spots. From Christina and Paul I received much hospitality. I enjoyed the company of your children and their many friends in the field, which made those days particularly treasurable. Peter is thanked for performing the groundwater measurements with such loyalty and precision. My friends of the Kitui Tourist Hotel, you felt like my own family after the 2 month stay. Thank you, it was a memorable experience.

My dearest Jasper and Cedrick; we formed a great team! I have many happy memories of our journeys and adventures and consider it an unforgettable time.

Finally, I would like to express my deepest gratitude to my family, especially Anneke, Piet, Daniel and Oma for everlasting love and support, and to my friends, who have made my study period one of great pleasure.

# References

ALRMP – Arid Lands Resource Management Project. http://www.aridland.go.ke

Andersen M.P., Woessner W.W. (2002). *Applied groundwater modeling – Simulation of flow and advective transport.* Academic Press, USA.

Andersen N.J., Wheater H.S., Timmis A.J.H., Gaongalelwe D. (1998). *Sustainable development of alluvial groundwater in sand rivers of Botswana.* Sustainability of Water Resources under Increasing Uncertainty, IAHS No. 240, pp. 367-376.

Beenke, H., Blom M., Hoogmoed M., Peña Arancibia J. (2006). *Hydrological and hydrogeological research of the western part of the Rio Boco catchment, Province of Aveiro, Portugal – June/July 2005*. Vrije Universteit, Amsterdam.

Borst L., de Haas S. (2006). *Hydrology of Sand Storage Dams – A case study in the Kiindu catchment, Kitui District, Kenya.* VU University, Amsterdam.

Biamah E.K., Stroosnijder L., Omuto C.T. (2004). *Watershed conservation in semi-arid Kenya.* University of Nairobi, Kenya.

Butterworth J.A., Mugabe F., Simmonds L.P., Hodnett M.G. (1999a). *Hydrological processes and water resources management in a dry land environment II: Surface redistribution of rainfall within fields.* Hydrology and Earth System Sciences, Volume 3, pp. 333-343.

Butterworth J.A., Macdonald D.M.J., Bromley J., Simmonds L.P., Lovell C.J., Mugabe F. (1999b) *Hydrological processes and water resources management in a dry land environment III: Groundwater recharge and recession in a shallow weathered aquifer.* Hydrology and Earth System Sciences, Volume 3, pp. 345-352.

CIS: http://srtm.csi.cgiar.org

De Bruijn E., Rhebergen W. (2006) *Socio-economic Impacts of the Construction of Sand Dams on Communities in Kitui District, Kenya. VU University Amsterdam.*

De Hamer W. (2007). *Potential Water Supply of the Mnyabezi Catchment: a case study of a small reservoir and alluvial aquifer system in the arid region of southern Zimbabwe*. Universiteit van Twente, Enschede.

Jansen J. (2007). *The influence of sand dams on rainfall-runoff response and water availability in the semi-arid Kiindu catchment, Kitui District, Kenya.* VU University, Amsterdam.

Gijsbertsen C., Hoogmoed M., Segers W. (2006). *Chemical analysis of the springs in the catchment of the Rio Boco, Province of Aveiro, Portugal*. VU University, Amsterdam.

Gijsbertsen C. (2007). *A research to upscaling of the sand storage dam principle and sedimentation processes behind sand storage dam*. VU University, Amsterdam.

Hellwig D.H.R. (1973). *Evaporation of water from sand 4: The influence of the depth of the water table and particle size distribution of the sand.* Journal of Hydrology, 18, pp. 317-327.

Hut R., Joeman N., Vergeer N. (2005). *Sand storage dams – Research on effectiveness.* Technische Universiteit, Delft.

Jothinyangkoon C., Sivapalan M., Farmer D.L. (2001). *Process controls of water balance variability in a large semi-arid catchment: downward approach to hydrological model development.* University of Western Australia, Australia.

Katumo V. (2001). *Environmental Impact assessment of Kiindu and Kyuusi rivers, Kitui District, 5th annual report 2000.* SASOL and the Department of Range Management, University of Nairobi,106 p. [1]

Kigomo, B.N. (unknown publication date). *Restoring the Vegetation and Improving the Livelihood of the Kamba and Maasai People in Kenya*. Kenya Forestry Research Institute (KEFRI), Nairobi, Kenya.

Konikow L.F. (2004). *Use of numerical models to simulate groundwater flow and transport.* US Geological Survey, USA.

Louis Berger International Inc. (1983) *Arid and Semi-Arid Lands Development Project, Kitui District Water Resources Study, Executive Summary.* Government of the Republic of Kenya.

Mazor E., George R. (1992). *Marine airborne salts applied to trace evapotranspiration, local recharge and lateral groundwater flow in Western Australia.* Journal of Hydrology 139-63.

Munyao J.N., Munywoki J.M., Kitema M.I., Kithuku D.N., Munguti J.M., Mutiso S.M. (2004). *Kitui sand dams: Construction and operation.* SASOL foundation, Kitui Town, Kenya.

Nissen-Petersen (1997). *Water from sand-rivers*. 23rd WEDC Conference Durban, Water and sanitation for all: Partnerships and innovations, South Africa.

Nissen-Petersen (2006). *Water from dry riverbeds.* ASAL Consultants Ltd. Nairobi, Kenya.

Opere A.O., Awuor V.O., Koke S.O, Omoto W.O. (2002). *Impact of Rainfall Variability on Water Resources Management: Case Study in Kitui District, Kenya.* University of Nairobi, Kenya.

Orient Quilis R. (2007). *Modeling sand storage dams systems in seasonal rivers in arid regions. Application to Kitui District (Kenya)*. Technische Universiteit, Delft.

Orient Quilis R., Hoogmoed M., Ertsen M., de Vries A., Foppen J.W., Hut R. (2007). *Determining the reputation of a thousand years by the conduit of one hour – Modeling hydrological processes of sand-storage dams on different temporal scales.* Technische Universiteit, Delft.

Parissopoulos, G.A., Wheater H.S. (1991). *Effects of evaporation on groundwater recharge from ephemeral flows.* In: Advances in Water Resources Technology, Ed. G. Tsakiris, A.A. Balkema.

Reynolds J.M. (2003). *An introduction to Applied and Environmental Geophysics.* John Wiley & sons, pp. 415-490. West Sussex, England.

Rockstrom J. (2000). *Water resources management in smallholder farms in eastern and southern Africa: an overview*. Phys. Chem. Earth (B), Vol. 25(3), pp 275-283.

Rama Mohan Rao M.S., Adhikari R.N., Chittaranjan S., Chandrappa M. (1996). *Influence of conservation measures on groundwater regime in a semi arid tract of South India.* Agricultural water management 30, pp. 301-312.

Royal Haskoning (2004). *Triwaco Users Manual (Triwaco 3.x).*
http://www.triwaco.com/NL/Download/Frame.htm

TAIEX expert meeting (2007). *Calibrating groundwater models – M.Sc. J. Velstra.* Seminar on Groundwater Modelling – Water Framework Directive, Infra 23804.

Schechambo, Sosoveli and Danielson Kissanga, (1999). *Rethinking Natural Resource Degradation in Semi-Arid Sub-Saharan Africa: The Case of Semi-Arid Tanzania.* Institute of Research Assessment, Tanzania.

Solomatine D.P., Dibike Y.B., Kukuric N. (1999). *Automatic calibration of groundwater models using global optimization techniques. Hydrological Sciences Journal,* 44(6)

Triwaco: http://www.triwaco.com/NL/Default.htm

Tuinhof A., Heederik J.P. (2003). *Management of Aquifer Recharge and Subsurface Storage – Making Better Use of Our Largest Reservoir.* NNC-IAH publication No. 4, Netherlands National Committee – International Association of Hydrogeologists (NNC-IAH), pp. 98.

Uhlenbrook S., Wenninger J., Lorentz S. (2005). *What happens after the catchment caught the storm? Hydrological processes at the small, semi-arid Weatherley catchment, South-Africa.* European Geosciences Union, SRef-ID: 1680-7359/adgeo/2005-2-237.

USDA Natural Resources Conservation Service (1996). *Soil quality indicators: Soil Crusts.* USDA, USA.

Van Beers (1983). *The auger hole method. Bulletin 1 (Revised Edition).* International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands.

Viaene P., Vlieghe C., Bellon J., Buysse M., de Smedt P. (1998). *Vergelijk van vier softwarepakketten voor de modellering van grondwaterstroming.* Water nr. 101.

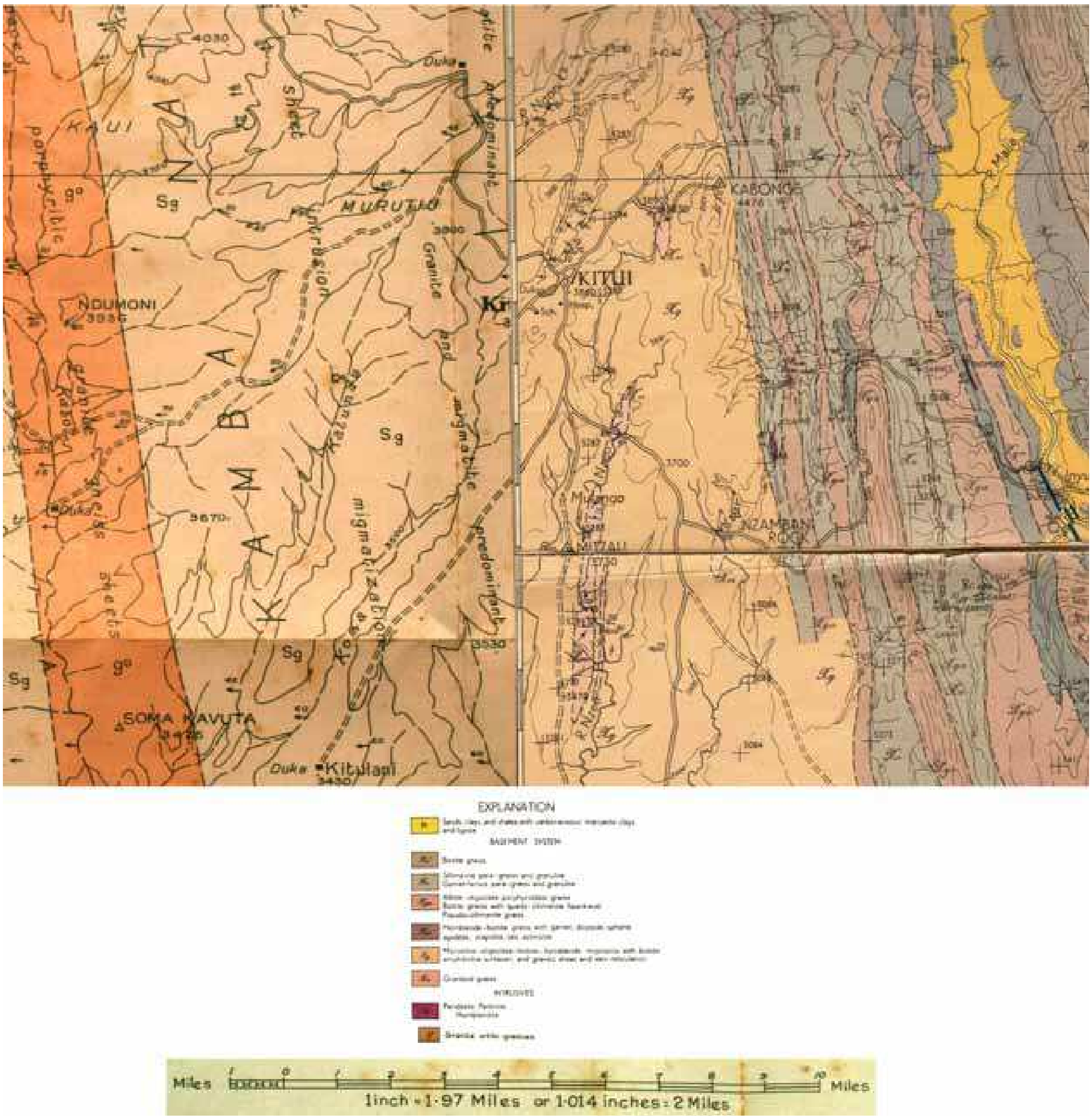
Waterloo M.J., Groen J., Groen M.A., Smit P., van Huissteden J., de Jeu R.A.M. (2005). *Field Course Netherlands (Instrumentation Techniques).* VU University, Amsterdam.

WWD: Westlands Water District (2000). *Water management handbook.* http://www.westlandswater.org/wtrcon/handbook/wmh0.htm

Wheater H.S. (unknown publication date). *Modeling Hydrological Processes in Arid and Semi Arid Areas – an Introduction to the Workshop.* Department of Civil and Environmental Engineering, London, UK.

Wheater H.S., Al Weshah R.A. (2002). *Hydrology of wadi systems*. In IHP regional network on wadi hydrology in the Arab region. UNESCO, Paris.

# Appendix 1 Geological map of the area around Kitui town




After Borst et al. (2006)

# Appendix 2 Poster presented at the EGU convention

## Water supply through sand dams (Kitui district – Kenya)
### Modelling a success story


Typical sand dam during the dry season


Typical sand dam during the wet season

**Sand dams**

One of the examples of successfully addressing water scarcity in rural areas is the construction of sand storage dams in ephemeral rivers in the Kitui district (Kenya). These dams are small concrete check dams (Figure 1 and photographs), build to a large extent by the beneficiary community. The program is funded by the Kenyan Ministry of Water and foreign agencies. To date, almost 500 dams have been constructed, supplying about 100 000 people with water during the dry season.

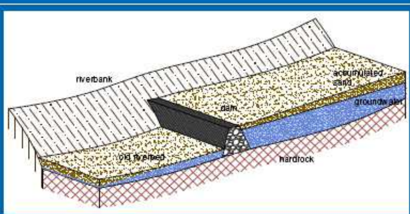


Figure 1 Schematic cross section of a typical sand dam (Borst et al, 2006)

**Relevance of the model**

A physically based numerical groundwater model (Triwaco) is set up to improve understanding of hydrological processes regarding the functioning of sand storage dams. Calibration data is gathered during 2 field campaigns (October 2005 and October 2006) in the Kiindu catchment, approximately 10 km from Kitui Town (UTM 38.02 m East, -1.367 m South, WGS 37S) and includes 1.5 years of groundwater level and precipitation measurements, among other data. The modelling effort will result in physical properties determining the successful functioning of sand dams. The outcome will increase the chance of lucratively applying this technology in other semi arid areas. Currently the Acacia Institute is, in cooperation with the Dutch RAIN Foundation and Kenyan and Ethiopian NGO's, in the process of identifying suitable catchments in southern Ethiopia to construct a cascade of several dams. This initiative is recently awarded the Swiss Re International ReSource Award for Sustainable Watershed Management.

The influence of increased river bank infiltration on groundwater recharge and availability in relation to sand dams is assessed using the same numerical model.

**Groundwater dynamics**

Groundwater levels in the river bed as well as in the river banks increase rapidly in response to precipitation. Amplitude increases and response time decreases with increasing distance from the river bed (Figure 2).

Due to dual porosity, two components can be distinguished in the groundwater recession curve; a steep initial decrease which, below a certain groundwater level, transits into a more gradual decrease. The shape of the recession curve is nevertheless constant and dependant of soil type. Sandy soils result in a steep linear decrease, whereas silty soils result in an exponential curve. In the upper aquifer, groundwater is present in a zone of maximal 20 meter along the channel at the end of the wet season. During the dry season, this zone decreases to less than 10 meter, depending on the relief. Outside this area, groundwater is present in fractures in the granite basement.

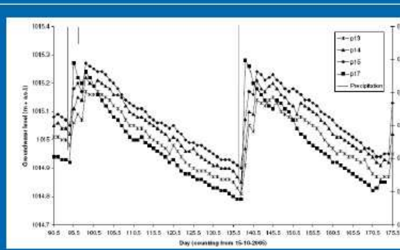


Figure 2 Detail of groundwater level fluctuations 100 m downstream of the Kwa Ndunda sand dam in four piezometers at increasing distance from the river bed

**Results and conclusions** *(preliminary)*

Model simulations have shown hydraulic conductivity and groundwater recharge strongly influencing the manner in which the groundwater table decreases. Higher groundwater recharge leads to a more gradual decrease, as does a larger hydraulic conductivity. As a consequence of interception, infiltration excess overland flow and evapo(transpi)ration, a mere 15 percent of the precipitation (avg. 1000 mm/yr) leads to groundwater recharge. Model simulations further indicate optimization of river bank infiltration leading to significantly increased groundwater recharge and therefore availability during dry seasons.

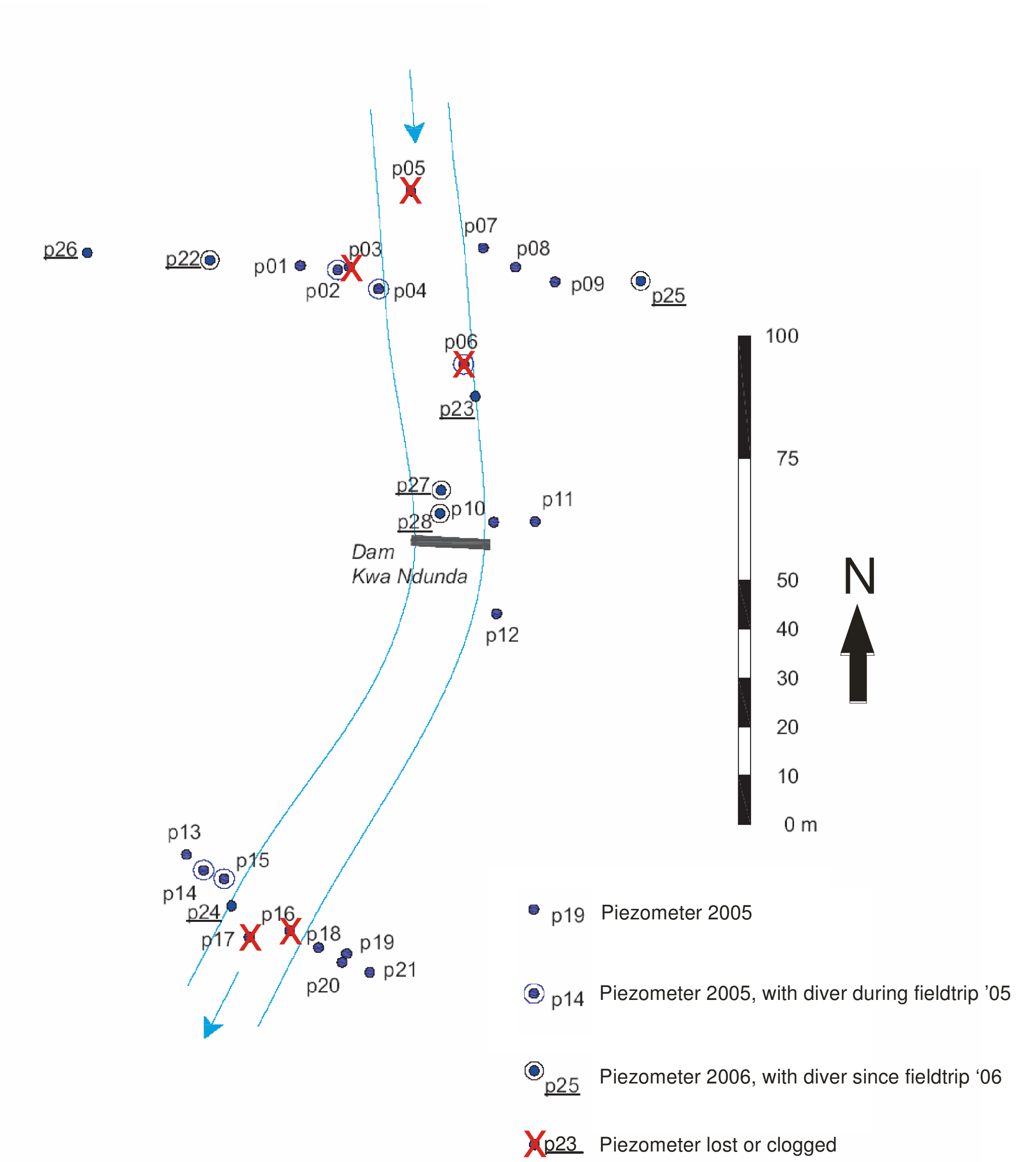
Although the sand dam prevents groundwater to flow downstream through the river bed, flow patterns indicate groundwater flow around the dam through the river banks. Currently, a water balance study is carried out to quantify the amount of water

Vrije Universiteit Amsterdam

Acacia Institute – Solutions in Groundwater
www.acaciainstitute.nl

**Contact**
Questions and comments can be directed to Merel Hoogmoed (e-mail hooe@geo.vu.nl)

# Appendix 3 Locations of piezometers around Kwa Ndunda dam



# Appendix 4 Referencing groundwater level data

Groundwater levels measured by the divers are referenced to the lowest level of the sand dam (LH2O || Ref level, Figure A.4) using Equation A4.1. Ltop of well || Ref level equals the height of the top of the piezometers with respect to the sand dam (Reference level), Lcable equals the depth of the diver with respect to the lid of the piezometer, LDiver equals the pressure measured by the diver and Lbaro equals the pressure measured by the barometric diver (Figure A4.1; Eijkelkamp, 2006).

LH2O || Ref level = Ltop of well || Ref level - Lcable + LDiver – Lbaro **Equation A4.1**

Manual measured groundwater levels are also referenced to the lowest level of the sand dam (LH2O || Ref level) using Equation A4.2, in which Ltop of well || Ref level equals the height of the top of the piezometers with respect to sand dam and LH2O || top of well equals measured groundwater level (Figure A4.1; Eijkelkamp, 2006).

LH2O || Ref level = Ltop of well || Ref level - LH2O || top of well **Equation A4.2**

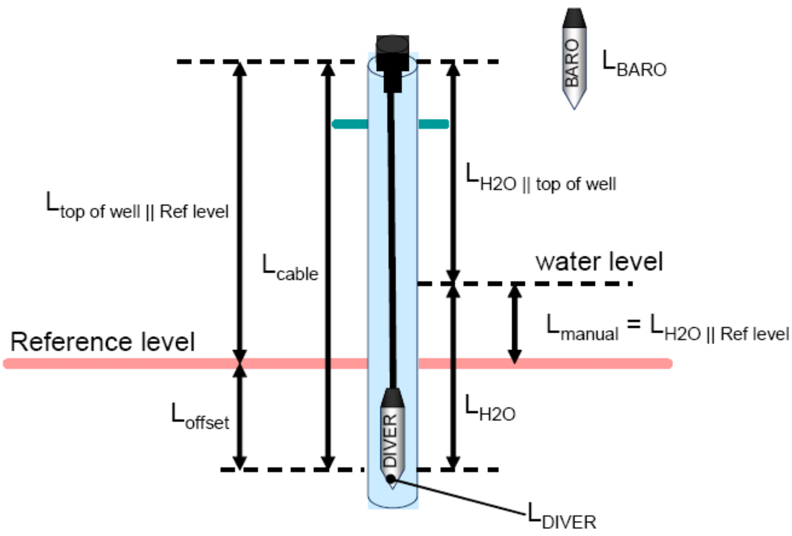



Figure A4.1 Visualisation of the compensation of the diver measurements for barometric pressure and to a reference level (after Eijkelkamp, 2006)

# Appendix 5 Characteristics of piezometers

| | UTM WGS84 37S | | Elevation top | Depth |
|---|---|---|---|---|
| Piezometer | Northing | Easting | (m + dam spillway) | (m) |
| p01 | 389165 | 9838443 | 2.428 | 0.90 |
| p02 | 389096 | 9838442 | 1.291 | 1.80 |
| p03 | 389175 | 9838443 | 1.088 | 1.87 |
| p04 | 389180 | 9838438 | 0.548 | 1.54 |
| p05 | 389187 | 9838458 | 0.341 | 1.68 |
| p06 | 389197 | 9838422 | -0.103 | 1.82 |
| p07 | 389201 | 9838446 | 0.860 | 1.50 |
| p08 | 389207 | 9838442 | 1.360 | 1.35 |
| p09 | 389215 | 9838439 | 2.011 | 4.85 |
| p10 | 389202 | 9838390 | 0.424 | #N/A |
| p11 | 389211 | 9838390 | 0.178 | #N/A |
| p12 | 389203 | 9838371 | 0.095 | #N/A |
| p13 | 389139 | 9838319 | 0.127 | 3.30 |
| p14 | 389142 | 9838316 | 0.118 | 3.82 |
| p15 | 389146 | 9838315 | -0.303 | 3.04 |
| p16 | 389160 | 9838306 | -2.075 | 0.56 |
| p17 | 389152 | 9838304 | -2.075 | 0.87 |
| p18 | 389166 | 9838303 | -0.678 | 1.69 |
| p19 | 389172 | 9838302 | -0.561 | 1.03 |
| p20 | 389171 | 9838300 | -0.561 | 1.26 |
| p21 | 389177 | 9838298 | -0.067 | 2.33 |
| p22 | 389200 | 9838442 | 3.168 | 3.50 |
| p23 | 389148.1 | 9838306 | -0.147 | 1.40 |
| p24 | 389197 | 9838423 | -2.327 | 1.70 |
| p25 | 389227 | 9838441 | 3.505 | 5.40 |
| p26 | 389123.6 | 9838440 | 5.804 | 0.90 |
| p27 | 389197 | 9838412 | -0.073 | 1.55 |
| p28 | 389197 | 9838412 | -0.073 | 0.20 |

# Appendix 6 Sensitivity analysis

To the aim of the sensitivity analysis, several simulations are performed with parameter values based on field values using multiplication factors of 0.5, 0.8, 0.9, 1.1, 1.2 and 1.5.

## Hydraulic conductivity of the sediment layer (aquifer 1)

Figure A6.1 shows the result of varying hydraulic conductivity of the sediment layer (e.g. aquifer 1) on model results. Variation using a multiplication factor of 0.8 and 1.2 seems to have little effect on model results, although amplitude of peaks in the riverbanks and gradient of recession curves everywhere increase with lower hydraulic conductivity. Furthermore, results of increasing $K_{sat}$ with 20 percent to an instability of the model during the dry period between 03-05-2006 and 15-10-2006. Another observed change is the higher level at which the model reaches a stable situation during the dry season resulting from a smaller hydraulic conductivity. Multiplication with 0.5 leads to a significantly more pronounced reaction of groundwater levels on precipitation in the riverbanks and a more gradual decrease of heads in the riverbed and -banks.

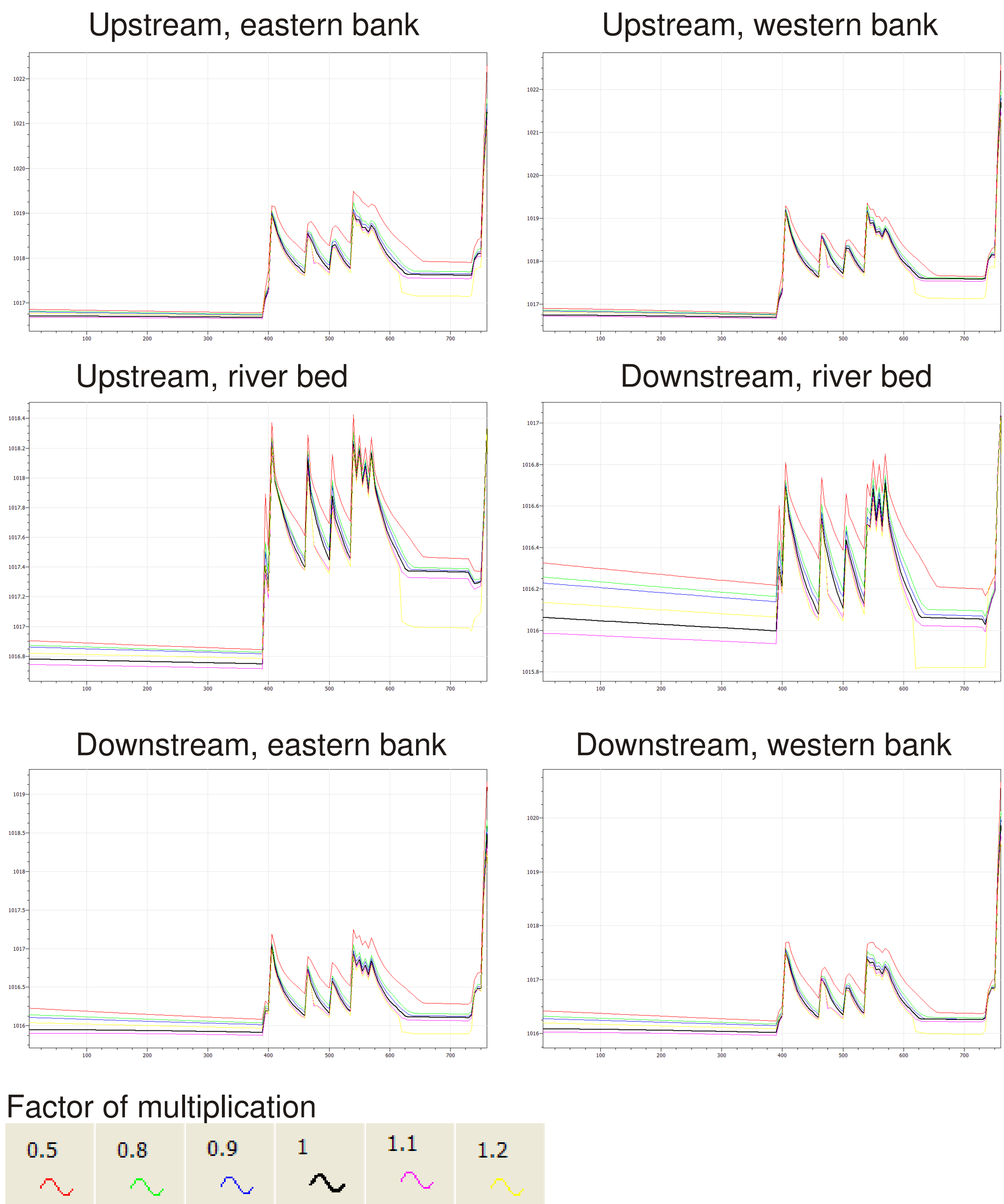



Figure A6.1 Influence of variation in the hydraulic conductivity of the sediment layer on the simulated groundwater levels at different locations around the Kwa Ndunda sand dam

## Hydraulic conductivity of the weathered rock layer (aquifer 2)

Figure A6.2 shows the effect of varying the hydraulic conductivity of the weathered rock layer (e.g. aquifer 2) on calculated groundwater levels. An increase of the hydraulic conductivity leads to a decrease of the gradient of the drawdown curves. Also, the response of groundwater levels to precipitation is less pronounced in the riverbanks. Timing and levels of raised heads are not influenced by varying $K_{sat}$ of aquifer 2. Increasing the hydraulic conductivity with 50 percent causes model instabilities, especially in the riverbed upstream of the sand dam during the dry period between 03-05-2006 and 15-10-2006. However, multiplication with 0.5 leads to a somewhat more pronounced reaction of groundwater levels on precipitation in the riverbanks and a slightly more gradual decrease of heads during the dry season in the riverbed and -banks.

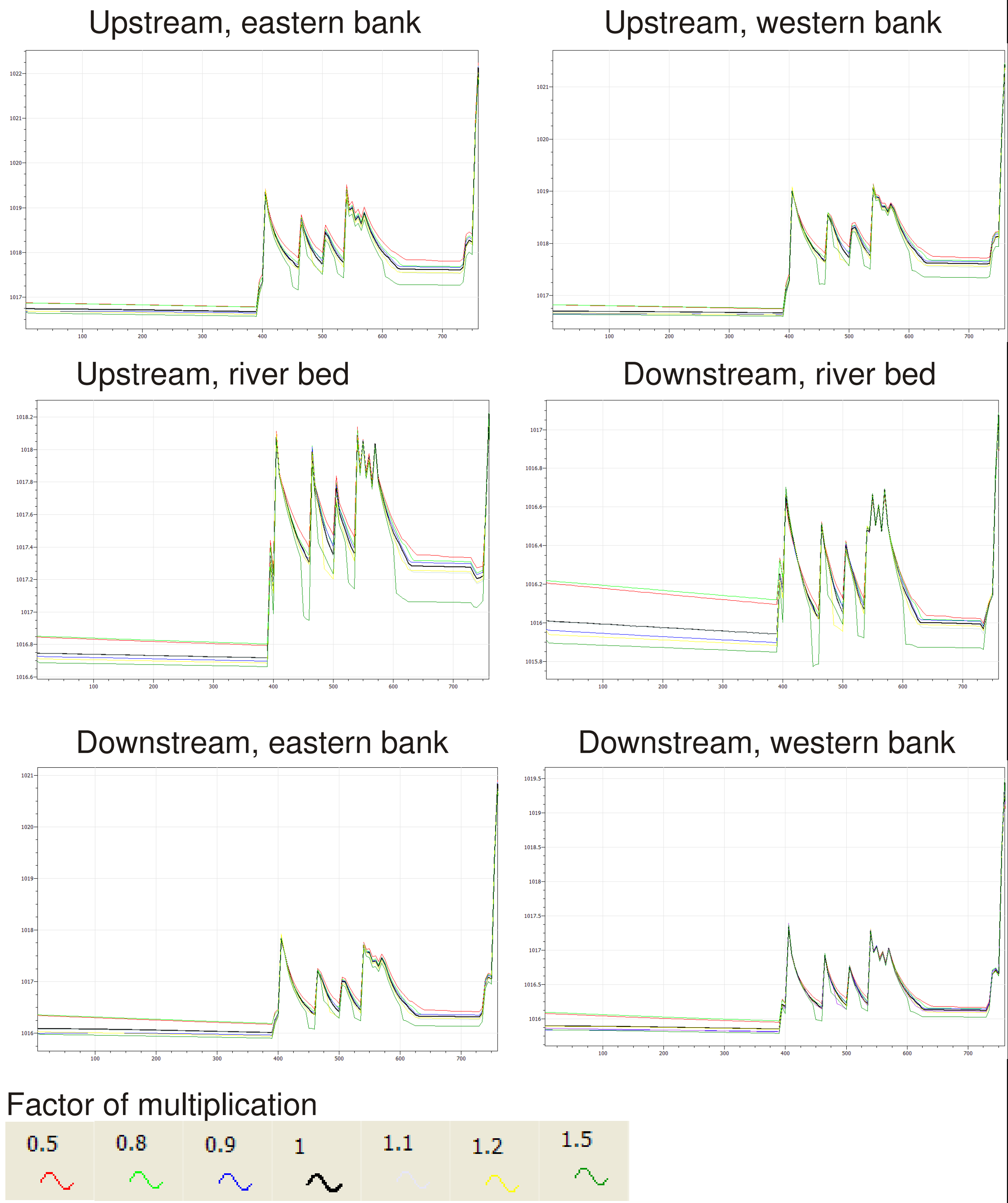



Figure A6.2 Influence of variation in the hydraulic conductivity of the weathered rock layer on the simulated groundwater levels at different locations around the Kwa Ndunda sand dam

### Thickness of the sediment layer on the riverbanks (aquifer 1)

Figure A6.3 shows the effect of changing the thickness of the sediment layer on groundwater levels as calculated by the model. Variation between 0.8 and 1.2 seems to have little effect on model results although amplitudes of peaks in the riverbanks and the gradient of recession curves everywhere increase with decreasing thickness. Instabilities are experienced when running the model with an increase of more than 20 percent, especially in the riverbed during the dry period between 03-05-2006 and 15-10-2006. Multiplication of the thickness of the sediment layer with 0.5 leads to a significantly more pronounced reaction of groundwater levels on precipitation in the riverbanks and a smaller gradient of the recession curves in the riverbed and banks.

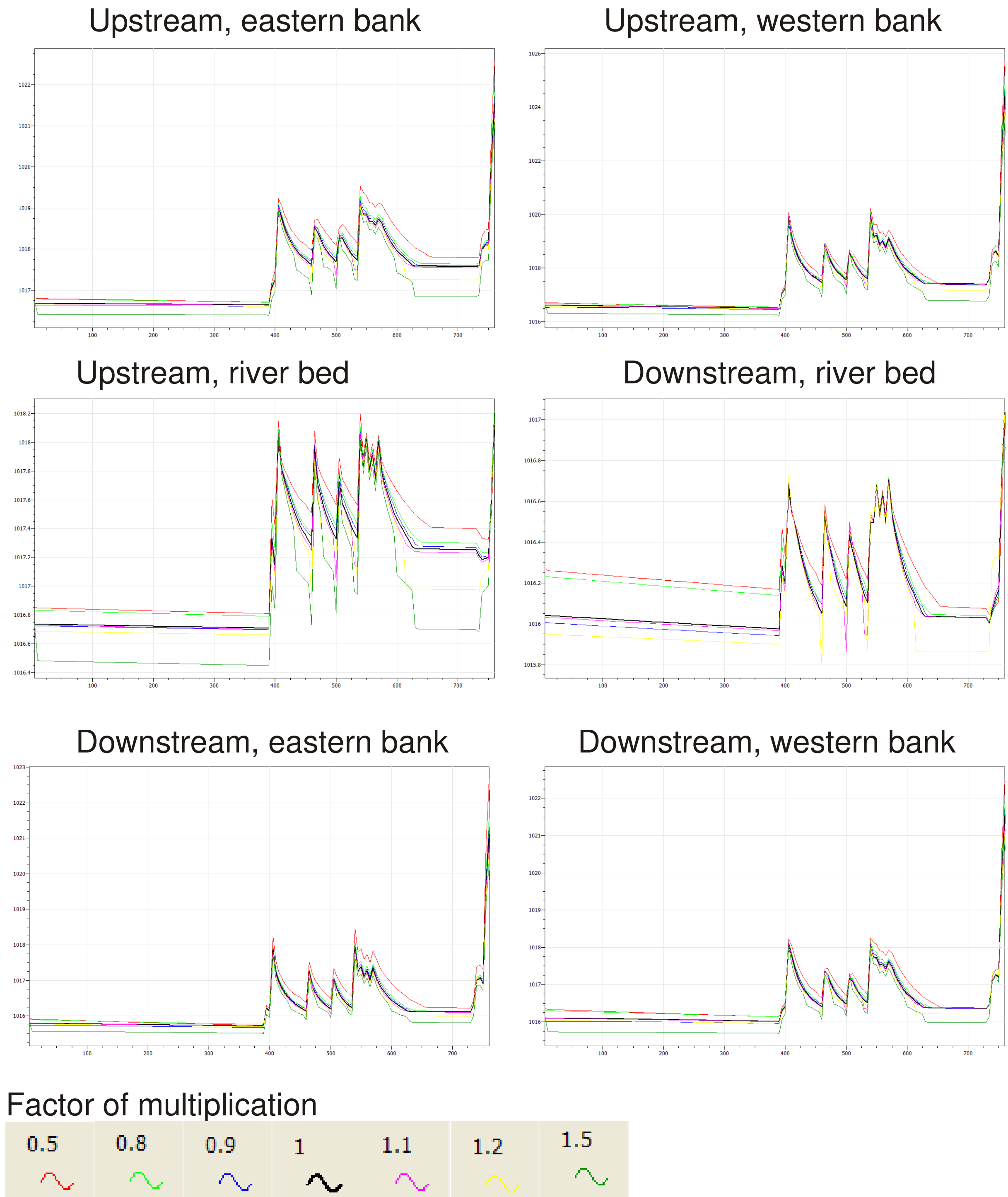



Figure A6.3 Influence of variation in the thickness of the sediment layer on the simulated groundwater levels at different locations around the Kwa Ndunda sand dam

### Thickness of the weathered rock layer on the riverbanks (aquifer 2)

Figure A6.4 shows the effect of varying the thickness of the weathered rock layer on groundwater levels computed by the model. Variation between 0.8 and 1.2 seems to have little effect on model results although amplitudes of peaks in the eastern riverbanks and gradients of recession curves everywhere increase with decreasing thickness. Instabilities are experienced when running the model with a 20 and 50 percent increase, especially in the riverbed during the dry period between 03-05-2006 and 15-10-2006. However, multiplication of the thickness with 0.5 leads to a somewhat more pronounced reaction of groundwater levels on precipitation in the riverbanks and a more gradual decrease of heads during the dry season in the riverbed and banks.

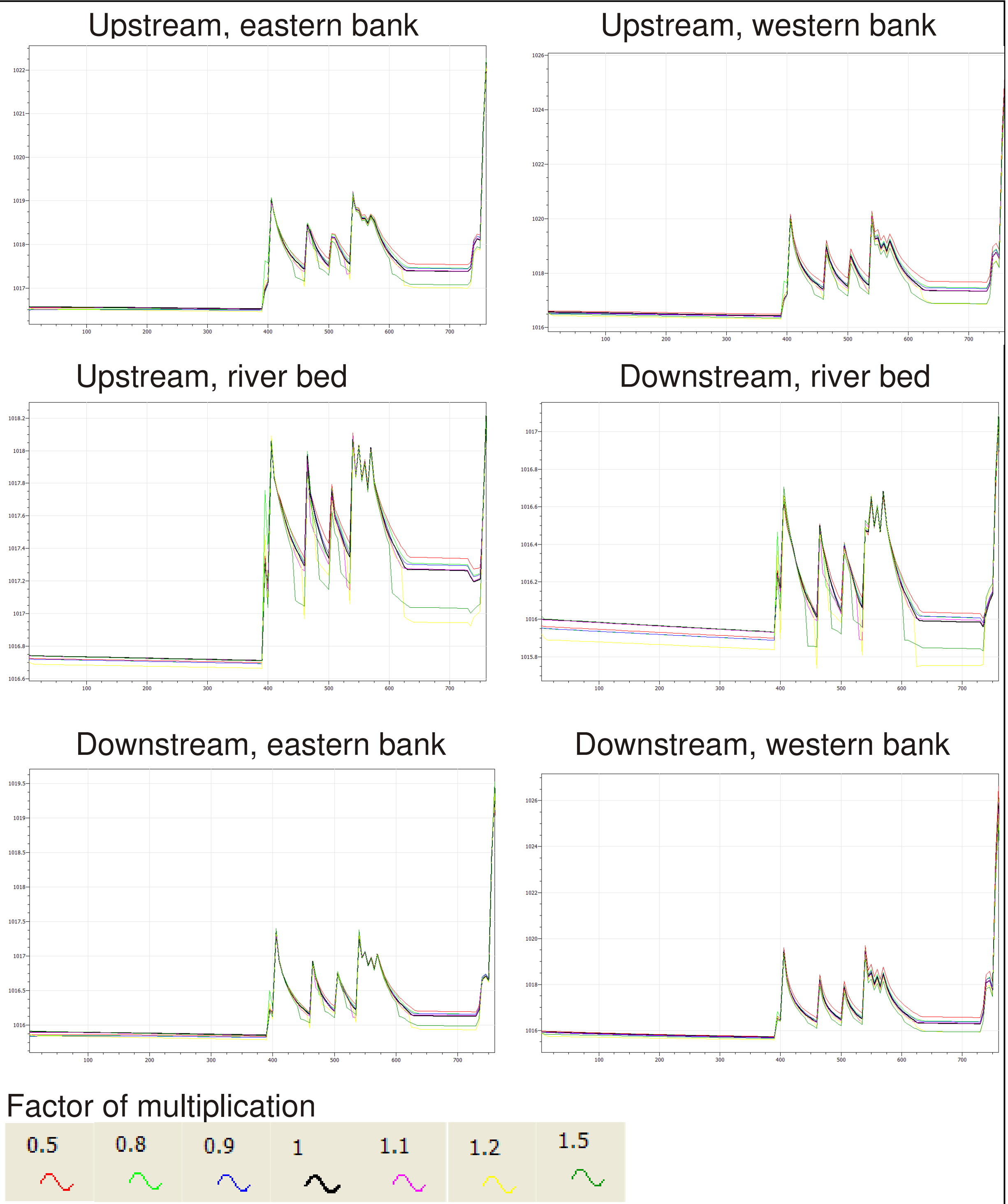



Figure A6.4 Influence of variation in the thickness of the weathered rock layer on the simulated groundwater levels at different locations around the Kwa Ndunda sand dam

### Thickness of the sand layer in the riverbed (aquifer 1)

Figure A6.5 shows the effect of changing the thickness of the sand layer in the riverbed on groundwater levels computed by the model. The effect on computed heads is largest in the riverbed. Decreasing the thickness leads to lower simulated groundwater levels, especially using a multiplication factor of 0.5, results in a slight decrease of the gradient of the drawdown curve. Increasing the thickness of the sand layer in the riverbed has a relative small effect on simulated groundwater levels compared to the same decrease of thickness.

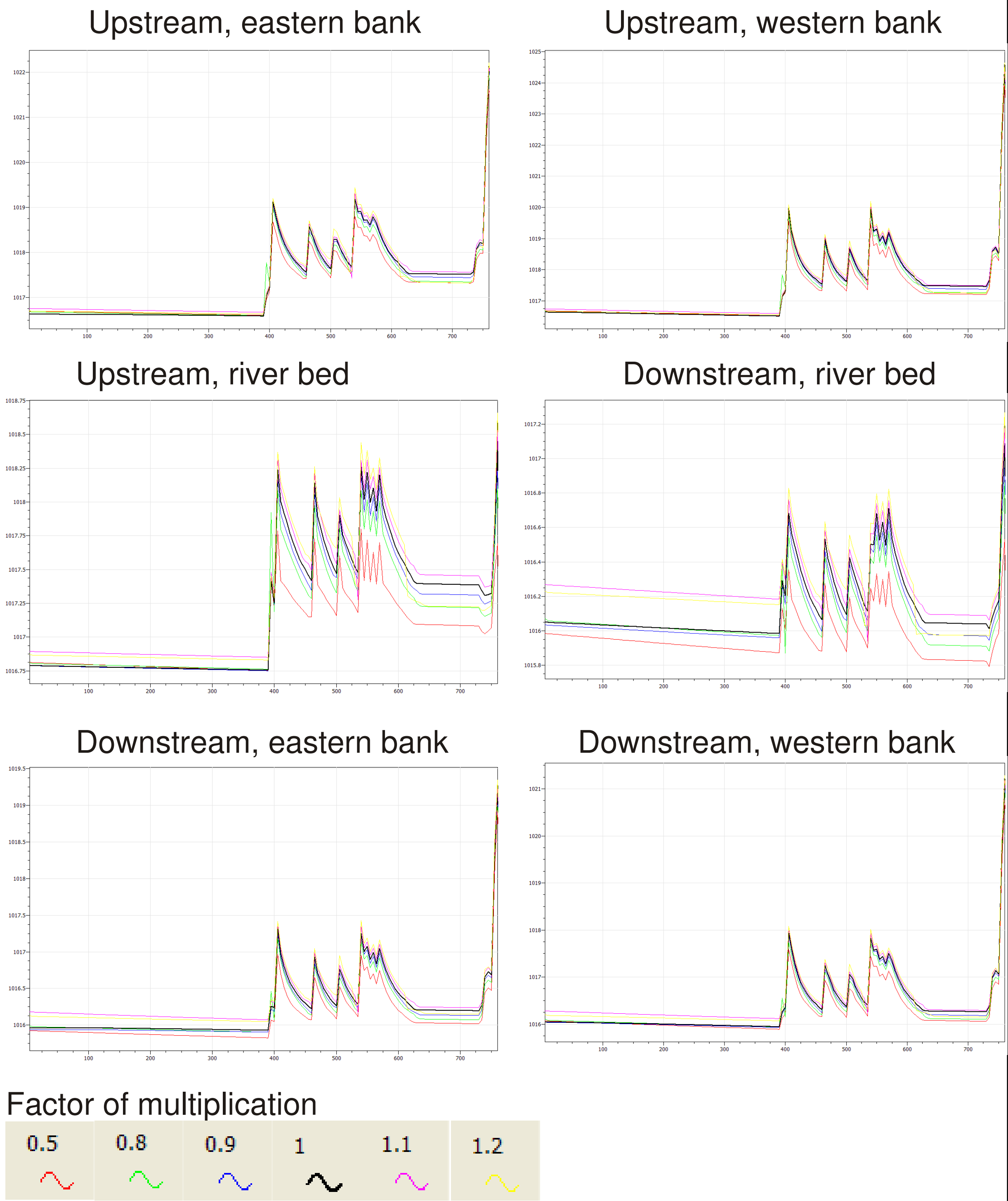



Figure A6.5 Influence of variation in the thickness of the sand layer in the riverbed on simulated groundwater levels at different locations around the Kwa Ndunda sand dam

## Groundwater recharge

The effect of groundwater recharge on computed heads is shown in Figure A6.6. Groundwater recharge influences peaks of heads in riverbanks as well as the gradient of the drawdown curves; larger groundwater recharge leads to a smaller gradient. The model becomes instable when groundwater recharge is reduced with 50 percent.

Decreasing the groundwater recharge with 20 percent leads to lower groundwater levels during the dry season in the riverbanks as well as the –bed.

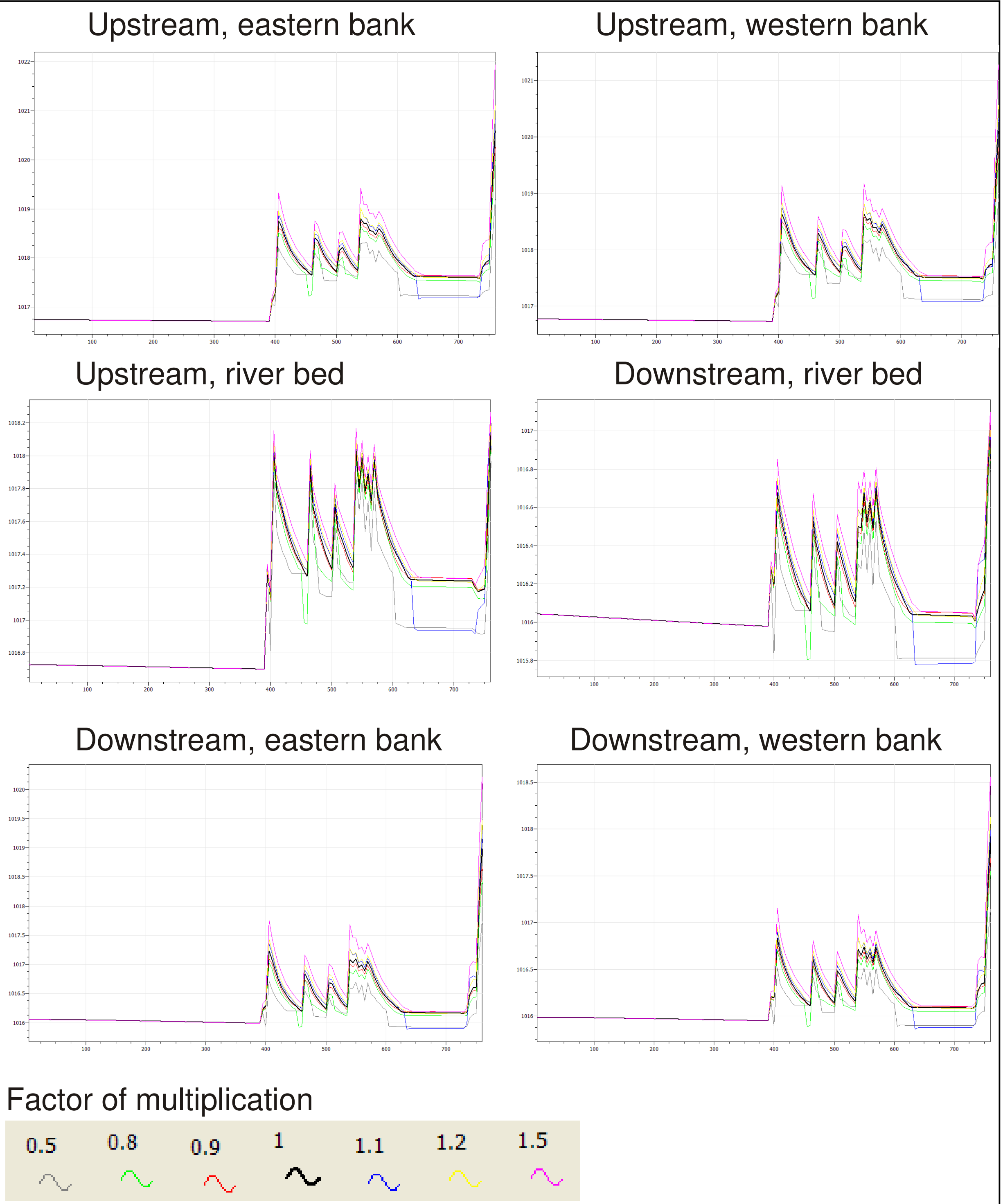



Figure A6.6 Influence of variation in the recharge rate of the groundwater on the simulated groundwater levels at different locations around the Kwa Ndunda sand dam

## Flood depth

Figure A6.7 shows the effect of thickness of flood depth on model results. Increasing the depth seems to have little effect, as does decreasing flood depth with maximal 20 percent. However, decreasing flood depth with 50 percent influences groundwater simulation in area upstream of the sand dam; peak elevation decrease as well the gradient of the recession curve. The effect is largest in the riverbed.

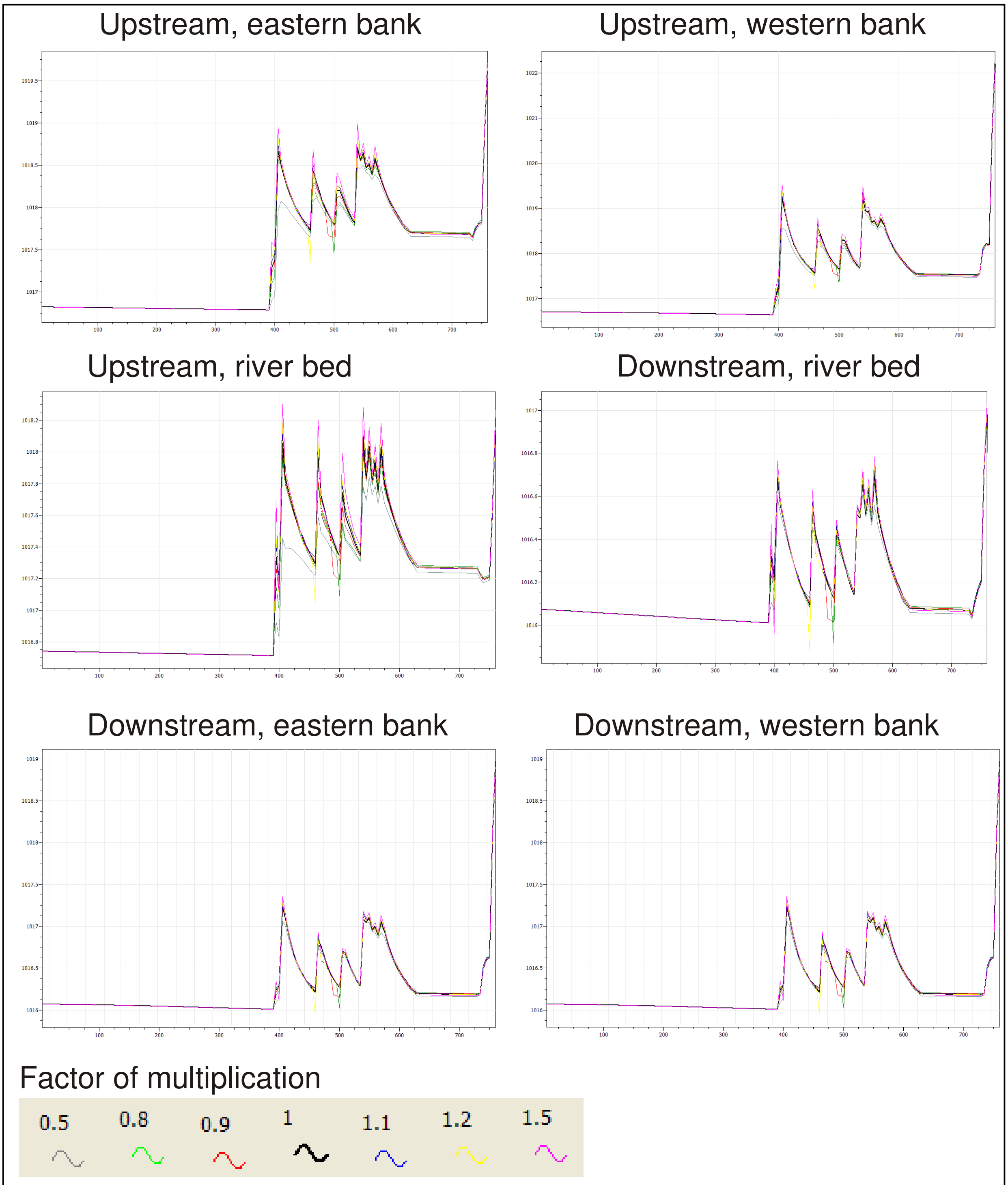



Figure A6.7 Influence of variation in the flood depth in the riverbed on the simulated groundwater levels at different locations around the Kwa Ndunda sand dam

# Appendix 7 Reliability analysis

To the aim of the reliability analysis, several simulations are performed with parameter values based on calibrated values using multiplication factors of 0.5, 0.8, 0.9, 1.1, 1.2 and 1.5.

## Hydraulic conductivity of the sediment layer (aquifer 1)

According to Figure A7.2, the influence of varying hydraulic conductivity between 20 percent of the calibrated values has little effect on groundwater levels in the riverbanks; changes in head are less than 10 centimeter. Heads in the riverbed seem to be more sensitive to variations in hydraulic conductivity. However, varying $K_{sat}$ with 50 percent leads to an evident increase in heads at all locations. The riverbed shows a maximum increase in head of 0.70 meter upstream and 0.30 meter downstream of the sand dam. Groundwater levels in the riverbanks increase also; 30 centimeter on average downstream of the riverbed and 0.15 meter upstream of the sand dam.

Figure A7.1 shows the effect of variation in hydraulic conductivity on the volume of groundwater storage ($m^3$) in the riverbed, which is quantified in Table A7.1. For all model runs, the effect (both positive and negative) is largest in Polygon 1. The effect of a certain change in hydraulic conductivity increases as the dry season proceeds. The maximum difference is experienced with a run in which the hydraulic conductivity is half the value it is in the calibrated model, i.e. 197.2 $m^3$, which is relatively large compared to storage increased due to reducing the conductivity with 10 or 20 percent. Increasing $K_{sat}$ with 20 percent leads to instabilities in calculating storage in Polygon 1 during the prolonged dry season. Figure A7.1 shows the same outcome; the instability is largest in the riverbed. An increase of 10 percent of the hydraulic conductivity leads to a decrease in volume of 52.4 $m^3$ on average and approximately 100 $m^3$ during the dry season.

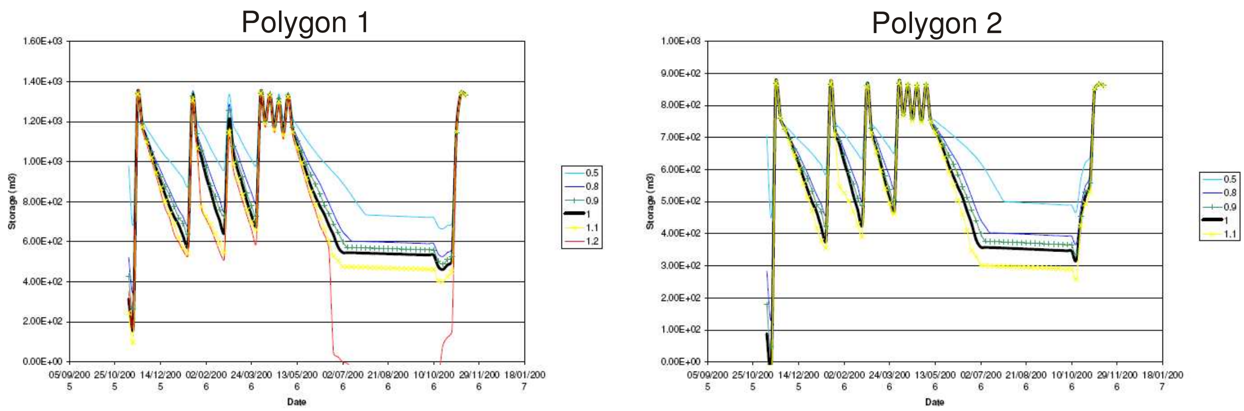



Figure A7.1 Influence of variation in hydraulic conductivity of aquifer 1 on calculated groundwater storage in the riverbed (m3)

| Factor | Diff. in polygon 1 | Diff. in polygon 2 |
|---|---|---|
| 0.5 | 197.2 | 118.2 |
| 0.8 | 68.2 | 42.0 |
| 0.9 | 35.2 | 20.4 |
| 1.1 | -52.4 | -34.5 |

Table A7.1 Average volume difference (m3/timestep) compared to the groundwater storage in the riverbed calculated by the calibrated model as an effect of variation in hydraulic conductivity of aquifer 1

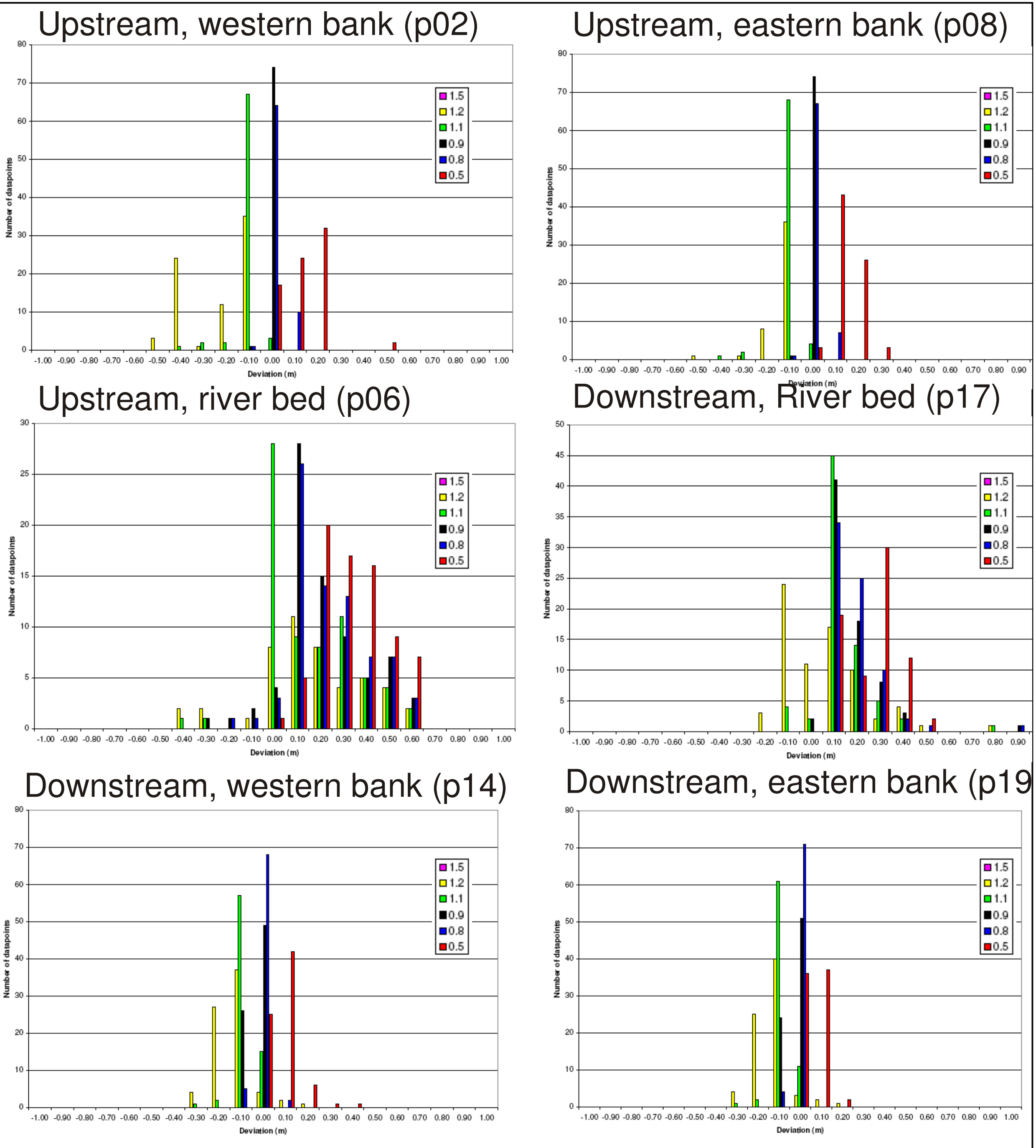



Figure A7.2 Quantification of the effect of varying the hydraulic conductivity of the sediment layer on the simulated groundwater levels at different locations around the Kwa Ndunda sand dam

## Hydraulic conductivity of the weathered rock layer (aquifer 2)

Figure A7.4 quantifies the effect of varying the hydraulic conductivity of the weathered rock layer. Deviations from the calibrated model are mainly within 10 centimeter in the riverbanks. Concluding from the relatively scattered deviation observed in the riverbed both up- and downstream of the sand dam, the riverbed seems a bit more sensitive to variation of this parameter. Decreasing the hydraulic conductivity with 50 percent leads to an elevation of water levels of 30 centimeter on average in the riverbed upstream of the sand dam. The riverbanks show variations of less than 10 centimeter except for piezometer p02 deviating 0.22 meter on average.

Figure A7.3 visualizes the effect of variation in hydraulic conductivity of aquifer 2 on groundwater storage in the riverbed. Table A7.2 quantifies the change in volume of water stored in the riverbed. Groundwater storage in Polygons 1 and 2 are influenced within the same range, which is largest during the dry season. Augmenting the hydraulic conductivity with 50 percent results in an increase in groundwater storage of 73.1 $m^3$ in Polygon 1, while storage in Polygon 2 increases with almost 69 $m^3$. Increasing $K_{sat}$ with 20 percent leads to a decrease in storage of 37.2 $m^3$ in polygon 1. The effect of applying a multiplication factor of 1.5 is not taken into account because of instabilities. The effect on groundwater storage increases as the dry season proceeds.

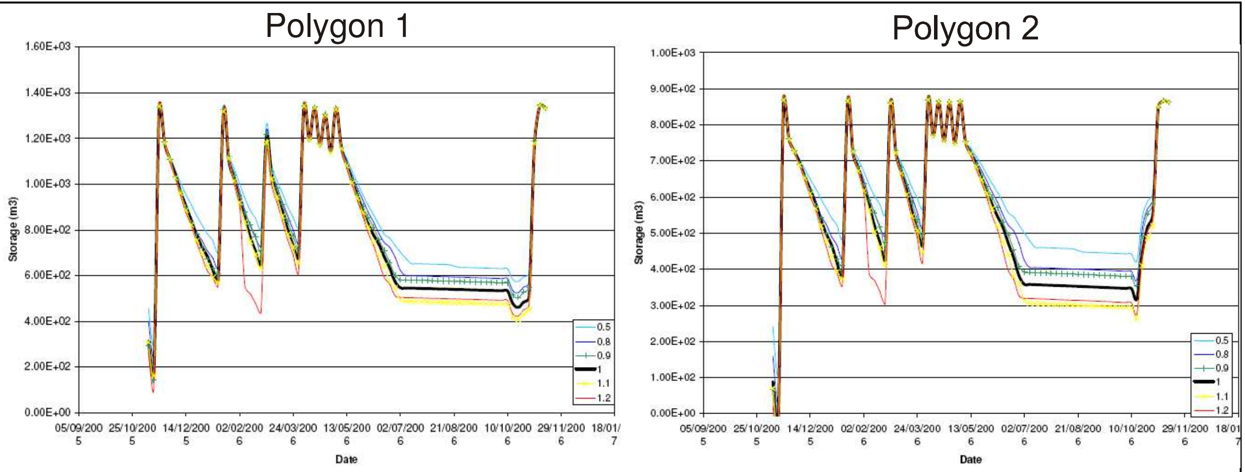



Figure A7.3 Influence of variation in hydraulic conductivity of aquifer 2 on groundwater storage in the riverbed ($m^3$)

| Factor | Diff. in polygon 1 | Diff. in polygon 2 |
|---|---|---|
| 0.5 | 73.1 | 67.8 |
| 0.8 | 39.1 | 33.0 |
| 0.9 | 24.6 | 20.0 |
| 1.1 | -30.5 | -25.9 |
| 1.2 | -37.2 | -33.7 |

Table A7.2 Average volume difference (m3/timestep) compared to the groundwater storage in the riverbed calculated by the calibrated model as an effect of variation in hydraulic conductivity of aquifer 2

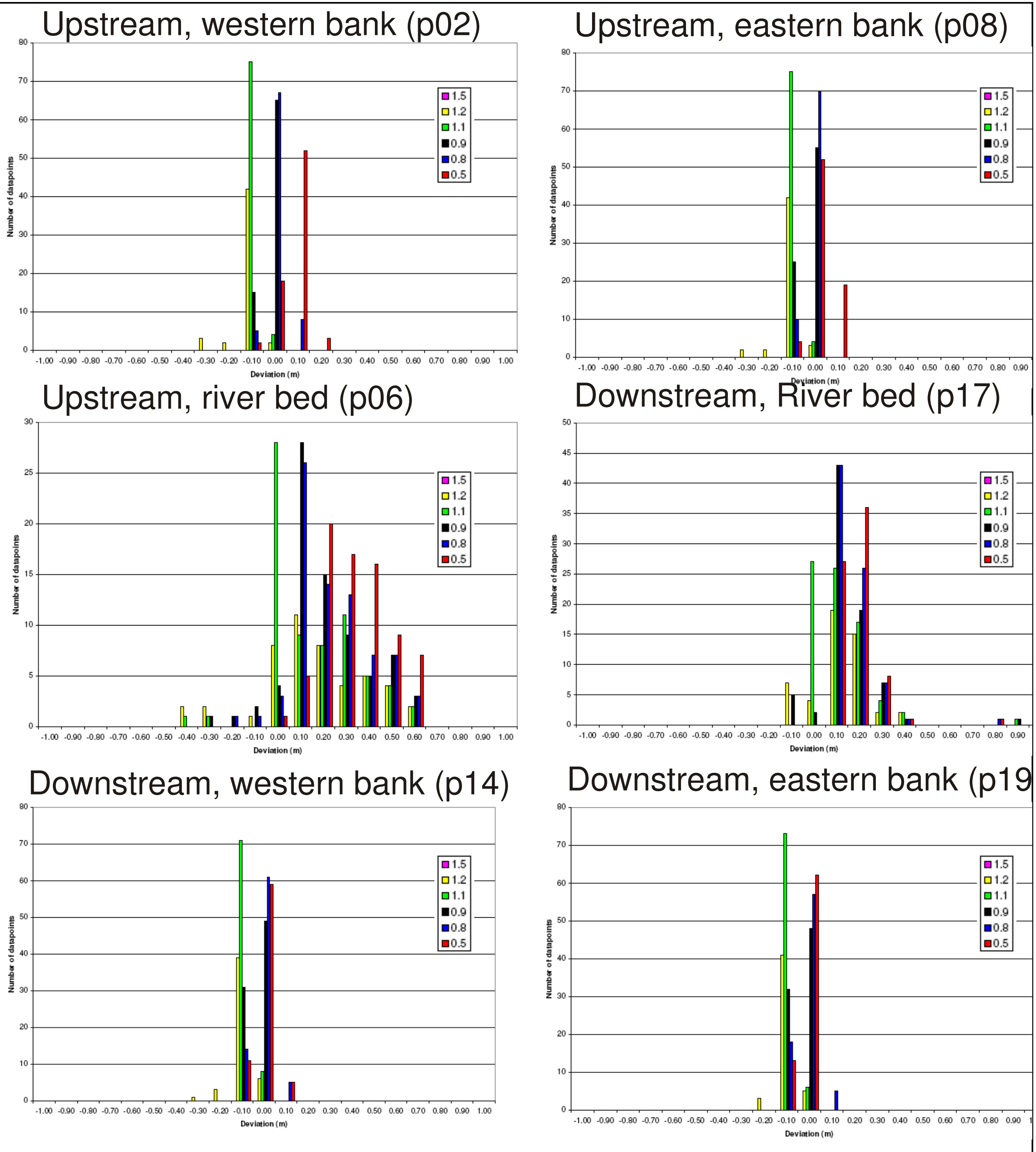



Figure A7.4 Quantification of the effect of varying the hydraulic conductivity of the weathered rock layer on the simulated groundwater levels at different locations around the Kwa Ndunda sand dam

### Thickness of the sediment layer on the riverbanks (aquifer 1)

Figure A7.6 quantifies the effect of varying the thickness of the sediment layer on groundwater levels around the sand dam. Variation between 20 percent from the calibrated value leads to differences in groundwater levels of less than 10 centimeter in the riverbanks. However, the riverbed seems more sensitive to variations and shows an average deviation of 28 centimeter due to 20 percent variation in the upstream riverbed versus 15 centimeter downstream. Varying the thickness of the layer with 50 percent leads to a more pronounced effect on computed groundwater levels in the riverbanks showing an increase of 15 centimeter on average. Heads in riverbanks rise up to 67 centimeter and averagely with 38 centimeter.

Figure A7.5 visualizes the effect of variation in thickness of the sediment layer on riverbanks on the volume of groundwater storage ($m^3$) in the riverbed, which is quantified in Table A7.3. For all model runs, the effect (both positive and negative) is approximately twice as large in Polygon 1 compared to Polygon 2. Differences in groundwater storage increase as the dry season proceeds, and level out at the start of the wet season. The maximum volume difference is experienced in Polygon 1 when decreasing the thickness of the sediment layer with 50 percent, namely 197.2 $m^3$ on an average volume of approximately 550 $m^3$. The difference is proportionally large compared to reducing layer thickness with 10 or 20 percent. Increasing layer thickness results in a decrease in groundwater storage within the same magnitude as a decrease with the same amount; approximately 30 $m^3$ resulting from a change of 10 percent.

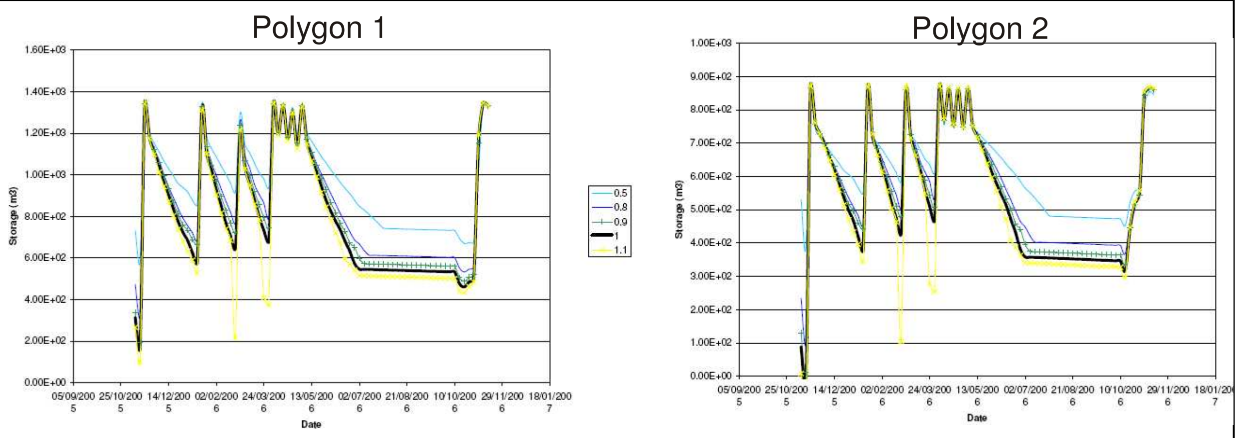



Figure A7.5 Influence of variation in thickness of aquifer 1 on calculated groundwater storage in the riverbed (m3)

| Factor | Diff. in polygon 1 | Diff. in polygon 2 |
|---|---|---|
| 0.5 | 185.1 | 92.8 |
| 0.8 | 69.6 | 36.7 |
| 0.9 | 35.6 | 17.7 |
| 1.1 | -28.1 | -15.1 |
| 1.2 | -55.5 | -38.2 |

Table A7.3 Average volume differences (m3/timestep) with the groundwater storage in the riverbed calculated by the calibrated model as an effect of variation in thickness of aquifer 1

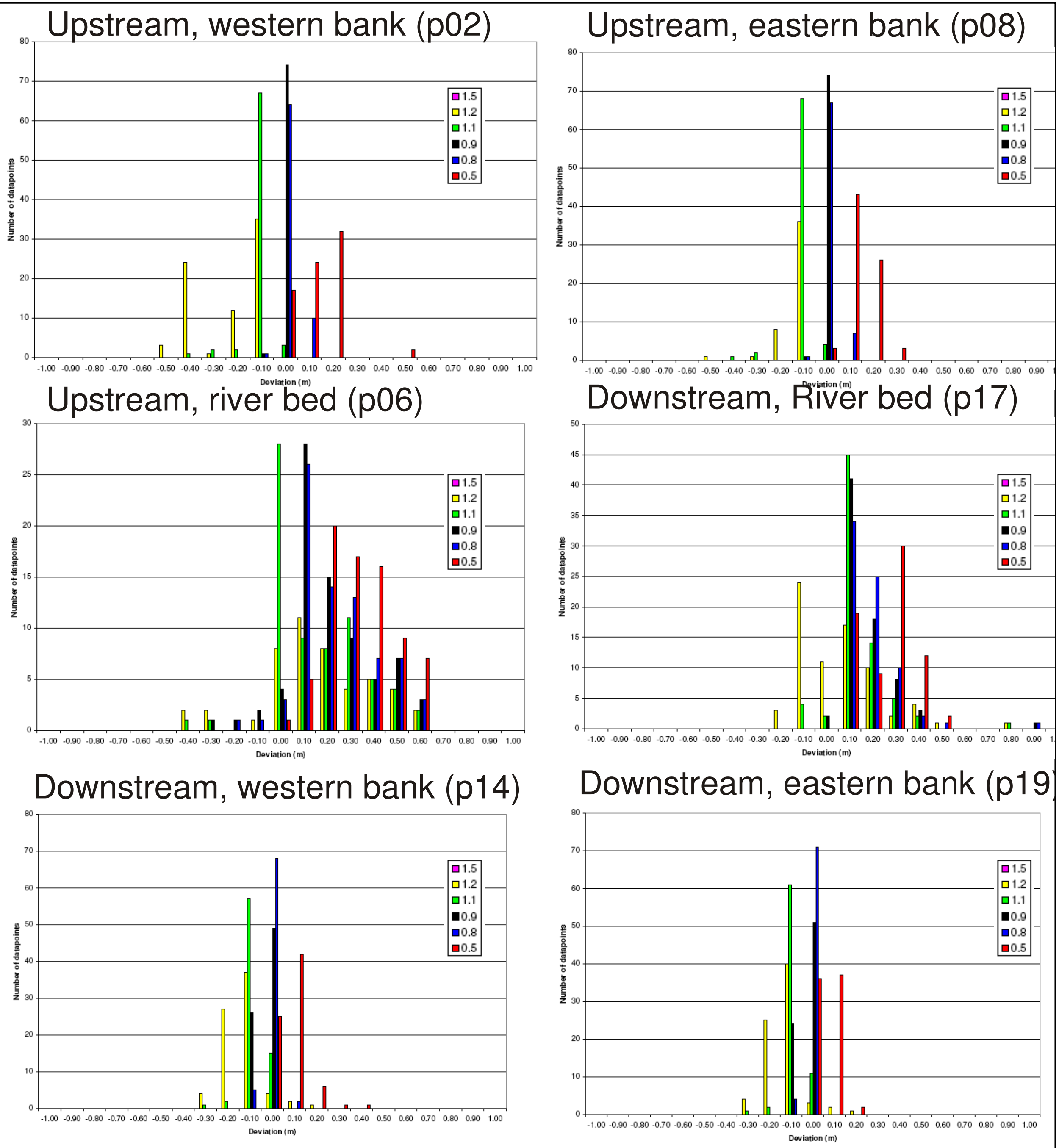



Figure A7.6 Quantification of the effect of varying the thickness of the sediment layer on the simulated groundwater levels at different locations around the Kwa Ndunda sand dam

## Thickness of the weathered rock layer on the riverbanks (aquifer 2)

Figure A7.8 quantifies the effect of varying thickness of the weathered rock layer on groundwater levels around the sand dam. Variation between 20 percent from the calibrated value leads to differences of approximately 5 centimeter in the riverbanks. However, the riverbed seems more sensitive to these variations and shows an average deviation of 23 centimeter due to a 20 percent variation. Varying the thickness of the layer with 50 percent leads to a slightly more pronounced effect on computed groundwater levels in the riverbanks showing an increase of 9 centimeter on average. Heads in the riverbanks rise up to 60 centimeter and averagely with about 0.25 meter.

The effect of differences in thickness of the weathered rock layer on the volume of groundwater storage ($m^3$) in the riverbed is shown in Figure A7.7 and quantified in Table A7.4. For all model runs, the effect (both positive and negative) in Polygon 1 is the same order of magnitude as Polygon 2. Differences in groundwater storage increase as the dry season proceeds, and level out at the start of the wet season. Decreasing the thickness of the weathered rock layer with 50 percent leads to an increase in volume of water stored in the riverbed of 86 $m^3$. Increasing the thickness seems to have a relatively small effect on groundwater storage compared a decrease in thickness with the same order of magnitude; a ten percent change leads to a change in storage of respectively -1.8 $m^3$ and 28.8 $m^3$.

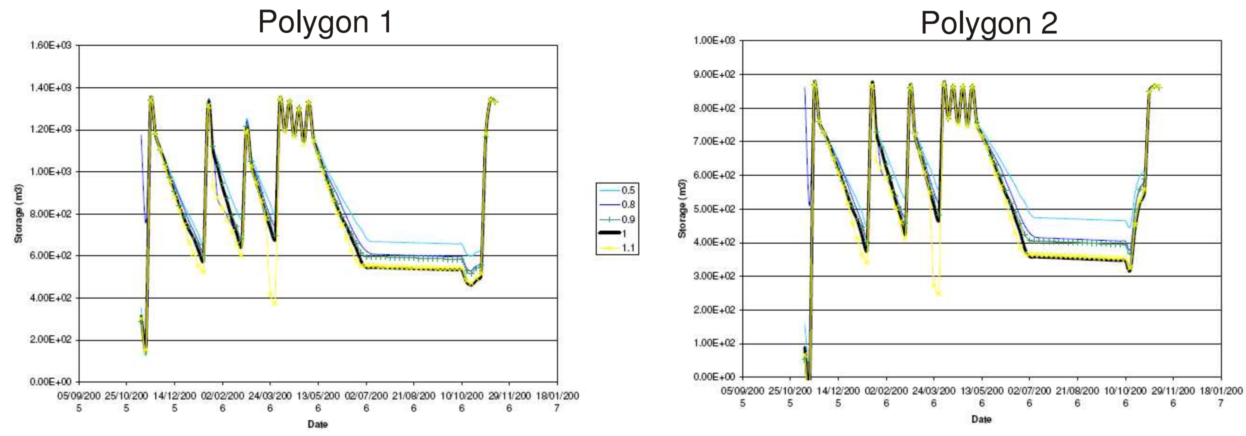



Figure A7.7 Influence of variation in thickness of aquifer 2 on calculated groundwater storage in the riverbed (m3)

| Factor | Diff. in polygon 1 | Diff in polygon 2 |
|---|---|---|
| 0.5 | 86.0 | 73.5 |
| 0.8 | 40.0 | 35.3 |
| 0.9 | 28.8 | 25.6 |
| 1.1 | -1.8 | -2.9 |

Table A7.4 Average volume differences (m3/timestep) compared to the groundwater storage in the riverbed calculated by the calibrated model as an effect of variation in thickness of aquifer 2

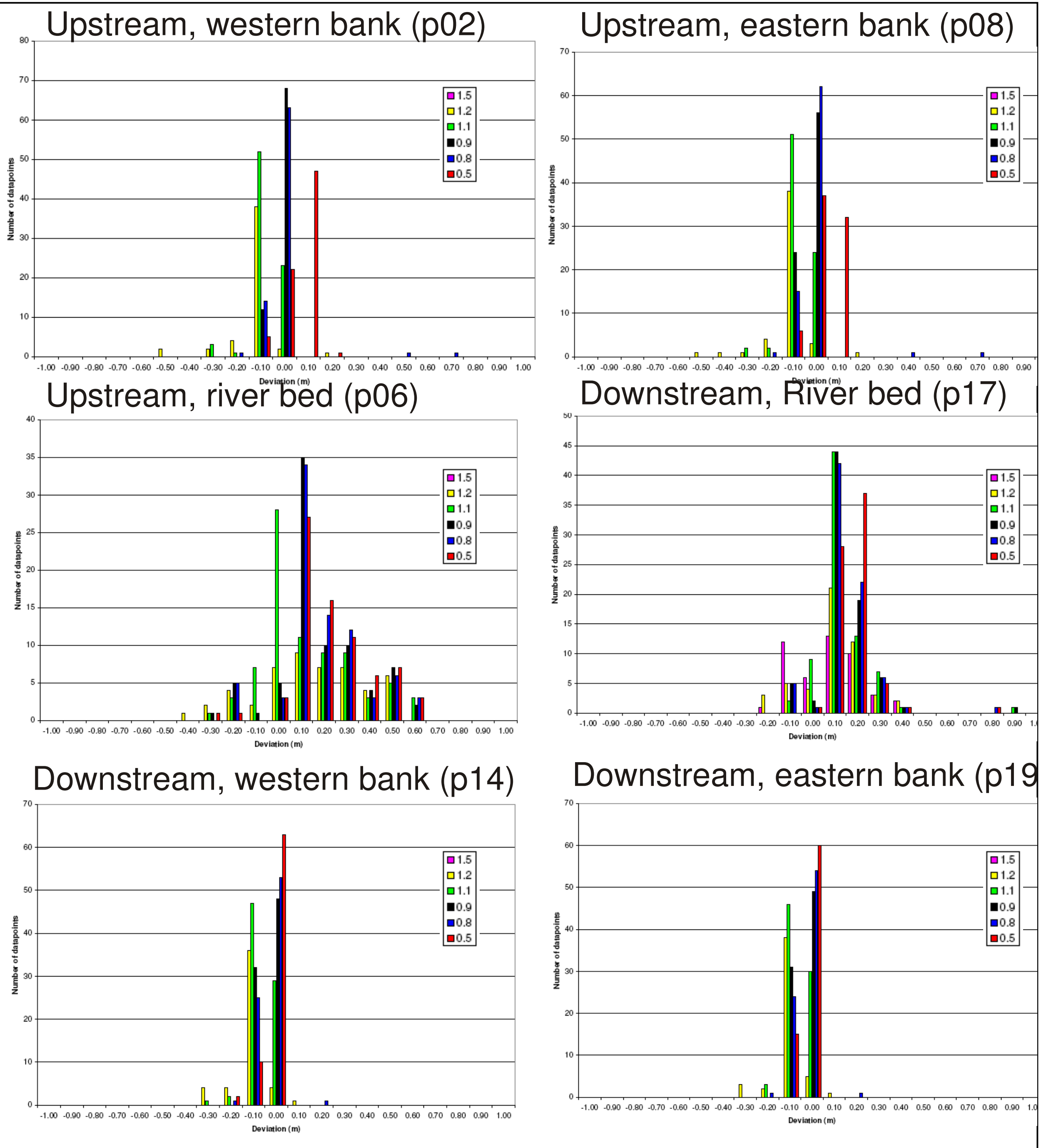



Figure A7.8 Quantification of the effect of varying the thickness of the weathered rock layer on the simulated groundwater levels at different locations around the Kwa Ndunda sand dam

## Thickness of the sand layer in the riverbed (aquifer 1)

Figure A7.10 quantifies the effect of varying the thickness sand layer in the riverbed on groundwater levels around the sand dam. Changes in riverbed thickness influence the head in the riverbanks linearly. An increase in thickness of 10 percent leads to an elevation of the groundwater level of 6 centimeter on average at all locations in the riverbanks, a decrease with the same percentage leads to a lowering of heads with 6 centimeter. A 20 percent increase leads to an increase of 12 centimeter, a decrease of 20 percent results in a drop in computed heads of 12 centimeter. Decreasing the thickness with 50 percent leads to a drop of 0.28 meter in downstream riverbanks, while upstream banks experience a decrease of 40 centimeter. Increasing the thickness with 50 percent leads to an increase of 0.3 meter at the same location.

The riverbed shows a different reaction. The effect of increasing the thickness of the riverbed is larger than of decreasing the riverbed with the same factor. An increase of 50 percent in thickness leads to an increase in head of 50 centimeter on average, while a decrease with the same factor leads to a decrease of heads of only 20 centimeter.

The effect of changing the thickness of the sand layer in the riverbed on the volume of groundwater storage ($m^3$) in time in the riverbed is visualized in Figure A7.9 and quantified in Table A7.5. The influence of increasing the thickness on storage is obvious; an increase of 10 percent leads to an increase of 91 $m^3$ increasing to 405 $m^3$ at an amplification of 50 percent. The average groundwater storage in the riverbed at the location of Polygon 1 is approximately 800 $m^3$, which implies a rough doubling-up of groundwater storage in the riverbed in time. Decreasing the parameter leads to changes in volume somewhat smaller than the equivalent positive change. The effect on the volume stored in Polygon 2 is smaller compared to Polygon 1.

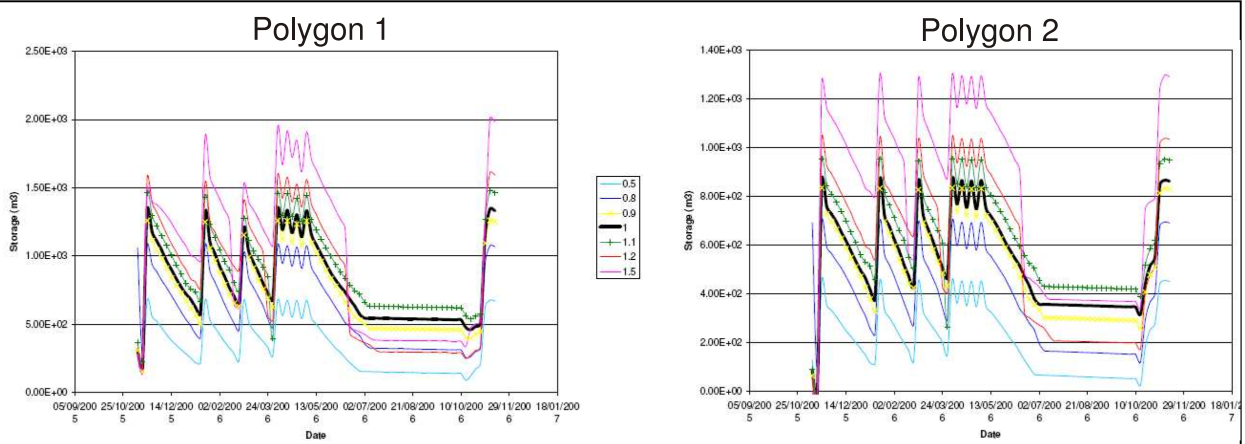



Figure A7.9 Influence of variation in thickness of the riverbed on calculated groundwater storage in the riverbed (m3)

| Factor | Diff. in polygon 1 | Diff. in polygon 2 |
|---|---|---|
| 0.5 | -459.6 | -331.4 |
| 0.8 | -209.3 | -170.3 |
| 0.9 | -62.8 | -39.7 |
| 1.1 | 91.4 | 80.3 |
| 1.2 | 191.6 | 156.3 |
| 1.5 | 406.5 | 383.3 |

Table A7.5 Average volume differences (m3/timestep) compared to the groundwater storage in the riverbed calculated by the calibrated model as an effect of variation in thickness of the riverbed

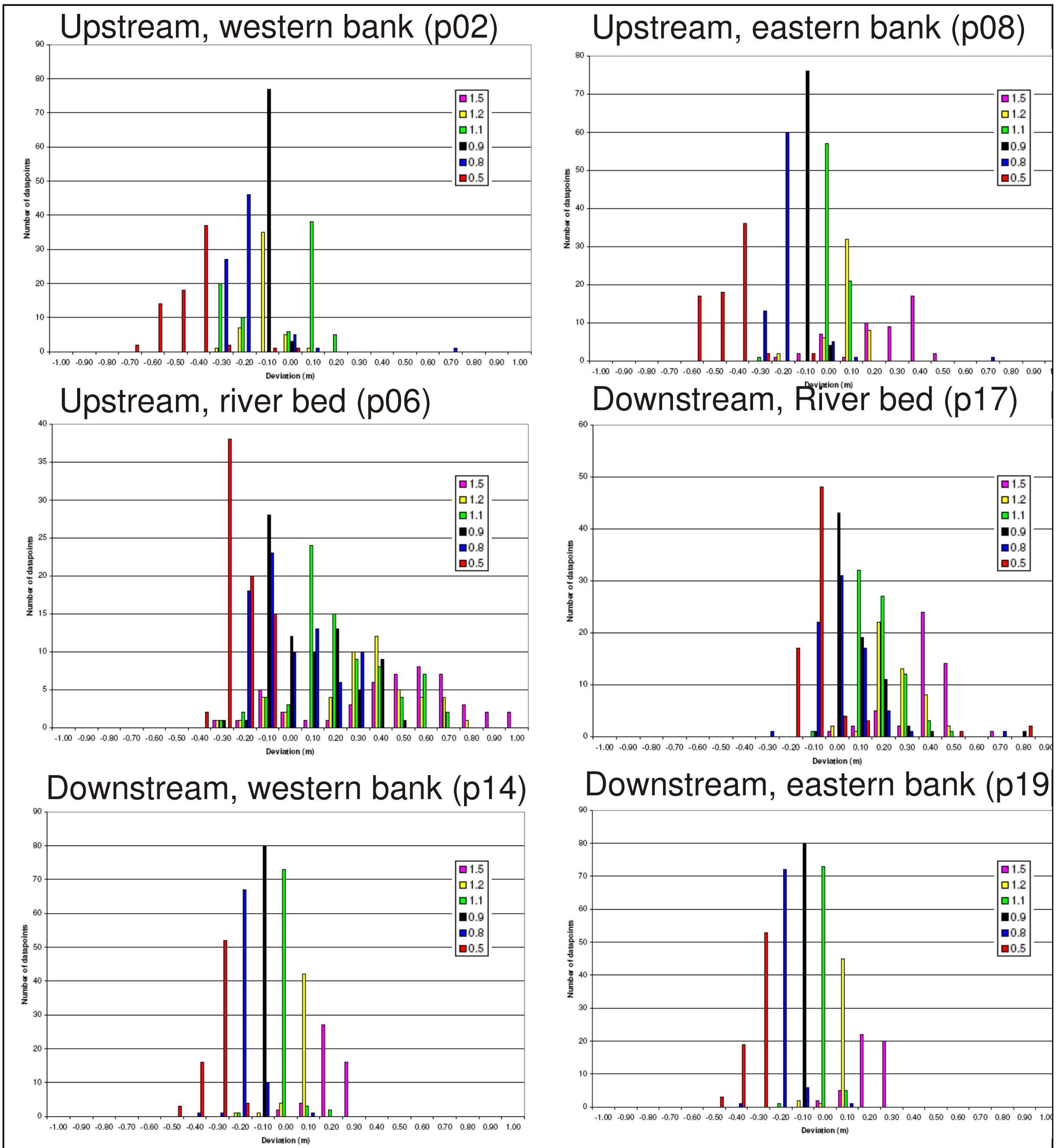



Figure A7.10 Quantification of the effect of varying the thickness of the riverbed on the simulated groundwater levels at different locations around the Kwa Ndunda sand dam

## Groundwater recharge

In the area downstream of the sand dam groundwater levels are influenced less by variation of groundwater recharge compared to the upstream area; varying groundwater levels within 20 percent effects computed groundwater levels with less than 10 centimeter on average. The exception is increasing recharge with 50 percent. Increase in groundwater levels is larger in the riverbed compared to the banks; 28 centimeter and 16 centimeter on average. In the downstream area the effect is larger in the riverbanks compared to the riverbed; 25 centimeter and 10 centimeter on average.

Figure A7.11 and Table A7.6 show the effect of changing the thickness of the riverbed on volumes of groundwater stored ($m^3$) in time in the riverbed. Increasing groundwater recharge results in larger groundwater availability; 24 $m^3$ with a 10 percent increase of groundwater recharge up to 106 $m^3$ due to an increase of 50 percent. The influence on groundwater storage in the upstream polygon is smaller; an increase of 65 $m^3$ due to a decrease of 50 percent.

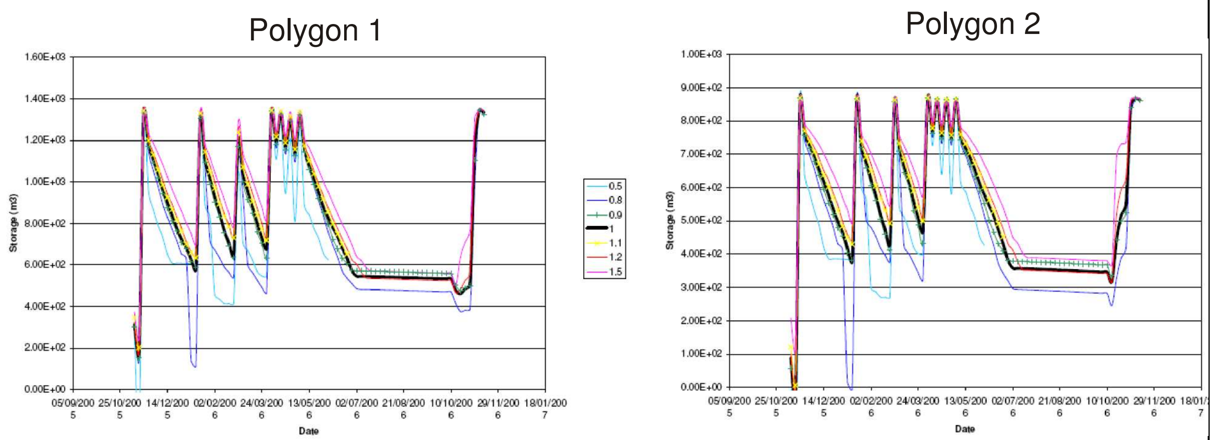



Figure A7.11 Influence of variation in groundwater recharge on calculated groundwater storage in the riverbed

| Factor | Diff. in polygon 1 | Diff. in polygon 2 |
|---|---|---|
| 0.5 | -373.1 | -246.9 |
| 0.8 | -82.8 | -64.6 |
| 0.9 | -4.2 | -2.9 |
| 1.1 | 24.3 | 8.8 |
| 1.2 | 46.8 | 24.0 |
| 1.5 | 106.7 | 65.8 |

Table A7.6 Average volume difference (m3/timestep) compared to the groundwater storage in the riverbed calculated by the calibrated model as an effect of variation in groundwater recharge

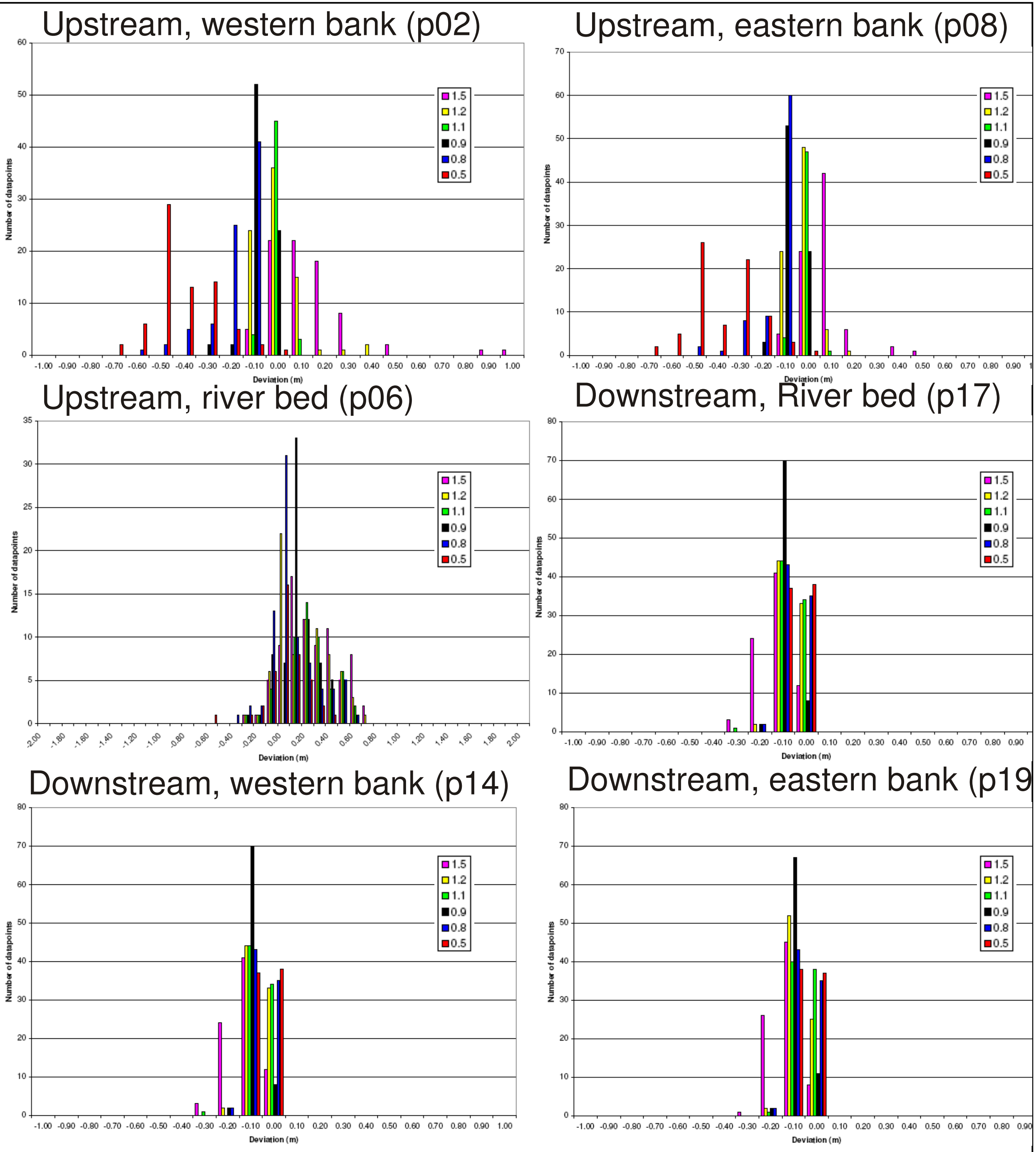



Figure A7.12 Quantification of the effect of varying groundwater recharge on simulated groundwater levels at different locations around the Kwa Ndunda sand dam

## Flood depth

Figure A7.14 quantifies the effect of variation of flood depth on groundwater levels around the sand dam. Groundwater levels are influenced very little by changes in this parameter, especially in the downstream area. A decrease of 50 percent of flood depth leads to a decrease of groundwater levels of only 2 centimeters in both the riverbed and –banks. In the upstream area, groundwater levels are reduced with less than 10 centimeter on average.

Table A7.7 and Figure A7.13 show the effect of changing flood depth on volumes of groundwater stored ($m^3$) in time in the riverbed. Decreasing flood depth has a larger effect on groundwater availability compared to increasing the flood depth with the same factor. A decrease of 50 percent leads to a change in volume of -78 $m^3$, using a multiplication of 1.5 results in an increase of 14.5 $m^3$.

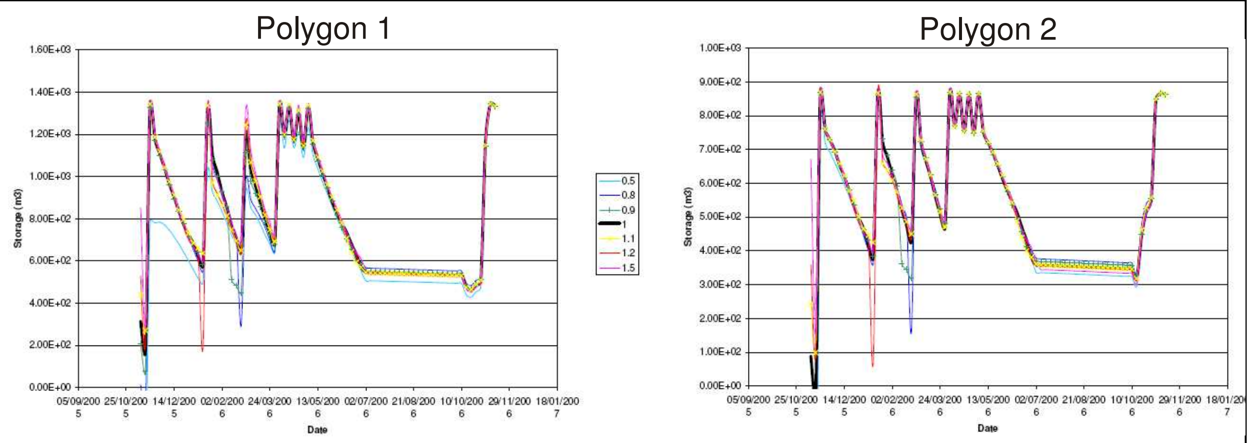



Figure A7.13 Influence of variation of flood depth on calculated groundwater storage in the riverbed (m3)

| Factor | Diff. in polygon 1 | Diff. in polygon 2 |
|---|---|---|
| 0.5 | -78.2 | -10.3 |
| 0.8 | -13.2 | 2.9 |
| 0.9 | -16.4 | -2.3 |
| 1.1 | 0.02 | 1.8 |
| 1.2 | 2.0 | -0.7 |
| 1.5 | 14.5 | 1.4 |

Table A7.7 Average volume differences (m3/timestep) compared to the groundwater storage in the riverbed calculated by the calibrated model as an effect of variation in flood depth

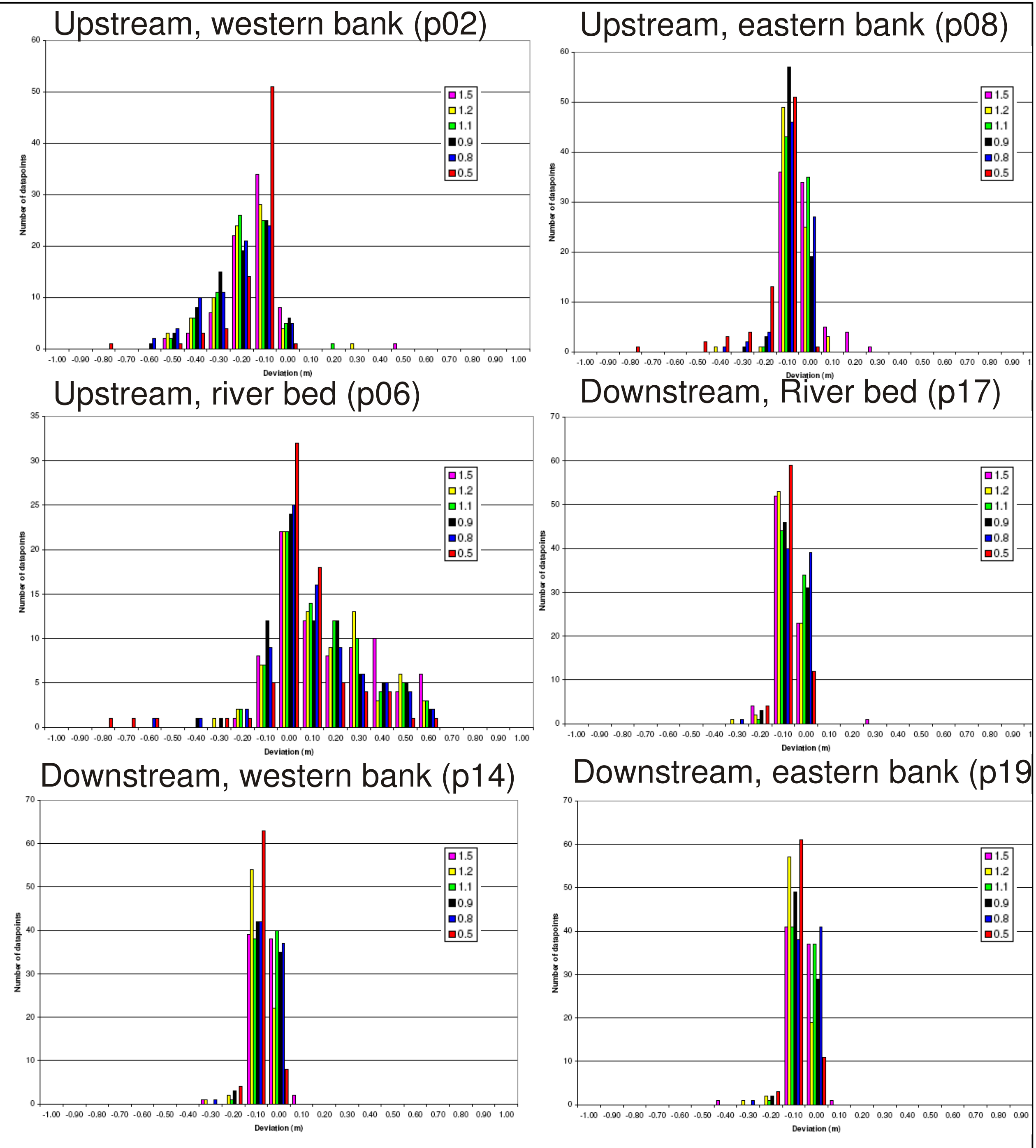



Figure A7.14 Quantification of the effect of varying flood depth on simulated groundwater levels at different locations around the Kwa Ndunda sand dam

# Appendix 8 Influence of the boundary conditions

To visualize the effect of variation of boundary condition on model results, results of model runs calculated with deviating boundary conditions is abstracted from those with original boundary conditions. The influence appears to be largest at the beginning of the dry season after the extended wet season of April 2006. Figure A8.1 shows the differences at this moment in time for model runs with a heads of +0.3 m, +0.1 m, -0.1 m and -0.3 m with respect to the boundary condition used in the calibrated model.

Influences are largest at the northern and southern boundary at the location of the river. Lowering the boundary condition with 0.3 meter leads to a lowering of head between 2 and 4 centimeter on average in the area of interest. Decreasing the head at the boundary with 0.1 meter results in an average decrease in computed head of 0 to 2 centimeter. Increasing the boundary condition with 0.1 meter leads to an increase in groundwater levels between 0 and 2 centimeter in the area of interest, as does increasing the head at the boundary condition with 30 centimeter.

From the above analysis, the conclusion is drawn that boundary conditions influence a small area near the boundary considerably, but do not significantly influence regional groundwater flow or model results in the area of interest.

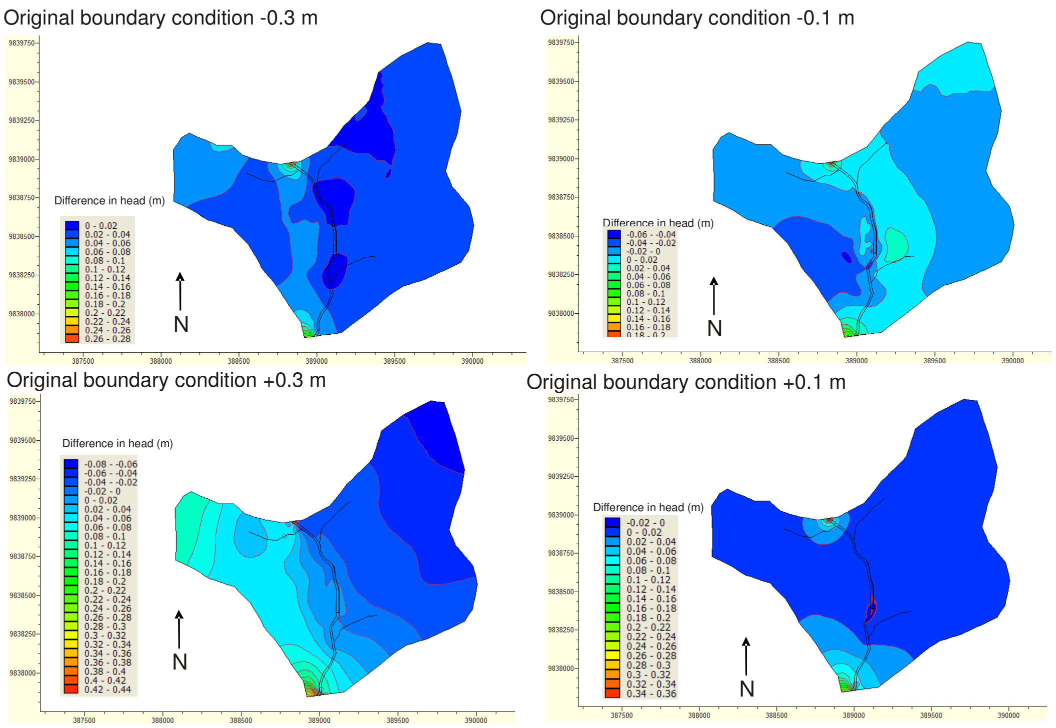



Figure A8.1 Quantification of the influence of boundary conditions on the model result