Hydrology of Sand Storage Dams
A case study in the Kiindu catchment, Kitui District, Kenya

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Master thesis Hydrogeology
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aqua for all

Acacia Institute
Solutions in Groundwater

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Cover: Sand storage dam Kwa Kangesa in the Kiindu catchment

Summary

Introduction

The current research is the first component 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. This project of the Acacia Institute and SASOL aims at using the experiences of the sand storage dams in Kitui to upscale the construction of sand storage dams in other regions. Since little is known about the hydrological processes around sand storage dams, this first component focuses on the hydrology of sand storage dams.

The Kitui district is one of the arid and semi-arid lands of Kenya. For (drinking)water most people heavily rely on water supply from the riverbeds of ephemeral rivers. SASOL is a local NGO which builds so called sand storage dams in ephemeral rivers to increase the water availability during the dry season. Sand storage dams are small (generally a few meters high) dams built in the riverbed behind which sand accumulates, enlarging the natural aquifer. The groundwater in the riverbed is obstructed by the dam and retained between the pores in the sand, making it available for people and animals during the dry season.
In October and November 2005 a field research was carried out in the Kitui District. A number of catchments, both with and without sand storage dams, were visited. As a case study the Kiindu catchment, located about 10 km South of Kitui town, was selected. In and around this catchment measurements and observations of meteorology, soils and (ground)water were carried out.

Methodology

Meteorological data of stations around Kitui town was obtained, compared and combined. In addition to these measurements a number of rain gauges (including one automatic rain gauge) was installed. In addition to the available open water evaporation measurements a sub-surface evaporation pan was installed in riverbed of the Kiindu river to quantify the amount of evaporation from the sand.
Augerings were made to install piezometers in two cross-sections near the dam Kwa Ndunda in the river Kiindu. Soil data from the augerings was used to create soil profiles. In total 21 piezometers were installed around the dam. In each of the piezometers inversed auger hole tests were carried out to determine the hydraulic conductivity.
The groundwater levels in all piezometers, the scoopholes of the riverbed and the wells were measured regularly. In five piezometers automated water level recording datalogger Divers were installed which measured the water level every thirty minutes.
The quality of the water in and around the riverbed was measured using the electrical conductivity (EC) as an indicator.

Results

Based on the comparison of the historical rainfall data back to 1904 the average annual rainfall in the Kiindu catchment was found to be 920 mm. Rainfall is strongly concentrated into two rainy seasons: the so called 'short rains' from October to February and the 'long rains' from March to May. In the dry period from April to September on average only 17 mm is recorded.
Average annual potential evaporation was determined at 1552 mm. Based on literature and the measurements of the sub-surface evaporation pan the evaporation from the sand in the riverbed only occurs when the water level is less than 1 m below surface level.
The soils on the riverbanks consist mainly of a top layer of silts and clays, under which a layer of weathered rock or sand is found until the hardrock is reached. The riverbed consists of coarse sand.
The response of the groundwater in the riverbed on rainfall and runoff is very rapid. A delayed rise of the groundwater levels in the riverbanks is observed. Within a few weeks however, both the sediments of the riverbed and the riverbanks are fully saturated. The effect of the sand storage dams on the water table in the riverbed is obvious since a step difference between the groundwater levels upstream and downstream can be seen.
The salinity (EC) of the groundwater shows large local differences and is in general between 2,000 and 10,000 μS/cm at the end of the dry season. During the rainy season the EC decreases to less than 600 μS/cm under the influence of the rainwater with a low EC.
Since rainfall is concentrated at the night, it was found that during the first weeks of the rainy season the river was found to be discharging only during the night. After the riverbed and riverbanks are fully saturated the river starts flowing continuously.

Hydrological system sand storage dams

Based on observations in the field and conversations with local people it was found that the reservoir upstream of a recently constructed dam fills up solely with coarse sand. Silt and clay particles which settle behind the dam are taken away with the river water when the river is flowing, or are blown away by wind. After 5 to 7 years the reservoir behind a dam is fully filled with sand and the dam is 'mature'.

During floods the river deposits a layer of silt and clay on the riverbed of the mature reservoir. Since the silt layer forms when most of the water has already infiltrated in the riverbed the infiltration is not obstructed. This layer is also taken up and discharged by subsequent river floods and blown away by wind.

When the groundwater level in the riverbed has increased it induces a sideward groundwater flow to the riverbanks where the groundwater level is still low, until the water level in the riverbed and riverbanks has levelled out.

The waterlevel then starts to decrease due to evaporation from the sand, groundwater flow trough the hardrock, leakage trough and around the dam, and the use of water by people and animals. When the groundwater level in the river decreases below the groundwater level in the banks, the water starts to flow from the riverbanks towards the riverbed.

A part of the water that has infiltrated on the hillslopes will flow down to the river as lateral baseflow and will recharge the groundwater in the riverbed. Better land management can increase the amount of infiltration, which leads to more potentially harvestable water.

The leakage of water through the hardrock and around the dam can be considered a loss in the case of a single dam. In case of a cascade of dams however this water will replenish the water in a downstream reservoir.

A water balance was set up for a segment of the catchment that drains between two dams. This was done to determine the effect of one dam without the influence of its location in the catchment and the effect of local differences such as rainfall or vegetation in upstream areas.

All inputs and outputs of the catchment segment are determined or estimated. It was found that the amount of water that is retained by a dam is only about 2% of the total amount of runoff, so the remaining 98% discharges as surface water through the river. When taking the upstream catchment area also into account (which is the case in real life) this amount only decreases.

The amount of water stored in a sand storage dam aquifer is mostly sensitive to the width and thickness of the sand in the riverbed and the lateral baseflow from the hillslopes. The thickness of the sand can be increased by building a (higher) sand storage dam. The amount of baseflow might be increased by increasing the amount of infiltration on the hillslopes by better land management.

Since the water stored in the riverbanks makes up an important part of the total amount of water retained (about 40%), the amount of water retained by a sand storage dam is much higher than just the amount of water stored in the sand of the riverbed.

The total amount of water abstractable for people and animals is calculated to be about 11.0 m^3 per day during the long dry season. The amount of water used by people is estimated at about 7.9 m^3 per day.

Recommendations

To reduce the risks of contamination and improve the quality of (drinking)water the knowledge and awareness of water pollution should be increased at community level and at SASOL.

More attention should be spent on the siting, monitoring, evaluation and documentation of dam construction and research projects by SASOL.

To increase the knowledge of the hydrological system around sand storage dams it is recommended to continue with the measurements in the Kiindu catchment and to expand the research to other parameters such as baseflow and deep groundwater. Groundwater modelling can give additional information on the groundwater system.

Since the height of the dam has a substantial influence on the amount of water abstractable, research studies to determine the optimal dam dimensions should be carried out.

Samenvatting

Introductie

Dit onderzoek is het eerste onderdeel van het "*Recharge Techniques and Water Conservation in East Africa – Up-scaling and Dissemination of the good practices with the Kitui sand storage dams* (Grondwater aanvullingstechnieken en Water conservering in Oost Afrika – Opschaling en verspreiding van de goede ervaringen met de Kitui zand opslag dammen)" project. Dit project van het Acacia Institute en SASOL richt zich op het gebruiken van de goede ervaringen met de sand storage dammen (zand opslag dammen) in Kitui om de bouw van sand storage dammen op te schalen naar andere regio's. Omdat er weinig bekend is over de hydrologische processen rondom sand storage dammen, richt deze eerste component zich op de hydrologie van sand storage dammen.

Het Kitui district is een van de *arid and semi-arid lands* (droge en semi-droge gebieden) van Kenia. Voor (drink)water zijn de meeste mensen grotendeels afhankelijk van de watervoorziening vanuit rivierbeddingen van tijdelijke rivieren. SASOL is een lokale *NGO* (non overheidsinstelling) die zogenaamde sand storage dammen bouwt in tijdelijke rivieren om de waterbeschikbaarheid gedurende het droge seizoen te vergroten. Sand storage dammen zijn kleine (over het algemeen een paar meter hoge) dammen gebouwd in de bedding van de rivier. Achter de dammen hoopt zich zand op, waarmee de natuurlijke aquifer vergroot wordt. Het grondwater in de rivierbedding wordt tegengehouden door de dam en vastgehouden in de poriën van het zand, waardoor het beschikbaar is voor mensen en dieren gedurende het droge seizoen.
In oktober en november 2005 is er een veld onderzoek uitgevoerd in het Kitui district. Een aantal stroomgebieden, zowel met als zonder sand storage dammen, is bezocht. Het Kiindu catchment, dat circa 10 km ten zuiden van Kitui stad is gelegen, is gekozen als een case study gebied. In en rondom het stroomgebied zijn metingen en observaties van meteorologie, bodem en (grond)water uitgevoerd.

Methodologie

Meteorologische gegevens van stations rond Kitui stad zijn verkregen, vergeleken en gecombineerd. Aanvullend hierop zijn een aantal regenmeters (waaronder een automatische regenmeter) geïnstalleerd. In aanvulling op de beschikbare open water evaporatie metingen is een ondergrondse evaporatie pan geplaatst in het rivierbed van de Kiindu rivier om de hoeveelheid evaporatie vanuit het zand te meten.
Om peilbuizen te installeren zijn boringen gemaakt in twee dwarsraaien in de omgeving van de dam Kwa Ndunda in de Kiindu rivier. Bodemgegevens van de boringen zijn gebruikt om bodemprofielen te maken. In totaal zijn er 21 peilbuizen geplaatst in de omgeving van de dam. In iedere peilbuis zijn *inversed auger hole tests* (inverse pompproeven) uitgevoerd om de doorlaatcoëfficiënt van de bodem te bepalen.
De grondwaterstand in alle peilbuizen, de *scoopholes* (gaten in het zand van waaruit water wordt geschept) in de rivierbedding en de putten zijn regelmatig gemeten. In vijf peilbuizen zijn automatisch registrerende water niveau datalogger Divers geïnstalleerd die de waterstand iedere dertig minuten hebben gemeten.
De kwaliteit van het water in en rond de rivierbedding is gemeten waarbij de elektrische geleidbaarheid (EC) is gebruikt als een indicator.

Resultaten

Op basis van de vergelijking van historische regen gegevens vanaf 1904 is de gemiddelde jaarlijkse neerslag in het Kiindu stroomgebied bepaald op 920 mm. De regen is sterk geconcentreerd in twee regenseizoenen: de 'korte regens' van oktober tot februari en de 'lange regens' van maart tot mei. In de droge periode van april tot september valt gemiddeld maar 17 mm neerslag.
De gemiddelde jaarlijkse potentiële verdamping is bepaald op 1552 mm. Gebaseerd op literatuur en de metingen van de ondergrondse verdampingspan vind er alleen verdamping vanuit het zand van de rivierbedding plaats wanneer het waterniveau zich op een diepte van minder dan 1 m onder het maaiveld bevindt.
De bodems van de rivierbanken bestaan over het algemeen uit een toplaag van silt en klei, met daaronder een laag verweerd gesteende totdat het vaste gesteente is bereikt. De rivierbedding bestaat uit grof zand.
De reactie van het grondwater in de rivierbedding op neerslag en afstromend water is heel snel. In de banken is een vertraagde reactie van het grondwater waargenomen. Binnen een aantal weken zijn echter de sedimenten van zowel de rivierbedding als de rivierbanken volledig verzadigd met water. Het effect van de sand storage dammen op de grondwaterstand in de rivierbedding is duidelijk te zien aan het verschil in grondwaterstand stroomopwaarts van de dam in vergelijking met de grondwaterstand stroomafwaarts.

De saliniteit (EC) van het grondwater laat grote plaatselijke verschillen zien, maar varieert over het algemeen tussen de 2,000 en 10,000 μS/cm aan het einde van het droge seizoen. Gedurende het regenseizoen daalt de EC naar waarden onder de 600 μS/cm onder invloed van regenwater met een lage EC.
Omdat de regen is geconcentreerd gedurende de nacht, heeft de rivier gedurende de eerste weken van het regenseizoen alleen 's nachts water afgevoerd. Nadat de rivierbedding en de -banken volledig verzadigd zijn begint de rivier doorlopend te stromen.

Hydrologische systeem sand storage dammen
Op basis van de waarnemingen in het veld en gesprekken met lokale mensen blijkt dat het reservoir stroomopwaarts van een recentelijk gebouwde dam zich opvult met enkel zand. Silt en klei deeltjes die sedimenteren achter de dam worden meegenomen door het water wanneer de rivier stroomt, of worden weggeblazen door de wind. Na 5 tot 7 jaar is het reservoir achter een dam volledig gevuld met zand en is de dam 'volwassen'.
Gedurende rivierafvoeren zal de rivier een laag silt en klei afzetten op de rivierbedding van een volwassen reservoir. Aangezien deze siltlaag zich vormt wanneer het grootste deel van het water al geïnfiltreerd is wordt de infiltratie in de rivierbedding niet belemmerd. Ook deze laag zal opgenomen en afgevoerd worden bij volgende rivierafvoeren, of worden weggeblazen door de wind.
Wanneer het grondwater in de rivierbedding is gestegen zorgt dit voor een zijwaartse stroming van grondwater richting de rivierbanken waar het grondwater nog laag staat, totdat de grondwaterstand in de rivierbedding en de -banken gelijk is.
De grondwaterstand in de rivierbedding begint dan te zakken door verdamping vanuit het zand, grondwaterstroming door het gesteente en rond de dam, en door gebruik van het water door mens en dier. Wanneer de grondwaterstand in de rivierbedding is gezakt tot onder het niveau van het grondwater in de banken begint het water vanuit de banken richting de bedding te stromen.
Een deel van het water dat op de hellingen is geïnfiltreerd zal richting de rivier stromen als laterale baseflow en het grondwater in het rivierbed aanvullen. Beter landbeheer kan de hoeveelheid infiltratie vergroten, wat kan leiden tot een grotere hoeveelheid water in het rivierbed.
De lekkage van water door het gesteente en rond de dam kan beschouwd worden als een verlies in het geval van een enkele dam. In het geval van een serie dammen zal dit water een benedenstrooms reservoir aanvullen.

Een waterbalans is opgesteld voor een segment van het stroomgebied dat afvoert tussen twee dammen. Dit is gedaan om het effect van een dam te bepalen, zonder de invloed van zijn locatie in het stroomgebied en van lokale verschillen zoals regenval of vegetatie in bovenstroomse gebieden.
Alle inkomende en uitgaande hoeveelheden water van het stroomgebied segment zijn bepaald of geschat. Het blijkt dat de hoeveelheid water die wordt vastgehouden door een dam maar 2% van de totale hoeveelheid afstromend water is. De resterende 98% stroomt weg als oppervlaktewater door de rivier. Wanneer ook het bovenstroomse stroomgebied in de beschouwing wordt meegenomen (wat het geval is in de eigenlijke situatie) neemt deze hoeveelheid alleen maar af.
De hoeveelheid water die opgeslagen wordt in een sand storage dam reservoir is vooral gevoelig voor de breedte en dikte van het zand in de rivierbedding en de laterale baseflow van de hellingen. De dikte van het zand kan worden vergroot door het bouwen van een (hogere) sand storage dam. De hoeveelheid baseflow kan mogelijk worden vergroot door het vergroten van de hoeveelheid infiltratie op de hellingen door beter landgebruik
Aangezien de hoeveelheid water die wordt vastgehouden in de rivierbanken een belangrijke component is van de totale hoeveelheid vastgehouden water (ongeveer 40%), is de hoeveelheid water die wordt vastgehouden door een sand storage dam veel groter dan alleen de hoeveelheid water die in het zand wordt vastgehouden.
De totale hoeveelheid water die beschikbaar is voor mens en dier is berekend op 11,0 m^3 per dag gedurende het lange droge seizoen. De hoeveelheid water die gebruikt wordt door mens en dier is geschat op circa 7,9 m^3 per dag.

Aanbevelingen
Om het risico van vervuiling te verkleinen en de kwaliteit van het (drink)water te verbeteren zal de kennis en het bewustzijn van gemeenschappen en SASOL moeten toenemen.
Er moet meer aandacht geschonken worden aan de locatie keuze, het monitoren, de evaluatie en documentatie van de bouw van dammen en de onderzoeksprojecten van SASOL.
Om de kennis over het hydrologische systeem van sand storage dammen te verbeteren wordt het aanbevolen om de metingen in het Kiindu stroomgebied voort te zetten en om het onderzoek uit te breiden naar andere

parameters zoals baseflow en diep grondwater. Grondwater modellering kan aanvullende informatie geven over het grondwater systeem.
Aangezien de hoogte van de dam een aanzienlijke invloed heeft op de hoeveelheid beschikbaar water wordt het aanbevolen om onderzoeksstudies uit te voeren om de optimale afmetingen van een dam te bepalen.

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1 Background

1.1 Introduction

Storage of water to bridge periods with low rainfall and dry rivers is a key element in securing water supply to rural and urban populations. This is particular the case in semi-arid and arid regions outside the reach of perennial rivers and where the availability of groundwater is limited. Storage needs are sharply increasing due to growing populations and water demand, catchment degradation and changes in climate variability. Provision of sufficient storage capacity will be the main challenge for water managers in reaching the Millennium Development Goals.

Water security for urban water schemes may include alternative options such as construction of dams, long distance conveyance of water, or deep wells. For rural water supply such solutions are generally too costly and complicated. Storage provisions for rural water supply require low cost systems with easy maintenance that can be constructed and operated with a high degree of community involvement.

Water conservation (or water harvesting) techniques are known since ancient times in arid and semi-arid regions, for example as described by Reij (1991). Also today there are numerous examples of rural communities which have, often with the help of NGO's and local water authorities, developed such systems in many countries. These systems include a variety of recharge and storage techniques and include both rainwater harvesting and conservation of surface run-off through (direct or indirect) groundwater recharge (Tuinhof & Heederik, 2003).

Although based on the same principle, the technology used in different countries or regions is generally adapted to the site specific (hydro-climatological and socio-economic) conditions. Small scale water saving structures have in common that:

- adaptation to the local conditions and circumstances is an important element for the success of these community based systems;
- often no use is made of existing good experiences in areas with comparable conditions (reinvention of the wheel effect) because in areas where water conservation schemes are developed there is generally no incentive to explore if use can be made of experiences elsewhere and in areas where good practices exist, there are generally no triggers to disseminate these experiences;
- community based water conservation systems are generally cost effective but serve a small number of families (20-50).

One of the successful examples of a rural water conservation programme is the construction of sand storage dams in the Kitui district in Kenya. This programme is a cooperation between the community and the Sahelian Solution Foundation (SASOL). SASOL, founded in 1992, assists Kitui communities to address household and production water scarcity through the sand storage dam technology.

The planning objective was to shorten the distances to water sources to below two kilometres whilst making water available for productive use. Typically, women walk 10-15 km to water sources in the district. To date, almost 500 dams have been constructed in central Kitui. The key success factors of the Kitui sand storage dams are firstly the high degree of community participation in the planning and construction and secondly the concept of cascades (many dams constructed in one riverbed), creating a substantial volume of storage in a small area and hence reaching a larger part of the population.

The Acacia Institute and SASOL funded by Partners for Water have 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 to use the experiences in Kitui as a case study to upscale the construction of sand storage dams in other parts of Kenya (including in Kitui district) and in the surrounding countries. The challenge is to develop an effective strategy to accelerate the construction of the systems without affecting the community based approach. Such a strategy should be based on an exchange of existing experiences and the dissemination of good practices.

The current research is part of the first component of the Recharge Techniques and Water Conservation in East Africa project and focuses on the hydrological evaluation of the Kitui sand storage dams. The research project was funded by Aqua for All (A4A) and the Vrije Universiteit Amsterdam (VUA) in cooperation with Sahelian Solutions Foundation (SASOL).

1.2 Objectives

The principles of sand storage dams are well documented (e.g. Nilsson, 1988; Nissen-Petersen and Lee, 1990), as well as their construction (e.g. Beimers *et al.*, 2001; Frima *et al.*, 2002; Burger *et al.*, 2003). On the hydrology of sand storage dams however, very little is known. This study aims to acquire insight in the hydrological processes, water flows and water quantities around a sand storage dam.

In order to upscale the application of sand storage dams to other parts of Kenya and Africa, this study aims to contribute to knowledge on the hydrological processes and the factors influencing them. To achieve this the following aspects have been studied:

- inventory of general literature related to (the hydrology of) sand storage dams;
- the response of groundwater levels in the riverbed and the riverbanks on rainfall and runoff;
- the effect of sand storage dams on the groundwater in a catchment;
- the storage capacity of sand storage dams and the amount of available water for people and cattle;
- general water balance of a sand storage dam;
- knowledge gaps and recommendations for further research.

Field visits were made to a number of catchments, both with and without sand storage dams. People were questioned and data was gathered at the SASOL field office, different Ministries and in the catchments. One catchment with sand storage dams was selected as a case study area for detailed hydrological research.

Data collection started in May 2005 in the Netherlands. In July a reconnaissance mission was carried out to gather information in Kitui, select an appropriate location for the case study and to install some equipment. In October and November 2005 hydrological field surveys were carried out in the Kitui district. A MSc. Hydrogeology student from the University of Nairobi and local inhabitants that cooperated in the project were instructed to continue with some of the measurements until (at least) April 2006.

1.3 Outline

This report reflects the results of a research project concerning the hydrology around sand storage dams. The report has the following structure. First a general introduction on the Kitui district area, the case study area, local water supply techniques and sand storage dam principle is given in Chapter 2.
Research methodology, the results and their interpretation are discussed in Chapters 3, 4, and 5 respectively.
In Chapter 6 the conclusions of the research are discussed, followed by the recommendations in Chapter 7.

2 Regional setting

2.1 Geography and climate

The Kitui district is part of Kenya's Eastern Province (Figure 2.1). The district extends for roughly 200 km from North to South and 120 km from East to West and has a surface area of 20,402 km^2. The district is bordered by Nyambene and Tharaka districts to the North, Taita-Taveta district to the South, Mbeere, Machakos and Makueni districts to the West and Tana River district to the East. The district's capital Kitui town is located about 150 km East of Nairobi. The Southern part of the district covers the uninhabited Tsavo East National Park. The district is bounded by to the North and East by UTM (zone 37S) coordinates 510000 m East, 10000000 m North, and to the South and West by 344000 m East and 9662000 m North. Data is based on the districts as at 2005, but the Kenyan government is planning to split up the Kitui district.

Figure 2.1 An overview map of Kenya with the Kitui District

The topography of the district can be divided into an Upland and a Lowland area. The Upland area covers the Yatta plateau and the hills and ridges in the East. Elevations in the Upland area vary between 600 and 1800 m above sea level. The Lowland area is a gently Eastward sloping plain from 600 to 400 m above sea level. Only some isolated inselbergs exist.

According to the 1999 census the district has a population of more than 515,000 people. Most of the inhabitants belong to the Kamba tribe. Most people live in communities consisting of small huts and buildings near their fields (shambas). Villages are small and consist of a few shops and other buildings.

The district falls within two climatic zones. The western part of the district has higher rainfall amounts and lower temperatures than the rest of the district and is classified as semi-arid. The Eastern and Southern part of the district fall within the arid climatic zone (Louis Berger International Inc., 1983). The district is therefore one of the arid and semi-arid land (ASAL) areas of Kenya.

Temperatures in the district are relatively high, 24 °C on average in the area. Rainfall in Kitui is seasonal with two rainy seasons, one from October to February and one from March to May. Most of the area receives less than 730 mm of rain per year (Figure 2.2). The higher areas around Kitui town however receive between 760 and 1270 mm.

Amounts decline to the South and East. Annual totals in these lowland areas are less than 500 mm. Average annual potential evaporation is approximately 1800 mm per year.

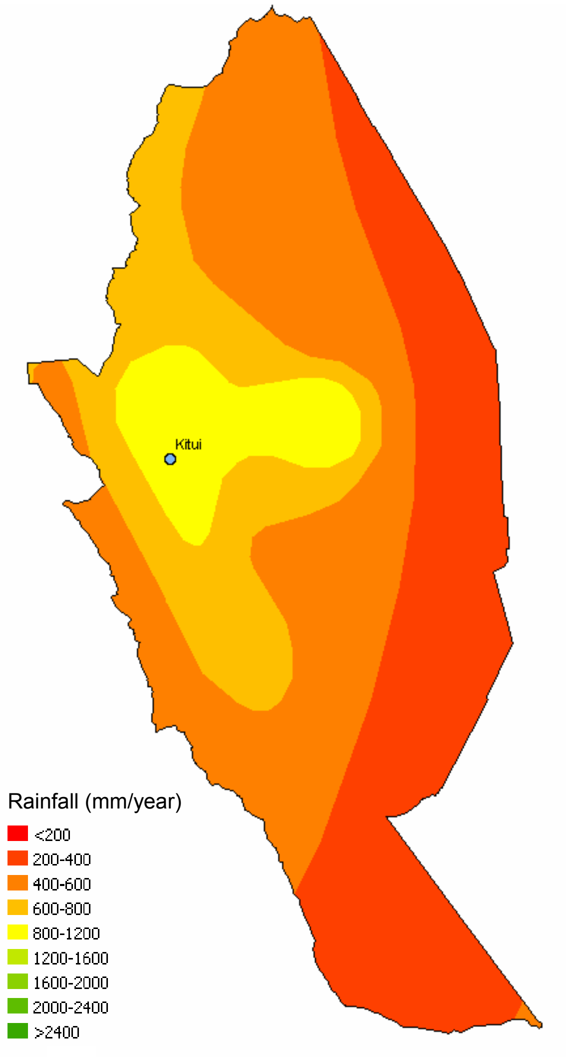

Figure 2.2 Rainfall distribution in the Kitui District

Rains are concentrated in two short seasons (March – May and October – February) with wide fluctuations from year to year. Even though average annual rainfall at some places is more than 1000 mm a year (to compare: average annual rainfall in The Netherlands is 750 mm a year), it is common for rains to fail in one or both seasons. Local lore states that rains completely fail at least one year in four (Thomas, 1999), so it is common for long periods of drought and food shortage to occur (Table 2.1).

1868	drought and famine known as *Yua ya Ngovo*
1870	drought and famine known as *Yua ya Ngeetele*
1878	prolonged drought and famine known as Yua ya Kiasa, when many people migrated from Kitui to neighbouring districts in search of food
1880	drought and famine known as *Yua ya Ndata*
1898	drought and famine known as *Yua ya Muvunga*, when famine relief rice was brought from Mombasa on the newly constructed railway
1908	drought and famine known as *Yua ya Malakwe*
1914-1916	drought and famine known as *Yua ya Kalungu*
1918	drought and famine known as *Yua ya Imili*
1924-1925	drought and famine known as *Yua ya Kukwatwa Syua* (solar eclipse)
1928-1930	prolonged famine known as *Yua ya Nzalukangye na Kakuti* due to drought and locust attacks
1942	a great famine that extended to central Kenya; many people relied on cassava for food
1944-1947	prolonged famine known as *Yua ya Mwanga* due to drought and locust attacks
1949-1950	drought and famine
1959-1960	drought and famine
1961	famine due to severe drought followed by flooding, known as *Yua ya Ndeke* because relief food was dropped from the air
1966	drought and famine
1970-1976	prolonged Sahelian drought causing serious famine in Kitui and other dry areas of Kenya
1984	drought and famine
1992	drought and famine
1997	drought and famine

Table 2.1 History of drought and famine in Kitui District (source: National Environmental Secretariat 1981 and Francis M. Kioko)

2.2 Case study area

The hydrological case study was carried out in the river Kiindu, a seasonal river about 10 km South of Kitui town. The Kiindu 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, after this the river flows into the Nzeeu river in the South (UTM 389990 m East, 9831850 m North). The entire catchment has a surface area of about 37 km^2. The elevation varies between 950 and 1140 m above sea level with a lowering trend Southward. A topographic map of the Kiindu catchment is given in Appendix A.

Between 1995 and 1997 SASOL has build a total of almost 500 sand storage dams in the Kiindu river and its tributaries. Figure 2.3 shows the locations of the dams in the Kiindu river.

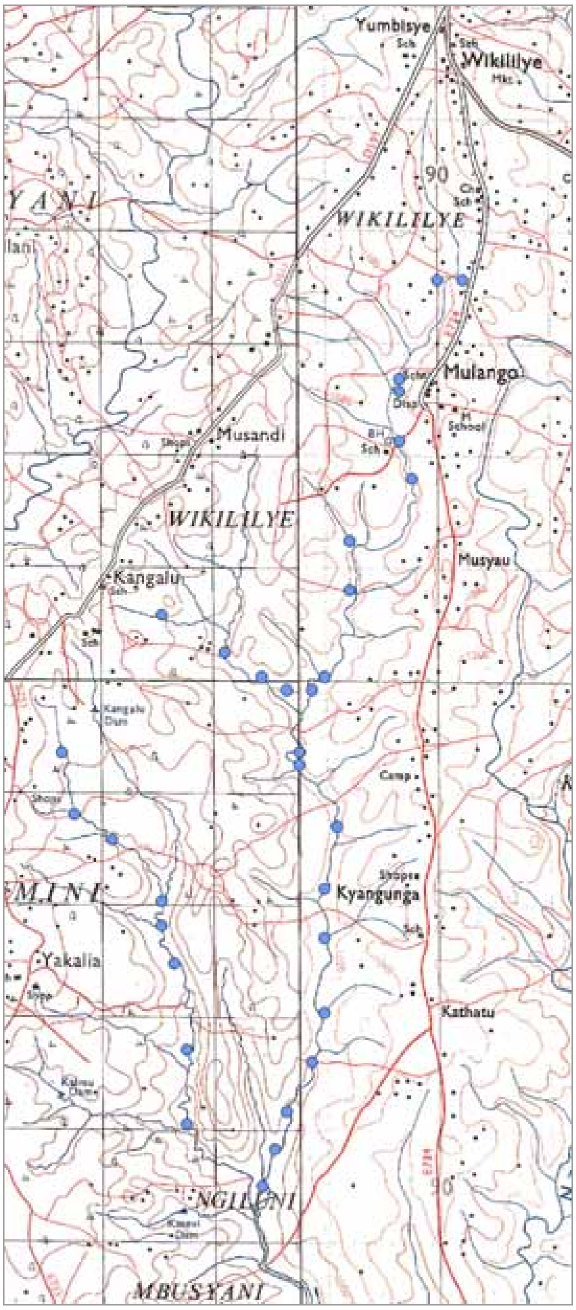

Figure 2.3 Location of the sand storage dams in the Kiindu catchment

The Kiindu catchment has been selected for the hydrological research for a number of reasons. First of all (and most importantly) the dams in the Kiindu river are all mature: the area behind the dams has fully sedimented with sand, and since the dams have been build more then 10 years ago, it can be assumed that any changes in the hydrological process have fully settled. Besides the hydrology, the Kiindu catchment is close to Kitui, easy accessible and the surroundings of the river are suitable to place piezometers.

The main research area comprises a stretch of almost 2 km of river with from North to South the following dams: Yoani, Kyangunga, Kwa Kangesa, Kwa Ndunda and Kwa Langwa. Dam Kwa Ndunda, where the piezometers (pipes to measure the groundwater level) were installed, is located in the middle of the stretch (UTM 389200 m East, 9838380 m North). The distance between the dams in the Kiindu river is more or less 500 m.

2.3 Vegetation

Around Kitui town the vegetation is sparse and predominantly drought resistant. The case study area is somewhat drier than Kitui town, so even less vegetation is present. The vegetation consists mainly of Acacia's and other thorny bushes (a.o. *Acacia clavigera*, *Acacia nilotica*, *Acacia seyal*, *Terminalia combretum*, *Commiphora sp.*; Katumo, 2001) as can be seen in Figures 2.4 and 2.5. Along the river course however some more types of vegetation can exist.

Figure 2.4 Vegetation along the river. On the right Napier grass is planted

Figure 2.5 Acacias along the riverbed

The local people are in need of firewood to prepare food, to boil water to disinfect it, to cook and to make charcoal, which is sold in town. To get this wood, lots of trees and shrubs are cut down, leaving large areas of bare land which are much more vulnerable to erosion.

On the banks of the river some agricultural activity takes place. On small plots (about 500 – 2000 m2) crops are cultivated, such as sukuma wiki (sort of spinach or collard greens), mango, papaya and some banana (Figure 2.6). A tree nursery is also present, next to dam Kwa Kangesa.

Figure 2.6 Small scale agriculture on the riverbanks.

To protect the banks from erosion by the river stream Napier grass is planted, which retains the soil (Figure 2.4). Most dams are constructed close to villages, where people also have their agricultural plots. Because people want to protect their agricultural plots, most of the Napier grass is found near agricultural plots and dams.

The land looked quite bare and dry during the dry season. To make a rough inventory of the vegetation during the dry and wet seasons overview pictures were taken at the same locations at three moments in time.
The first set was taken during the dry season at 14 October 2005. At 7 November when there had only been little rain the second set was taken, and the third set was taken after two weeks of rainy season at 24 November. These were put in sequence in Figures 2.7.A-C and 2.8.A-C to make an overview.

A: 14 October 2005

B: 7 November 2005

C: 24 November 2005

Figure 2.7.A-C View on dam Kwa Ndunda at three dates.


A: 14 October 2005


B: 7 November 2005


C: 24 November 2005

Figure 2.8.A-C Downstream view on Kiindu river at three dates.

It is clearly visible after the rains a lot more vegetation is present, since the vegetation responds rapidly to the rains.

2.4 Geology

2.4.1 Regional setting

The Kitui District area is largely covered by Precambrian (540 Ma BP and older) crystalline rocks, which mainly consist of gneisses, granulites, schists, migmatites, with minor intrusives. These Precambrian rocks are generally referred to as the "basement system" and generally show a regional structural North-South trend of foliation.

This regional setting is in agreement with the geology of the Mozambique belt, which is of Proterozoic (2,500 Ma – 540 Ma BP) age. This geological feature is to be found in large parts of East Africa and stretches from Mozambique in the South through Kenya to Ethiopia and Sudan in the North.

Since the Archaean (2,500 Ma BP and older) metamorphism the rocks have been subjected to continuous erosional processes, which led to different erosional levels. Tectonic activity and these erosional processes shaped the coarse outlines of the present morphological features, which influenced later distribution of deposits. Tertiary (65 Ma – 2 Ma BP) and Quaternary (2 Ma BP until present) deposits are present on the hillslopes and in the riverbed. In the South-eastern corner of the Kitui district Paleozoic sandstones occur.

Due to complex tectonic activity most of the primary structures and textures have been lost through crystallisation and recrystallisation. However it is still recognized that the sandstones, greywackes and other sedimentary rocks were metamorphed to a.o. gneisses, which form the lithology at present.

At present the land is a peneplain, in which few inselbergs are present (e.g. Nzambani Rock, Figures 2.9 and 2.10). A geological map is enclosed in Appendix B.

Figure 2.9 View on peneplain from Nzambani rock

Figure 2.10 Peneplain and Nzambani Rock at the horizon

The area has been incised by rivers, which have created valleys. At the low areas in these valleys, the stream courses, coarse material accumulates.

An overview of the geological processes which took place is given in Table 2.2 (Louis Berger International Inc., 1983; Schoeman, 1948; Sanders, 1954).

Period	Process	products
Precambrium (Archaean, Proterozoic)	Tectonics and metamorphism	gneisses and schists
	Erosion, peneplanation	
Paleozoic (Carboniferous – Permian)	Forming of basin by tectonic activity and faulting.	Shales, sandstones
Tertiary (Miocene)	Tectonic activity	Intrusives and dikes
Quaternary (Recent)	Erosion, local sedimentation	Soils, sands, alluvium, limestone, clays, silts

Table 2.2 Overview of most important geological events of Kitui.

2.4.2 Case study area

In the case study area in the Kiindu catchment rock types are found, mainly gneisses, such as granitoid gneiss (feldspar, quartz and muscovite), biotite gneiss (biotite, feldspar and quartz), intersected with pegmatite veins (Figure 2.11). The gneisses appear in bands differing in width from half a meter to tens of meters. Locally some quartzites appear between the gneisses. The structural trend of all rocks found in the research area are between 0° and 35°

Figure 2.11 Granitoid gneiss (left) and biotite granitoid gneiss (right) with pegmatite veins

All of these rocks dissolve slowly in water, therefore the water chemistry doesn't change rapidly. At some locations however bands of saline rock were found (Figure 2.12), which tasted very saline, but only when it is weathered. Unfortunately this rock could not exactly be identified. This saline rock influences the water quality much more than the other rocks: the salinity of the water increases dramatically.

Figure 2.12 The white part is sodic feldspar and is about 1 meter wide

The sodic feldspar is much more sensitive to erosion than the gneisses, since it is much softer. The granitoid gneiss is a little harder than biotite granitoid gneiss, as can be seen from the erosion depth (see Figure 2.11).

At some locations along the river course a layer of limestone is visible. This is known as the Kunkar Limestone and is only to be found locally. This limestone originates from weathering of other rocks, after which it precipitates and accumulates. The accumulated precipitates form the very brittle Kunkar limestone.

The riverbed itself is filled with coarse sand (about 600 μm), which is a erosional product of the different local lithological units, mainly gneisses, (Figure 2.13) and forms a phreatic aquifer has a thickness varying from a few centimetres to more than 2 meters.

Figure 2.13 The riverbed is filled with coarse sand

2.5 Hydrology and hydrogeology

2.5.1 Surface water

Virtually all of Kitui District's total area belongs to the Tana River drainage basin. Only a narrow strip along the south and southwest border drains to the Athi River. These two rivers form the northern, western and southern boundaries of the district. The Tana river is Kenya's largest river and drains the Eastern flank of the Aberdares and the Southern slopes of Mount Kenya. Both of the rivers discharge to the Indian Ocean.

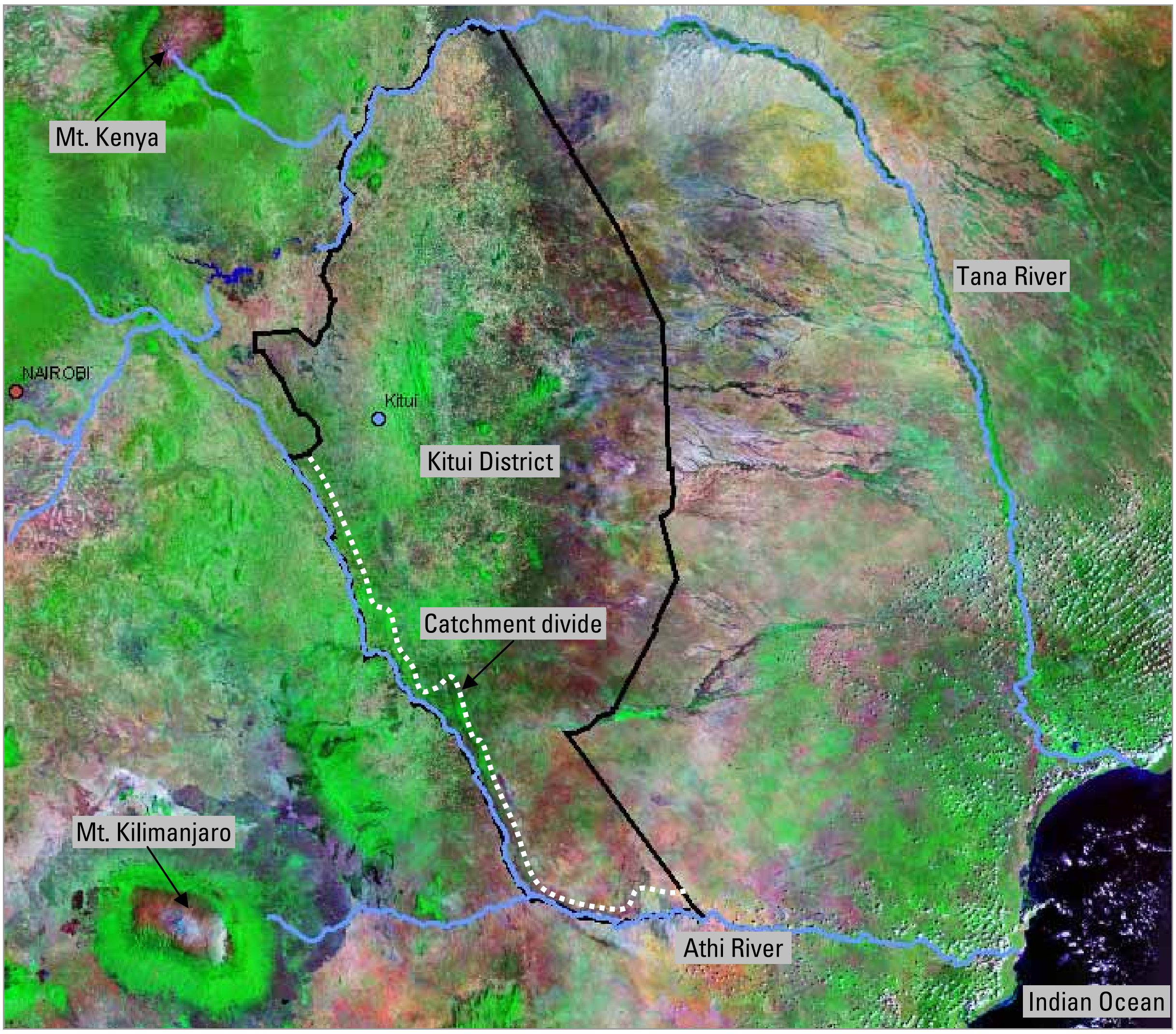

Figure 2.14 False colour composite satellite image of the Southern part of Kenya (source: USGS and NASA)

There are no perennial rivers in the District except the Tana River. In spite of perennial headwaters, the Athi often runs dry due to evaporation and infiltration losses. All of Kitui's rivers, including the Tana River, are strongly characterized with high flows in April-May and November-December and very low (or nil) flows in the intervening dry periods. Most of the ephemeral streams that drain into the Tana River generally become dry within one month after the rainy season.

Figure 2.15 Water users in one of the larger rivers in the Southern part of the district, near the Athi river

Figures 2.16 and 2.17 show the mean monthly discharges for the Tana River and a smaller seasonal river, the Kalundu river, located near Kitui town. The seasonal character of the flow is evident. In addition the inter-annual variation is significant (Louis Berger International Inc., 1983). It should be noted that the Kalundu river is located on the high-rain plateau near Kitui, smaller seasonal rivers in these areas and rivers in the dryer lower areas will have an even more accentuated variability.

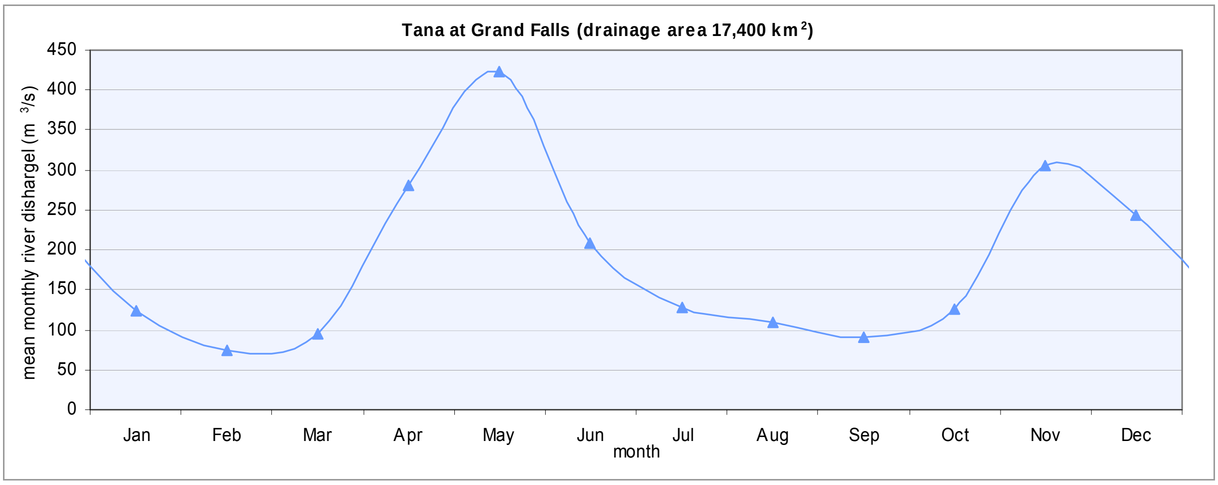

Figure 2.16 Mean monthly discharge of Tana River (1948-1971) (data: Louis Berger International Inc., 1983)

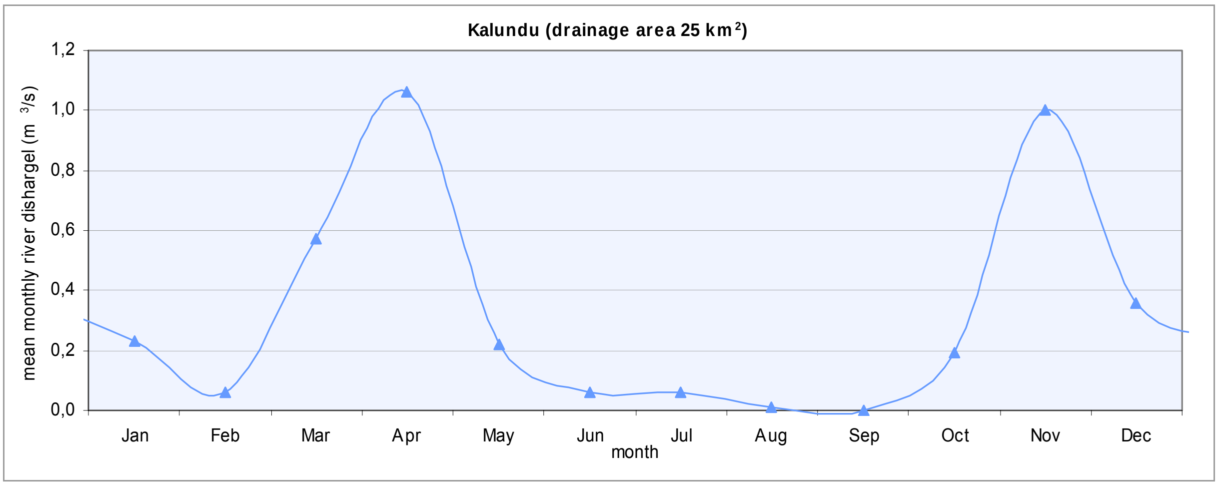

Figure 2.17 Mean monthly discharge of Kalundu river (1961-1976) (data: Louis Berger International Inc., 1983)

2.5.2 Groundwater

In the Kitui District four main groups of aquifers are recognized (Louis Berger International Inc., 1983):
- Quaternary superficial deposits;
- Tertiary rocks;
- Paleozoic sedimentary rocks;
- Precambrium crystalline rocks.

The Quaternary superficial deposits consist of alluvium aquifers and Quarternary deposits. The Alluvium aquifers are sands and gravels along river channels. Where the river channel crosses resistant rocks, natural subsurface barriers are formed which form good shallow aquifers. The other type of Quaternary aquifers are formed by deposits of talus or loose unconsolidated materials, e.g. at the base of steep slopes.

The tertiary volcanic rocks that outcrop in the plains and along the Eastern boundary of the district have a low porosity and form poor aquifers. Only when water is trapped in open joints small springs can occur.

In the South-East corner of the district (mainly in Tsavo East National Park) shales, grits and sandstones of Paleozoic age form good aquifers in which large quantities of water are stored.

Most of the Kitui District is underlain by metamorphosed crystalline Precambrian rocks. In general, these rocks from poor aquifers, although locally water can be stored in fractures, faults, joints and weathered zones. The schists are on the whole unfavourable as aquifers since cracks in mica schists are often sealed by the clay resulting from their weathering. However, at some locations, especially where faults have been occupied by quartzite vein materials, these rocks may yield water supplies. The water supply at Ithookwe, which provides the water supply for Kitui town, is an example of this. The aquifer properties of the quartzite veins are completely dependent on the presence of sufficiently interconnected joints.

Recharge of the groundwater comes solely from rainfall, either directly or indirectly through local areas with concentrated recharge (i.e. near stream or areas with ponds). Major groundwater recharge zones are on the hill ranges of North and Central Kitui. Places with the most favourable conditions for groundwater recharge are the Miambani and Migwani Ridges where runoff from the hills in channelled over the permeable Mui-Ikoo-Mutito fault zone with direct connection to the quaternary alluvial and Precambrian fractured rock aquifers.

For details about groundwater levels and quality in the Kitui district the reader is referred to reports by Earth Water Ltd. (2003) and Wotuku (2001a and 2001b).

2.6 Water supply in Kitui

In Kitui district people obtain water in different ways. Since not everywhere the conditions are the same, not every technique is suitable at every location. Some most practiced techniques and methods used in Kitui are discussed below.

2.6.1 Scoopholes

In river beds groundwater is still present after the river stopped flowing and no surface water remains. Every season holes are dug, so the water in the phreatic aquifer of the riverbed can be scooped out. Because during the rainy season the river fills up the holes with sediment, the holes have to be dug every season again, some even up to 10 m deep. (Figure 2.18)

Figure 2.18 Water is taken from the riverbed in a scoophole

2.6.2 Wells

Close to the riverbed shallow wells are dug. Two types of wells exist: open wells and closed wells. The open wells do not have a lid and water is taken out by a bucket and rope, or someone climbs in and fetches the water (Figure 2.19).
The closed wells have a lid and a handpump is mounted on the well. Although the construction is more expensive than an open well, it has large benefits, such as no trash can be thrown in and no contamination with polluted buckets and ropes occur. (Figure 2.20).
Most wells of both types are a few meters deep.

Figure 2.19 Open well

Figure 2.20 Closed well

2.6.3 Sand storage dams

Sand storage dams are being built in the river bed, perpendicular to the flow direction. Behind these dams the river bed fills up with sand, enlarging the natural aquifer (Figure 2.21). During the dry season water will be stored in the area for a longer period. More water can be harvested from scoopholes and wells, providing water to the people for a longer period. The sand storage dam concept will be explained more elaborate in paragraph 2.7.

Figure 2.21 Sand storage dam

2.6.4 Subsurface dams

In the same way the sand storage dam retains water, a dam can be build in an aquifer, forming an obstruction for the groundwater flow. A sand storage dam is built above surface level, creating an aquifer, a subsurface dam however is built below ground level in a natural aquifer.

2.6.5 Rock catchments

If water from rock surfaces can be collected in a reservoir, a so called rock catchment is a good provider of water. However, it can easily be polluted and attract vermin, since it is surface water. Also a substantial part of the water evaporates.

2.6.6 Roof catchments

From the roof of a building rain can be collected and stored in a reservoir (Figure 2.22). This is low tech and cheap and can provide good quality water. If rain is somewhat distributed over the year, a small reservoir is sufficient to store enough water for all year around. In the Kitui area however, rain events occur twice a year. Still a large part of domestic water can be harvested using roof catchments, but not enough for both domestic use and irrigation.

Figure 2.22 Reservoir containing rain water collected from roof

2.6.7 Boreholes

From boreholes in the hardrock groundwater is harvested from depths of 30 to 80 meters. However, few boreholes for individuals are made, since the costs of drilling of the hole and pumping equipment are rather high. The basement aquifer does not yield enough water to serve all people with drinking water and enough irrigation water (The Consortium for International Development, 1978).

2.6.8 Waterworks

In Kitui town waterworks are present, which provide drinking water to the people. This water is harvested by the water supply company from deep groundwater wells in the basement aquifer. However, this is expensive and only available in Kitui town. Due to the high costs even in town people also rely on other sources.

2.7 Sand storage dams

2.7.1 Introduction and principle

Water is taken from rivers for domestic and agricultural purposes in many places. If it concerns an ephemeral river however, water will not be available all year around. The water in the river will flow away, leaving behind a dry riverbed.

In order to bridge periods of drought, water can be retained by building a dam. In many cases a dam can be built behind which surface water is stored. However, surface water storage has some negative side effects, such as evaporation. To overcome such problems the water can be stored subsurface, if the local conditions allow subsurface storage. This storage can be reached by building a dam, behind which sand accumulates, enlarging the natural aquifer. The groundwater in the riverbed is obstructed by the dam and retained in the pores in the sand (Figure 2.23). The water can be harvested using scoopholes or wells.

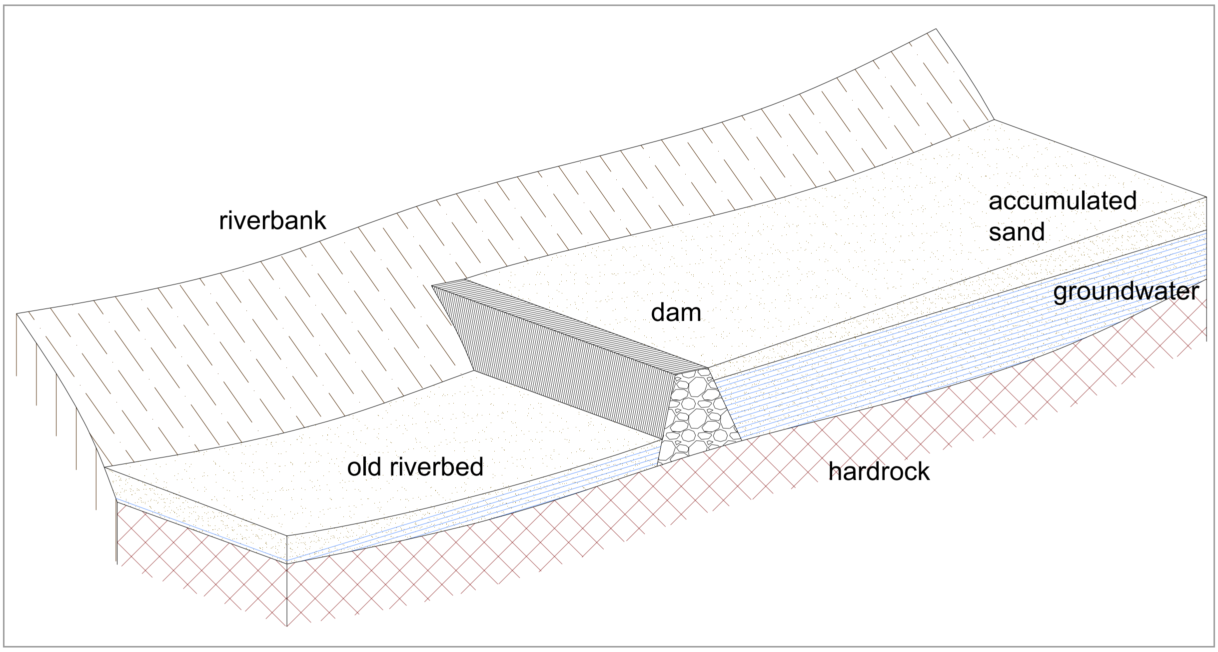

Figure 2.23 Principle of a sand storage dam

2.7.2 History

In Kitui district sand storage dams have been built during the nineteen fifties and sixties by the Colonial Government and by different organisations since then. The concept however is not new and the method has been applied in many places around the world since a long time. For example groundwater blocking structures were found on the island of Sardinia, Italy, where dams were built in Roman times. In Tunisia, North Africa, dams of similar age were found. In the eighteenth century sand storage dams were built in Arizona, United States of America. More recently various small-scale groundwater damming structures have been built in many parts of the world, but mainly in India, Brazil, South and East Africa (Nilsson, 1988) and Pakistan. Although all these structures are more or less similar, different names are used in different parts of the world. For instance these structures are referred to as sand storage dams, sand dams, check dams, trap dams, sponge dams, or desert water tanks (Van Haveren, 2004).

Figure 2.24 Sand storage dams in Tunisia

2.7.3 Advantages

Subsurface water storage has some clear advantages over open water storage. Less water evaporates, since no water is subjected to direct solar radiation. Since salinity increases with evaporation, water quality remains more constant and is better. Groundwater is also less affected by biological contamination than open water (Tuinhof and Heederik, 2003; Giraud, 1989). As water flows subsurface it is also filtered and bacteria and other biological threats are reduced (Huisman and Wood, 1974). Since the groundwater is in the soil, it is much less subjected to littering than open water. Another major advantage is that much less mosquitoes are present in the area, since mosquitoes need surface water for breeding grounds.

2.7.4 SASOL

In the Kitui district dams are being constructed by a.o. the local NGO Sahelian Solutions Foundation (SASOL). SASOL was founded in 1992 to provide the local people with water, since in recent times droughts and famines had struck the arid region. A second reason was that women had to travel long distances to fetch water. For instance during the dry season (March to November) women typically had to walk one hour from Kiindu river to Nzeeu river and one hour back (Thomas, 1999).
As a result of the sand storage dams water is available for a longer time in the dry season and people don't have the necessity of walking for hours anymore. The time saved can be spent on other activities, such as agriculture or weaving baskets. Also more water for irrigation is available, boosting up crop growth and providing extra income.

First SASOL only concentrated on wells, but in 1995 the first sand storage dams were built. According to SASOL almost 500 dams were constructed in the Kitui district during the following decade, providing approximately 120,000 people with water. SASOL now plans to disseminate the knowledge to other areas and countries in East-Africa, and build another 500 dams in and around Kitui district in the coming decade, at a cost of approximately € 9,000 each.

SASOL builds dams and wells with community participation and only facilitates the local communities with materials and knowledge, but the community itself has to demand for a dam and provide labour. In this way the community itself has to invest in their water resources, enlarging responsibility, since the dam will be owned by the community. The community then is trained how to operate and maintain dams and wells and how to prevent erosion.

Figure 2.25 A recently finished dam build by SASOL near Kanziku, Kitui District

2.7.5 Building a dam

For many situations a sand storage dam can be a good source of water. The success and effectiveness of the dam depends on the local and environmental situation, as well as on the dam design. In most cases the ideal situation is not present, but still an effective dam can be built. A set of advisory recommendations is available for building a sand storage dam, and dam builders can use these as a guide (e.g. Nissen-Petersen, 2000). The most important and desirable situations are discussed and illustrated in Figure 2.26.

Preferably the local and environmental situation meet a set of criteria, concerning foundation and materials. Firstly water can be lost from the sand storage dam aquifer through leakage to deep groundwater. An impermeable layer underneath the dam and the sandy aquifer is desirable, leaving little water to be lost to deeper aquifers. The dam should not be built on sand, but preferably on hardrock or a clay layer. Secondly a location in the river with a natural rock outcrop is preferred to build a dam. The outcrop forms a natural barrier, behind which water and sand already accumulate. If the dam is built on top of the outcrop, it doesn't have to be as large as it would be in case it would be built on a deeper part, which means less effort and costs. Thirdly the river system has to contain the right depositional material. If the final enlarged natural aquifer behind the sand storage dam consists of silts and clay little water can infiltrate and be harvested. Sand is much more favourable, since the yield is much higher.

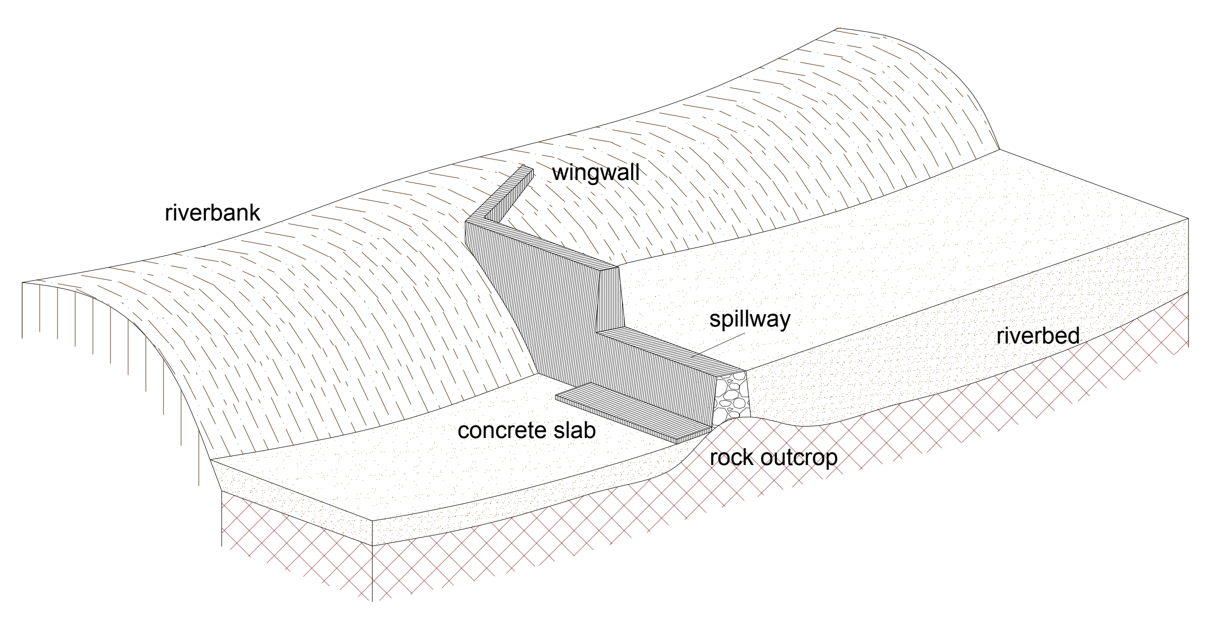

Figure 2.26 The different aspects of an effective sand storage dam

The dam has to meet some technical engineering criteria as well. Firstly to prevent water to flow around the dam and erode the banks wingwalls have to be constructed, which are being built into the banks. Secondly a spillway has to be made to channel the river. This also prevents the river from eroding the banks around the construction. The spillway has to be large enough to keep the channel the river, also during high discharge events. Without wingwalls and a spillway the river will erode the banks and shift its course, flowing around the structure. Thirdly the dam has to be built of good materials that can withstand the forces of the river and are maintenance free. The materials of which the dam is constructed of can be bricks or rocks, gathered in the vicinity of the building site. These can be cemented together by a mason. Finally in case the dam is not built on hardrock, a concrete slab on the downstream side of the dam has to be made on top of the riverbed to prevent erosion and undermining of the structure.

In case the dam is designed to be high, care should be taken with siltation. If the water and the silt cannot leave, the aquifer will not only consist of sand, but also of silt, which has negative effects on yield and infiltration. To prevent this dams often are being built in stages, heightening the dam a few meters each year. The maximum height per season is said to be about 2 meters (Hofkes and Visscher, 1986), however this is not proved by research, but more an estimate. In the Kitui area most dams are not that large and building dams in stages is therefore not necessary. However, it should be noted that the height of the dam depends heavily on the amount of silt and sand. In the Kiindu case most depositional material is coarse sand, which is the ideal situation.

The reservoir behind the dam will not be fully filled with sand and fully functioning immediately, but this will take some time. After about 7 years the dam is “mature” and the enlarged natural aquifer is built up to the level of the spillway. A non-mature dam can be seen in Figure 2.25, where a dam has just been finished in Kanziku, Kitui district.

For a more elaborate technical description the reader is referred to manuals on design and construction of sand storage dams by Nissen-Petersen and Lee (1990), and Nissen-Petersen (2000) and a handbook from SASOL (Munyao *et al.*, 2004).
A number of other reports, books and articles concerning aspects of groundwater obstructing structures in general (Guiraud, 1989; Van Haveren, 2004; Hofkes and Visscher, 1986; Nilsson, 1988; Nissen-Petersen, 1997; Tuinhof and Heederik, 2003), socio-economic (Mutiso, 2002; Rhebergen and De Bruijn, in preparation; Thomas, 1999; Ngigi, 2002) and environmental (Katumo, 2001) have been published.
Furthermore a number of student reports, mainly relating to the construction of sand storage dams is written in cooperation with SASOL by students from Delft Technical University (Arnold *et al.*, 2002; Beimers *et al.*, 2001; Bossenbroek and Timmermans, 2003; Burger *et al.*, 2003; Frima *et al.*, 2002), Katholieke Universiteit Leuven (Neessen, 2004; Puttemans, 2004) and the University of Nairobi (Munyoki, undated).

3 Methodology

3.1 Field visits and conversations

During the fieldwork visits to a number of rivers with sand storage dams in the Kitui district have been carried out. Both old and recent dams built by SASOL have been visited, as well as dams built by other organizations. For comparison, a number of catchments without sand storage dams have been visited too.
During the fieldwork conversations with SASOL staff, students carrying out work experience projects, a number of Ministries and local inhabitants were made.
In November 2005 a short field visit has been paid to three dams built by the Westerveld Conservation Trust in the Tsavo river near Voi.

3.2 Meteorology

Historical rainfall data has been collected from seven stations within the Kitui district. The nearest station to the Kiindu catchment is Kitui Agricultural station, which is located in Kitui town. For this station monthly data of the period 1904 – 1990 has been obtained from the Food and Agriculture Organization of the United Nations (FAO) and the Royal Netherlands Meteorological Institute (KNMI). For the period 1926 – 1980 monthly data of this station has been obtained from Arid and Semi-Arid Lands Development Project (Louis Berger International Inc., 1983). Puttemans (2004) obtained daily data for 1979 – 1999 of the Kitui Agricultural station and the Ithookwe Agriculture substation (3 km West of Kitui town) from the Institute of Meteorological Training & Research (IMTR) in Nairobi.
At the compound of the Ministry of Water and Irrigation, District Water Office Kitui a meteorological station is located. The station consists of a totaliser rain gauge, an automatic rain gauge (not functioning), a Class-A evaporation pan, an anemometer and a thermometer (not functioning). Daily measurements from June 2004 until November 2005 of rainfall and pan evaporation of this station have been obtained from the Ministry of Water and Irrigation, District Water Office Kitui.

Figure 3.1 Meteorological station at the District Water Office Kitui

During the 2005 field research three additional locally produced totaliser rain gauges were installed at locations around the Kiindu catchment. Two rain gauges were installed at secondary schools near the Kiindu catchment: one at Kyangunga Secondary School and one at Mulango Girls' Secondary School. One rain gauge was installed at the home of Mr. Cephason Peter Kilonzi in Kangalu.
A manual with datasheets was written, and the teachers and students were instructed to carry out the daily rainfall measurements. The measurements started in October 2005 and the schools have the intention to continue with the measurements.

Figure 3.2 The locally produced totaliser rain gauges

Next to the totaliser rain gauge at Mulango Girls' Secondary School an automated tipping bucket rain gauge (VU tipping bucket system TBL 1) was installed. In this rain gauge the rain is collected in a funnel, this funnel leads the rain to a small spoon which tips over and empties when it is full. Each tip corresponds to 0.1 mm of rain. The time at which the spoon tips over is recorded by a data logger. The tipping bucket rain gauge has recorded the rainfall from 1 August to 24 November 2005.

To get an indication of the amount of evaporation from the sand of the riverbed a sub-surface evaporation pan was installed in the Kiindu river. A circular plastic container (diameter approximately 0.5 m, height 0.5 m) was dug into the sand of the riverbed. A small piezometer was placed in the container after which the container was filled with the sand from the riverbed and saturated with water. The container was subsequently covered with sand and left alone for a few days to settle. After a few days the water depth in the sub-surface evaporation pan was monitored during a dry period of 16 days until the first rains arrived.

Figure 3.3 Sub-surface evaporation pan during installation

The locations of the meteorological stations and instruments are indicated in Figure 3.4.

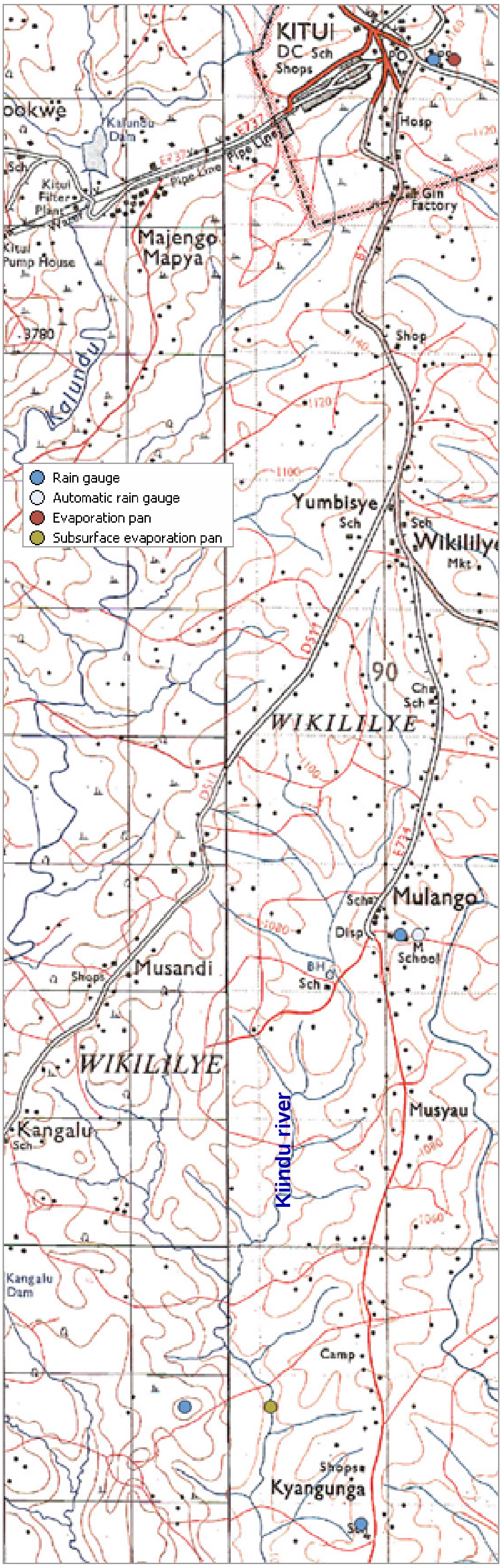

Figure 3.4 Meteorological instruments around the Kiindu catchment

3.3 Soils

An important part of the research is to get insight in groundwater flow and soil characteristics that are connected with this flow. In order to get this insight 21 piezometers were installed. For the placing of the piezometers boreholes were made. The borehole descriptions made at the site of the augerings were used to make a schematic cross-section.

To make an estimate of the available water in the riverbanks and bed and the flow patterns different soil properties have to be known. The values needed for this estimation are pore volume, specific yield and hydraulic conductivity.

To make an estimate of the hydraulic conductivity (K-value) inversed auger hole tests (also known as Porchet test) were carried out. The piezometers were filled with water very quickly, after which the lowering of the water level in the piezometer was monitored every 2 seconds using a 'Diver', and automated water level recording datalogger (Van Essen Instruments). The velocity of lowering of the water table in the piezometer is determined by the infiltration rate of water from the piezometer into the soil. This then can be calculated to a value of hydraulic conductivity. This test was conducted 3 times for every piezometer to get an average value and to minimize the effect of errors.
The pore volume and specific yield of the soil layers were taken from literature.

3.4 Groundwater

3.4.1 Piezometers

The groundwater level in the riverbed and banks was monitored using piezometers. Those piezometers were installed upstream and downstream of the dam Kwa Ndunda to monitor the groundwater levels before, during and after the rainy season. One cross-section of 9 piezometers is located 50 m upstream of the dam, one cross-section of 9 piezometers is located 100 m downstream of the dam and 3 extra piezometers were placed just a few meters from the dam. An overview of the piezometers is given in Figure 3.5.

The piezometers were constructed of a PVC pipe, in which slots were made to create a screen. The screen length of the piezometers is not the same for all piezometers, but are depending on the length of the piezometer, depth and soil material. For most piezometers 1 meter was taken. The lengths of the piezometers and the screens are given in Appendix C. Because no regular piezometer filter was available to protect the piezometer from sand coming in, panty stockings were put over the screens. Coarse river sand was used to fill the borehole around the piezometer. The top was closed off by a lid, secured with a lock. The piezometers were protected by a cemented or brick perimeter, as can be seen in Figure 3.6. The cement was also used to seal of the top of the soil, so no water can infiltrate along the piezometer.
The whole was covered by a branch of thorny bush to protect it from animals stepping on it.

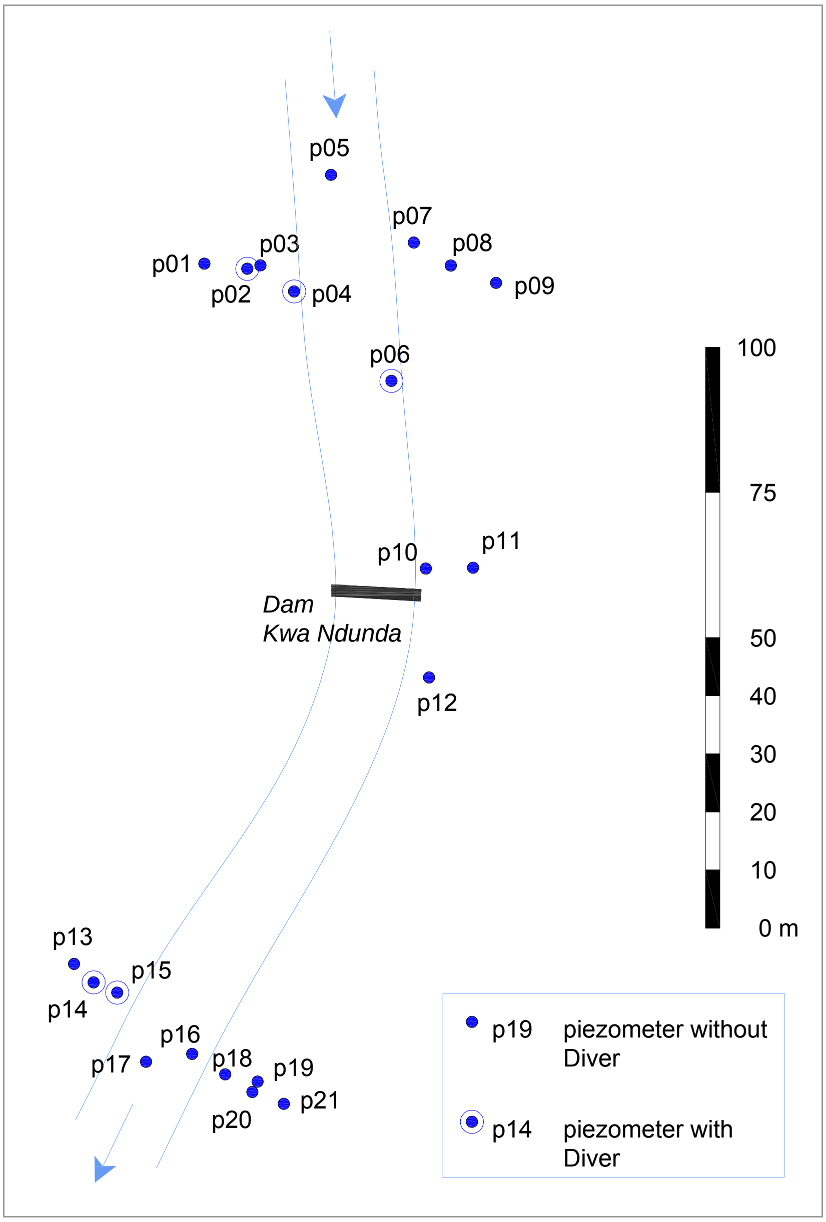

Figure 3.5 Overview of piezometers

Figure 3.6 Piezometer

To monitor the water levels two types of measurements were used: manual measurements and automated measurements using Divers.

The manual measurements were carried out by measuring the water depth from the top of the piezometers using a sounding device with measuring tape (Eijkelkamp Agrisearch Equipment). The measurements were carried out in all 21 piezometers twice a day: in the morning and late in the afternoon.
In five piezometers Diver dataloggers (Van Essen Instruments) were installed, and one Diver datalogger for barometric corrections was used. Diver dataloggers automatically measure and store the water level and temperature at a preset interval. The interval used is 30 minutes. The groundwater monitoring Diver dataloggers were applied in piezometers of which the most significant results were expected. Those were piezometers 2, 4 and 6 in the upstream cross-section and 14 and 15 in the downstream cross-section. The barometric diver was placed just under the lid of piezometer 13.
Despite the precautions of a lid and a lock, the Diver datalogger in piezometer 13 was stolen on 4 November. The Diver datalogger from piezometer 14 was reinstalled and used as barometric datalogger from then on.
On 29 November a second Diver datalogger, from piezometer 6, was stolen, after which all Diver dataloggers were removed.

To relate the water levels in the piezometers to each other the elevation of the tops of the piezometers was surveyed using a spirit level (Sokkia C330). The elevations are given in Appendix C.

3.4.2 Water levels and electrical conductivity in the longitudinal profile

The water level and the electrical conductivity (EC) of the water in the scoopholes in the riverbed and in the wells on the sides of the river have been measured a number of times from the end of the dry period to the start of the rainy season. The EC was measured to get a quick indication of the water quality (salinity). The EC was measured with a handheld conductivity meter (Greisinger GLM 20). Measurements have been carried out for a stretch of the river Kiindu of almost 2 km, between dam Yoani in the North and dam Kwa Langwa in the South. Dam Kwa Ndunda, where the piezometers where installed is located in the middle of the stretch.

Since the hydraulic conductivity in the coarse sand of the riverbed is high, the water level in the scoopholes is assumed to be a good representation of the groundwater level in the riverbed. When during the measurements the water from a scoophole in the riverbed had just been taken out, the measurements were taken only after the water level had risen to its original level. It must be noted that, especially at the end of the dry period, the water level in a number of scoopholes decrease below the sand bed, so the scoopholes where dug into the weathered hardrock. When the water was scooped out, the water could be observed flowing out of the weathered hardrock. The rate of outflow of the weathered hardrock was clearly much slower than the rate of outflow from the sand in the riverbed. At the locations where the water was scooped out of the weathered hardrock the measured water level was lower than the actual groundwater level. At one location the local women who used the water told that in the morning, when the water had been able to flow out of the weathered hardrock all night, the water level was about 0.4 m higher than during the day when the water was taken out by the women.

The profile of the sand surface in the river and the water levels has been measured with a spirit level instrument (Sokkia C330 and Leica NA-720). The UTM coordinates were measured using a handheld Garmin GPS receiver. During the first visit to the area in August 2005, no spirit level instrument was available, so the water levels were measured with a measuring tape, relative to the sand surface. Since no water had been flowing in the river between August and October 2005 the sand level in the riverbed has only been disturbed by humans and cattle walking through the river. The measurements carried out with the spirit level instrument in October 2005 were therefore used to relate the measurements with the measuring tape to each other.

At the end of the dry season, when the water level was at its lowest and most of the scoopholes were dry, the depth of the hardrock under the sand of the riverbed was determined. A metal rod (about 1.5 m long) was hammered into the sand of a scoophole until the hardrock was reached. The depth of the rod relative to the sand surface of the riverbed was measured with a measuring tape. For each location this was done five times to make sure the measured obstacle was actually the hardrock and not a loose stone.

3.5 River Discharge

During the field campaign measuring the river discharge had no priority, since it was not a key issue for the objectives of this research. Still a few discharge measurements were carried out. Since the start of the rainy season the river was flowing during and just after rain events, but since most rain events occur during the night, river discharge was not actually encountered until the last days of the field campaign. The discharge was estimated at two moments, which gives an idea of the magnitude of the discharge. This estimate was done by estimating the water depth, river width and flow velocity.

An other useful estimation of the discharge can for instance be done obtained by the Chezy equation, using a.o. floodmarks, the slope of the riverbed and the Manning roughness coefficient. This method was used by different researchers in the Kitui district (e.g. Bossenbroek and Timmermans, 2003).

Figure 3.7 River discharge

4 Results

4.1 Field visits and conversations

4.1.1 Water supply

Most of the scoopholes are fenced off by thorn bushes to prevent animals from reaching the water. Different scoopholes are used to water the cattle and to fetch water for drinking and cooking. Most of the scoopholes for the cattle have wooden sticks in the water to prevent the cattle from stepping and urinating in the water, but allow them to drink.

Figure 4.1 Scoophole fenced off with thorn bush and protected against animals to reach the water

Scoopholes used for drinking water for people and for cattle, although separated from each other, are sometimes in very close distance of each other (less than 5 m). Conversations with users of the water indicated that the knowledge was present that the water in the scoopholes used for the cattle could be polluted by the cattle. The awareness however that those pollutants could be transported by groundwater flow towards the scoophole used for drinking water was not present.

Figure 4.2 Cattle near the water supply for people

At the end of the dry season (October) it was observed that an increasing number of scoopholes in the Kiindu river dried up and could not be dug deeper because the hardrock was reached. People had to go to other scoopholes in the Kiindu river or to the Nzeeu river to fetch water. Some people also bought water from people with deeper wells. At one location it was observed that a scoophole that had been used for cattle until the first half of October and was heavily polluted by the cattle, was being used by people during the second half of October, due to a lack of water.

In the Kiindu river only a small number of shallow wells exist. All the shallow wells in the area between dam Yoani and Kwa Langwa are open wells. People have to lower buckets to fetch the water, or at the end of the dry period when the water was too low, people climb down in the well to fetch the shallow remaining layer of water.
Near the dams more recently constructed by SASOL, closed shallow wells with hand pumps are installed. According to SASOL a shallow well with a handpump is build near every new dam that is being built. Although equipped with a handpump it was observed that some communities still prefer to use the water from scoopholes instead of the well. According to the communities the water from the well tastes less good, is saline, or is more polluted than the water from the scoophole, while measurements don't confirm this. Besides that, the people are just used to fetch water from the scoopholes and prefer to keep using them instead of the wells.

Figure 4.3 A child drinking directly from a shallow scoophole

4.1.2 Sand storage dams

In Kiindu river it was observed that some dams had more water, or had water for a longer time in the dry period than others. At some dams this was clearly the effect of malfunctioning of the dam (leakage), while at others no clear cause could be found.

Dam siting for the SASOL dams is a combined activity of the community and SASOL technicians. SASOL asks the community to indicate a number of favourable locations for a sand storage dam, based on hardrock outcrops, bank stability, walking distance and land ownership. The community is let to select the locations. After a week or so SASOL personnel returns to the community, walks with them trough the river and reviews the locations selected by the community. Based on this review a location is selected.

From experiences of Dutch students who helped building the dams in the Southern part of the Kitui district it sometimes occurs that during digging of the trench the impervious layer (hardrock or clay) is found to be at more than 4 m depth. Since the depth of the impervious layer is unknown, the motivation of the community to continue digging decreases and to be able to finish the dam before the rainy season starts it sometimes occurs that a dam is being constructed without an impervious foundation (C. van der Steen and M. Kool, Ex-change; personal communication).

In the area of Voi, near Tsavo National Park, some dams built by the Westerveld Conservation Trust were visited. Here the dams were combined with so called water dispersion units. This is a system to irrigate the land by trenches, which channel the river water into the agricultural land and harvest surface runoff from rain. This system looks interesting, but to quantify the effect and the limitations of the system experts should evaluate the principles and working of the system.

After the rainy season, it is observed that water seeps out of the hardrock to the side of a dam. During the fieldworks this was only observed at some locations, while in other years this process is visible at more dams (Munyoki, University of Nairobi; personal communication). This is probably caused by the below average rainfall during the long rains (February to May) of 2005.

A number of dams (mostly elder ones) are not functioning anymore since the river changed its track to the side of the dam. All dams where this happened did not have a spillway in the dam, nor did they have wing walls. However, some older dams built by the colonial government (so more than 40 years old) are found to be still fully functioning.

4.1.3 Land degradation

At a number of locations Napier grass (*Pennisetum purpureum*) is planted to protect the banks from erosion by the river. At some locations it is observed that since Napier grass is only planted on one of the riverbanks the river tends to erode the other side and thus change its track.

Intense soil erosion is observed on riverbanks and on the slopes of catchments. Deep gullies (up to 3 m deep) have formed and are still increasing in depth, width and extend (Figure 4.4).

Figure 4.4 Soil erosion in the Kiindu catchment

Cutting of trees for firewood and shrubs for protection of the scoopholes and agricultural plots takes place at a large scale, leaving behind large areas of the land poorly protected against erosion.

At a number of locations terraces are constructed on the agricultural plots to protect the land against soil erosion and to improve infiltration in the soil (Figure 4.5). At some locations it is observed that terraces are constructed not parallel to the altitude lines. So education on soil conservation measures is necessary.

Figure 4.5 Terraces in the Kiindu catchment

Near a dam constructed in 2005 the water in a well was found to be 2 m lower than the surface water pool just next to it, even though the surface water pool was already there for two weeks. The surface water pool formed after the first rains since the construction of the dam, and no surface water had yet been flowing over the dam. So possibly the change in water level between the surface water and the groundwater is caused by the silt layer deposited by the first flood. The silt layer might significantly reduce the infiltration rate of the water. Another possibility is that the infiltration rate of the water in the well is very low. Since this place was only visited once, at the end of the fieldwork, no definitive reason can be given.

4.1.4 Kiindu catchment

Since the dams in the Kiindu river are the first dams SASOL has built, the design of the dams has improved since then. The dams in the Kiindu river are for example not equipped with a spillway, which has caused a number of dams to malfunction since the river changed it's path to the side of the dam (Figure 4.6), or the dam broke through.

Figure 4.6 Change of river path next to a dam

From observations in scoopholes in a number of catchments around Kitui town it was found that in most of the cases the sediment in the riverbed consists solely of coarse sand with bands of fine gravel. At some locations minor silt layers are observed in the sediment of the riverbed. In the Kiindu catchment no silt layers were observed in the sediment.

Figure 4.7 A scoophole in the riverbed of Ithimani river with one the highest amount of silt layers observed

When walking upstream (Northern direction) trough the river Kiindu it can be seen that the vegetation cover increases. This is consistent with the annual rainfall amount which also increases in Northern direction.

Local communities are in serious need of water and are willing to take action to improve their situation. When for example, during augering near the tree nursery at Kwa Kangesa the groundwater was reached the local community immediately started digging to construct a well. Only one week later a 3 m deep open well with brick walls was constructed and in use.

Effectiveness of the actions can however be limited by local and social issues. In another catchment for example, people were found to be waiting for more than 4 hours next to a newly constructed well with hand pump which was closed of with a padlock because the key keeper was not present.

4.2 Meteorology

4.2.1 Rainfall

All the historical rainfall data sets have gaps in the data sets and irregularities between the different sources. The six data sets were combined to decrease the amount of missing data from 19 to 6 %. From 1994 to present most of the monthly data is missing from all data sets. The combined precipitation data set is given in Appendix D. The newly created data set is further referred to as the combined data set.

Based on the combined data set, the mean annual rainfall in Kitui town is 1006 mm, with a standard deviation of 288 mm. Rainfall data measured in Kitui town (combined data set) for the period 1904 – 2005 is plotted in Figure 4.8. Only the years with a complete record are plotted.

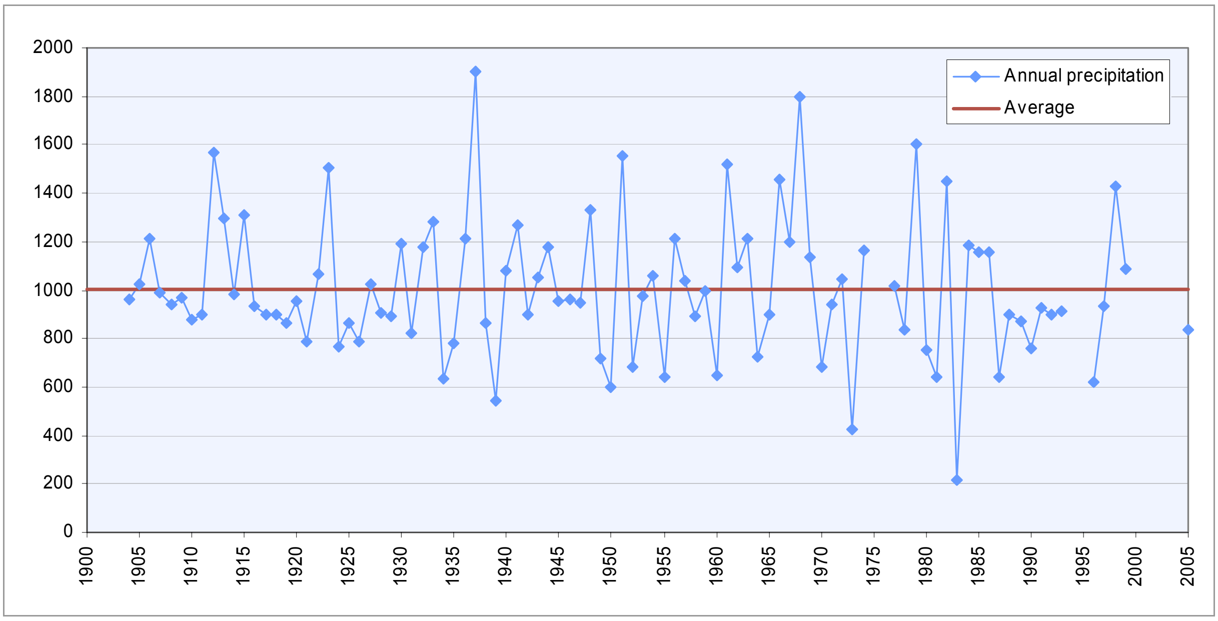

Figure 4.8 Annual precipitation in Kitui (1904 – 2005)

Rainfall is mostly concentrated into two rainy seasons: the so called “long rains” which last from March to May and the “short rains” which last from October to February (see Figure 4.9). Mean total rainfall during the long rains is 385 mm, with a standard deviation of 116 mm. Mean rainfall during the short rains is 590 mm, with a standard deviation of 138 mm. The names “long rains” and “short rains” are not related to the length or amount of the rains, but refer to the length of individual rainfall events.

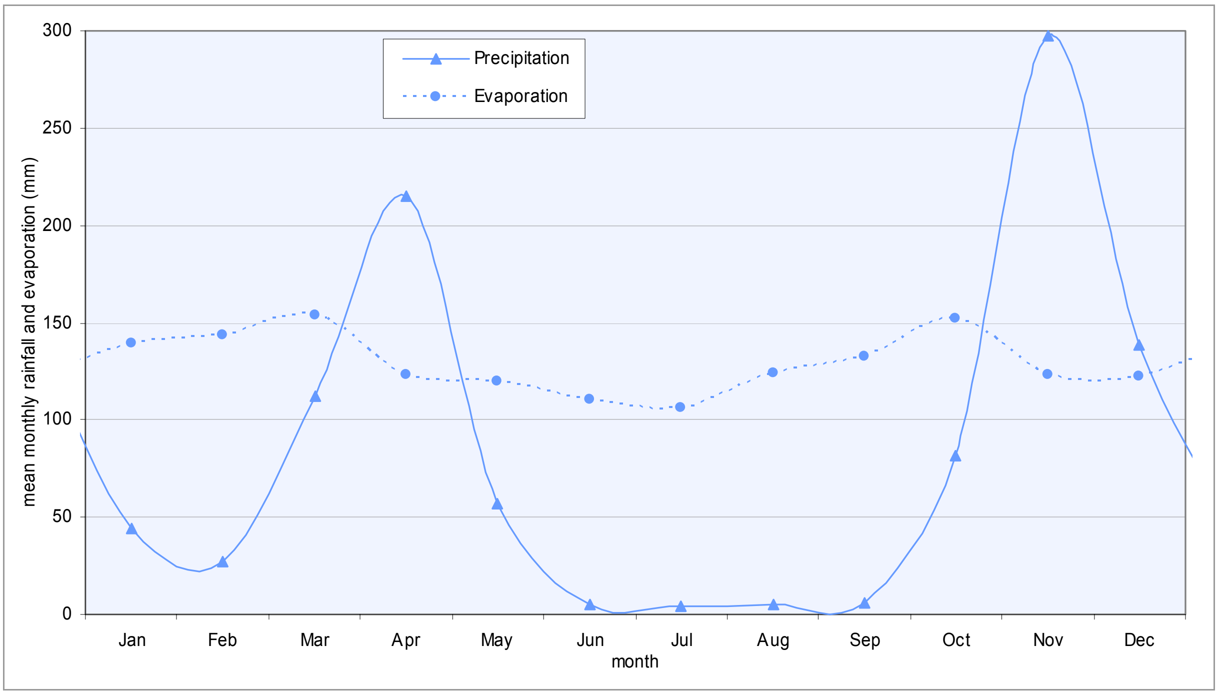

Figure 4.9 Monthly variations of rainfall and evaporation in Kitui

Total annual rainfall in 2005 was 834 mm, 172 mm less than average. During the long rains of 2005 the total amount in rain in Kitui town was 274 mm, while the average is 385 mm. Data for the short rains is not yet available at the time of publishing.

Rainfall in Kitui is, just as in most Semi-Arid areas, characterized by a high spatial and temporal variation in rainfall (Louis Berger International Inc., 1983). Based on the measurements and experiences during the fieldwork this certainly is the case for the Kiindu catchment and surroundings. A number of times it was experienced that a heavy rainfall event in Kitui town had been much less heavy, or had even not occurred in the Kiindu catchment, although it is only 10 km away.
To get an estimation of the rainfall in the Kiindu catchment, the combined rainfall data set for Kitui town has been compared to several other rainfall data sets with a larger spatial extent. The result of the comparison is given in Table 4.1.

Source	Type	Interval	Mean annual precipitation (mm/year)
Combined data set Kitui town	Data sheet	Monthly	1006
DESFIL (USAID, 2001)	GIS Map	Quarterly	907
FAO LocClim (FAO, 2002)	Software program	Monthly	1066
New LocClim (FAO, 2005)	Software program	Monthly	999

Table 4.1 Comparison of sources for rainfall in Kitui town

The interpolated average annual precipitation for Kitui town calculated by New LocClim (v. 1.06, FAO, 2005) resembles the combined data set the closest (1% difference). The LocClim and New LocClim programs use a statistical analysis based on data from about 30,000 meteorological stations around the world to estimate climate data for any location.

The calculated monthly data does also correspond very well with the combined data set. The New LocClim program is thus assumed to be best suitable to calculate the rainfall for the Kiindu catchment. Since New LocClim and FAO LocClim cannot work with UTM coordinates, but require the location to be entered in degrees the following coordinates are used for Kitui town and Kiindu catchment:
Kitui town: lon 38.02°, lat -1.37°, alt 1177 m;
Kiindu catchment: lon 38.00°, lat -1.46°, alt 1040 m.

The New LocClim program has been used to calculate the rainfall in the Kiindu catchment. The calculated rainfall is given in Table 4.2.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
24	37	109	190	41	3	2	4	8	77	280	145	920
(9,8)	(17,0)	(32,7)	(36,0)	(17,1)	(2,2)	(1,1)	(2,3)	(5,2)	(22,9)	(66,6)	(26,6)	

Table 4.2 Average monthly rainfall in the Kiindu catchment in mm (standard error is between brackets)

From the monthly data the enormous differences between the two rainy periods and the dry period can be seen. Table 4.3 shows that of the yearly 920 mm, on average only 17 mm falls in the dry period from June to September.

Long rains (March – May)	Dry period (June - September)	Short rains (October - February)
340 mm	17 mm	563 mm

Table 4.3 Rainfall in the rainy seasons and the dry period

During the fieldwork rain gauges were installed at three additional places around the Kiindu catchment. Figure 4.10 shows the rainfall for these stations for November and December 2005. The tabulated rainfall data is given in Appendix E. Clear differences between the stations indicate local rain events, but can also be caused by errors in the measurements, as the difference between the automatic rain gauge and the manual one show.

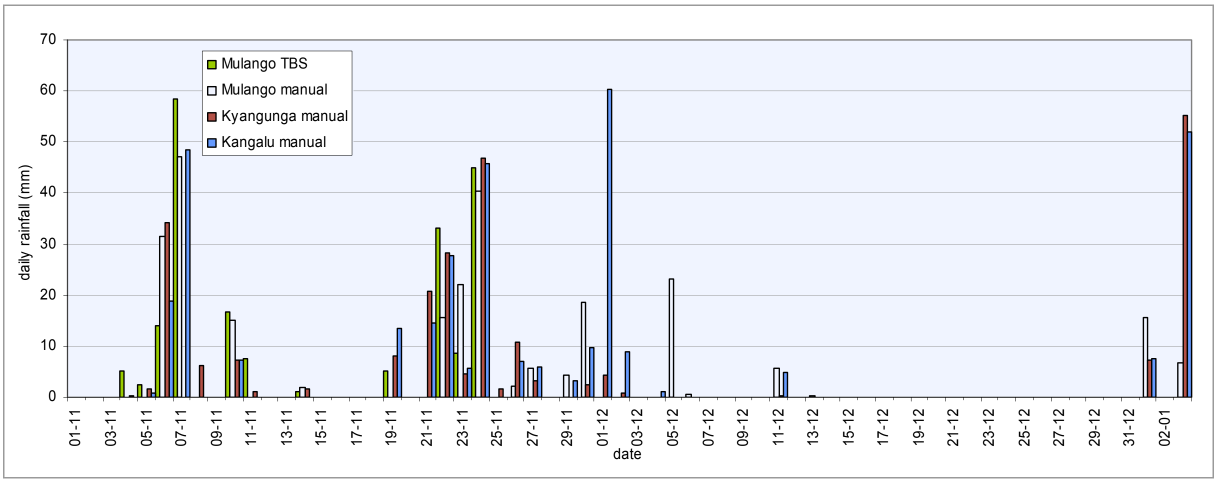

Figure 4.10 Daily precipitation around Kiindu catchment (October – December 2005)

Most of the rainfall events occur during the night, and intensities can be quite high, up to 50 mm/hr (Munyoki, undated). In Figure 4.11 the distribution event in 10 minute time steps of a single rainfall during the night of 6 to 7 November is plotted. The high concentrations and intense start of the event can be seen.

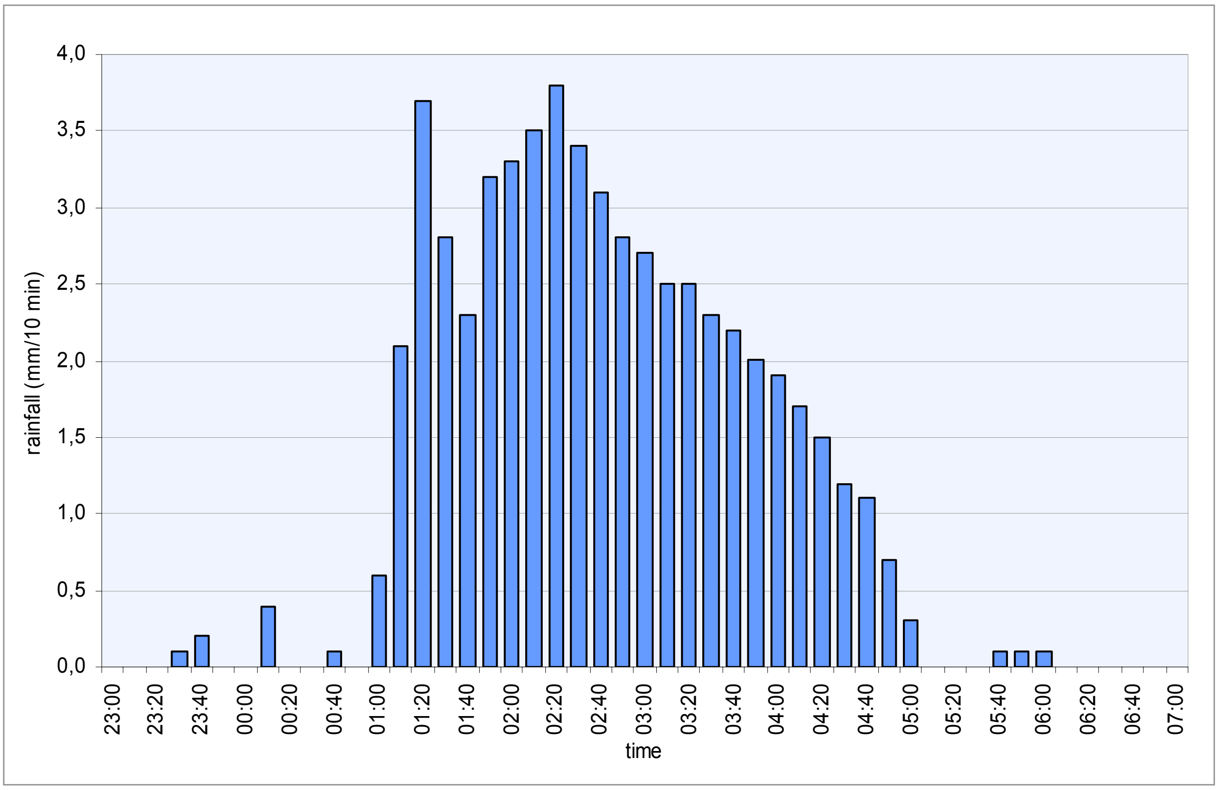

Figure 4.11 Rainfall distribution in 10 minute timesteps of one rainstorm at Mulango Girls's Secondary School

4.2.2 Evapotranspiration

A number of terms and definitions related to evaporation and evapotranspiration exist. As an introduction to this paragraph were sources with different types of evapotranspiration data are compared shows Table 4.4 the definitions of a number of terms related to evaporation and evapotranspiration.

Evaporation	E	Is a term used to describe the amount of water that passes or could pass into the atmosphere across a soil/air, water/air or plant/air interface.
Evapotranspiration	ET	Is often used interchangeably with evaporation but is intended to stress the point that water can cross plant/air interfaces i.e. it is common to use "evaporation" when talking about open water surface and bare soil, but "evapotranspiration" when referring to land surfaces with plants. This is the way the terms are used in this handbook.
Potential evapotranspiration	ET_{pot}	Is the maximum amount of water that can evaporate/transpire from a surface where water availability is not limiting (i.e. a well watered surface or open water body).
Reference crop evapotranspiration	ET_0	Is formally defined as "the rate of evapotranspiration from a hypothetical crop with an assumed crop height (0.12 m) and a fixed canopy resistance (70 s mol) and albedo (0.23) which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water" (Smith *et al.*, 1992). This is commonly known as Penman-Monteith potential evapotranspiration for grass.

Table 4.4 Definition of evaporation and evapotranspiration terms (source: Grayson et al., 1996)

A number of sources of evaporation data were consulted.

Woodhead (1968) determined an empirical relationship between altitude and potential evaporation for Kenya (Louis Berger International Inc., 1983):

$E_0 = 2422 – 0,358 * h$ *Eq. 4.1*

In which:

E_0	= potential evaporation	(mm per year)
h	= altitude	(m)

According to Woodhead (1968) the potential evapotranspiration is 75% of the calculated potential evaporation for high altitudes, and 80% for low altitudes. When Kitui town (elevation = 1200 m) is considered to be at a low altitude (according to the Agro-Ecological Zones map, Kitui is in the Lower midland zone), the potential evapotranspiration is 1594 mm/year.

The USAID's Development Strategies for Fragile Lands project (DESFIL) has created a digital climate map of Kenya for USAID's Office for Foreign Disaster Assistance (OFDA). According to this map, the annual evapotranspiration in Kitui town is 1579 mm.

Puttemans (2004) calculated a reference evapotranspiration (ET_0) of 1661 mm for the Kitui Agricultural station based on data from the FAOCLIM CD-ROM (2000) and the Penman Monteith equation. The required humidity data for the Penman Monteith equation was missing from the FAOCLIM data, so these values have been estimated from the minimum temperature.

The New LocClim program (FAO, 2005) uses an updated version of the FAOCLIM database to calculate a potential evapotranspiration for Kitui town of 1552 mm.

At the Ministry of Water and Irrigation, District Water Office Kitui a meteorological station with a Class A evaporation pan is maintained. Daily pan evaporation values from 2004 and 2005 were obtained from the Ministry. Older data was not available at the office. The average daily pan evaporation is 4.7 mm for this period.
Pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on the evaporation from an open water surface. Although the pan responds in a similar fashion to the same climatic factors affecting crop transpiration, several factors produce significant differences in loss of water from a water surface and from a cropped surface (Allen *et al.*, 1998). The pan evaporation is related to the reference evapotranspiration by an empirically derived pan coefficient:

$ET_0 = K_p * E_{pan}$ *Eq. 4.2*

In which:

ET_0	= reference evapotranspiration	(mm/day)
K_p	= pan coefficient	(-)
E_{pan}	= pan evaporation	(mm/day)

The pan coefficient for the situation at the District Water Office Kitui is determined to be 0.8 according to the guidelines in the FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt, 1977). The annual reference evapotranspiration is calculated to be 1372 mm.

A comparison of the different sources and values of evaporation for Kitui town is given in Table 4.5.

Source	Type	Evaporation (mm/year)	Evaporation (mm/day)
DESFIL	ET	1579	4.32
Woodhead (1968)	ET_{pot}	1594	4.37
New LocClim (2005)	ET_{pot}	1552	4.25
Puttemans (2004)	ET_0	1661	4.55
District Water Office (2005)	ET_0	1372	3.76

Table 4.5 Comparison of evaporation sources

As can be seen in this table values of potential evapotranspiration and reference evapotranspiration do not differ a lot. The data of the District Water Office is thought to be unreliable since during the data collection at the

Ministry it was observed that multiple times there were (large) errors in the measurements and the conversions of units (inches to millimetres). Since the New LocClim data for rainfall were found to be the most reliable and for evaporation this source also agrees well with the other sources, the calculated evaporation from the New LocClim program is used for this research.

Since evapotranspiration is much less spatial variable than rainfall, the calculated potential evapotranspiration in the Kiindu catchment is the same as the potential evapotranspiration in Kitui town: 1552 mm per year.

4.2.3 Sub-surface evaporation

After the rainy season the water level in the riverbed is near the soil surface. The rate of evaporation from a soil will be lower than the evaporation rate from an open water surface because there is not a sufficient supply of water in the soil to be evaporated.

Hellwig (1973a) carried out a number of experiments to relate the effects of grain size and depth of water table to the rate of evaporation. Since water supply from the sand is not a limiting factor when the water table is at the sand surface, Hellwig (1973b) found that the grain size of sand does not affect the rate of evaporation when water level is at the surface. The rate of evaporation from a sand surface however is 8% lower than the evaporation from an open water surface. Probably because of a higher storage of energy in a water body compared to a sand – water mixture, resulting in a larger temperature gradient between the evaporation surface and the air during the night (Hellwig, 1973b).

When the water table drops below the sand surface the rate of evaporation largely depends on the capillarity of the soil. Since the capillarity increases when the sand becomes finer, the rate of evaporation from a fine sand will also be higher than that of a coarse sand. Hellwig (1973c) found that for a coarse sand (comparable to the sand in the Kiindu riverbed) the rate of evaporation decreases to about 30% of the open water evaporation when the water table is at 30 cm below the sand surface, and to about 10% when the water table is at 60 cm below the sand surface.

During the 2005 fieldwork the evaporation from the sand were measured with a sub-surface evaporation pan. Figure 4.12 shows the observed water depth in the sub-surface evaporation pan versus time. The average pan evaporation measured at the Ministry office in Kitui town for this period is 6.2 mm/day. The measured sub-surface evaporation is 2.4 mm/day, about 39% of the measured open water evaporation. Since the evaporation pan which was used is rather small (diameter is 0.5 m), the measured period is short, the temperature of the dry sand around the pan is higher than in the actual situation with a continuous water table, and taking the measuring errors into account, this value seems to correspond quite well to the observations (30% of open water evaporation) of Hellwig.

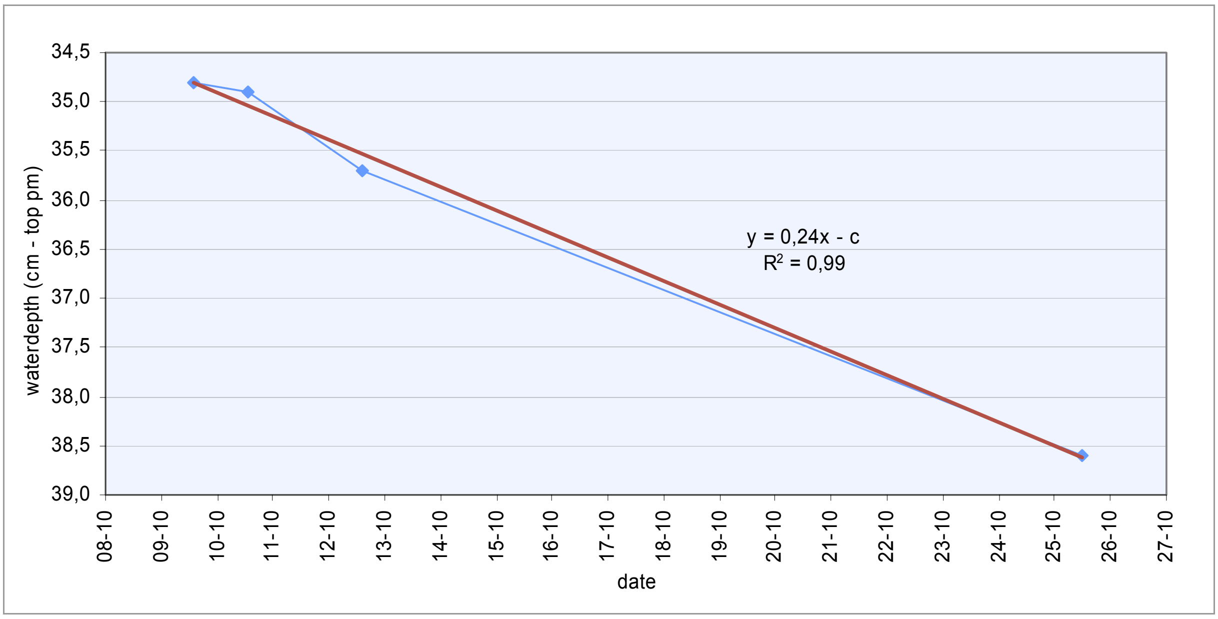

Figure 4.12 Observed evaporation in the sub-surface evaporation pan

4.3. Soils

In the case study area clayey and silty soils are found. The soils have developed on undifferentiated gneisses and are dark grey to brown with sandy clay, clay and silt. The soils are classified as Luvisols and Acrosols (The Consortium for International Development, 1978b).

The piezometers were placed by making boreholes. The borehole data for all separate augerings are given in Appendix F. The elevation of the piezometers and the land surface were measured using a spirit level. Using the borehole data and the spirit level measurements an upstream and a downstream cross-section were constructed. The boreholes were made at the end of the dry season, when the waterlevel was low.

4.3.1 Upstream cross-section

In the Westbank three piezometers were placed (number 1, 2 and 3). Here a clayey topsoil is present. Hardrock was found before the groundwater table was reached at a depth of about 1 ½ meters.

In the riverbed two piezometers were placed in the coarse sand (numbers 5 and 6). Number 5 was placed at the hardrock at 1.7 m below surface level, where no water was present. Number 6 however contained water at 1.7 m below surface level, and hardrock was found at 1.8 m.

Another three piezometers were placed in the Eastbank. In the Eastbank the topsoil consists of fine sand near the river to clayey to loamy material further away from the river. In the borehole a few meters from the river coarse sand was found, which indicated an old course of the river. Conversations with local people already indicated a changing riverbed.
Hardrock was met at varying depth. In the borehole farthest away from the river hardrock was found only at 4.9 m below the surface. Here at 3.85 m below surface water was found. In the other boreholes no water was found.

Using the borehole data the following cross-section is drawn (Figure 4.13). The waterlevel in piezometers 07 and 09 are almost the same, which indicates a connection, either through cracks and fissures, or by the absence of the hardrock outcrop in the longitudinal direction.

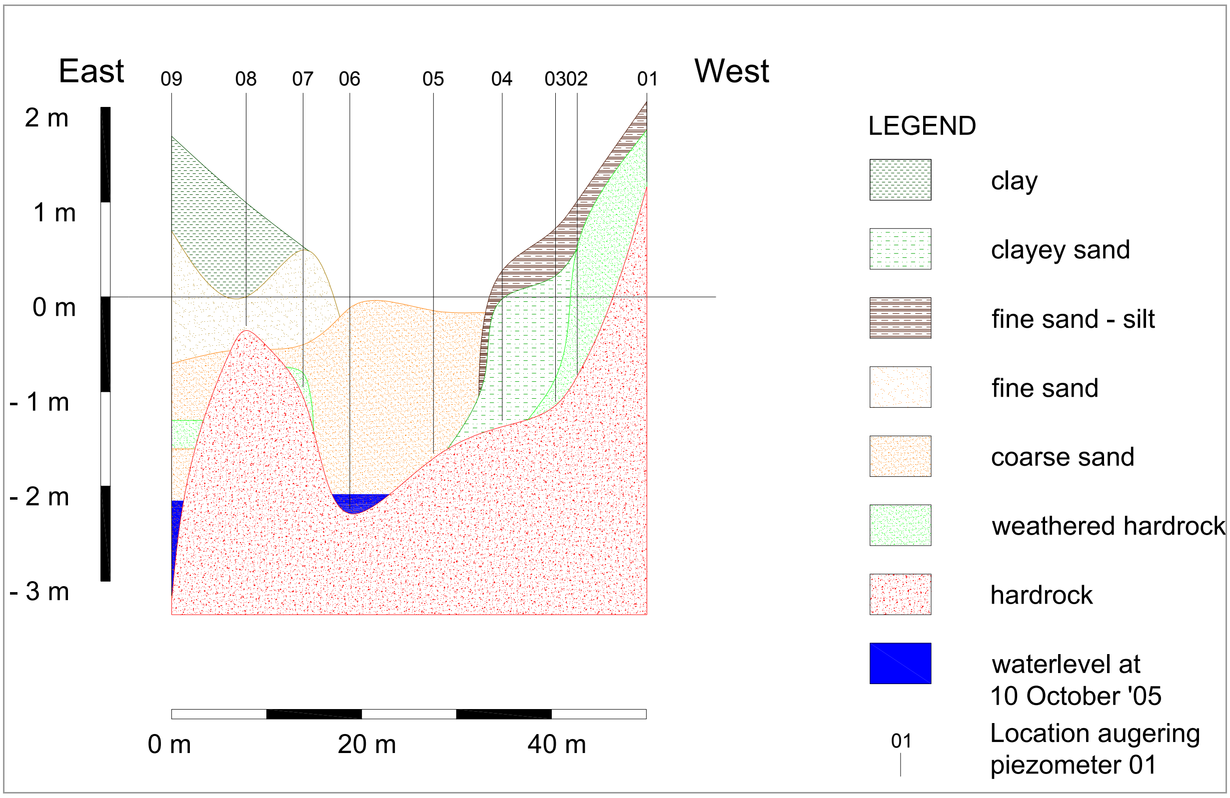

Figure 4.13 Upstream cross-section. The direction of sight is downstream

4.3.2 Downstream cross-section

In the Westbank three piezometers (piezometers 13, 14, 15) were placed until a depth of about 3 ½ m, until hardrock was encountered. The topsoil consists of a 60 cm thick layer of silt and fine sand, overlying a 1 m thick layer of fine sand and sand. A clay layer was also found. Beneath the clay layer coarse sand was found, which is probably riverine sediment from an old river course. In piezometer 14 water was present immediately after placing, but 13 and 15 were dry.

In the riverbed two short piezometers were placed (piezometers 16 and 17). The hardrock was found at about 90 cm beneath the riverbed surface. The riverbed consists solely of coarse sand. Initially both piezometer 16 and 17 were dry.

In the Eastbank four piezometers were placed (piezometers 18, 19, 20 and 21). 19 and 20 are only 1 m apart, so if differences at this small scale exist, it can be seen. The topsoil consists of fine sand and silt, which is ½ m thick close to the river and 1 m thick at 15 m from the river. Under the topsoil coarse sand and weathered rock is present, until a depth of about 1 ½ meter, where hardrock is found.

Using the borehole data the following cross-section is drawn (Figure 4.14).

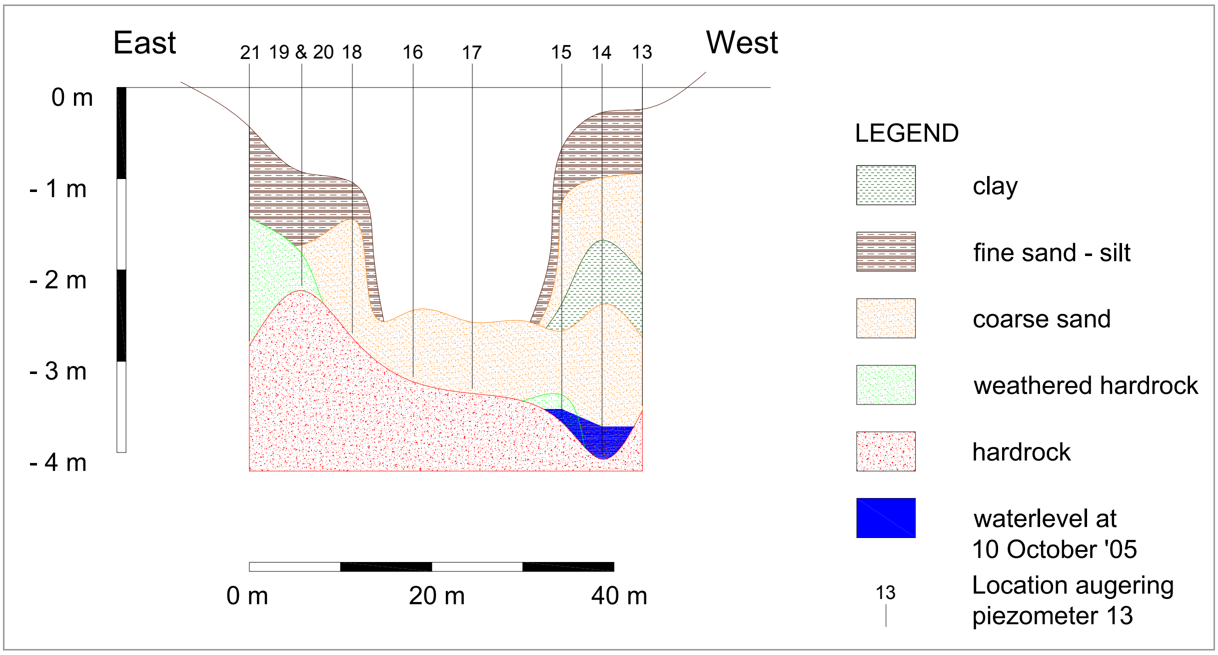

Figure 4.14 Downstream cross-section. The direction of sight is downstream

4.3.3 Midsection

Close to the dam three piezometers were placed in the Eastbank (piezometer 10, 11 and 12). Two were placed a few meters upstream of the dam and one was placed 5 meters downstream of the dam. In this way changes in the groundwater level close to the dam can be seen.

4.3.4 Soil properties

For every piezometer the hydraulic conductivity was tested by means of the inversed auger hole method. The measurements are given in Appendix G.

The hydraulic conductivity can be estimated using the equation:

$$K_s = 1.15r \frac{\log(h_0 + \frac{r}{2}) - \log(h_t + \frac{r}{2})}{t} \qquad \text{Eq. 4.3}$$

In which:

K_s	= hydraulic conductivity	(cm/s)
r	= radius of the borehole	(cm)
h_0	= water level at t1	(cm)
h_t	= water level at t2	(cm)
t	$= t_2 - t_1$	(s)
t_1, t_2	= time	(s)

The lower 5 cm of the piezometer are semi-impermeable, due to construction tape, which results in a slow waterlevel decrease over the lowest 5 cm in the tests.

According to the literature a straight line of time vs. log (waterlevel + ½ x piezometer diameter) should be obtained. However in this case a straight line was not obtained as can be seen in Figure 15 for instance. It is quite normal that the first part of the graph is not straight, but in this case there is no semi-straight part at all (Van Hoorn, undated). With a non straight line the result of the determination of the K-value varies from very high to very low, depending on which part of the line is taken to be representative. Not all tests in all piezometers gave strange results. Piezometers 03 and 12 for instance gave quite nice results. However most tests did not result in a straight line as expected. This can be the result of different causes, but no conclusive cause could be determined. A possible explanation can be that the borehole around the piezometer was not filled with the original material, but with coarse sand, or this method is not suitable for this purpose with a hardrock layer at the bottom.

Since the tests did not result in useful data, these test results were not used.

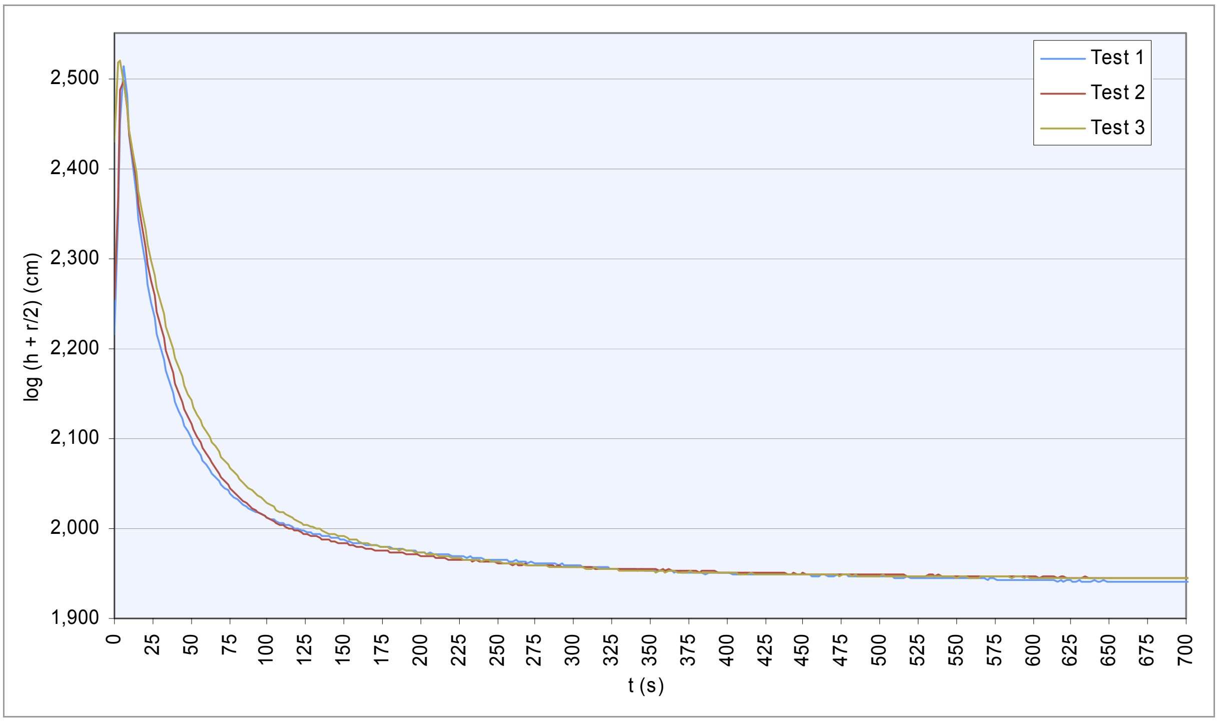

Figure 4.15 Results from inversed auger hole tests in piezometer 15

Values of porosity and specific yield were taken from literature (Domenico and Schwartz, 1998). Specific yield is the available volume of water that can freely drain from a saturated rock or soil under the influence of gravity, and it is normally expressed as a percentage of the total volume of the aquifer (not just the pore space). A part of the water will remain in the soil and can't be used, so the specific yield will be smaller than the porosity.
The hydraulic conductivity was also taken from literature, since the test method failed.

Material	**Porosity** (%)	**Specific yield** (%)	**Hydraulic conductivity** (m/s) (literature)
Coarse sand	31-46	27	$9 * 10^{-7} – 6 * 10^{-3}$
Medium sand	n.a.	28	$9 * 10^{-7} – 5 * 10^{-4}$
Fine sand	26-53	23	$2 * 10^{-7} – 2 * 10^{-2}$
Silt	34-61	8	$1 * 10^{-9} – 2 * 10^{-5}$
Clay	34-60	3	$1 * 10^{-11} – 5 * 10^{-9}$

Table 4.6 Soil properties (Domenico and Schwartz, 1998)

4.4 Groundwater levels

To convert the meandering pattern of the river to a length profile the path of the river has been assumed to be a straight line between a number of fixed points. Figure 4.16 shows the actual path of the river (all the measured scoopholes) and the applied simplification.

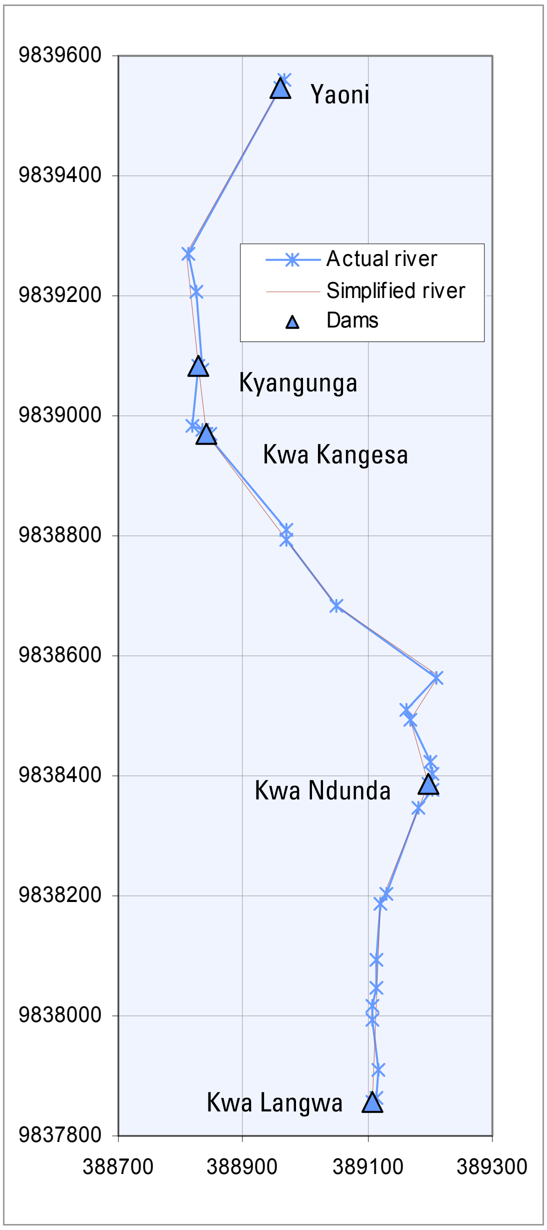

Figure 4.16 Actual and simplified path of river (UTM coordinates)

A formula was used to convert the measured GPS coordinates (UTM projection to a distance along the path of the river. This distance is used to create a longitudinal profile of the river. Figure 4.17 shows the surface level of the sand in the riverbed and the depth of the hardrock measured with the metal rod. The details of the measurements are given in Appendix H. The average gradient of the riverbed between the dams in this area is 0.4 %. The "sand storing" effect of the dams can clearly be seen in this figure as the gradient of the dams is more or less constant with step changes at the locations of the dams.

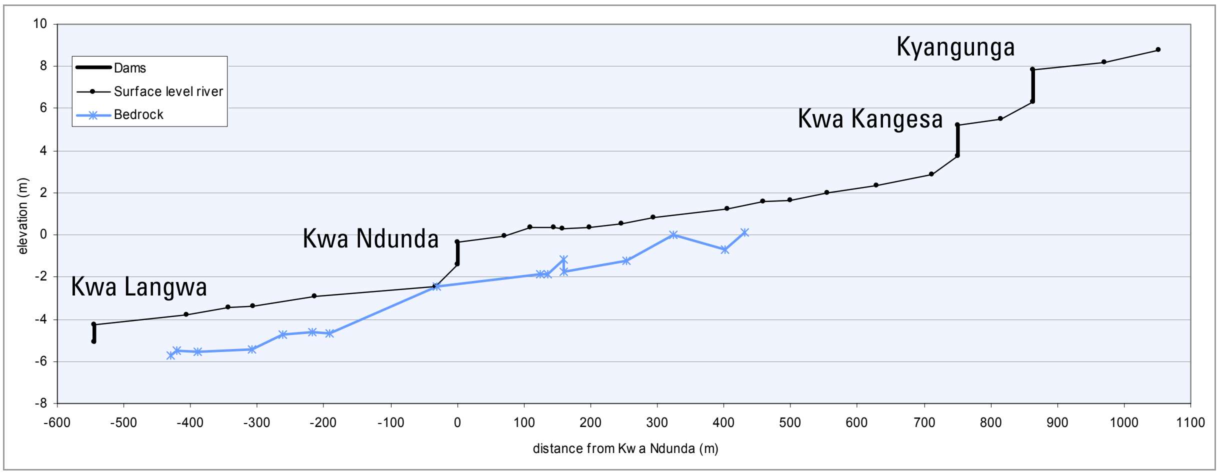

Figure 4.17 Longitudinal profile of the surface level of the river and the hardrock

From the start of the measurements in August up to 5 November, it was (almost) dry and the water level was slowly decreasing. On 6 November, the day after the first heavy rain shower, the water level in a number of scoopholes South of Kwa Ndunda raised rapidly, almost until the sand surface. South of Kwa Ndunda marks of flowing water in the riverbed (silt layers, flow patterns in the sediment, etc.) could be observed. Water had only been flowing during the night during (and shortly after) the rain event, since in the morning of 6 November the river was already dry again.
Some scoopholes where obviously filled with surface water flowing directly into the scoophole (Figure 4.18). The water had deposited a silty layer in the riverbed and on the sides of the scoopholes. In Figure 4.20 it can be seen that the water level South of Kwa Ndunda had risen in those scoopholes, while in others the water level was still low. It appeared to be a local rain event, since North of Kwa Ndunda only locally some evidence of surface water could be observed near gullies and tributaries (Figure 4.19). The water level was still low everywhere.

Figure 4.18 Scoophole filled with surface water during the night

Figure 4.19 Traces of water flowing from a gully

During the night from 6 November to 7 November it rained again and evidence of flowing surface water during and shortly after the rain event were also seen North of Kwa Ndunda. In the morning of 7 November the riverbed was dry again.

A few days later, at 9 November, the water level had risen everywhere along the riverbed and was almost at surface level. Most of the scoopholes had collapsed and were filled with sediment or with water. The week after this there were only some minor rain events and the water level lowered slightly but gradually all throughout the riverbed. Figure 4.20 shows the water levels before the rains (blue line), just after the first rains (yellow line) and a few days after the rains (red line). Note the increase in waterlevel just after the rains in some scoopholes South of dam Kwa Ndunda, while the water level in others remained low.

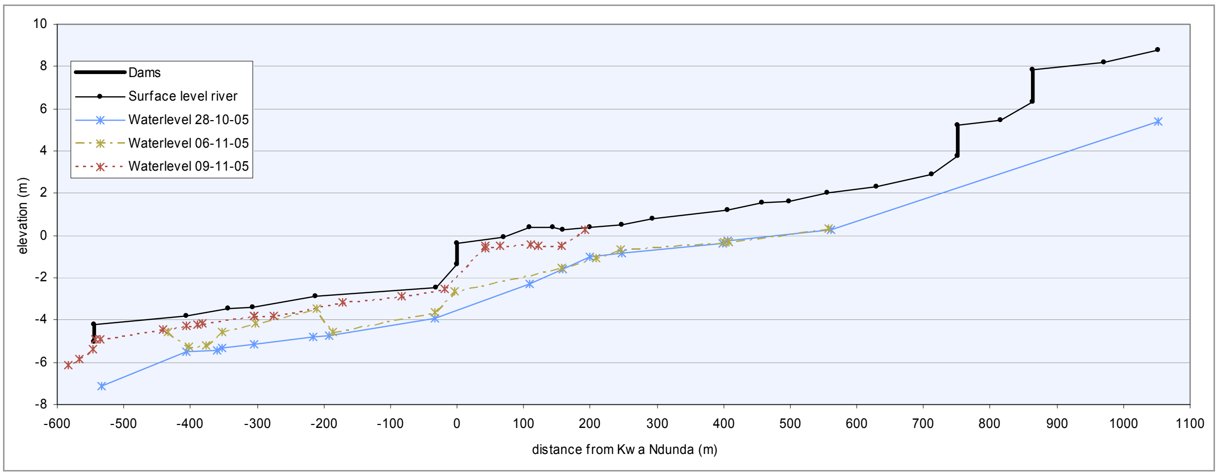

Figure 4.20 Longitudinal profile with changing water levels

Figure 4.21 is a detail of the graph above and clearly shows the effect of a sand storage dam. The dam causes a step change in the water level: just upstream of the dam the water level is 2 m higher than a few meters downstream of the dam. Figure 4.22 shows the same in a photograph of a dam in a catchment near Kitui town.

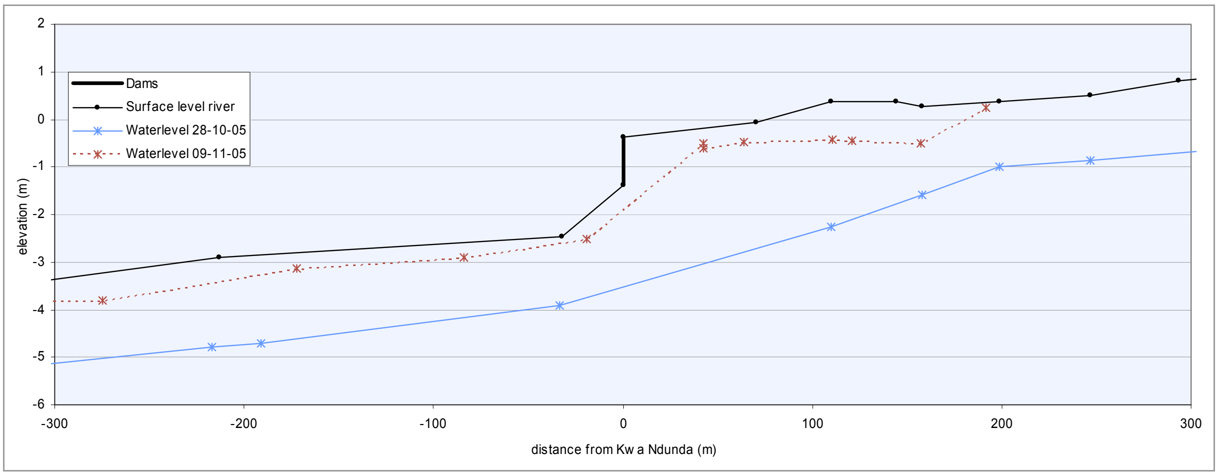

Figure 4.21 Detail of the step change in water levels around dam Kwa Ndunda

Figure 4.22 Waterlevel up- and downstream of a dam at ground level; the dam is approximately 2.5 m high

The water level measured with the Diver datalogger in the riverbed North of the dam (piezometer 6) shows the same trend (Figure 4.23): the first few weeks a gradual decrease of the water level, after the first rains a large and very rapid increase, followed by a decline until the next rain event when the water level rises again. The water level in the banks increases much slower, as can be seen from the manual measurements of piezometer 9 in Figure 4.23.

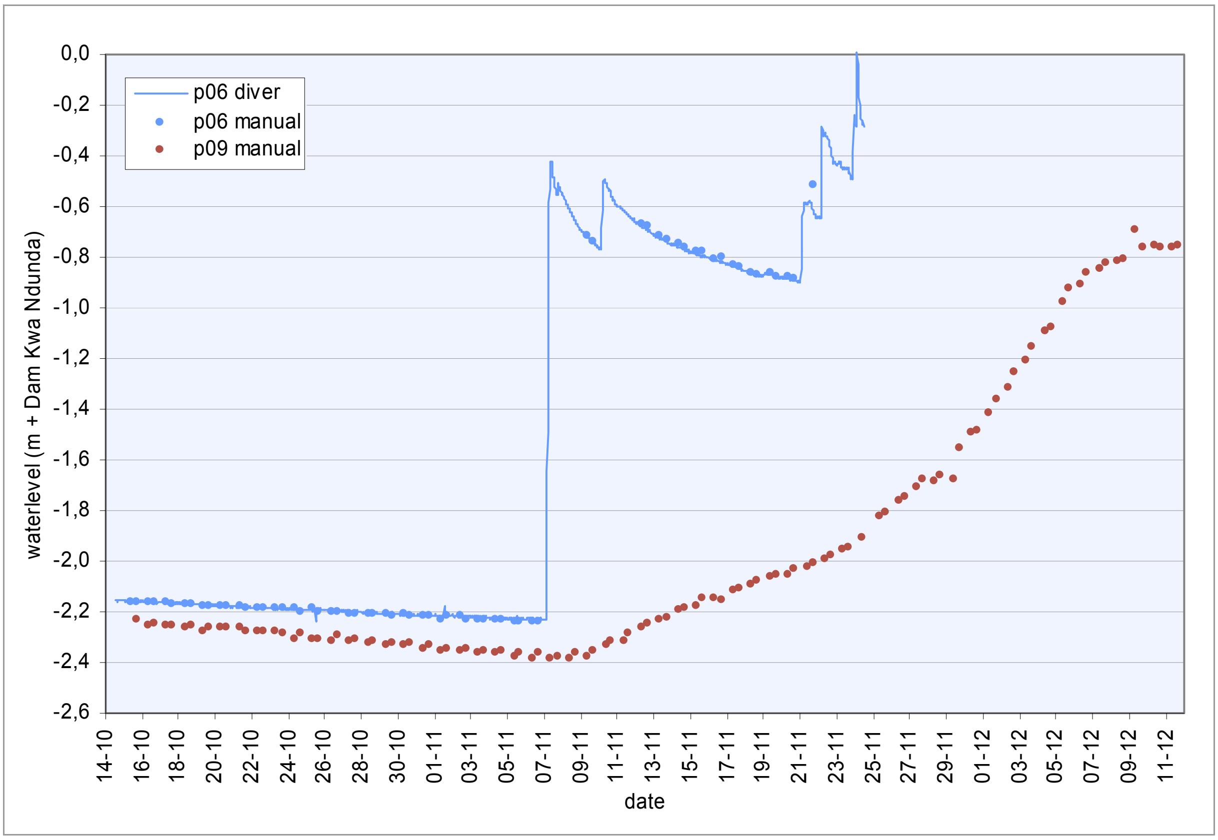

Figure 4.23 Water level in the riverbed and the riverbank (p06 and p09)

Figure 4.24 shows the piezometers in the Southern cross-section. The piezometer the closest to the river shows the first increase, followed by the piezometers a little further from the riverbed.

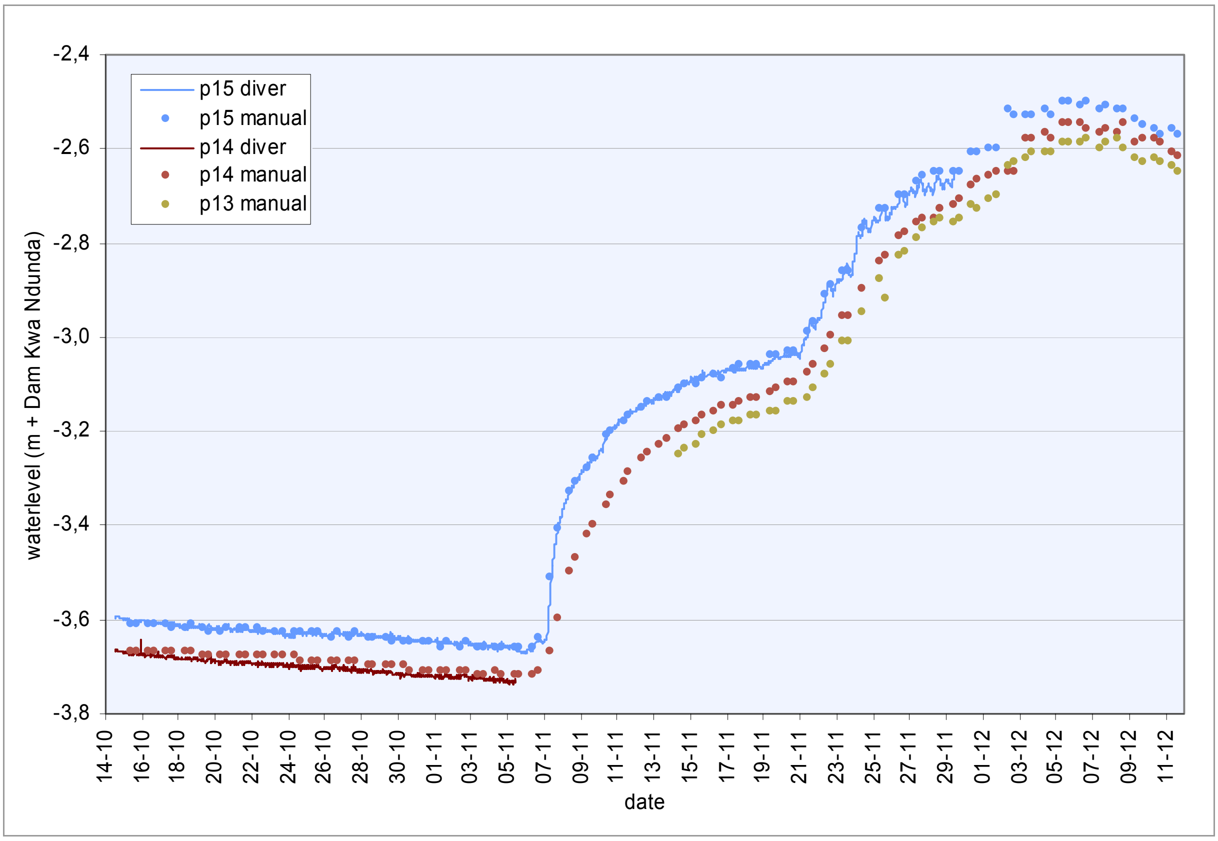

Figure 4.24 Water level in the riverbanks

Figure 4.25 shows the upstream cross-section with the water levels at four times between 16 October and 11 December 2005. At 16 October the water level is observed in only 2 piezometers, since it was not possible to drill the other piezometers deep enough to reach the water table. At 8 November the water level in the riverbed has increased due to the rains in the preceding days, the water level in the bank however is still low, even lower than it was in October. At 24 November the water level in the riverbed has reached the surface level, and in the banks the water has started to rise too. At 11 December, the water level in the river is still almost at surface level, and increasing in the banks.

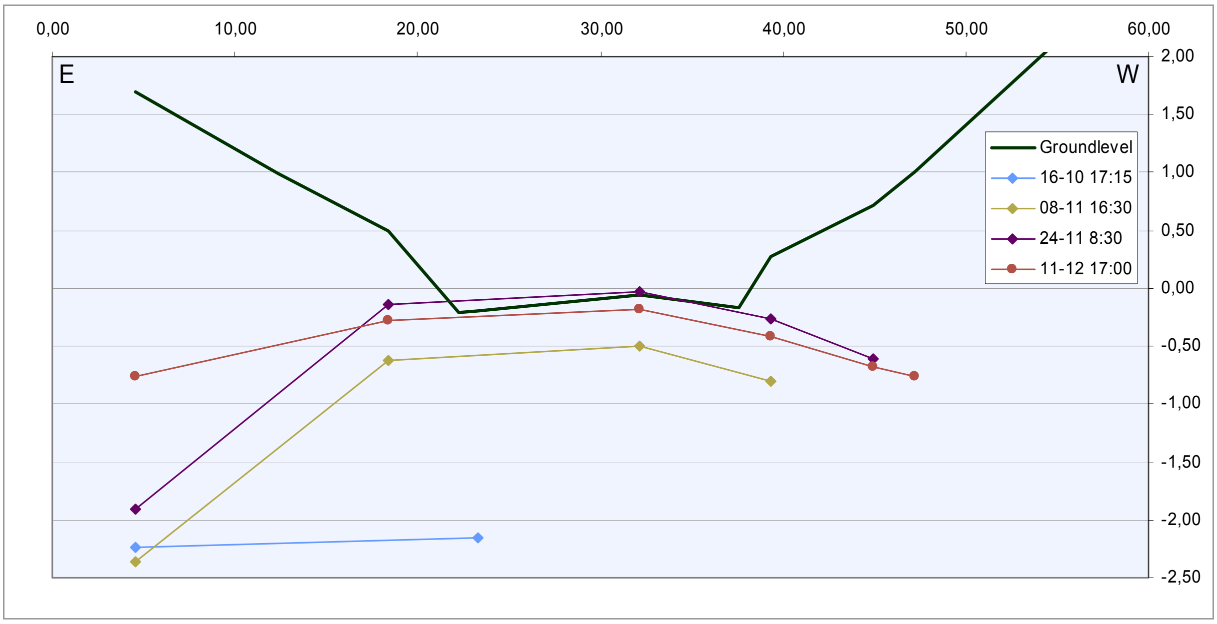

Figure 4.25 Upstream cross-section with changing water levels in time

Figure 4.26 shows the downstream cross-section through the river and the water levels at five times between 16 October 2005 and 3 January 2006. Just as in the upstream cross-section, the water level in the riverbed increases first, followed by the water level in the banks. After a few dryer weeks in December the water level in the riverbed starts to decrease, while the water level in the banks remains high. From 19 December on, the water level in the banks is higher than the water level in the riverbed.

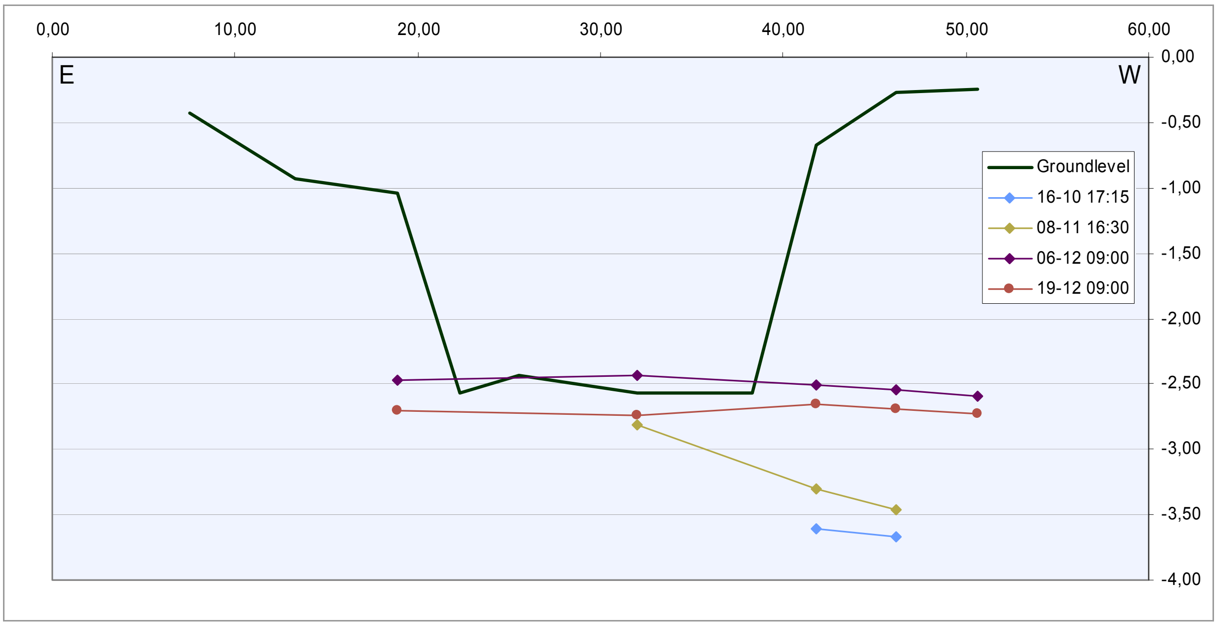

Figure 4.26 Downstream cross-section with changing water levels in time

The measured water levels in all piezometers are tabulated in Appendix I and graphs of the water levels are plotted in Appendix J.

4.5 Groundwater quality

The EC in the scoopholes and wells along the river was also measured a number of times. Within a short distance, large variations in salinity are observed. EC's vary between less than 1000 μS/cm to more than 20,000 μS/cm. The highest EC's are generally observed in a scoophole just South of dam Kwa Ndunda, although during the first weeks at less than 40 m from the saline scoophole with an EC of 10,000 μS/cm there was another scoophole which had an EC of only 1,600 μS/cm.

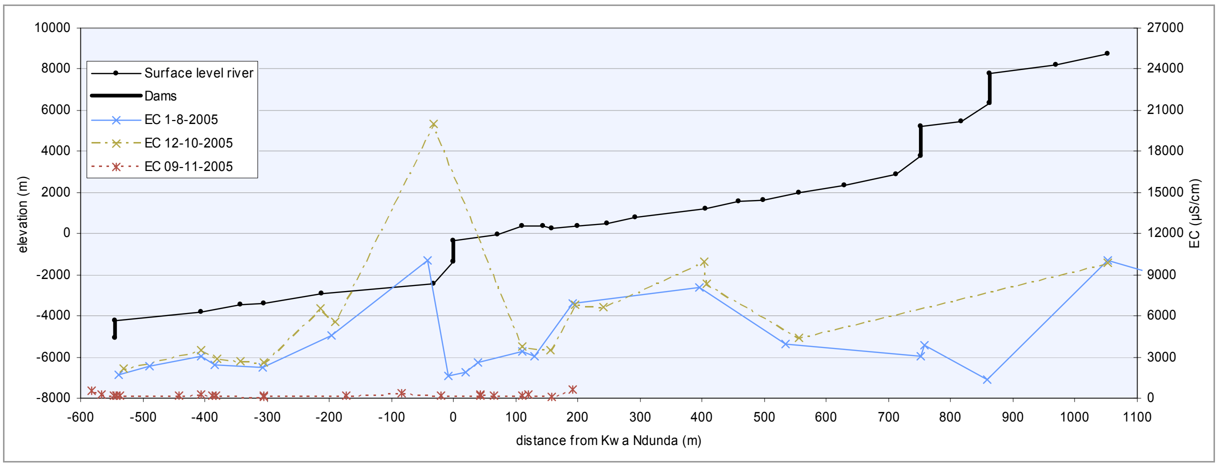

Figure 4.27 Longitudinal profile with EC

After the first rains the EC was everywhere below 600 μS/cm and the water in the scoopholes and wells, even the ones that were not in use, had a brown/orange colour. Since even the wells that had not been in use did have this colour, it could not be caused by disturbance after infiltrating into the well, but it should have been brought in with the water. It was assumed that the colour is caused by very fine sediment particles in the water that could even be transported between the grains of the sand in the riverbed. To check this, a sample from a well was taken and let to settle for a few days. The water sample before and after settling can be seen in Figure 4.28.

Figure 4.28 Sample with water from a well before (left) and after (right) settling

4.6 River discharge

Since rainfall events occur mostly at night, most of the river discharge occurs at night as well. After about 3 weeks of nightly rains and discharges, the river was expected to discharge small quantities continuously.

The discharge was only measured at two days. During the field campaign flowing water in the river was only encountered at the very last day. The discharge was estimated at 23 November 2005 at 23:00 (Figure 4.29) and at 24 November at 10:00 (Figure 4.30). with discharges of 0.2 m^3/s and 0.02 m^3/s respectively.
The water level was measured in piezometer 06 by a Diver (Figure 4.31). The water level in the piezometer will be about the same as the surface water level, because this piezometer is situated just next to the course of the river. This can be assumed, since after 2 weeks of rains, the sand in the riverbed was fully saturated.

Figure 4.29 Discharge at 23 November 23:00: 0.2 m^3/s

Figure 4.30 Discharge at 24 November 10:00: 0.02 m^3/s

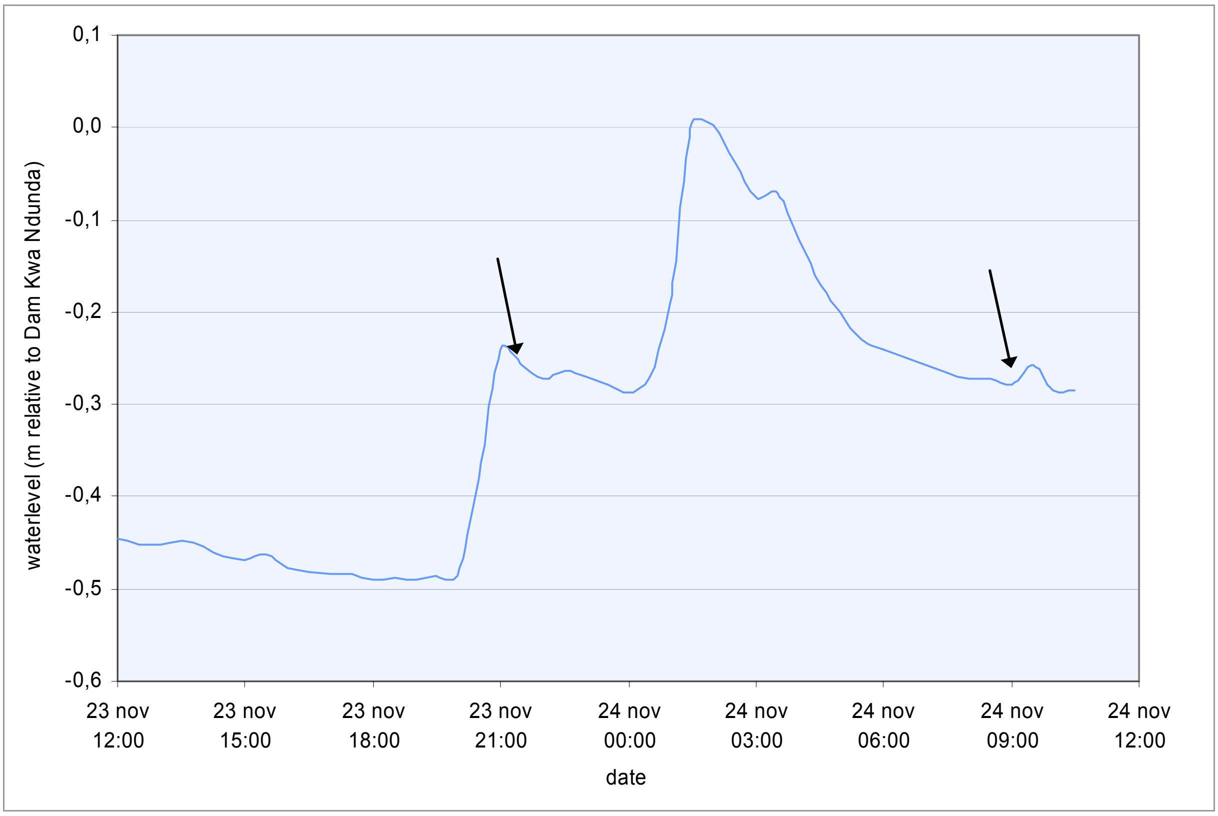

Figure 4.31 Water level in piezometer 6 at 23 and 24 November, on which discharge estimates were made. The arrows indicate the moments of discharge estimates

As can be seen in the photographs and the graph the water level at the two moments is almost the same, but the estimated discharge differs by a factor of 10. This is probably because of small differences in the height of the spillway, due to which the river flows over the total width (23 November) or only a small part (24 November). Due to differences in river width the discharge differs a lot, while the waterlevel remains almost the same.

5 Hydrogeological system sand storage dams

5.1 Introduction

In the following two paragraphs the hydrogeological system around the sand storage dams in the Kiindu catchment is described. This description is based on the observations and measurements in the Kiindu catchment, but will probably also apply for sand storage dams in similar environments.

5.2 Development of a sand storage dam aquifer

After the construction of a sand storage dam the first few years the area upstream of the dam is not fully sedimented, so a surface water pool will form during the rainy season (Figure 5.1). During and after the flood sediment will accumulate upstream of the dam.

Figure 5.1 Surface water pool behind a recently constructed dam

Based on the observations in a large number of scoopholes (about 100) in a number of catchments around Kitui town, these sediments mainly consist of coarse sand (locally small gravel and/or silt layers are found). The larger particles will sedimentate first, followed by finer particles. Based on the observations and interviews with people who are involved in the construction of dams the finer particles that have sedimented upstream of a dam are taken away during the next flood (Figure 5.2). The flood works around and takes up sediment from the top part of the sediment upstream of the dam. Since this top part contains the highest concentration of fine particles and these fine particles are also taken up in suspension more easily, most of the fine particles are taken in suspension and transported over the dam, leaving behind only the coarse sand. This process will repeat itself, thus increasing the level of the coarse sand behind a dam while the finer particles are removed by every flood (Figure 5.3).

Figure 5.2 Sediment flowing over a dam

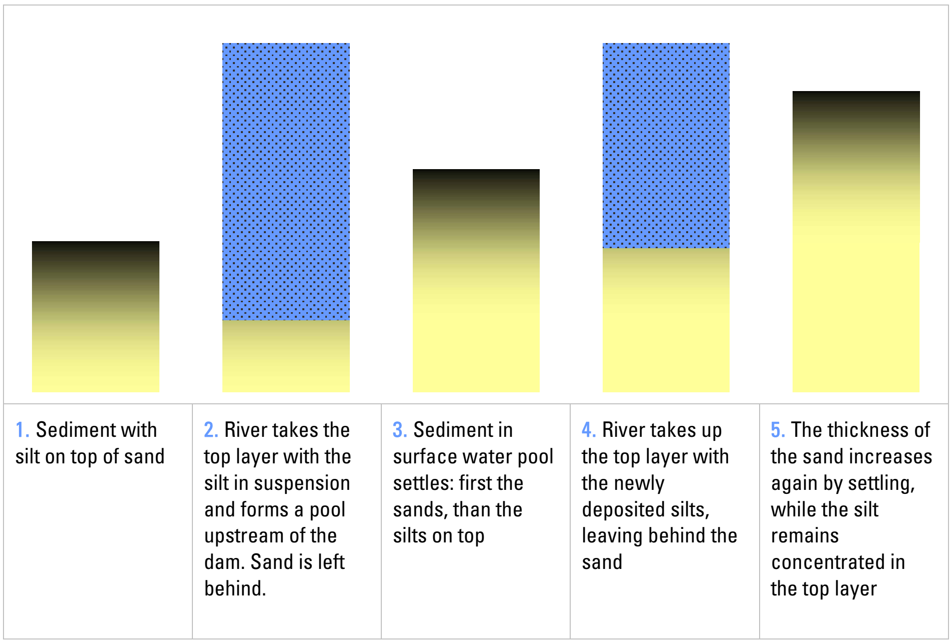

Figure 5.3 The process of sedimentation upstream of a sand storage dam

After 5 to 7 years the dam is 'mature': the area upstream of the sand storage dam is fully filled with sand up to the level of the spillway of the dam. The following description of the hydrogeological system of sand storage dams focuses on the system around mature dams.

5.3 Hydrological functioning of a sand storage dam aquifer

5.3.1 Filling of the sand storage dam aquifer

Rainfall in the Kiindu catchment is characterized by heavy rainfall events, mostly during the night.

Only a minor part of the rain will infiltrate in the soils on the slopes of the catchment, since they mainly consist of bare, low permeable, clays and silts and the slopes are poorly protected against erosion. Since the rainfall intensity is larger than the infiltration rate a large part of the rain will flow as overland flow (Horton overland flow) towards the riverbed, either directly or via an uncontrolled gully or one of the tributaries. Since most of the land is bare at the start of the rainy season leaving the soils poorly protected against soil erosion, the silt and sand load in the water is high.

The coarse sands in the riverbed will allow a rapid infiltration of the water into the sand. During the first few rain showers this will lead to a large and rapid increase in the groundwater level in the riverbed (Figure 4.23). The river will only flow for a short period during and shortly after the rains, which was observed during the first rains of the fieldwork, and was described by local inhabitants.
The first flush of runoff from the banks will bring a large amount of erosion material with it, after the first few rains the coarse sand of the riverbed was covered with a few centimetres thick silt and clay layer (Figure 5.4). This silt layer will decrease the infiltration capacity of the sand, but since the river only flowed a few hours during and directly after the first rains (after this all the water had infiltrated) this silt layer is most probably formed after most of the water has already infiltrated.

Figure 5.4 Silt layer on top of the coarse sand of the riverbed

Remarkably a large part of the silt was removed during a few dry days after the deposition. Once the silt has dried (which happens within a day) people and cattle walking in the riverbed will pulverize and grind the silt layer into fine particles. These small particles are easily blown away by wind. Subsequent surface water flows during the next weeks will also take away a (large?) part of these fine particles.
During the first few floods the surface water in the riverbed will sometimes flow directly into a scoophole. It was observed and measured that the morning after the first rains the water level in a number of scoopholes into which the surface water had flown directly was very high, while the water level in others (where no surface had flown into) was still low (Figure 5.5).

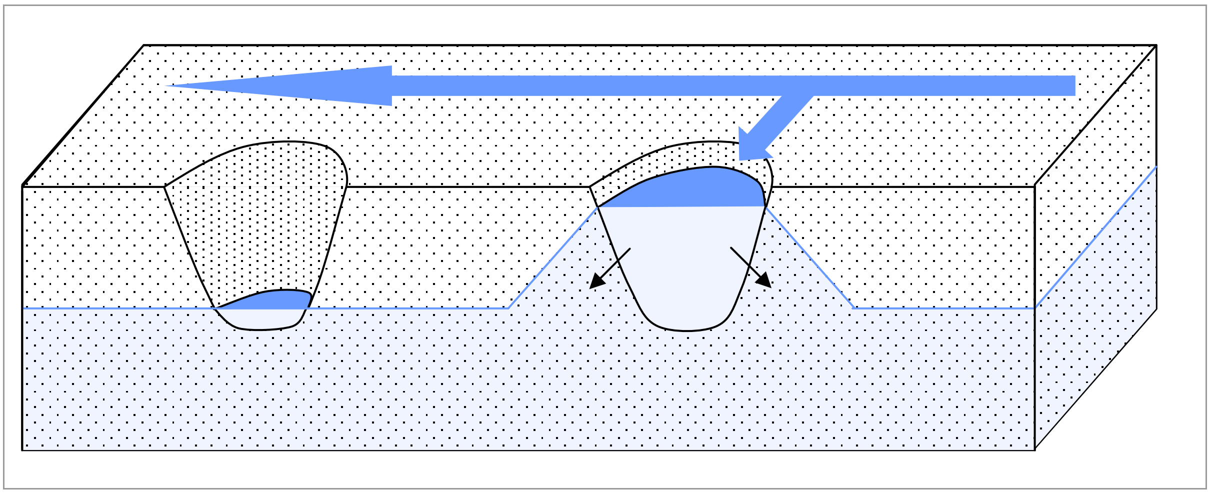

Figure 5.5 River water flowing into a scoophole, while the waterlevel in an other scoophole remains low

From a silt layer which is deposited on the sides of the water filled scoopholes it can be seen that the water level had lowered quite rapidly since the surface water flow had stopped (Figure 5.6). Since the water level in the scoopholes filled with surface water was high, but the water level in the other scoopholes was still low the water is infiltrating from the water filled scoopholes into the sand of the riverbed. The small silt layer did not obstruct this, but only reduced the speed of this process. A few days later the groundwater level in all scoopholes had flattened out and was at an equal depth relative to the surface level in all scoopholes.

Figure 5.6 Silt layer on the sides of a scoophole

Once the sand in the riverbed is fully saturated, the discharge of the river will increase and the river will start to flow for a longer period. Based on the descriptions by local people the river will flow for a few weeks after the rainy season, depending on the amount and intensity of the rains.
The increased amount and velocity of the water will disturb the sediment in the riverbed, take the remaining silts into suspension and discharge them downstream over the dam.

Based on the measurements of the groundwater levels the increased water level in the riverbed will induce a sideward flow of groundwater from the riverbed towards the riverbanks (Figure 4.25). After a few weeks the water level in the banks has reached the same level as the water level in the riverbed and the sideward flow will stop.

5.3.2. Emptying of the sand storage dam aquifer

Once the rainy season is over, the water level in the riverbed will start to decline due to a number of reasons. Firstly a part of the water will evaporate from the sand. Since evaporation is decreased by 90% when the water level is at 60 cm below the sand surface, evaporation will only take place if the water level is less than 1 m below sand surface. Secondly water will flow slowly through the weathered top layer of the hardrock and through cracks and fissures in the hardrock. A part of this water will flow downward and recharge the deep groundwater. Another part might flow in longitudinal direction through the weathered top layer of the hardrock (shallow longitudinal baseflow) or trough cracks in deeper parts of the hardrock (deep longitudinal baseflow) and seep back up in the riverbed somewhere downstream of the dam. Thirdly, groundwater flow around the dam through the riverbanks and leakage through and underneath the dams is another component of loss from the sand reservoir. In the case of a series of cascading dams in one river, as in the case of the Kiindu river and most of the SASOL dams, this water will return into a downstream sand storage dam aquifer and will remain available for the water supply (Figure 5.7). Fourthly and finally, a significant part of the water will be extracted by humans and animals as drinking, cooking and irrigation water.

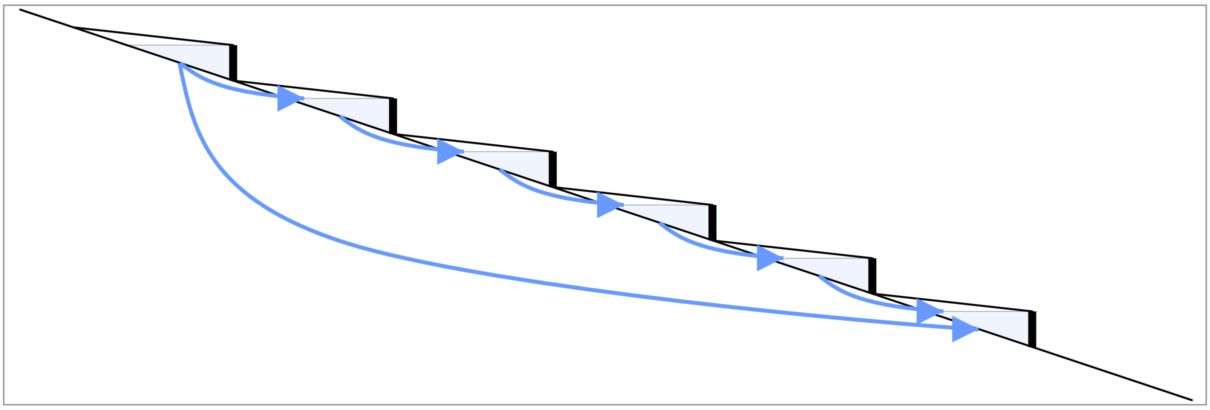

Figure 5.7 Schematic longitudinal section with longitudinal baseflow (shallow and deep)

The groundwater in the riverbed will however be replenished by slow groundwater baseflow from the slopes. Part of the water from rainfall that has infiltrated into the soils will be evapotranspirated. The remaining part will flow as interflow (lateral movement of percolated water) towards the river and will reach the groundwater table. This groundwater will, under the influence of gravity, flow slowly down towards the river, recharging the groundwater in the riverbed.

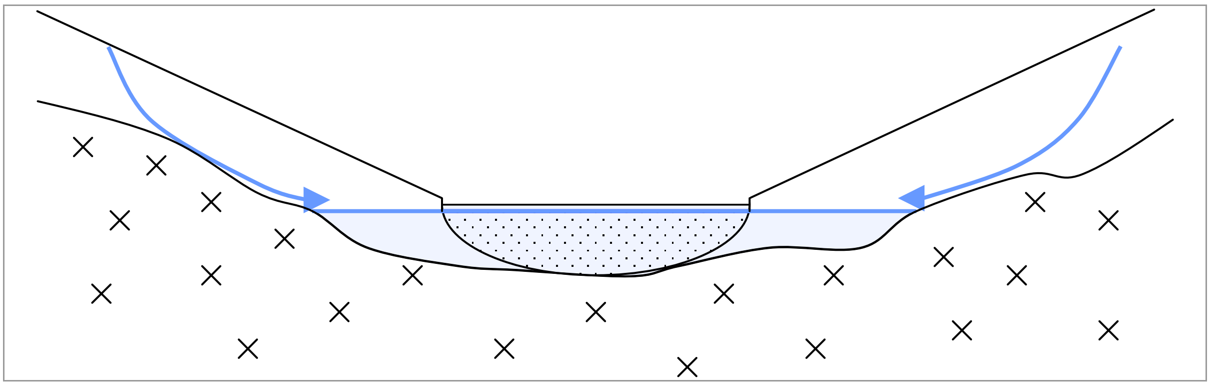

Figure 5.8 Schematic cross-section with lateral baseflow

Because of evaporation and use of water from the riverbed, the water level in the riverbed will decrease more rapidly than the water level in the riverbanks. Once the water level in the riverbed is lower than the water level in the banks a baseflow from the riverbanks towards the riverbed will occur, and thus increasing the amount of available water in the riverbed. This was observed in the Southern cross-section (Figure 4.26). The water level in the riverbed will continue to decline until the start of the next rainy season. The process is schematically depicted in Figure 5.9.

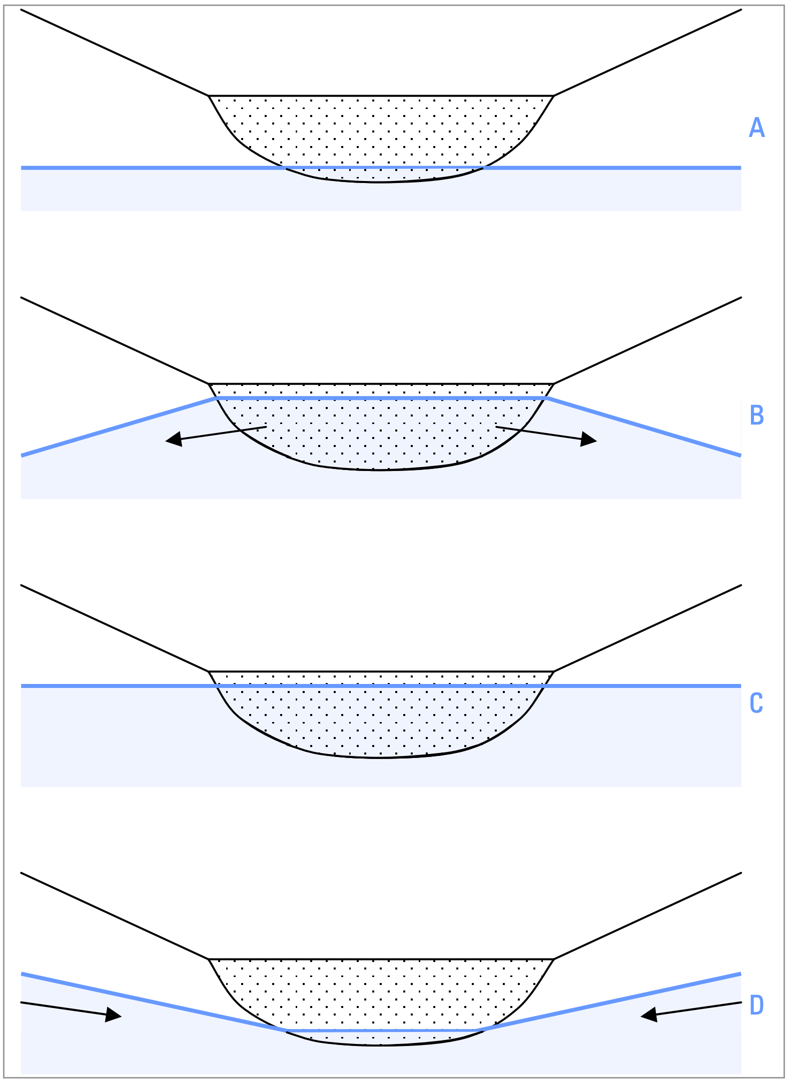

Figure 5.9 Schematic cross-sections over the riverbed: low water level (A), recharge from the riverbed to the banks (B), high water level (C) and recharge from the banks to the riverbed (D).

5.4 Water balance of the sand storage dam catchment segment

5.4.1 Introduction

To get insight in the different fluxes and amounts of water in the system around a sand storage dam a water balance was set up. All potentially present fluxes are discussed, so in other situations this balance can be used as a guide. The main aim of putting up this water balance is to determine the amount of water available for human use and the effect of sand storage dams on this amount.

Only the part of the catchment that directly drains to the part of the river between two dams is taken into account for the water balance (Figure 5.10). This makes the water balance independent of the location of the dam in the total catchment. The segment is also independent of differences in a.o. runoff and precipitation in the upstream part of the catchment. By doing this, the study can easily be repeated for other areas or catchment segments. The water balance is set up for the catchment segment between the dams Kwa Kangesa and Kwa Ndunda.

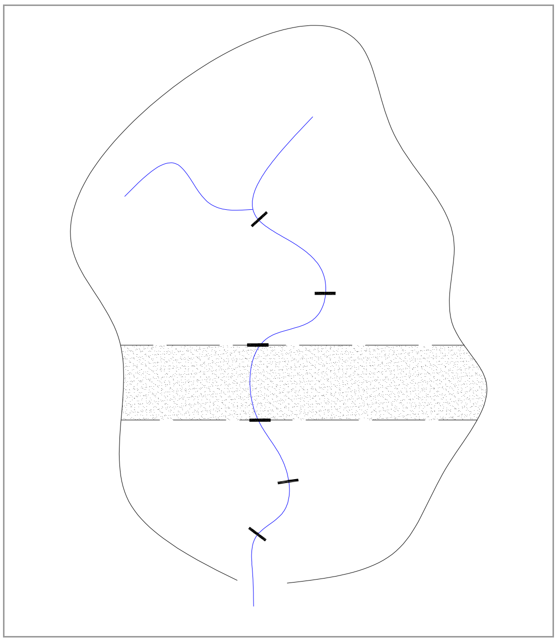

Figure 5.10 Schematised catchment with the segment of the catchment that is taken into account into the water balance

A standard water balance consists of input (I), output (O) and change of storage (ΔS):

$$I = O + \Delta S$$ *Eq. 5.1*

When it is assumed that the system is in equilibrium, then ΔS is 0 (zero) and the equation becomes:

$$I = O$$ *Eq. 5.2*

In the sand storage dam case fluxes within the system also occur, which will be quantified. Table 5.1 gives all inputs, outputs and fluxes within the system and the schematised system is given in Figure 5.11.

Input		Fluxes in system		Output	
Precipitation	P	Surface runoff from slopes to river	R	Outflow from leakage through and around dam	L_{out}
River discharge inflow over upstream dam	Q_{in}	Lateral baseflow from recharge higher parts of the banks	B_s	Evapotranspiration from hillslopes	ET
Inflow from leakage through and around upstream dam	L_{in}			Recharge from riverbed and banks to basement aquifer	G_r
Shallow and deep longitudinal baseflow	$B_{l\,in}$			Evaporation from riverbed	E
				Shallow and deep longitudinal baseflow	$B_{l\,out}$
				River discharge outflow over the downstream dam	Q_{out}
				Abstractable water by people and animals	U_p

Table 5.1 Overview of potential fluxes in catchment segment

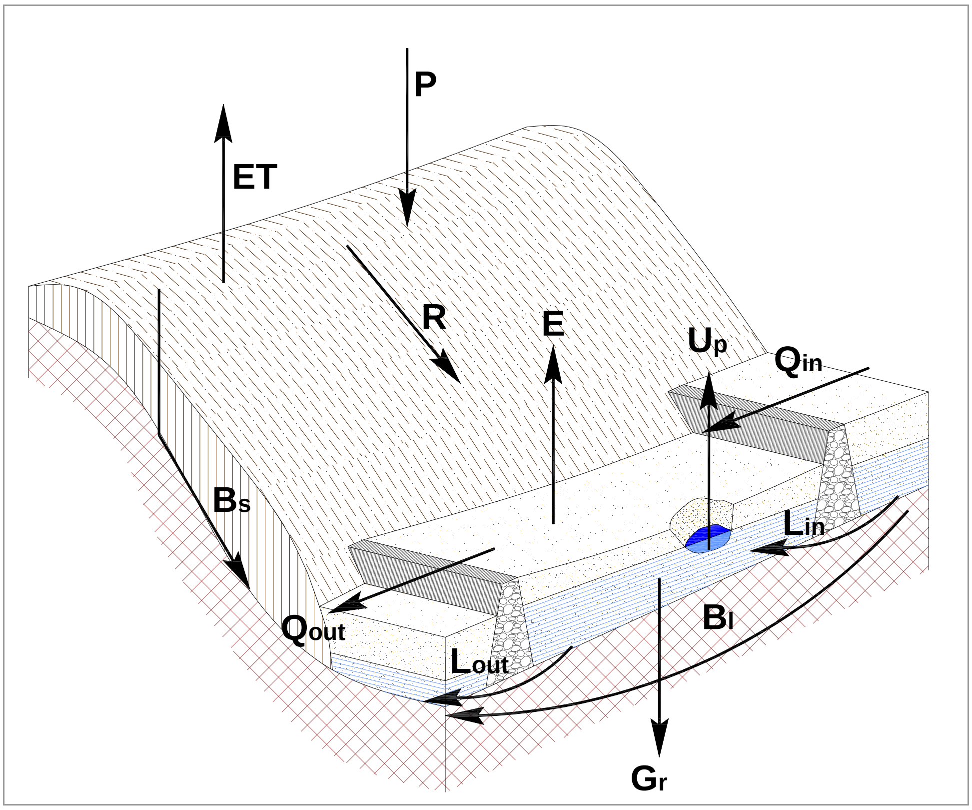

Figure 5.11 Schematic water balance of the sand storage dam

Since it is said by critics of the sand storage dam concept that less water might be available downstream, the ratio of the amounts of water that is retained by the dam over the total runoff is calculated. A comparison with the situation without a dam is also made.

For the study area the length of the river segment is measured to be 660 m. The average width of the catchment segment is 1750 m according to the topographical map. This makes the study area between the dams Kwa Kangesa (upstream) and Kwa Ndunda (downstream) approximately 1.2 km^2.

The water balance of the sand storage dam is put up for two periods: the period from the start of the long rains to the start of the short rains (March – October), and the period from the start of the short rains to the start of the long rains (November – February). The season from March to October is taken to be 256 days, and the season from November to February 109 days. Some components are the same in both situations, where others are depending on the season.

A basic assumption of the water balance set up here is that the reservoir behind the dam is empty at the start of the rainy period. In reality some water still may be in the reservoir.

5.4.2 Inputs

P - Precipitation

The precipitation differs between the long and short rains. The average precipitation is determined at 357 mm for the season from March to October and 563 mm for November to February (New LocClim, 2005). For the total catchment segment this means a total volume of 412,335 m^3 during the March to October season and 615,265 m^3 during the November to February season.

Q_{in} - River discharge inflow over upstream dam

The inflow of surface water over dam Kwa Kangesa is a significant amount of water with respect to the other components. However, the effects of one dam on its catchment segment are being studied, so the river discharge inflow is left out of the calculation. In a later stadium, the inflow can easily be added to the inputs.

L_{in} - Inflow from leakage through and around upstream dam
The dams themselves and their foundation are not completely impermeable. A part of the water can flow underneath and around the upstream dam Kwa Kangesa through the soil, adding to the reservoir behind Kwa Ndunda.
However, the downstream dam, Kwa Ndunda, will also have some leakage, which is subtracted from the study area. The water leaking from the Kwa Ndunda again will add to the catchment segment downstream. The inputs by leakage through and around the upstream dam are assumed to be equal to the amount of outflow from leakage trough and around the downstream dam, so the net effect of this component is assumed to be zero.

It should be noted however that in a real situation the input will not be equal to the output due to local differences in dam construction, cracks in the hardrock, etc. For one dam the input will be larger than the output, while for another it will be the other way round. For a series of dams the net effect will be zero.

B_{lin} - Shallow and deep longitudinal baseflow
Behind one dam water infiltrates in the hardrock and can flow through cracks and fissures. This water can surface downstream, adding up to the amount of water there. This flow can occur both at shallow and larger depths.
The input of longitudinal baseflow from upstream infiltration is assumed to be equal to the output of locally originated baseflow, so the net effect becomes zero, similar to the inflow and outflow through and around dams.

5.4.3 Fluxes within the system

R - Runoff on hillslopes
Part of the precipitation that falls in the catchment segment will flow down as surface runoff (R) towards the river. The part that runs off is calculated using the runoff coefficient. The runoff coefficient differs per season, since rainfall intensities differ between the two rainy seasons. Since the daily rain intensity of the November rainy season is smaller than that of the March rainy season, more water is able to infiltrate in the soil in November, leaving less water left to run off.
Close to Kitui town in Kalundu catchment measurements of runoff were carried out by Louis Berger International Inc. (1983). The average runoff coefficients for the March - October period were found to be about 50%, and for the period November – February it was found to be 30%. Although some differences exist between the two catchments, such as the catchment size (Kalundu catchment is a few times larger than the Kiindu catchment), these runoff coefficients are taken as representative values for the Kiindu case, since slopes, geology and soils are believed to be more or less the same. The total runoff towards the river then will be 206,168 m^3 and 195,080 m^3 for the March to October and the November to February seasons respectively.

B_s - Lateral baseflow
In Figure 5.12 the fluxes on the hillslopes are shown. As just describes, a part of the precipitation will flow down as surface runoff. The remaining part of the precipitation will infiltrate in the soil or evaporate immediately. The infiltrated part will evapotranspirate or recharge to the groundwater in the basement aquifer. The latter will flow down towards the river and add to the volume in the riverbed. This amount is called the lateral baseflow (B_s), which flows through cracks in the upper part of the hardrock and on the surface of the hardrock.

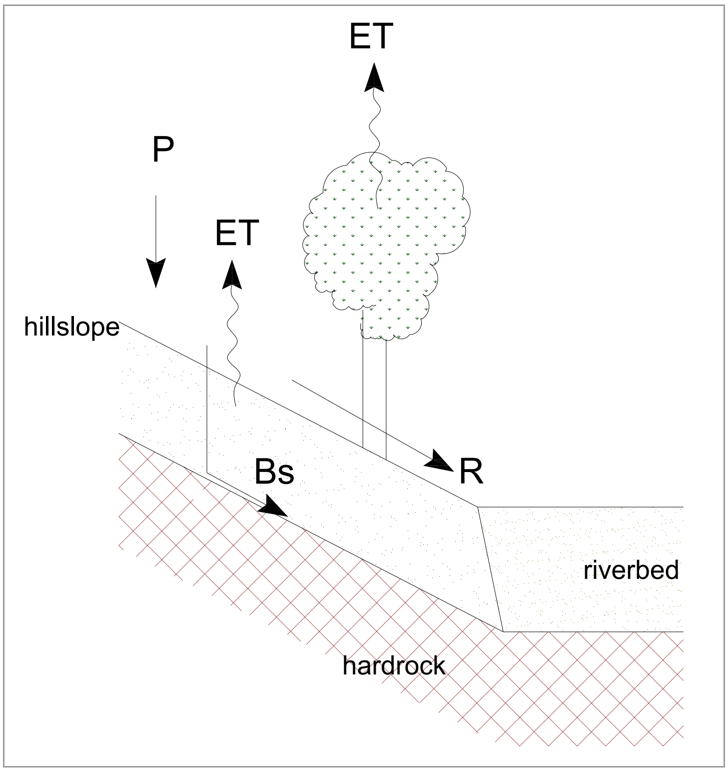

Figure 5.12 Cross-section over the hillslope with the present fluxes

Through cracks and fissures water will recharge to the groundwater and subsequently flow towards the river. According to Wotuku (2001a and 2001b) the recharge in the area amounts about 700 mm. This amount is not used for the water balance, because this value seems very high, since the total annual rainfall is about 900 mm. It is assumed that the value is erroneous, or misinterpreted.

Beekman and Xu (2003) however found a value between about 5 and 50 mm. Lerner *et al.* (1990) compared different research results of more or less similar areas as the case study area and found a value between 20 and 45 mm per year.

However, if a value of 30 mm for instance is used, a total volume of 22,408 m^3 during the March to October season and 9,541 m^3 during the November to February season will add to the amount of abstractable water. This is a very large volume, since the total use is about 2,000 m^3 during the longest season, March to October, after which little water remains. These values from literature are probably valid for flat areas, but not for the slopes of the river valleys. Also the unsaturated zone on the hillslopes is quite thin (about one to two meters), little recharge is expected. If it is assumed that only a small part of the water in the soil recharges and flows down as lateral baseflow, the volumes become more logical. If it is assumed for the March to October season that of the total of 206,168 m^3 in the soil only 1% recharges and 99% evapotranspirates, 2,062 m^3 will add to the abstractable amount through lateral baseflow, which is a lot. However, if 0.25% is taken, 515 m^3 will add to the abstractable amount, which seems more logical. The value of 0.25% corresponds to height of 0.4 mm during the March to October season and 1.0 mm during the November to February season.

With this value of 0.25% a recharge and baseflow of 515 m^3 and 1,338 m^3 for the seasons March to October and November to February are found. It should be kept in mind that this amount is highly debatable, but since no reasonable values from other research was available, this estimation was made. Values of 0.1, 0.5 and 1.0% are being dealt with in the sensitivity analysis.

5.4.4 Output

L_{out} - Outflow from leakage through and around dam

As discussed before, the inflow of leakage through and around Kwa Kangesa dam is taken to be equal to the outflow of leakage thtough and around Kwa Ndunda.

ET - Evapotranspiration from hillslopes
A part of the water on the hillslopes and in the soil will evaporate almost directly. A part runs off as surface runoff and a part infiltrates in the soil. Of this infiltrated water a part will recharge and a part will evaporate and be transpired by vegetation (Figure 5.12).
The potential evapotranspirations for the March to October and November to February seasons are 1089 mm and 448 mm respectively (New LocClim, 2005). Since the thickness of the layer of clay and silt on the slopes is around one meter and the material has large capillary working, the evapotranspiration will be high. As discussed in paragraph 5.4.3, lateral baseflow, it is assumed that 99.75% of the water in the soil that doesn't recharge to the basement aquifer and will evapotranspirate. The amount sof evapotranspiration will then be 205,652 m^3 for the March to October season and 454,048 m^3 for the November to February season. These values correspond to 178 and 393 mm of evapotranspiration respectively.

G_r - Recharge from riverbed and banks to basement aquifer
Water in the riverbed and in the banks will flow through cracks and fissures, recharging the basement aquifer. In literature values of around 30 mm per year are found (e.g. Beekman and Xu, 2003), but these are average values over large areas. Since water is present in the riverbed most of the time the recharge to the basement aquifer is expected to be much higher. A value of 100 mm per year is taken to be a reasonable estimate, which leads to a total recharge to the basement aquifer from the riverbed and banks of 1,424 m^3 during the March to October season and 606 m^3 during the November to February season.

E - Evaporation from riverbed
Water that accumulated behind the dam in the sand is also subjected to evaporation. Below a depth of about 60 cm evaporation hardly occurs (Chapter 4.3.2). To calculate the evaporation from the riverbed some simplifications are made. First of all it is assumed for the calculation that the water evaporates as if the waterlevel doesn't lower due to use and other outputs, so evaporation is the only output. This means that the calculated evaporation will be slightly overestimated. Secondly if the evaporation is less than 60 cm deep, an average of 0.3 times the potential evaporation is taken to be a good measure. This value of 0.3 is about the average over the depth of 0 to 60 cm (Hellwig 1973c).
The potential annual evaporation is 1552 mm (New LocClim, 2005), which leads to a potential evaporation during the March to October season of 1089 mm (256/365 x 1552). The evaporation from the riverbed will then be 327 mm. Using a porosity of 35%, the amount of water evaporated will be:

$$E = L \times W_r \times 0.3 \times E_{pot} \times n \qquad \textit{Eq. 5.3}$$

With:

E	= total evaporation	(m^3)
L	= length of river segment	(m^1)
W_r	= width of river	(m^1)
E_{pot}	= potential evaporation	(mm)
n	= porosity of the sand in the riverbed	(%)

This leads to a total evaporation from the riverbed of 762 m^3 for the March to October season and 324 m^3 for the November to February season.

$B_{l\,out}$ - Shallow and deep longitudinal baseflow
As discussed at the inputs, the outflow of the longitudinal baseflow is assumed to be equal to the inflow. This is the case for a cascade of dams, in the case of a single dam this may be a significant loss.

U - Abstractable water
For the use a distinct difference is made between the abstractable water and the actual use. The abstractable water is the amount that in theory could be harvested from the riverbed, and the actual use is the amount that according to local people is really used. In this paragraph the amount of abstractable water will be determined, after which the actual use is discussed.

The amount that can be harvested is the total of the amounts that can be yielded from the riverbed and riverbank plus the lateral baseflow that adds to the amount in the riverbed during the season, minus evaporation from the riverbed and recharge to the basement aquifer. This is:

$U = Y_r + Y_b + B_s - E - G_r$ *Eq. 5.4*

In which:

U	= abstractable water
Y_r	= amount of extractable water from riverbed
Y_b	= amount of extractable water from riverbanks
B_s	= lateral baseflow
E	= evaporation
G_r	= leakage from riverbed

Not all water present in the sediment can be harvested, since a small film of water remains around the soil particles. The amount that can be harvested is the specific yield. Since a part of the water remains in the soil, during the next rainy season not the total porespace has to be filled up again, but only the specific yield has to be added.

Using a value for specific yield of 27% the amount extractable from the riverbed equals

$Y_r = L \times W_r \times D_r \times S_{yr}$ *Eq. 5.5*

In which:

Y_r	= amount of extractable water from riverbed	(m^3/season)
L	= length of river segment	(m^1)
W_r	= average width of river	(m^1)
D_r	= average thickness of the riverbed	(m^1)
S_{yr}	= specific yield riverbed	(%)

For the river segment of the case study area the amount is 2,976 m^3 per season.

The riverbank however, doesn't consist of one layer, but several layers are found. This is simplified to two layers. On the hardrock a 0.65 m thick layer of weathered rock is present, which is overlain by a layer of clay and silt with a thickness of 1.00 m. The total thickness is taken to be the same as the thickness of the riverbed. The slope of the banks is on average about 8%. The width of the riverbank in which the waterlevel is raised, subsequently is 20.7 m. The simplified cross-section is schematised in Figure 5.13.

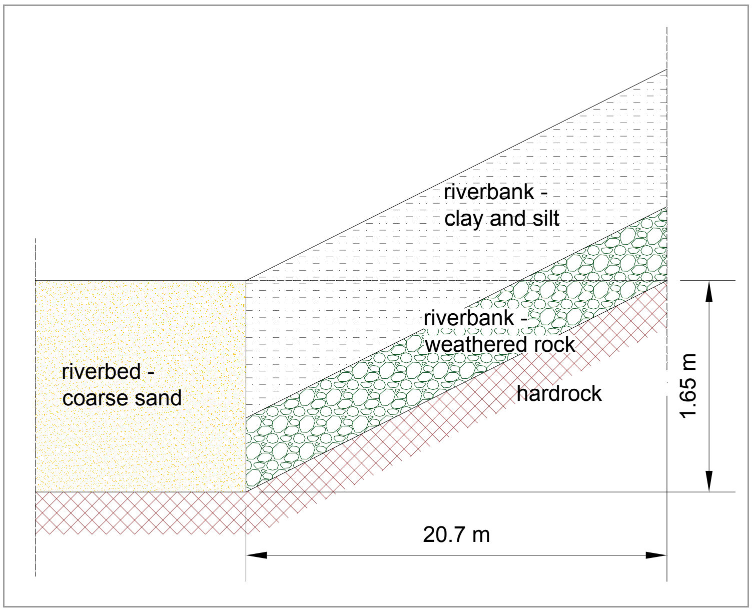

Figure 5.13 Schematised cross-section of the riverbank

For the yield from the banks the same calculation goes as for the yield from the riverbed. The amount extractable from the weathered rock with a yield of 10% and banks at two sides of the river, then becomes 1,425 m^3 per season. The same goes for the amount from the layer of clay and silt, which has a specific yield of 5%. The amount then is 416 m^3 per season for two sides of the river. The total amount yielding from the riverbanks subsequently amounts 1,841 m^3 per season.

The total potential amount that can be harvested then is (Eq. 5.4) 3,146 m^3 for the March to October season and 5,024 m^3 for the November to February season, which is the same as 12.3 m^3 per day and 46.1 m^3 per day respectively. This shows that during the short season from November to February there is an abundance of water.

Qo - River discharge
During rainy season the riverbed and banks fill up with runoff water. The rest of the runoff will leave the catchment segment as river discharge. The amount of river discharge during the March to October season will be 201,351 m^3, and 190,263 m^3 during the November to February season. This means that of the total runoff produced in this catchment segment 2.3% and 2.5% respectively is retained by the sand storage dams.

Actual use by people and animals
The amount of water used by people for domestic purposes as drinking, cooking and cleaning, as well as for irrigation is assumed to remain the same all year around. In the area of the Kwa Ndunda dam about 150 people are living, with on average 7 people per households. In this area 70% of the households use water for small scale irrigation purposes. Households that do not use irrigation water use about 91 l/day, but with irrigation 450 l/day per household is used (Rhebergen and De Bruijn, 2006).

The cattle, donkeys and goats also use water for drinking. Little data was available, so it was estimated that on average each household in the area has about 2 cattle and 5 goats. The use of water by cattle and donkeys is estimated at 6 litres/day/animal and for the goats 3 litres/day/animal is taken.

This leads to a daily use of 7.9 m^3. The total use per season then is 2,026 m^3 from March to October and 863 m^3 from November to February. This is less than the amount of abstractable water calculated before.

5.4.5 Overview

All fluxes are determined, of which an overview is given in Table 5.2.

	Fluxes	March - October	November - February	
INPUT				
P	Precipitation	412,335	650,265	m^3/season
Q_{in}	River discharge inflow over upstream dam	$Q_{in} = Q_{out}$	$Q_{in} = Q_{out}$	
L_{in}	Inflow from leakage through and around upstream dam	$L_{in} = L_{out}$	$L_{in} = L_{out}$	
$B_{l\,in}$	Shallow and deep longitudinal baseflow	$B_{l\,in} = B_{l\,out}$	$B_{l\,in} = B_{l\,out}$	
	Total	**412,335**	**650,265**	m^3/season
OUTPUT				
L_{out}	Outflow from leakage through and around dam	$L_{out} = L_{in}$	$L_{out} = L_{in}$	
ET	Evapotranspiration from hillslopes	205,652	454,048	m^3/season
G_r	Recharge from riverbed and banks to basement aquifer	1,424	606	m^3/season
E	Evaporation from riverbed	762	324	m^3/season
$B_{l\,out}$	Shallow and deep longitudinal baseflow	$B_{l\,out} = B_{l\,in}$	$B_{l\,out} = B_{l\,in}$	
Q_{out}	River discharge outflow over the downstream dam	201,351	190,263	m^3/season
U_p	Potential estimated use by people and animals	3,146	5,024	m^3/season
	Total	**412,335**	**650,265**	m^3/season
U_a	Actual use by people and animals	2,026	863	m^3/season
	Remaining/not used/errors in calculation	1,186	4,189	m^3/season

Table 5.2 Overview of fluxes in catchment segment, amounts in m^3 per season

A part of the abstractable water is not used, or there are some minor errors in the calculation. This amounts to an imbalance of 1,186 m3 for the March to October season and 4,189 m3 for the November to February season. If water remains in the system however, during the next rainy season this water does not have to be added anymore.

A more elaborate overview of the different parameters and fluxes is given in Appendix K. The results of the water balance are given in Figure 5.14.

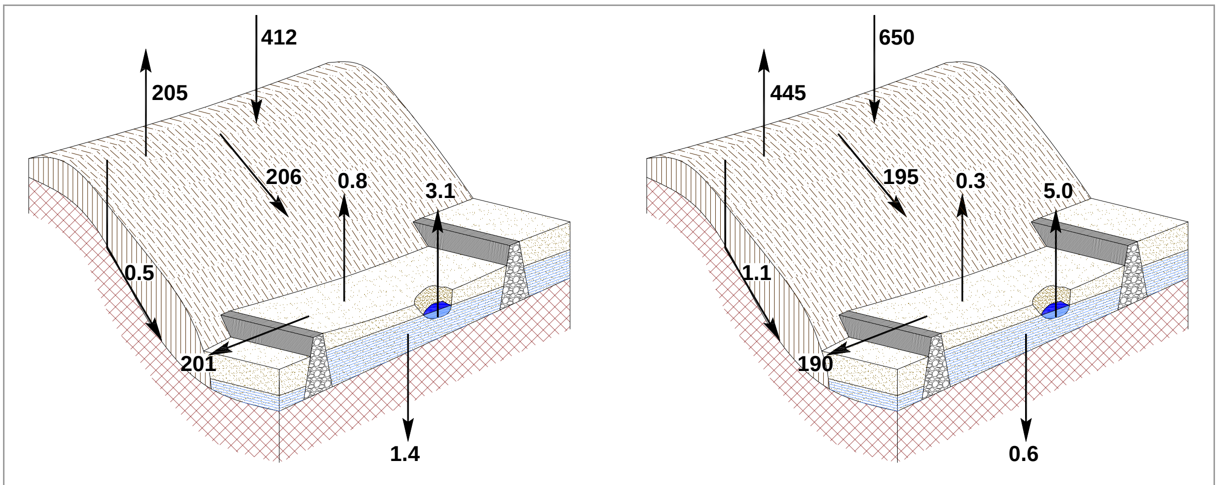

Figure 5.14 Water balances for the season March to October (left) and November to February (right); values in thousands of m^3 per season

5.4.6 Upstream catchment taken into account

As discussed in 5.4.1 and 5.4.2 the inflow of river discharge was left out of the previous water balance to quantify the effect on one single sand storage dam on a catchment segment. However, in reality river discharge inflow does occur in the catchment segment of the study area.

The total catchment upstream of Kwa Kangesa, the upstream dam in the previous calculation, has an area of about 14 km^2. It is assumed that all other parameters are the same. The total precipitation than will be 5,110,000 m3 and 7,880,000 m3 for the March to October and November to February seasons respectively. The runoff to the river is 2,550,000 and 2,360,000 m3 per season. If the same percentage of runoff is retained by the upstream dams as by the dam in the case study area, the total amounts retained by multiple dams are 59,000 and 58,000 m3 per season. The discharge over Kwa Kangesa into the catchment segment of the case study area will subsequently be 2,490,000 and 2,310,000 m3 for the March to October and November to February seasons respectively. Taking into account this extra input in the catchment segment of the case study area, only about 0.18 and 0.19% respectively of the total runoff is retained by the dam Kwa Ndunda.

If all other parameters as precipitation, percentage retained in the catchment, runoff etcetera are assumed to be the same as in the water balance of the catchment segment, the fluxes will be as shown in Table 5.3. In reality those parameters will slightly differ, but only an estimation is made of the total catchment to get insight in the magnitude of the fluxes.

5.4.7 Catchment without a sand storage dam

In order to determine the effect of the sand storage dam a comparison has to be made with the situation before the dam was built. Of the situation without the dams no measurements exist, but an attempt is made to reconstruct this situation. It is assumed that the alluvium of the riverbed increased most close to the dam Kwa Ndunda, and remained the same close to the dam Kwa Kangesa. This is schematised in Figure 5.15.

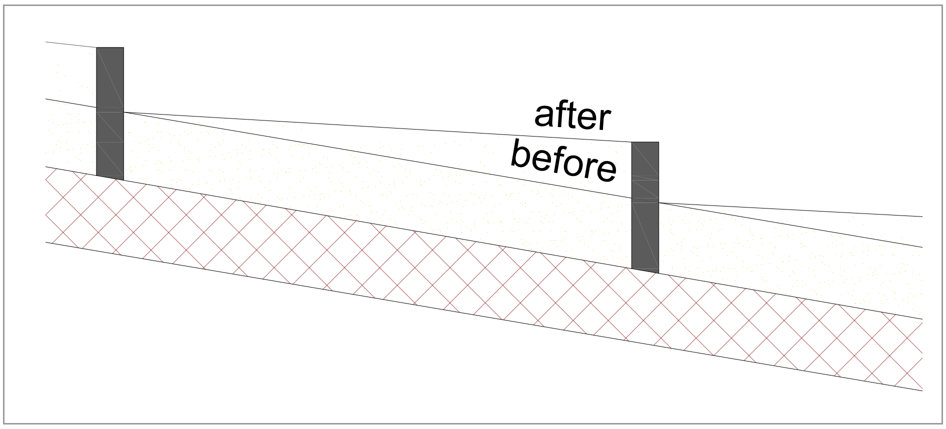

Figure 5.15 Alluvial aquifer before and after construction of the sand storage dam

The average thickness of the riverbed is 1.65 m in the current situation. If the height of the dam is taken to be 1.5 m, the average thickness of the aquifer was 1.65 – (1.5 / 2) = 0.9 m thick. This results in an amount of abstractable water of 1,037 m^3 from March to October and 2,666 m^3 from November to February. Since 2,026 and 863 m^3 are used by people, the amount during the March to October season is clearly too little to support the people, forcing them to get water from other sources, such as Nzeeu river.

Because the thickness of the alluvium in the riverbed is smaller, the amount of runoff retained is also smaller. In the case without dams about 1.1 % and 1.2 % respectively of the runoff is retained. If this is compared to the amount retained in the case with a dam (2.3 and 2.5 %), the retained amount is doubled, but because of the dam, the amount of water that flows downstream has only decreased by about 1%. The effect downstream will therefore be very insignificant.

5.4.8 Sensitivity Ananlysis

Since some parameters were not known, some misestimations can have been made. To quantify the effect of these misestimations or changing factors (e.g. climate change) a sensitivity analysis of the used parameters is made. Using this analysis, a simple, rough estimation can be made for other catchments.

The twelve parameters which are analysed are:

- River width;

- Thickness of the alluvium in the riverbed;
- Specific yield from alluvium in riverbed
- Recharge to basement aquifer from riverbed;
- Slope of the banks;
- Specific yield of the clay;
- Thickness of the layer of weathered rock;
- Specific yield of the weathered rock;
- Precipitation;
- Evaporation from riverbed.
- Runoff coefficient;
- Lateral baseflow,

The most striking effects are being discussed. Together with the results the expected bandwidth of the estimation error is discussed.

River width
With increasing river width the total water yielding from the riverbed also increases. It is expected that the estimation of the river width doesn't vary more than 25% on average. The abstractable water decreases with 13% with a 25% smaller river width. A 25% wider river results in 13% more water abstractable.

Thickness of the alluvium in the riverbed
The thickness of the alluvium was determined by hammering in a probing rod, which has some limitations. It is expected that the depth varies less than 25%. With a 25% thicker bed 37% more water can be used, and 33% less water is abstractable with a 25% smaller riverbed. This is quite important, since the thickness will change by building a sand dam. It is quite striking that the banks store twice the amount of water if the thickness of the riverbed is 25% larger. This is because the groundwater will saturate a much wider part of the banks.

Specific yield of the sand in the riverbed
The specific yield used for the calculation is quite high, 27%. However, since the sand is very coarse, it is quite possible to have such a large specific yield. If a value of 30% is used, about 9% more water is abstractable. If a value of 20% is used, 20% less water is abstractable.

Recharge to basement aquifer from riverbed
The recharge to the basement aquifer from the riverbed is taken from literature, but is highly dependable on cracks and fissures. The error in estimating this parameter can be quite large, even up to a few times the used value. If the value is taken twice as large as is used in the calculation, the amount that is abstractable for human use will decrease by 14%. If the value is half the used value however, the amount of abstractable water will increase with 14%.

Slope of the banks
The slope of the banks affects the area over which the water can be stored in the riverbanks. The value used is an average over a larger height difference, but is expected not to vary more than about 25%. With a 25% smaller slope (less steep) 9% more water can potentially be used. A 25% steeper slope will decrease the amount of abstractable water with 6%. This is due to the effect of the area of the banks over which water can be stored.

Specific yield in the banks
The specific yield of the clay and weathered rock in the banks is taken from literature, but is assumed to be a quite good estimate, and certainly will not vary more than 25%. If the specific yield from the clay or weathered rock increases or decreases, the water abstractable for humans will increase or decrease with 3% and 3% respectively.

Thickness of the layer of weathered rock
The banks are schematised as a two-layer system, which in reality it is not. If the layer of the weathered hardrock is thicker, the layer of clay and silt has to be taken smaller. It is assumed that the error in estimation of the average thickness of the layers is within 50%. A 50% thicker layer of weathered hardrock results in 6% more water abstractable and a 50% thinner layer leads to 8% less water abstractable.

Precipitation
Since the precipitation was taken from multi-year measurements, the reliability is quite high. However, due to climatic change the precipitation can change. With changing precipitation other parameters will also change, such as infiltration, evaporation, vegetation, runoff coefficient etcetera. All these interrelations however are not accounted for in the water balance. This means that according this calculation the amount of water that can be harvested will start to decrease only when the lateral baseflow and the water in the bed and banks are less than the runoff. This means that only effects are found if precipitation is less than about 9 mm per season. In reality the lowest amount of rainfall measured in one year was about 200 mm. However, it should be kept in mind that other parameters will also change.

Runoff coefficient
The runoff coefficient was taken from an other catchment and can differ quite due to vegetation cover, geology and slopes for instance. It is believed that the coefficient has a reliability of 50%. With changing runoff coefficient the infiltration will change, as well as the lateral baseflow. With changing baseflow, the water availability increases. According to the calculation the amount of abstractable water increases with 7% if runoff coefficient decreases with 50%. This can be reached by promoting recharge, by building terraces for instance. The abstractable water related to this part however is highly dependable on the lateral baseflow.

Evaporation from riverbed
The evaporation from riverbed was estimated from potential evaporation and literature. It can be that the evaporation is up to 50% higher or lower. 50% more evaporation from the riverbed decreases the amount of abstractable water by 8%, and a decrease of 50% evaporation leads to 8% more water.

Lateral baseflow
The magnitude of lateral baseflow is highly uncertain. In the calculation a value of 0.25% of the water in the soil was used. If instead of 0.25% percentages of 0.1, 0.5 or 1.0 are used, the amounts available for people become 2,837 m^3, 3,661 m^3 and 4,692 m^3 respectively for the March to October season, and 4,341 m^3, 6162 m^3 and 8438 m^3 for the November to February season. It appears that by promoting infiltration a lot more water can be harvested from the riverbed. The values of 0.1, 0,5 and 1.0% correspond to heights of 0.2, 0.9, 1.8 mm during the March to October season and 0.4, 2.0 and 3.9 mm during the during the November to February season.

The effects are graphically displayed in Figure 5.16.

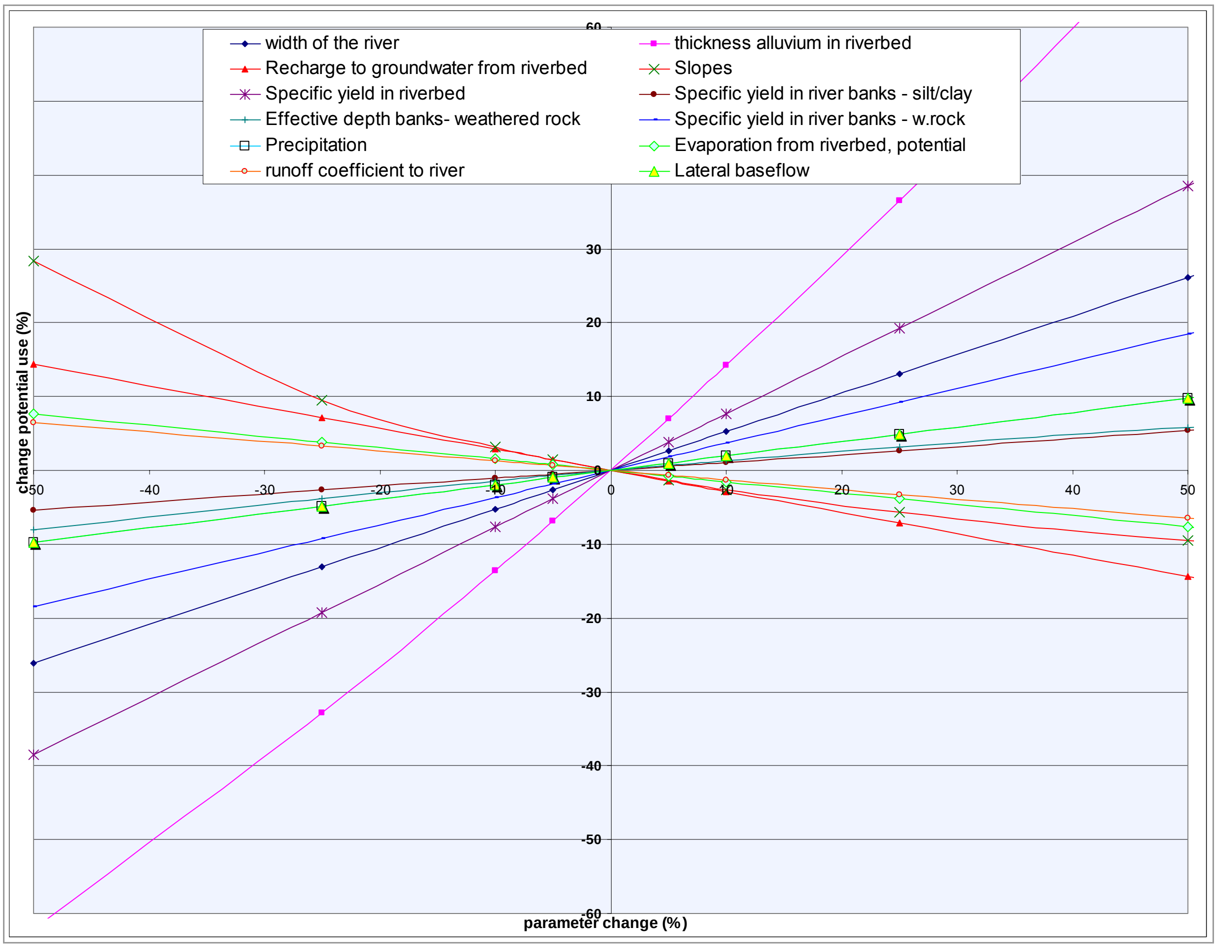

Figure 5.16 Effects of changing parameters on abstractable water for people and animals

6 Conclusions

6.1 On the hydrological functioning of sand storage dams

The filling of the reservoir behind a newly constructed dam with sand takes place in about 5 to 7 years. The coarse particles (i.e. sand) sediment first, after which the smaller silts sediment. The top layer consists mostly of the silts and the deeper layer of the coarser material. With the next flood the fine top layer is eroded by the water again, leaving the sand behind, after the whole sequence is started over again. Each flood sand is left behind and the silt is transported downstream, increasing the thickness of the sand.

The hydrogeology of the sand storage dams in the Kiindu river is characterized by a very rapid infiltration of water in the sands of the riverbed and from there a slower recharge of the groundwater towards the banks. When the water level in the riverbed decreases, the groundwater in the banks will slowly recharge the water in the riverbed. This process does also occur in a non-perennial river with a sand bed without dams, but the sand storage dams increase the thickness of the sand in the river, thus enlarge the storage in the sand. By increasing the level of the sand in the river, the 'base level' of the groundwater flow is also raised, thus increasing the amount of water that is stored in the banks and the abstractable water for people. The amount of water stored behind a sand storage dam is thus (much) higher than just the amount of water stored in the sand behind the dam.

In the case of the coarse sand in the riverbed of the Kiindu catchment the sand was fully saturated just after a few rain events. It is however imaginable that in case of finer sediment in the riverbed, a higher silt load in the discharged water and/or less rainfall, the infiltration rate might be too low to allow the riverbed to saturate fully during a rainy season.

The electrical conductivity (EC) of the water can be very high at some locations, probably due to the dissolution of salts. At the end of the dry season values typically between 2,000 and 10,000 µS/cm were found. Since the EC of rain water is much lower than the EC of the groundwater the EC in the riverbed decreased rapidly as soon as the rainy season started. The EC in the riverbed decreased to values below 600 µS/cm.

A series of dams ('cascade') as has been built in the Kiindu river might (significantly) increase the water storage effect of the sand storage dams, since water that flows downstream through leakage of the dams or through the (weathered) hardrock, and is thus lost in one sand reservoir, returns in a downstream sand reservoir.

6.2 On the water balance of sand storage dams

The water balance was set up, however not all parameters are known and some parameters had to be estimated. According to the calculation enough water is available to meet the needs of the people. In the situation without a dam however, the calculation shows that a water shortage exists.

The storage in the banks, is estimated at 40% of the total stored volume of water (in the case of the Kiindu catchment). Based on the short period of measurements available, it was not possible to estimate the amount of baseflow from infiltrated water on the slopes that reaches the groundwater and will flow from the banks towards the river. It is however possible that this baseflow makes up an important part of the water balance.

Since sand storage dams in the Kiindu river only store a small (about 2%) part of the river discharge generated in catchment of one dam, negative downstream effects are not expected. In a situation without dams, already about 1% of the runoff is stored in the sand, so the dam only stores about 1% extra. Since there are even accounts of increased water availability downstream of sand storage dam(s) it is plausible that leakage of dams, groundwater flow around dams and downstream groundwater flow through the hardrock increases the baseflow in the riverbed and thus increases the water availability downstream.

Without the dams about 500 m^3 of water is available during the March to October season, which is about 2 m^3 per day. Almost 8 m^3 per day is used in the present situation, which stresses the shortage before the dams were built.

Nowadays, with the sand storage dams, about 2,800 m^3 is available during the period from March to October, which is about 11 m^3 per day.

Since some parameters were estimated, the influence of misestimations was tested. The width of the river, the specific yield of the weathered rock in the banks and the slope of the banks have the most dramatic effects on water availability. A higher dam, wider river, higher yield and smaller slope increase the availability of water.

The effectivity of the sand storage dams is less sensitive to the amount of rainfall. Even when there is much less rainfall, the amount of stored water remains the same. Only when the amount of rainfall drops below a certain threshold the amount of abstractable water will decrease. This threshold is dependant on the properties of the catchment. For the Kiindu catchment decreased water availability due to insufficient rainfall will only occur when the annual rainfall drops below about 20 mm per year (if all other parameters remain the same).

Since the rainfall is much less sensitive to changes, the application of sand storage dams is possible in sandy riverbeds with a (more or less) impervious basement in a much larger area than the Kiindu district. Indigenous sand storages dams in North Africa and India dated back hundreds of years proof this.

6.3 On the applicability of sand storage dams in other areas

One of the key factors for the success of the Kitui sand storage dams is the geology of the region. The weathering of local rocks produces a coarse sand which is deposited in the riverbed. This sand makes sure that the water can rapidly infiltrate in the sand. Another important factor for a sand storage dam is the foundation with a low permeability which has to be present to prevent large losses in the vertical direction.

The most important conditions for the application of sand storage dams in other areas are:

- Coarse material in the riverbed.
- (Semi-) impermeable layer underneath the proposed dam site.
- High intensity rainfall, that can work around and remove silt layers in the sand dam aquifer.
- Organised community to participate in constructing and maintaining the dam.

7 Recommendations

7.1 On community information

Knowledge and conception of communities on safe fetching, handling and transport techniques of drinking water should be improved. It should be noted that knowledge alone is not enough, because of habits and traditions communities tend to stick to less safe techniques, although knowledge on risks and on improvements is present.

The working of sand storage dams, the filtering through sand and the advantages over open water storage have to be made clear to the community.

Knowledge of water quality, water pollution and risks related to poor water quality has to be improved, both at community level, but also at SASOL personnel.

Water supply for humans and cattle has to be properly separated to avoid pollution of the water by cattle. Experiments should be started with introducing groundwater protection zones around wells and appointing scoopholes for cattle downstream of scoopholes for human use.

Figure 7.1 A closed well built by AMREF in the Kitui district with a proper fencing to restrict the access of animals to the well

7.2 On SASOL and dam-construction

More attention should be spent on information, documentation and administration of projects and reports.

Monitoring and evaluation of projects should be improved, either by SASOL, by the communities (with the help of SASOL), or through combined (student)research projects of SASOL and other organisations.

Based on field visits to other dam sites and interviews with people involved in the construction of the dams it is recommended to pay more attention to the siting of locations for new dams. Information from the local community and field observations by experts should be combined with (simple and cheap) field explorations to identify the best location for a sand storage dam. Simple, quick and cheap techniques such as augering, metal rod probing or geophysics (VES or seismic) (Gough and Van Niekerk, 1957) can be applied to get an indication of the depth of the hardrock underneath the riverbed. This information can be useful for selecting the location, planning and calculation of the construction and to prevent problems that can occur if the impervious layer is too deep and the dam has to be constructed on sand.

With sand storage dams the amount of abstractable water for the communities has doubled. However, the communities have to deal with more problems, such as land degradation, leaving the land infertile. Along with dam building the communities have to be trained in sustainable agriculture. SASOL already does this, by a.o. training in terrace building.

7.3 On research

The findings of this research should be checked with observations and measurements in other catchments to determine whether they are generally applicable.

An effort should be made to identify, list and make available all relevant information (books, reports, interviews with experts, etc.) concerning the sand storage dams (technical, agricultural, socio-economical, etc.) for further research. This information should be accessible for everybody who is interested, including people from developing countries, e.g. through an internet based database.

Continue with the measurements of groundwater levels in the Kiindu catchment. Data on groundwater levels around sand storage dams is very sparse and information on the groundwater levels during a longer period will be extremely useful for further research projects on the processes around and the functioning of sand storage dams. Continuation of the measurements in the Kiindu catchment will reveal information on the processes occurring in the banks at the end of the rainy season and during the dry season.

Expand the research on the phreatic groundwater near the dam to other parameters that would give more detailed information on the different components of the water balance. Measurements of (for instance) river discharge, lateral baseflow from the banks, longitudinal baseflow under the river, deep groundwater, meteorological parameters and water use from scoopholes and wells can improve the insight in the water balance and give better information on the quantities of water involved. Since the EC of the groundwater and the rainwater differs a lot, the EC should be considered as a tracer.

Transient groundwater modelling, both in detail and on catchment scale, would give additional information on the hydrological processes around sand storage dams. This modelling would be helpful in understanding the working of sand storage dams and can provide necessary information for the application of sand storage dams in other regions or countries.

The storage of water in the banks should be modelled (e.g. with the Edelmann method) to get insight in the amount and flows of water in the banks.

Efforts should be made to combine the hydrological research with (bio)chemical water research. Potential risks of water pollution and ways to prevent the pollution should be identified.

Experts should quantify processes of sedimentation behind a newly build dam, and the risks of sedimentation of too fine materials in the reservoir behind the dam in relation to the height of the dam.

Since the height of the dam has the largest effect on the amount of water stored behind a dam, studies should be carried out to determine the optimal height of the dam and its spillway in relation to construction, sedimentation, water storage properties and costs.

Better land management can increase the amount of infiltration, which leads to more potentially harvestable water. The effects of e.g. terracing should be researched.

In an ideal situation it would be preferable to carry out a research on the hydrology of a catchment, gradient and sediment of the riverbed, water quality, etc. before the construction of a (series of) dams. After construction and maturing of the dams this research should be repeated and compared with the situation before the dam. This would give proper insight on the effects of a sand storage dam on waterflows, sediment and water quality. Although this kind of research would academically be very interesting, the practical possibilities for such a research are quite difficult. Because it takes 5 to 7 years for a dam to mature, a research project before building and after maturing would take at least 10 years.

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[2] = Kitui Ministry Library
[3] = Vrije Universiteit library
[4] = Internet resources via Vrije Universiteit library
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Internet GIS resources

International Livestock Research Institute (ILRI)
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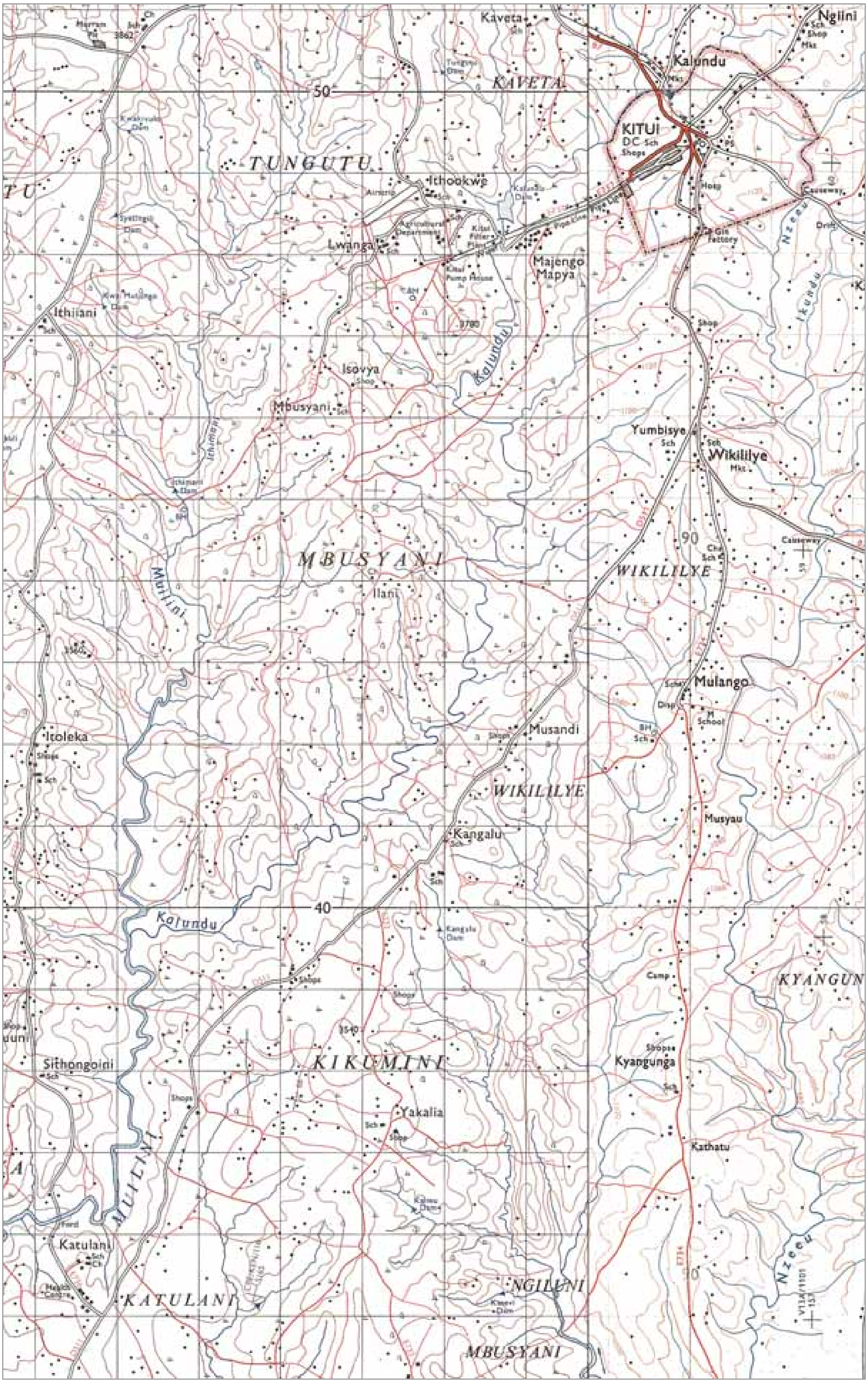
European Digital Archive of Soil Maps (EuDASM)
http://eusoils.jrc.it/esdb_archive/EuDASM/Africa/lists/cke.htm

Global Land Cover Facility (GLCF) Earth Science Data Interface (ESDI)
http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp

Appendices

Appendix A Topographic map of the Kiindu catchment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KITUI
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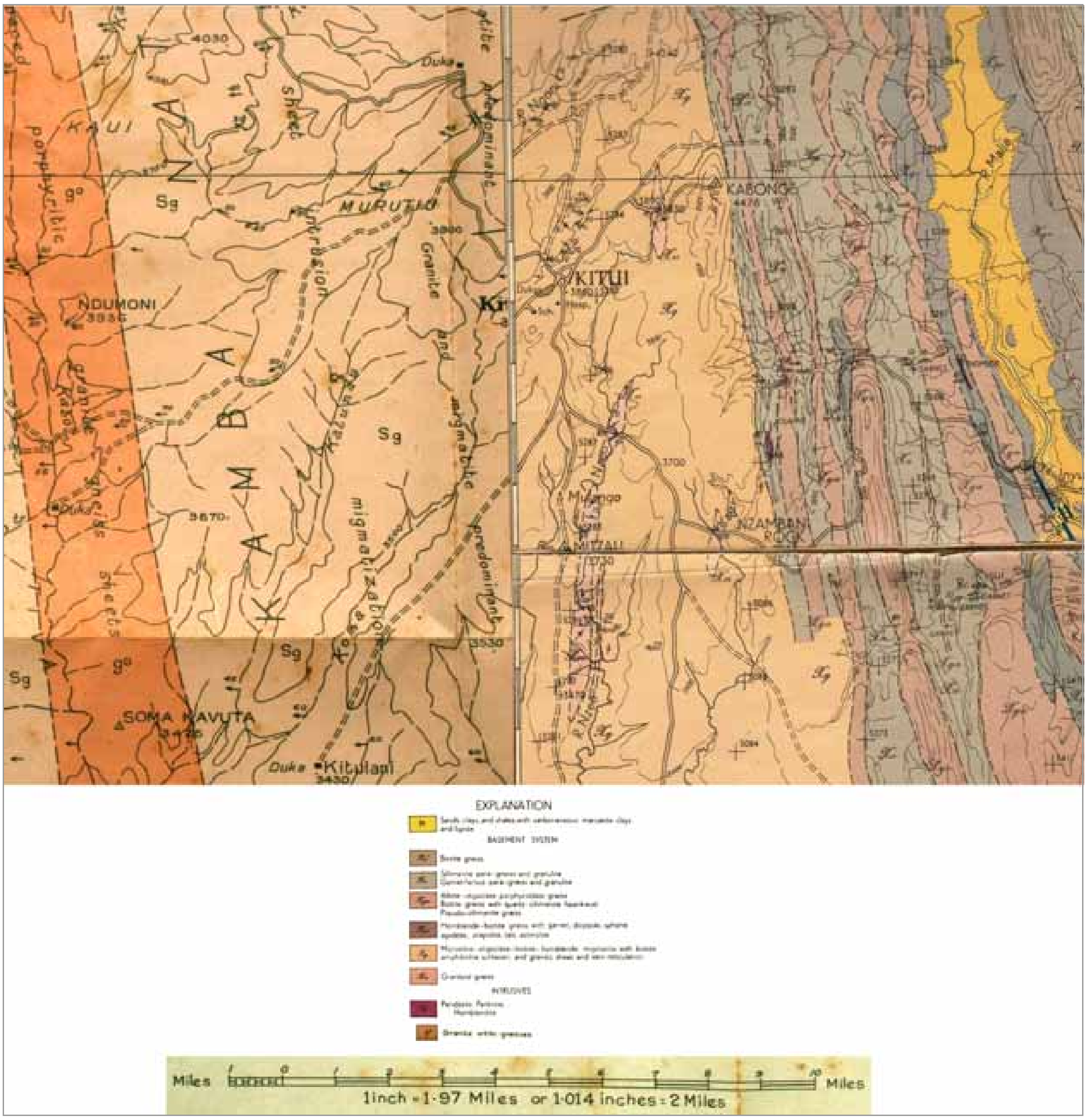
Causeway
TUNGUTU
Ithookwe
Airstrip
Lwanga
Majengo
Mapya
Ithiiani
Isovya
Mbusyani
Yumbisye
Wikililye
90
WIKILILYE
MBUSYANI
Ilani
Mutiini
Kalundu
Mulango
Musandi
Itoleka
WIKILILYE
Kangalu
Musyau
40
Kalundu
KYANGUN
Sithongoini
KIKUMINI
Kyangunga
Yakalia
Kathatu
MUTIINI
Katulani
KATULANI
NGILUNI
Nzeeu
MBUSYANI

Appendix B Geological map of the area West of Kitui



Combined geological map after Schoeman (1948, left) and Sanders (1954, right)

Appendix C Piezometers

nr		x	y	elevation top	depth	screenlength
		(m, UTM)	(m, UTM)	(m + dam crest)	(m)	(m)
p01		389165	9838443	2,063	0,90	0,50
p02		389172	9838442	0,926	1,80	1,00
p03		389175	9838443	0,723	1,87	1,00
p04		389180	9838438	0,183	1,54	1,00
p05		389187	9838458	-0,024	1,68	1,00
p06		389197	9838422	-0,468	1,82	1,00
p07		389201	9838446	0,495	1,50	1,00
p08		389207	9838442	0,995	1,35	1,00
p09		389215	9838439	1,646	4,85	2,50
p10		389202	9838390	0,059	#N/B	#N/B
p11		389211	9838390	-0,187	#N/B	#N/B
p12		389203	9838371	-0,270	#N/B	#N/B
p13		389139	9838319	-0,238	3,30	1,00
p14		389142	9838316	-0,247	3,82	1,50
p15		389146	9838315	-0,668	3,04	1,00
p16		389160	9838306	-2,440	0,56	0,40
p17		389152	9838304	-2,440	0,87	0,30
p18		389166	9838303	-1,043	1,69	1,00
p19		389172	9838302	-0,926	1,03	0,50
p20		389171	9838300	-0,926	1,26	0,50
p21		389177	9838298	-0,432	2,33	1,50

Appendix D Combined precipitation data set

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1904	37	0	42	110	171	0	0	0	0	95	464	43	**962**
1905	25	0	221	197	40	6	0	3	2	40	389	104	**1027**
1906	0	53	339	320	10	19	5	0	0	70	216	182	**1214**
1907	198	0	0	373	46	0	0	12	1	21	298	38	**987**
1908	19	25	52	156	42	2	156	0	0	191	216	82	**941**
1909	9	0	12	69	12	8	29	13	3	65	348	399	**967**
1910	36	0	105	164	44	0	2	0	0	25	369	135	**880**
1911	0	0	21	225	95	0	0	0	0	0	469	86	**896**
1912	28	142	82	294	25	0	0	0	3	2	569	422	**1567**
1913	22	134	283	268	54	2	1	0	2	220	223	88	**1297**
1914	167	37	54	167	86	3	0	20	0	21	396	29	**980**
1915	5	0	243	468	188	24	10	0	4	58	215	93	**1308**
1916	86	0	64	219	32	0	4	10	34	4	331	149	**933**
1917	126	27	209	286	85	0	0	4	0	16	142	1	**896**
1918	6	2	0	427	23	0	20	0	1	76	181	163	**899**
1919	24	37	188	115	2	1	3	20	10	254	144	69	**867**
1920	0	2	204	226	9	0	0	1	1	168	233	111	**955**
1921	69	0	50	147	118	0	0	0	0	47	186	172	**789**
1922	38	12	158	146	29	4	0	6	3	52	355	260	**1063**
1923	105	15	314	457	68	8	0	5	0	17	416	102	**1507**
1924	27	48	97	99	5	32	0	0	2	9	335	115	**769**
1925	42	15	89	96	11	1	12	4	4	61	437	95	**867**
1926	14	18	238	194	52	5	0	0	3	44	130	89	**787**
1927	1	9	155	220	3	0	0	1	6	178	223	226	**1022**
1928	205	0	39	99	42	21	0	1	3	124	274	99	**907**
1929	17	0	49	140	5	1	2	7	37	106	300	225	**889**
1930	3	6	354	286	141	4	11	1	0	47	236	106	**1195**
1931	1	59	61	179	32	0	8	0	5	19	344	111	**819**
1932	101	21	199	361	46	0	4	15	19	46	226	137	**1175**
1933	236	2	57	76	5	0	2	9	3	103	542	250	**1285**
1934	0	0	3	213	95	13	4	1	3	95	105	102	**634**
1935	0	75	63	158	47	2	0	36	6	21	300	70	**778**
1936	89	98	102	364	20	16	1	7	13	102	290	112	**1214**
1937	52	0	104	462	92	1	0	8	11	407	407	359	**1903**
1938	37	1	161	157	24	0	2	3	1	26	259	192	**863**
1939	41	84	6	125	60	1	0	6	1	16	168	38	**546**
1940	9	117	122	457	22	0	3	12	6	58	189	86	**1081**
1941	0	1	135	369	43	6	1	0	2	61	410	240	**1268**
1942	43	2	185	100	67	4	0	2	0	150	267	78	**898**
1943	0	110	98	309	149	18	2	0	0	7	168	190	**1051**
1944	52	0	76	543	14	4	2	1	4	17	247	215	**1175**
1945	7	14	136	171	116	5	1	2	21	2	395	86	**956**
1946	1	2	44	198	9	0	0	3	49	293	241	123	**963**
1947	15	1	201	177	157	2	1	1	11	8	159	217	**950**
1948	9	41	83	366	2	8	2	0	1	93	415	311	**1331**
1949	5	0	44	342	2	0	4	5	4	11	124	178	**719**
1950	5	3	197	129	37	0	1	1	3	1	183	38	**598**
1951	0	13	104	438	70	0	3	0	7	173	453	290	**1551**
1952	0	1	60	151	51	0	0	0	3	85	235	100	**686**
1953	56	1	135	54	58	0	1	5	1	44	454	169	**978**
1954	0	1	0	396	86	4	0	1	2	56	461	52	**1059**
1955	44	36	120	80	50	1	0	0	0	43	145	119	**638**
1956	168	8	32	59	1	1	0	1	1	72	679	191	**1213**
1957	38	14	124	236	102	1	5	1	13	56	307	140	**1037**
1958	33	29	88	267	91	18	7	0	0	3	268	90	**894**
1959	73	1	153	161	95	0	0	4	7	0	431	75	**1000**
1960	15	0	107	275	2	0	0	0	0	108	67	71	**645**
1961	0	85	22	130	120	0	0	0	47	350	682	85	**1521**
1962	57	20	95	365	20	0	0	12	0	110	275	140	**1094**
1963	31	76	358	206	41	20	2	38	18	12	57	354	**1213**
1964	32	3	168	179	0	0	0	0	0	13	41	286	**722**
1965	65	0	41	106	10	6	0	2	10	121	479	61	**901**
1966	60	62	353	251	76	1	0	5	0	164	424	58	**1454**
1967	2	16	55	185	24	9	0	37	44	271	558	0	**1201**
1968	0	138	280	468	63	27	0	2	4	32	604	177	**1795**
1969	16	216	190	130	26	3	0	10	0	27	379	138	**1135**
1970	107	0	298	56	112	0	0	7	5	0	98	0	**683**
1971	0	0	42	295	108	6	0	2	0	187	187	113	**940**
1972	36	43	151	73	13	3	0	1	12	183	381	149	**1045**
1973	19	18	1	8	119	0	0	0	8	0	203	52	**428**
1974	0	42	179	408	41	6	17	0	0	35	344	92	**1164**
1975	0										300	16	
1976	0	51	33	305	23		0	8	50	15	48	122	
1977	46	7	96	249	103	0	0	17	8	10	260	224	**1021**
1978	34	247	127	104	6	0	0	0	0	65	78	173	**835**
1979	312	3	206	620	135	21	13	0	0	81	189	21	**1600**
1980	0	0	14	165	10	0	0	20	0	4	405	137	**756**
1981	0	0	0	194	42	0	0	6	9	69	210	110	**639**
1982	3	0	28	218	130	3	9	11	21	532	314	180	**1450**
1983	0	0	0	108	27	4	4	0	0	0	74	0	**217**
1984	14	0	17	165	26	9	11	0	1	319	485	142	**1188**
1985	41	62	66	46	339	5	5	6	8	127	268	187	**1160**
1986	0	0	28	280	104	8	2	4	0	34	569	129	**1159**
1987	26	0	35	202	50	6	0	23	0	18	247	34	**641**
1988	75	6	136	235	3	5	0	20	13	13	261	130	**897**
1989	125	0	183	232	47	36	0	3	0	59	110	74	**869**
1990	62	34	133	131	94	2	0	0	0	30	128	147	**761**
1991	31	13	161	172	49	0	31	20	0	34	301	120	**930**
1992	1	0	0	163	23	0	0	0	0	47	341	327	**902**
1993	266	22	61	35	38	4	0	0	0	60	246	182	**913**
1994	0	22	99	87	40	1	4		0	274		308	
1995	0	0	0	0	0	0			0		0	2	
1996	9	0	133	11	42	6	0	0	0	0	419	0	**621**
1997	24	0	34	270	81	0	0	0	9	162	0	355	**934**
1998	312	101	158	186	95	0	9	0	2	3	491	73	**1429**
1999	48	0	251	121	1	0	0	0	0	0	433	235	**1089**
2000													
2001													
2002													
2003													
2004			1			5	0	0	0	154	652	217	
2005	25	3	25	144	101	7	3	4	12	69	367	75	**834**

Appendix E Precipitation and evaporation around the Kiindu catchment

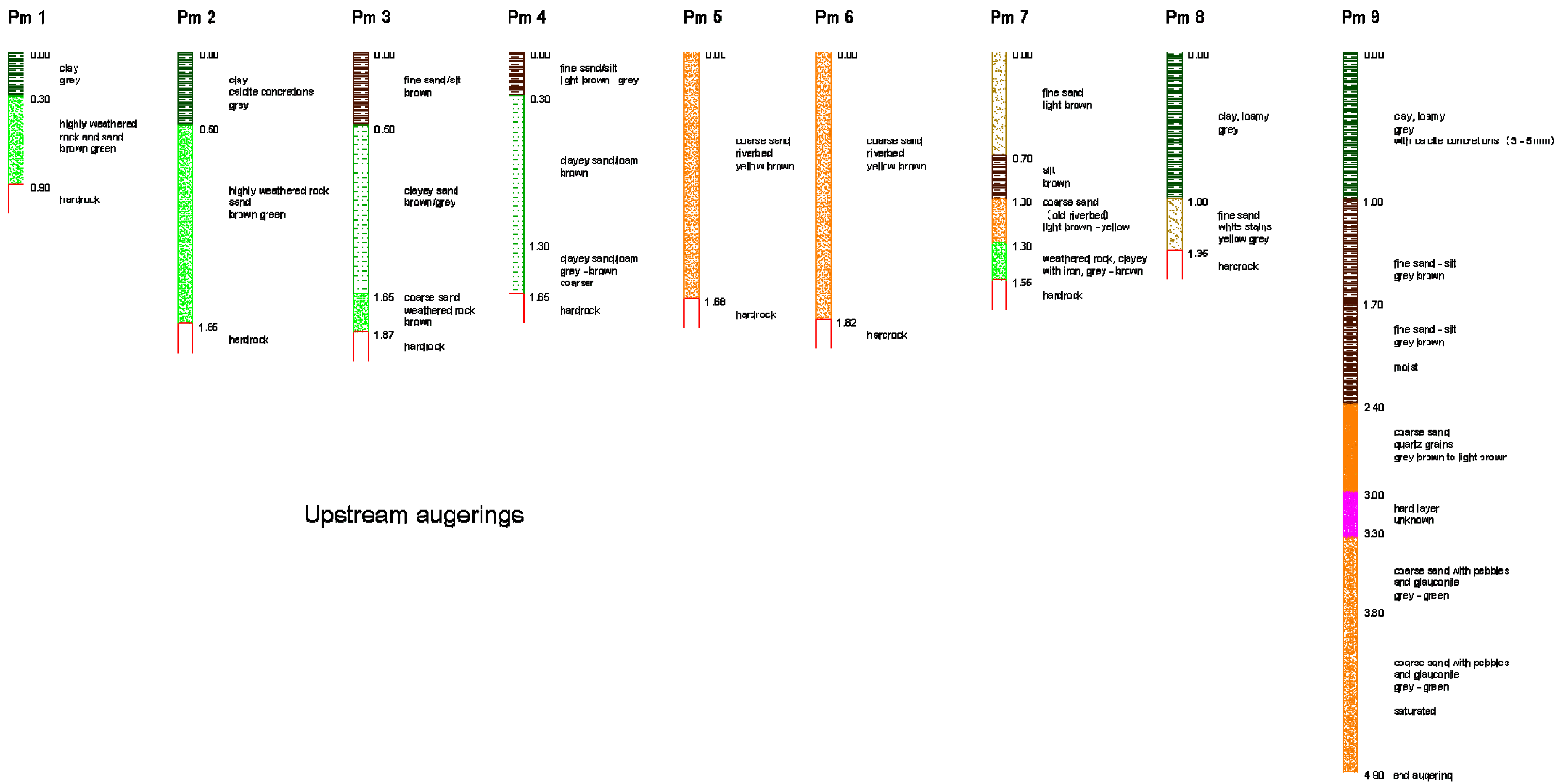
	Precipitation Mulango TBS mm	Mulango mm	Kyangunga mm	Kangalu mm	Water yard mm	Evaporation Water yard mm
ma 01-08					0,2	2,2
di 02-08	0,0				0,4	1,4
wo 03-08	0,0				0,0	3,0
do 04-08	0,0				0,0	3,5
vr 05-08	0,0				0,0	4,0
za 06-08	0,0				0,0	3,0
zo 07-08	0,0				0,0	4,0
ma 08-08	0,0				0,4	2,9
di 09-08	0,0				0,0	3,5
wo 10-08	2,8				1,5	2,0
do 11-08	0,0				0,0	2,5
vr 12-08	0,0				0,0	3,0
za 13-08	0,3				0,0	3,5
zo 14-08	0,0				0,0	3,5
ma 15-08	1,1				0,0	3,5
di 16-08	0,0				0,0	3,0
wo 17-08	0,0				0,4	3,4
do 18-08	0,0				0,0	3,0
vr 19-08	0,0				0,0	3,0
za 20-08	0,0				0,0	4,5
zo 21-08	0,0				0,0	4,0
ma 22-08	0,0				0,0	5,0
di 23-08	0,0				0,0	5,0
wo 24-08	0,0				0,0	6,0
do 25-08	0,0				0,0	4,0
vr 26-08	0,0				0,6	4,1
za 27-08	0,0				0,0	5,0
zo 28-08	0,0				0,0	3,5
ma 29-08	0,0				0,0	4,5
di 30-08	0,0				0,0	5,5
wo 31-08	0,0				0,6	2,6
do 01-09	0,0				0,0	6,0
vr 02-09	0,0				0,0	4,0
za 03-09	0,0				0,0	5,0
zo 04-09	0,0				0,0	4,5
ma 05-09	0,0				0,0	6,0
di 06-09	0,0				0,0	4,0
wo 07-09	0,0				0,0	7,0
do 08-09	0,0				0,0	5,0
vr 09-09	0,0				0,0	3,5
za 10-09	0,0				0,0	4,0
zo 11-09	0,0				0,0	7,0
ma 12-09	0,0				0,0	4,0
di 13-09	0,0				0,0	7,0
wo 14-09	0,0				0,0	4,0
do 15-09	0,0				0,0	5,0
vr 16-09	0,0				0,0	6,0
za 17-09	0,0				0,0	4,0
zo 18-09	0,0				0,0	5,0
ma 19-09	0,0				0,0	4,0
di 20-09	0,0				0,0	5,0
wo 21-09	0,0				0,0	4,0
do 22-09	0,0				11,0	12,5
vr 23-09	0,0				0,0	4,0
za 24-09	0,0				0,0	4,0
zo 25-09	0,0				0,0	6,0
ma 26-09	0,0				0,0	5,0
di 27-09	0,0				0,0	5,5
wo 28-09	0,0				0,8	3,8
do 29-09	0,0				0,0	3,5
vr 30-09	0,0				0,6	0,6
za 01-10	0,0	0,0			0,0	5,0
zo 02-10	0,0	0,0			0,0	5,0
ma 03-10	0,0	0,0			0,0	5,0
di 04-10	0,0	0,0			0,0	7,0
wo 05-10	0,0	0,0			0,0	7,0
do 06-10	0,1	0,0			0,0	6,0
vr 07-10	0,0	0,0			0,0	5,0
za 08-10	0,0	0,0			0,0	6,0
zo 09-10	0,0	0,0			0,0	7,0
ma 10-10	0,0	0,0			0,0	5,0
di 11-10	0,0	0,0			0,0	6,0
wo 12-10	0,0	0,0			0,0	7,0
do 13-10	0,0	0,0			0,0	7,0
vr 14-10	0,0	0,0			0,0	6,0
za 15-10	0,0	0,0			0,0	4,0
zo 16-10	0,0	0,0			0,0	7,0
ma 17-10	0,0	0,0			0,0	7,0
di 18-10	0,0	0,0			0,0	7,5
wo 19-10	0,0	0,0			0,0	7,0
do 20-10	0,0	0,0			0,0	5,0

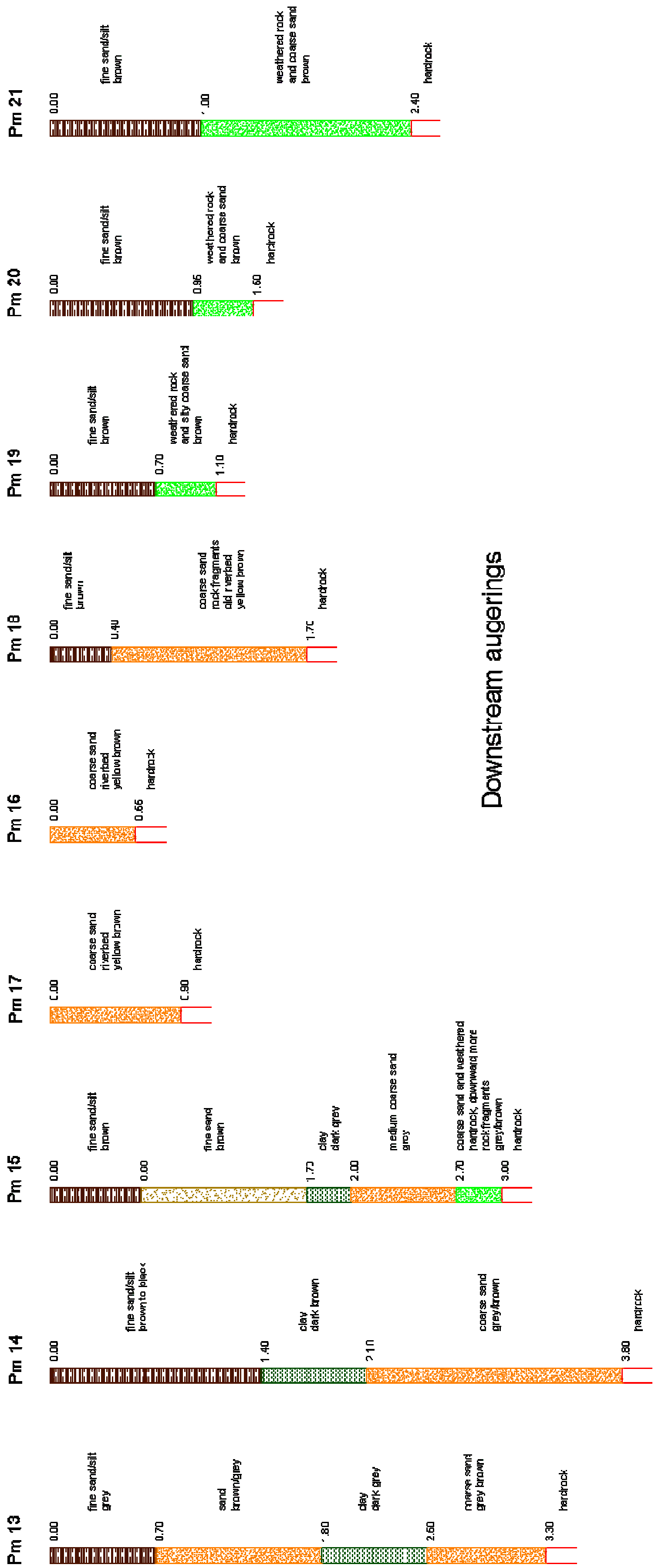
	Precipitation Mulango TBS	Mulango	Kyangunga	Kangalu	Water yard	Evaporation Water yard
	mm	mm	mm	mm	mm	mm
vr 21-10	0,0	0,0			0,0	6,0
za 22-10	0,0	0,0			0,0	5,0
zo 23-10	0,0	0,0			0,0	6,0
ma 24-10	0,0	0,0			0,0	5,5
di 25-10	0,2	0,0			0,0	7,0
wo 26-10	1,3	0,0			53,4	38,4
do 27-10	4,2	0,0			9,0	4,0
vr 28-10	0,2	0,0			6,3	4,3
za 29-10	0,0	0,0		0,0	0,0	6,0
zo 30-10	0,0	0,0		0,0	0,0	-5,0
ma 31-10	0,0	0,0		0,0	0,0	-4,5
di 01-11	0,0	0,0	0,0	0,0		4,0
wo 02-11	0,0	0,0	0,0	0,0	0,0	4,5
do 03-11	0,0	0,0	0,0	0,0	0,0	5,0
vr 04-11	5,0	0,0	0,2	0,0	16,3	0,0
za 05-11	2,5	0,0	1,7	0,8	1,3	1,5
zo 06-11	14,0	31,6	34,3	18,9	83,6	0,0
ma 07-11	58,4	47,2		48,5	12,5	7,0
di 08-11	0,0	0,0	6,3	0,0	0,0	5,0
wo 09-11	0,0	0,0	0,0	0,0	0,0	5,5
do 10-11	16,7	15,0	7,3	7,3	23,1	0,0
vr 11-11	7,5	0,0	1,2	0,0	3,6	0,0
za 12-11	0,0	0,0	0,0	0,0	1,2	3,0
zo 13-11	0,0	0,0	0,0	0,0	2,1	0,0
ma 14-11	1,2	1,8	1,6	0,0	1,9	0,0
di 15-11	0,0	0,0	0,0	0,0	0,4	4,5
wo 16-11	0,1	0,0	0,0	0,0	7,6	0,0
do 17-11	0,0	0,0	0,0	0,0	0,0	3,0
vr 18-11	0,0	0,0	0,0	0,0	0,0	5,0
za 19-11	5,0	0,0	8,2	13,5	1,3	2,0
zo 20-11	0,0	0,0	0,0	0,0	2,7	3,0
ma 21-11	0,0	0,0	20,8	14,4	3,6	1,0
di 22-11	33,1	15,7	28,2	27,8	52,2	0,0
wo 23-11	8,5	22,2	4,5	5,6	29,0	0,0
do 24-11	45,0	40,5	46,8	45,9	36,6	0,0
vr 25-11		0,0	1,7	0,0	15,9	0,0
za 26-11		2,2	10,8	7,0	10,9	0,0
zo 27-11		5,7	3,3	5,9	1,9	0,0
ma 28-11		0,0	0,0	0,0	0,0	4,0
di 29-11		4,2	0,1	3,2	1,0	3,0
wo 30-11		18,5	2,4	9,7	57,9	0,0
do 01-12		0,0	4,4	60,3	100,9	
vr 02-12		0,0	0,8	9,0		
za 03-12		0,0	0,0	0,0		
zo 04-12		0,0	0,0	0,9		
ma 05-12		23,1	0,0	0,0		
di 06-12		0,6	0,0	0,0		
wo 07-12		0,0	0,0	0,0		
do 08-12		0,0	0,0	0,0		
vr 09-12		0,0	0,0	0,0		
za 10-12		0,0	0,0	0,0		
zo 11-12		5,5	0,4	4,7		
ma 12-12		0,0	0,0	0,0		
di 13-12		0,2	0,0	0,0		
wo 14-12		0,0	0,0	0,0		
do 15-12		0,0	0,0	0,0		
vr 16-12		0,0	0,0	0,0		
za 17-12		0,0	0,0	0,0		
zo 18-12		0,0	0,0	0,0		
ma 19-12		0,0	0,0	0,0		
di 20-12		0,0	0,0	0,0		
wo 21-12		0,0	0,0	0,0		
do 22-12		0,0	0,0	0,0		
vr 23-12		0,0	0,0	0,0		
za 24-12		0,0	0,0	0,0		
zo 25-12		0,0	0,0	0,0		
ma 26-12		0,0	0,0	0,0		
di 27-12		0,0	0,0	0,0		
wo 28-12		0,0	0,0	0,0		
do 29-12		0,0	0,0	0,0		
vr 30-12		0,0	0,0	0,0		
za 31-12		0,0	0,0	0,0		
zo 01-01		15,5	7,3	7,4		
ma 02-01		0,0	0,0	0,0		
di 03-01		6,8	55,2	51,9		

(yellow) at 30-09-2005 TBS read out, but mechanics were stuck due to spiderweb, so measurements are not correct. Spiderweb removed at 30-09-2005

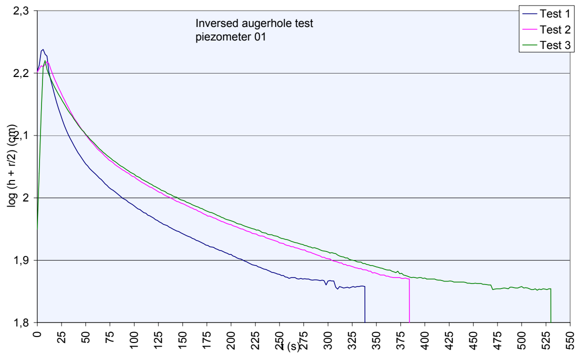
(cyan) strange values, probably error in measurements or calculation

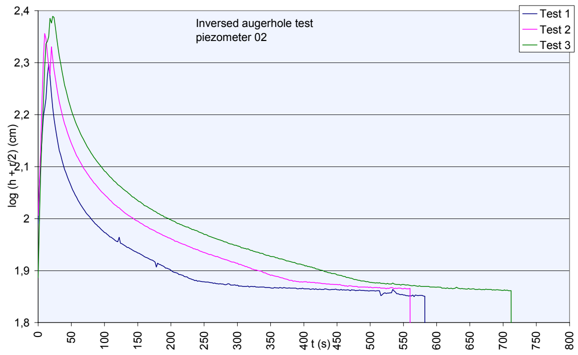
Appendix F Augerings

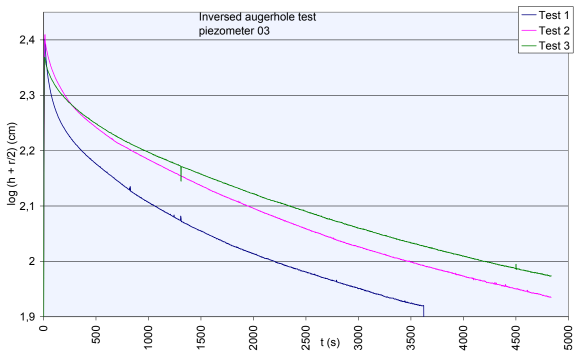

Pm 1
0.00
clay
grey
0.30
highly weathered
rock and sand
brown green
0.90
hardruck
Pm 2
0.00
clay
calcite concretions
grey
0.60
highly weathered rock
sand
brown green
1.65
hardrock
Pm 3
0.00
fine sand/silt
brown
0.60
clayey sand
brown/grey
1.65
coarse sand
weathered rock
brown
1.87
hardrock
Pm 4
0.00
fine sand/silt
light brown grey
0.30
clayey sand/loam
brown
1.30
clayey sand/loam
grey -brown
coarser
1.65
hardrock
Pm 5
0.00
coarse sand
riverbed
yellow brown
1.68
hardrock
Pm 6
0.00
coarse sand
riverbed
yellow brown
1.82
harcrock
Pm 7
0.00
fine sand
light brown
0.70
silt
brown
1.30
coarse sand
(old riverbed)
light brown - yellow
1.30
weathered rock, clayey
with iron, grey - brown
1.56
hardrock
Pm 8
0.00
clay, loamy
grey
1.00
fine sand
white stains
yellow grey
1.36
harcrock
Pm 9
0.00
cay, loamy
grey
with calcite concretions (3 - 5 mm)
1.00
fine sand - silt
grey brown
1.70
fine sand - silt
grey brown
moist
2.40
coarse sand
quartz grains
grey brown to light brown
3.00
hard layer
unknown
3.30
coarse sand with pebbles
and glauconite
grey - green
3.80
coarse sand with pebbles
and glauconite
grey - green
saturated
4.90
end augering
Upstream augerings

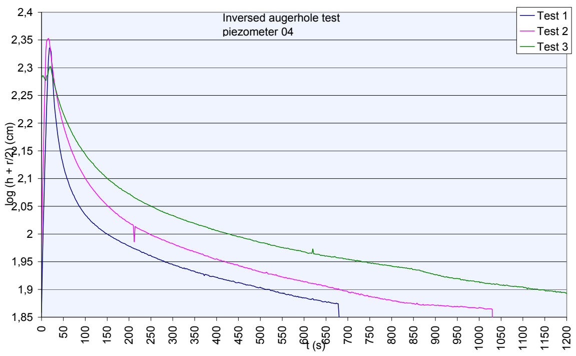

Downstream augerings
Pm 21
0.00
fine sand/silt
brown
weathered rock
and coarse sand
brown
2.40
hardrock
Pm 20
0.00
fine sand/silt
brown
0.96
weathered rock
and coarse sand
brown
1.60
hardrock
Pm 19
0.00
fine sand/silt
brown
0.70
weathered rock
and silty coarse sand
brown
1.10
hardrock
Pm 18
0.00
fine sand/silt
coarse sand
rock fragments
old riverbed
yellow brown
1.70
hardrock
Pm 16
0.00
coarse sand
riverbed
yellow brown
0.66
hardrock
Pm 17
coarse sand
riverbed
yellow brown
hardrock
Pm 15
0.00
fine sand/silt
brown
fine sand
brown
clay
dark grey
2.00
medium coarse sand
grey
2.70
coarse sand and weathered
hardrock, downward more
rock fragments
grey/brown
3.00
hardrock
Pm 14
0.00
fine sand/silt
1.40
clay
dark brown
coarse sand
grey/brown
3.80
hardrock
Pm 13
0.00
fine sand/silt
grey
0.70
sand
brown/grey
clay
dark grey
2.60
coarse sand
grey brown
3.30
hardrock

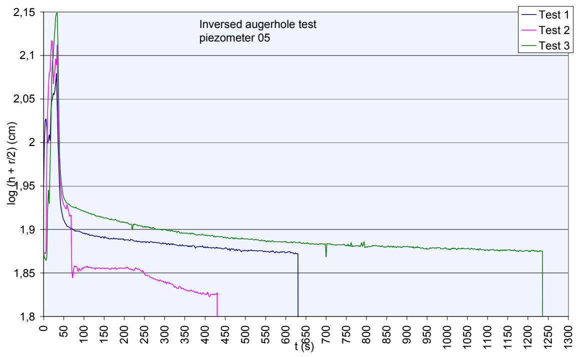
Appendix G Inversed auger hole tests

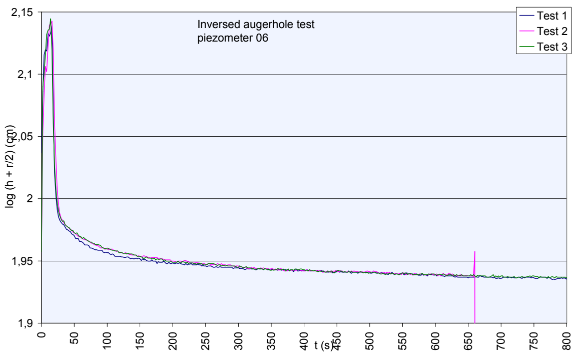

Inversed augerhole test
piezometer 01
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

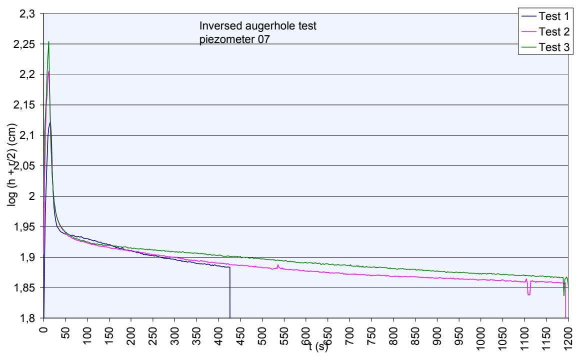

Inversed augerhole test
piezometer 02
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

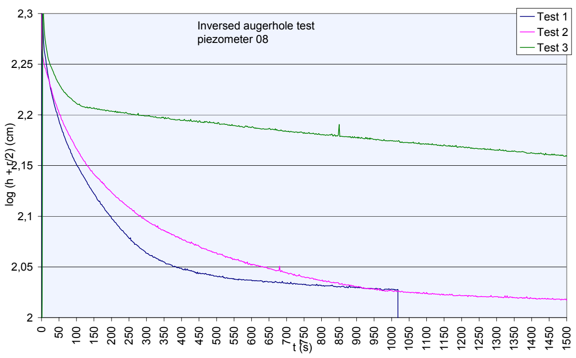

Inversed augerhole test
piezometer 03
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

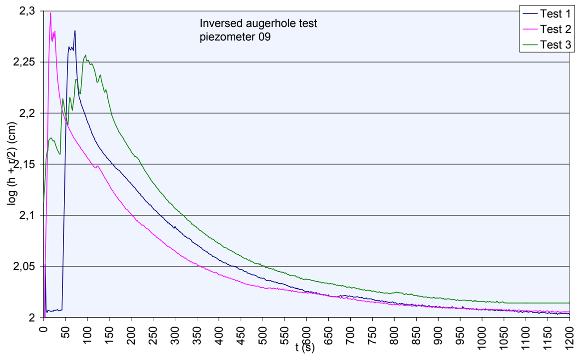

Inversed augerhole test
piezometer 04
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

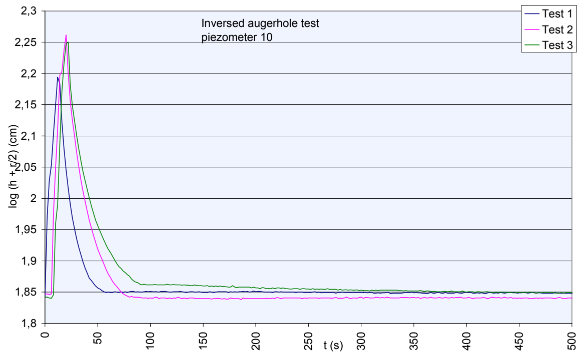

Inversed augerhole test
piezometer 05
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

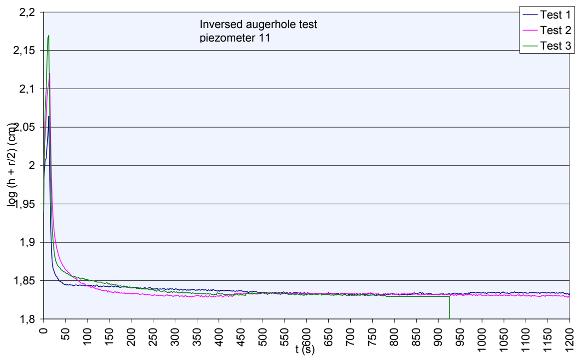

Inversed augerhole test
piezometer 06
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

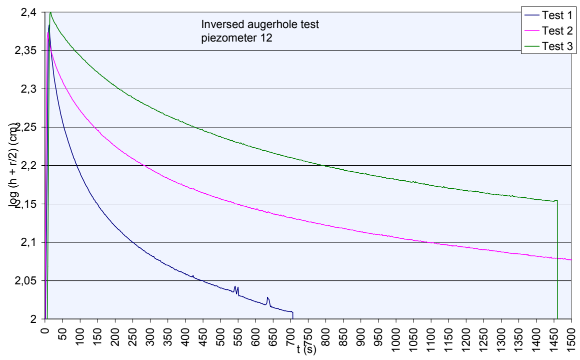

Inversed augerhole test
piezometer 07
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

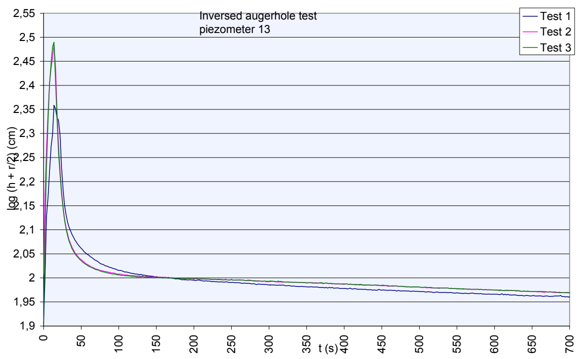

Inversed augerhole test
piezometer 08
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

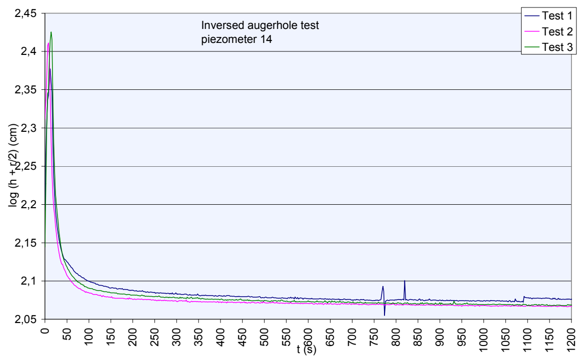

Inversed augerhole test
piezometer 09
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

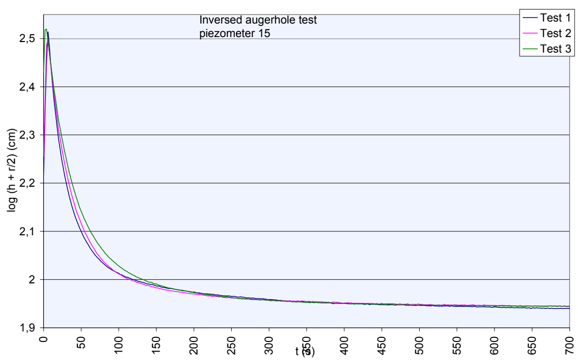

Inversed augerhole test
piezometer 10
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

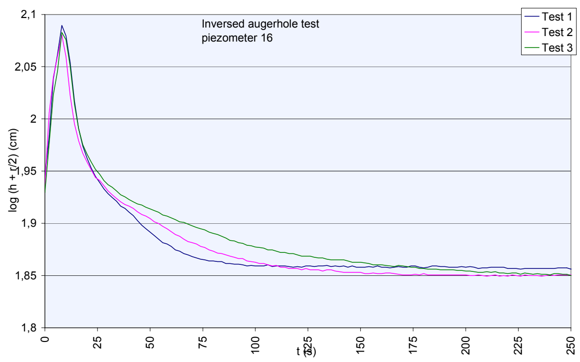

Inversed augerhole test
piezometer 11
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

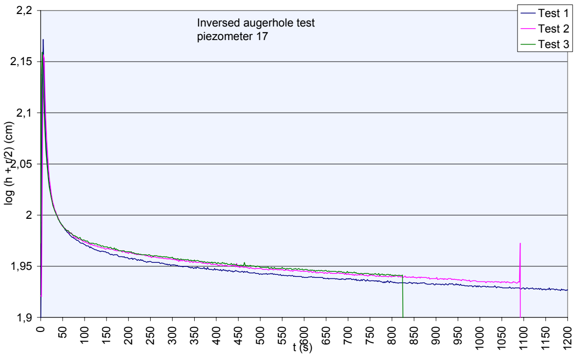

Inversed augerhole test
piezometer 12
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

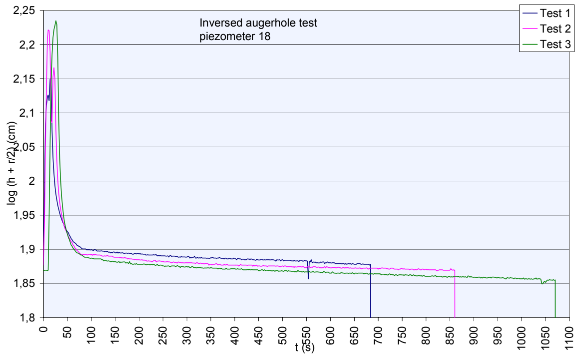

Inversed augerhole test
piezometer 13
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

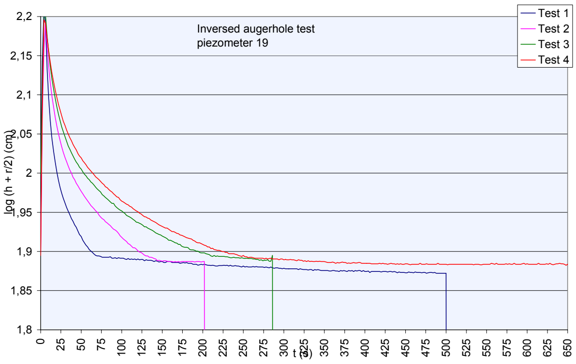

Inversed augerhole test
piezometer 14
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

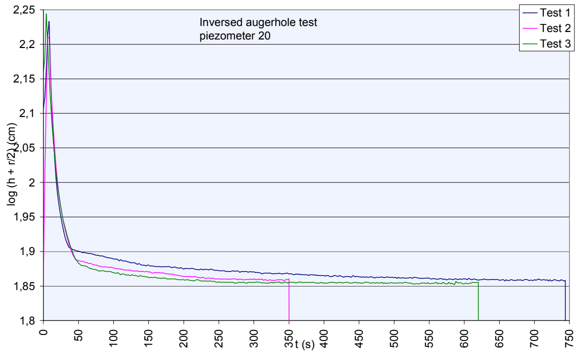

Inversed augerhole test
piezometer 15
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

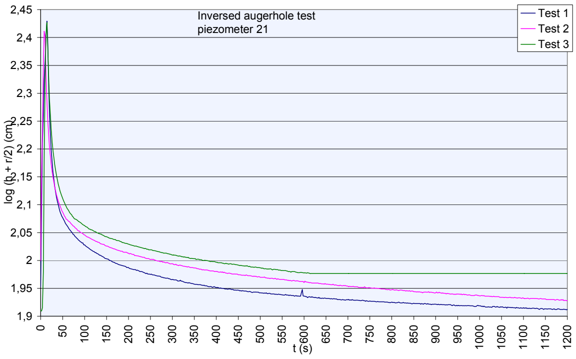

Inversed augerhole test
piezometer 16
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)


Inversed augerhole test
piezometer 17
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)


Inversed augerhole test
piezometer 18
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)


Inversed augerhole test
piezometer 19
Test 1
Test 2
Test 3
Test 4
log (h + r/2) (cm)
t (s)


Inversed augerhole test
piezometer 20
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)


Inversed augerhole test
piezometer 21
Test 1
Test 2
Test 3
log (h + r/2) (cm)
t (s)

Appendix H Depth of hardrock

location	A	B	C	D	E	F	G	H	I	J
1	2.18	2.25	3.23	2.37	1.42	1.90	0.98	1.70	1.20	2.55
2	2.28	2.14		1.93	1.45	1.65	0.91	1.73	1.37	
3	2.61	2.22		1.89	1.50	1.90	0.90	2.00	1.00	
4	1.90	2.29		2.00	1.47	1.60	1.15	2.10	1.45	
5	2.14	2.23		1.92	1.47	1.60		2.00	1.50	
average	2.22	2.23	3.23	2.02	1.46	1.73	0.99	1.91	1.30	2.55
sd	0.178	0.037	0.000	0.139	0.022	0.136	0.083	0.153	0.163	0.000
Average depth of hardrock in riverbed: 1.65 m										

Appendix I Waterlevels (table)

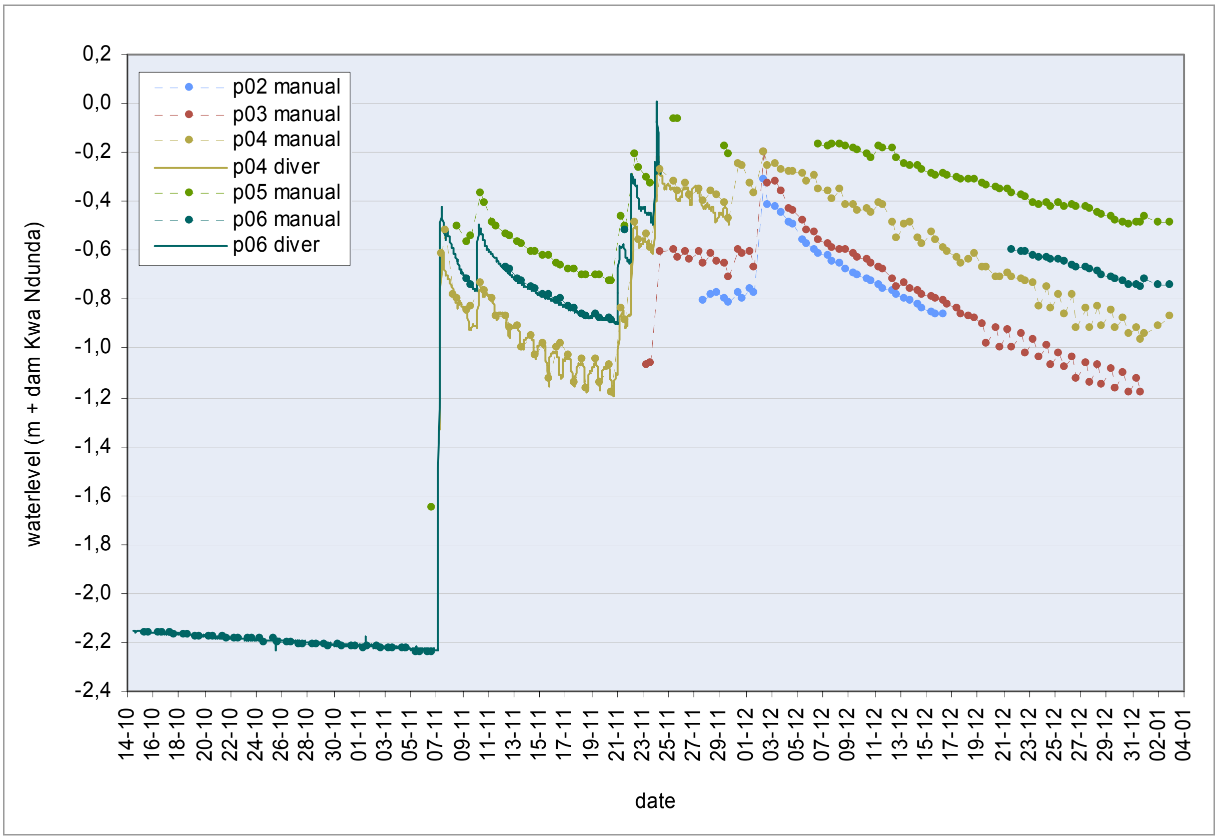
	p01	p02	p03	p04	p05	p06	p07	p08	p09	p10	p11	p12	p13	p14	p15	p16	p17	p18	p19	p20	p21
elevation top	2,063	0,926	0,723	0,183	-0,024	-0,468	0,495	0,995	1,646	0,059	-0,187	-0,27	-0,238	-0,247	-0,668	-2,44	-2,44	-1,043	-0,926	-0,926	-0,432
(m + dam Kwa Ndunda)																					
15-10-05 09:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,69	#N/B	1,29	3,39	#N/B	#N/B	#N/B	#N/B	3,42	2,94	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
15-10-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,69	#N/B	1,33	3,88	#N/B	#N/B	#N/B	#N/B	3,42	2,94	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
16-10-05 09:30	#N/B	#N/B	#N/B	#N/B	#N/B	1,69	#N/B	1,36	3,90	#N/B	#N/B	#N/B	#N/B	3,42	2,94	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
16-10-05 17:15	#N/B	#N/B	#N/B	#N/B	#N/B	1,69	#N/B	#N/B	3,89	#N/B	#N/B	#N/B	#N/B	3,42	2,94	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
17-10-05 07:30	#N/B	#N/B	#N/B	#N/B	#N/B	1,69	#N/B	#N/B	3,90	#N/B	#N/B	#N/B	#N/B	3,42	2,94	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
17-10-05 16:20	#N/B	#N/B	#N/B	#N/B	#N/B	1,70	#N/B	#N/B	3,90	#N/B	#N/B	#N/B	#N/B	3,42	2,95	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
18-10-05 08:45	#N/B	#N/B	#N/B	#N/B	#N/B	1,70	#N/B	#N/B	3,91	#N/B	#N/B	#N/B	#N/B	3,42	2,95	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
18-10-05 16:30	#N/B	#N/B	#N/B	#N/B	#N/B	1,70	#N/B	#N/B	3,90	#N/B	#N/B	#N/B	#N/B	3,42	2,94	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
19-10-05 08:10	#N/B	#N/B	#N/B	#N/B	#N/B	1,71	#N/B	#N/B	3,92	#N/B	#N/B	#N/B	#N/B	3,43	2,95	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
19-10-05 16:20	#N/B	#N/B	#N/B	#N/B	#N/B	1,71	#N/B	#N/B	3,91	#N/B	#N/B	#N/B	#N/B	3,43	2,96	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
20-10-05 07:05	#N/B	#N/B	#N/B	#N/B	#N/B	1,71	#N/B	#N/B	3,91	#N/B	#N/B	#N/B	#N/B	3,43	2,96	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
20-10-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,71	#N/B	#N/B	3,91	#N/B	#N/B	#N/B	#N/B	3,43	2,95	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
21-10-05 08:30	#N/B	#N/B	#N/B	#N/B	#N/B	1,71	#N/B	#N/B	3,91	#N/B	#N/B	#N/B	#N/B	3,43	2,95	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
21-10-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,72	#N/B	#N/B	3,92	#N/B	#N/B	#N/B	#N/B	3,43	2,95	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
22-10-05 08:30	#N/B	#N/B	#N/B	#N/B	#N/B	1,72	#N/B	#N/B	3,92	#N/B	#N/B	#N/B	#N/B	3,43	2,95	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
22-10-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,72	#N/B	#N/B	3,92	#N/B	#N/B	#N/B	#N/B	3,43	2,96	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
23-10-05 08:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,72	#N/B	#N/B	3,92	#N/B	#N/B	#N/B	#N/B	3,43	2,96	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
23-10-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,72	#N/B	#N/B	3,93	#N/B	#N/B	#N/B	#N/B	3,43	2,96	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
24-10-05 08:30	#N/B	#N/B	#N/B	#N/B	#N/B	1,72	#N/B	#N/B	3,95	#N/B	#N/B	#N/B	#N/B	3,43	2,96	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
24-10-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,73	#N/B	#N/B	3,93	#N/B	#N/B	#N/B	#N/B	3,44	2,96	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
25-10-05 08:30	#N/B	#N/B	#N/B	#N/B	#N/B	1,72	#N/B	#N/B	3,95	#N/B	#N/B	#N/B	#N/B	3,44	2,96	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
25-10-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,73	#N/B	#N/B	3,95	#N/B	#N/B	#N/B	#N/B	3,44	2,96	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
26-10-05 09:30	#N/B	#N/B	#N/B	#N/B	#N/B	1,73	#N/B	#N/B	3,96	#N/B	#N/B	#N/B	#N/B	3,44	2,97	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
26-10-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,73	#N/B	#N/B	3,94	#N/B	#N/B	#N/B	#N/B	3,44	2,96	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
27-10-05 09:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,74	#N/B	#N/B	3,96	#N/B	#N/B	#N/B	#N/B	3,44	2,97	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
27-10-05 15:30	#N/B	#N/B	#N/B	#N/B	#N/B	1,74	#N/B	#N/B	3,95	#N/B	#N/B	#N/B	#N/B	3,44	2,96	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
28-10-05 09:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,74	#N/B	#N/B	3,97	#N/B	#N/B	#N/B	#N/B	3,45	2,97	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
28-10-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,74	#N/B	#N/B	3,96	#N/B	#N/B	#N/B	#N/B	3,45	2,97	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
29-10-05 09:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,74	#N/B	#N/B	3,98	#N/B	#N/B	#N/B	#N/B	3,45	2,97	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
29-10-05 15:30	#N/B	#N/B	#N/B	#N/B	#N/B	1,75	#N/B	#N/B	3,97	#N/B	#N/B	#N/B	#N/B	3,45	2,98	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
30-10-05 09:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,74	#N/B	#N/B	3,98	#N/B	#N/B	#N/B	#N/B	3,45	2,98	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
30-10-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,75	#N/B	#N/B	3,97	#N/B	#N/B	#N/B	#N/B	3,46	2,98	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
31-10-05 09:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,75	#N/B	#N/B	3,99	#N/B	#N/B	#N/B	#N/B	3,46	2,98	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
31-10-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,75	#N/B	#N/B	3,98	#N/B	#N/B	#N/B	#N/B	3,46	2,98	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
01-11-05 08:15	#N/B	#N/B	#N/B	#N/B	#N/B	1,76	#N/B	#N/B	4,00	#N/B	#N/B	#N/B	#N/B	3,46	2,99	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
01-11-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,75	#N/B	#N/B	3,99	#N/B	#N/B	#N/B	#N/B	3,46	2,98	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
02-11-05 09:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,75	#N/B	#N/B	4,00	#N/B	#N/B	#N/B	#N/B	3,46	2,99	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
02-11-05 17:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,76	#N/B	#N/B	3,99	#N/B	#N/B	#N/B	#N/B	3,46	2,98	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
03-11-05 08:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,76	#N/B	#N/B	4,01	#N/B	#N/B	#N/B	#N/B	3,47	2,99	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
03-11-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,76	#N/B	#N/B	4,00	#N/B	#N/B	#N/B	#N/B	3,47	2,99	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
04-11-05 09:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,76	#N/B	#N/B	4,01	#N/B	#N/B	#N/B	#N/B	3,46	2,99	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
04-11-05 16:40	#N/B	#N/B	#N/B	#N/B	#N/B	1,76	#N/B	#N/B	4,00	#N/B	#N/B	#N/B	#N/B	3,47	2,99	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
05-11-05 09:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,77	#N/B	#N/B	4,02	#N/B	#N/B	#N/B	#N/B	3,47	2,99	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
05-11-05 16:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,77	#N/B	#N/B	4,01	#N/B	#N/B	#N/B	#N/B	3,47	2,99	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
06-11-05 09:00	#N/B	#N/B	#N/B	#N/B	#N/B	1,77	#N/B	#N/B	4,03	#N/B	#N/B	#N/B	#N/B	3,47	2,99	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
06-11-05 16:00	#N/B	#N/B	#N/B	#N/B	1,63	1,77	#N/B	#N/B	4,01	#N/B	#N/B	#N/B	#N/B	3,46	2,97	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
07-11-05 09:00	#N/B	#N/B	#N/B	0,80	#N/B	#N/B	#N/B	#N/B	4,03	0,81	#N/B	#N/B	#N/B	3,42	2,84	#N/B	0,00	#N/B	#N/B	#N/B	#N/B
07-11-05 17:00	#N/B	#N/B	#N/B	0,70	0,00	0,00	#N/B	#N/B	4,02	0,76	#N/B	#N/B	#N/B	3,35	2,74	#N/B	0,26	#N/B	#N/B	#N/B	#N/B
08-11-05 09:00	#N/B	#N/B	#N/B	0,96	#N/B	#N/B	1,12	#N/B	4,03	0,82	0,95	#N/B	#N/B	3,25	2,66	#N/B	0,35	#N/B	#N/B	#N/B	#N/B
08-11-05 16:30	#N/B	#N/B	#N/B	0,98	0,48	0,00	1,12	#N/B	4,01	0,83	0,90	#N/B	#N/B	3,22	2,64	#N/B	0,37	#N/B	#N/B	#N/B	#N/B
09-11-05 08:30	#N/B	#N/B	#N/B	1,03	0,54	0,25	1,15	#N/B	4,02	0,88	0,84	#N/B	#N/B	3,17	2,61	#N/B	0,41	#N/B	#N/B	#N/B	#N/B
09-11-05 16:00	#N/B	#N/B	#N/B	1,01	0,52	0,27	1,16	#N/B	4,00	0,89	0,83	#N/B	#N/B	3,15	2,59	#N/B	0,42	#N/B	#N/B	#N/B	#N/B
10-11-05 09:00	#N/B	#N/B	#N/B	0,92	0,34	0,00	1,06	#N/B	3,98	0,68	0,76	#N/B	#N/B	3,11	2,54	#N/B	0,37	#N/B	#N/B	#N/B	#N/B
10-11-05 16:00	#N/B	#N/B	#N/B	0,95	0,38	0,00	1,05	#N/B	3,96	0,70	0,72	#N/B	#N/B	3,09	2,53	#N/B	0,38	#N/B	#N/B	#N/B	#N/B
11-11-05 08:00	#N/B	#N/B	#N/B	0,98	0,46	0,00	1,07	#N/B	3,96	0,75	0,68	#N/B	#N/B	3,06	2,51	#N/B	0,40	#N/B	#N/B	#N/B	#N/B
11-11-05 15:30	#N/B	#N/B	#N/B	1,05	0,48	0,00	1,09	#N/B	3,93	0,77	0,67	#N/B	#N/B	3,04	2,50	#N/B	0,41	#N/B	#N/B	#N/B	#N/B
12-11-05 09:00	#N/B	#N/B	#N/B	1,05	0,51	0,20	1,11	#N/B	3,91	0,80	0,67	#N/B	#N/B	3,01	2,48	#N/B	0,42	#N/B	#N/B	#N/B	#N/B
12-11-05 17:00	#N/B	#N/B	#N/B	1,10	0,52	0,21	1,12	#N/B	3,89	0,81	0,68	#N/B	#N/B	3,00	2,47	#N/B	0,42	#N/B	#N/B	#N/B	#N/B
13-11-05 08:00	#N/B	#N/B	#N/B	1,09	0,54	0,25	1,15	#N/B	3,88	0,84	0,70	#N/B	#N/B	2,98	2,46	#N/B	0,43	#N/B	#N/B	#N/B	#N/B
13-11-05 16:30	#N/B	#N/B	#N/B	1,18	0,55	0,26	1,16	#N/B	3,87	0,85	0,70	#N/B	#N/B	2,97	2,46	#N/B	0,43	#N/B	#N/B	#N/B	#N/B
14-11-05 09:00	#N/B	#N/B	#N/B	1,13	0,58	0,28	1,18	#N/B	3,84	0,87	0,71	#N/B	3,01	2,95	2,44	#N/B	0,43	#N/B	#N/B	#N/B	#N/B
14-11-05 17:00	#N/B	#N/B	#N/B	1,21	0,58	0,29	1,18	#N/B	3,83	0,87	0,71	#N/B	3,00	2,94	2,43	#N/B	0,43	#N/B	#N/B	#N/B	#N/B
15-11-05 08:00	#N/B	#N/B	#N/B	1,16	0,60	0,31	1,20	#N/B	3,82	0,90	0,73	#N/B	2,99	2,93	2,43	#N/B	0,44	#N/B	#N/B	#N/B	#N/B
15-11-05 16:00	#N/B	#N/B	#N/B	1,31	0,60	0,31	1,20	#N/B	3,79	0,90	0,73	#N/B	2,97	2,92	2,42	#N/B	0,43	#N/B	#N/B	#N/B	#N/B
16-11-05 08:00	#N/B	#N/B	#N/B	1,18	0,63	0,34	1,22	#N/B	3,79	0,93	0,75	#N/B	2,96	2,91	2,41	#N/B	0,45	#N/B	#N/B	#N/B	#N/B
16-11-05 17:00	#N/B	#N/B	#N/B	1,16	0,64	0,33	1,21	#N/B	3,80	0,92	0,74	#N/B	2,95	2,90	2,42	#N/B	0,44	#N/B	#N/B	#N/B	#N/B
17-11-05 07:30	#N/B	#N/B	#N/B	1,21	0,65	0,36	1,24	#N/B	3,76	0,95	0,77	#N/B	2,94	2,90	2,40	#N/B	0,46	#N/B	#N/B	#N/B	#N/B
17-11-05 16:00	#N/B	#N/B	#N/B	1,32	0,65	0,37	1,25	#N/B	3,75	0,95	0,78	#N/B	2,94	2,89	2,39	#N/B	0,45	#N/B	#N/B	#N/B	#N/B
18-11-05 08:00	#N/B	#N/B	#N/B	1,23	0,68	0,39	1,26	#N/B	3,74	0,98	0,80	#N/B	2,93	2,88	2,39	#N/B	0,47	#N/B	#N/B	#N/B	#N/B
18-11-05 14:30	#N/B	#N/B	#N/B	1,35	0,68	0,40	1,27	#N/B	3,72	0,97	0,80	#N/B	2,93	2,88	2,39	#N/B	0,47	#N/B	#N/B	#N/B	#N/B
19-11-05 09:00	#N/B	#N/B	#N/B	1,23	0,68	0,39	1,27	#N/B	3,71	0,97	0,79	#N/B	2,92	2,87	2,37	#N/B	0,41	#N/B	#N/B	#N/B	#N/B
19-11-05 16:00	#N/B	#N/B	#N/B	1,32	0,68	0,41	1,28	#N/B	3,70	0,97	0,80	#N/B	2,92	2,86	2,37	#N/B	0,40	#N/B	#N/B	#N/B	#N/B
20-11-05 09:00	#N/B	#N/B	#N/B	1,25	0,70	0,41	1,29	#N/B	3,70	0,99	0,81	#N/B	2,90	2,85	2,36	#N/B	0,44	#N/B	#N/B	#N/B	#N/B
20-11-05 15:30	#N/B	#N/B	#N/B	1,36	0,70	0,42	1,29	#N/B	3,68	0,99	0,81	#N/B	2,90	2,85	2,36	#N/B	0,44	#N/B	#N/B	#N/B	#N/B
21-11-05 09:00	#N/B	#N/B	#N/B	1,02	0,44	0,00	1,17	#N/B	3,67	0,75	0,71	#N/B	2,89	2,83	2,32	#N/B	0,24	#N/B	#N/B	#N/B	#N/B
21-11-05 17:00	#N/B	#N/B	#N/B	1,07	0,48	0,05	1,11	#N/B	3,65	0,74	0,67	#N/B	2,87	2,81	2,30	#N/B	0,28	#N/B	#N/B	#N/B	#N/B
22-11-05 09:00	#N/B	#N/B	#N/B	0,67	0,18	0,00	0,91	#N/B	3,64	0,47	0,52	#N/B	2,84	2,78	2,24	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
22-11-05 17:00	#N/B	#N/B	#N/B	0,74	0,24	0,00	0,90	#N/B	3,62	0,52	0,47	#N/B	2,82	2,75	2,22	#N/B	0,15	#N/B	#N/B	#N/B	#N/B
23-11-05 09:00	#N/B	#N/B	1,79	0,72	0,28	0,00	0,90	#N/B	3,60	0,55	0,44	#N/B	2,77	2,71	2,19	#N/B	0,12	1,53	#N/B	#N/B	#N/B
23-11-05 16:00	#N/B	#N/B	1,78	0,77	0,30	0,00	0,92	#N/B	3,59	0,57	0,44	#N/B	2,77	2,71	2,19	#N/B	0,19	1,56	#N/B	#N/B	#N/B
24-11-05 08:30	#N/B	#N/B	1,33	0,45	0,00	0,00	0,64	#N/B	3,55	0,40	0,24	#N/B	2,71	2,65	2,10	#N/B	0,00	1,39	#N/B	#N/B	#N/B
24-11-05 17:00	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B	#N/B
25-11-05 09:00	#N/B	#N/B	1,32	0,50	0,04	0,00	0,70	#N/B	3,47	0,47	0,30	#N/B	2,64	2,59	2,06	#N/B	0,00	1,43	#N/B	#N/B	#N/B
25-11-05 17:00	#N/B	#N/B	1,35	0,54	0,04	0,00	0,72	#N/B	3,45	0,48	0,32	#N/B	2,68	2,58	2,06	#N/B	0,00	1,44	#N/B	#N/B	#N/B
26-11-05 09:00	#N/B	#N/B	1,33	0,51	0,00	0,00	0,70	#N/B	3,41	0,47	0,32	#N/B	2,59	2,54	2,03	#N/B	0,00	1,44	#N/B	#N/B	#N/B
26-11-05 17:00	#N/B	#N/B	1,36	0,56	0,00	0,00	0,73	#N/B	3,39	0,48	0,33	#N/B	2,58	2,53	2,03	#N/B	0,00	1,46	#N/B	#N/B	#N/B
27-11-05 09:00	#N/B	#N/B	1,33	0,53	0,00	0,00	0,72	#N/B	3,35	0,47	0,33	#N/B	2,55	2,51	2,00	#N/B	0,00	1,44	#N/B	#N/B	#N/B
27-11-05 17:00	#N/B	1,73	1,38	0,58	0,00	0,00	0,71	#N/B	3,32	0,49	0,32	#N/B	2,53	2,50	1,99	#N/B	0,00	1,45	#N/B	#N/B	#N/B
28-11-05 09:00	#N/B	1,71	1,34	0,54	0,00	0,00	0,70	#N/B	3,33	0,48	0,33	#N/B	2,52	2,50	1,98	#N/B	0,00	1,45	#N/B	#N/B	#N/B
28-11-05 17:00	#N/B	1,70	1,37	0,56	0,00	0,00	0,72	#N/B	3,31	0,49	0,34	#N/B	2,51	2,48	1,98	#N/B	0,00	1,47	#N/B	#N/B	#N/B
29-11-05 09:00	#N/B	1,72	1,38	0,59	0,15	0,00	0,77	#N/B	3,32	0,50	0,36	#N/B	2,52	2,47	1,98	#N/B	0,14	1,49	#N/B	#N/B	#N/B
29-11-05 17:00	#N/B	1,74	1,43	0,65	0,18	0,00	0,79	#N/B	3,20	0,52	0,37	#N/B	2,51	2,46	1,98	#N/B	0,16	1,50	#N/B	#N/B	#N/B
30-11-05 09:00	#N/B	1,70	1,32	0,43	0,00	0,00	0,64	#N/B	3,14	0,40	0,32	#N/B	2,48	2,43	1,94	#N/B	0,00	1,39	#N/B	#N/B	#N/B
30-11-05 17:00	#N/B	1,72	1,34	0,44	0,00	0,00	0,65	#N/B	3,13	0,41	0,34	#N/B	2,49	2,42	1,94	#N/B	0,00	1,40	#N/B	#N/B	#N/B

	p01	p02	p03	p04	p05	p06	p07	p08	p09	p10	p11	p12	p13	p14	p15	p16	p17	p18	p19	p20	p21
01-12-05 09:00	#N/B	1,68	1,33	0,51	0,00	0,00	0,70	#N/B	3,06	0,46	0,32	#N/B	2,47	2,41	1,93	#N/B	0,00	1,43	#N/B	#N/B	#N/B
01-12-05 17:00	#N/B	1,70	1,39	0,55	0,00	0,00	0,72	#N/B	3,01	0,47	0,33	#N/B	2,46	2,40	1,93	#N/B	0,00	1,45	#N/B	#N/B	#N/B
02-12-05 09:00	#N/B	1,24	0,92	0,38	0,00	0,00	0,40	#N/B	2,96	0,36	0,00	1,79	2,40	2,40	1,85	#N/B	0,00	1,32	#N/B	#N/B	#N/B
02-12-05 17:00	#N/B	1,34	1,05	0,44	0,00	0,00	0,53	#N/B	2,90	0,40	0,00	1,80	2,39	2,40	1,86	#N/B	0,00	1,36	#N/B	#N/B	#N/B
03-12-05 09:00	#N/B	1,35	1,04	0,43	0,00	0,00	0,59	#N/B	2,85	0,42	0,00	1,79	2,38	2,33	1,86	#N/B	0,00	1,38	#N/B	#N/B	#N/B
03-12-05 17:00	#N/B	1,37	1,08	0,45	0,00	0,00	0,61	#N/B	2,80	0,43	0,00	1,79	2,37	2,33	1,86	#N/B	0,00	1,39	#N/B	#N/B	#N/B
04-12-05 09:00	#N/B	1,41	1,15	0,46	0,00	0,00	0,65	#N/B	2,74	0,45	0,28	1,77	2,37	2,32	1,85	#N/B	0,00	1,41	#N/B	#N/B	#N/B
04-12-05 17:00	#N/B	1,42	1,16	0,46	0,00	0,00	0,67	#N/B	2,72	0,46	0,28	1,77	2,37	2,33	1,86	#N/B	0,00	1,42	#N/B	#N/B	#N/B
05-12-05 09:00	#N/B	1,48	1,20	0,47	0,00	0,00	0,67	#N/B	2,62	0,46	0,31	1,76	2,35	2,30	1,83	#N/B	0,00	1,42	#N/B	#N/B	2,34
05-12-05 17:00	#N/B	1,50	1,24	0,50	0,00	0,00	0,69	#N/B	2,57	0,47	0,33	1,67	2,35	2,30	1,83	#N/B	0,00	1,42	#N/B	#N/B	2,32
06-12-05 09:00	#N/B	1,52	1,25	0,48	0,00	0,00	0,70	#N/B	2,55	0,47	0,34	1,75	2,35	2,30	1,84	#N/B	0,00	1,43	#N/B	#N/B	2,33
06-12-05 17:00	#N/B	1,54	1,28	0,53	0,14	0,00	0,71	#N/B	2,51	0,47	0,34	1,77	2,34	2,31	1,83	#N/B	0,00	1,44	#N/B	#N/B	2,32
07-12-05 09:00	#N/B	1,55	1,3	0,54	0,15	0,00	0,72	#N/B	2,49	0,49	0,36	1,78	2,36	2,32	1,85	#N/B	0,00	1,45	#N/B	#N/B	2,31
07-12-05 17:00	#N/B	1,57	1,31	0,57	0,14	0,00	0,73	#N/B	2,47	0,48	0,35	1,78	2,35	2,31	1,84	#N/B	0,00	1,46	#N/B	#N/B	2,31
08-12-05 09:00	#N/B	1,58	1,32	0,53	0,14	0,00	0,73	#N/B	2,46	0,47	0,34	1,79	2,34	2,32	1,85	#N/B	0,00	1,48	#N/B	#N/B	2,32
08-12-05 17:00	#N/B	1,6	1,32	0,6	0,15	0,00	0,74	#N/B	2,45	0,46	0,35	1,8	2,36	2,3	1,85	#N/B	0,00	1,48	#N/B	#N/B	2,32
09-12-05 09:00	#N/B	1,62	1,34	0,6	0,16	0,00	0,76	#N/B	2,34	0,5	0,37	1,79	2,38	2,34	1,87	#N/B	0,16	1,51	#N/B	#N/B	2,32
09-12-05 17:00	#N/B	1,63	1,35	0,62	0,17	0,00	0,78	#N/B	2,41	0,51	0,39	1,8	2,39	2,33	1,88	#N/B	0,17	1,52	#N/B	#N/B	2,31
10-12-05 09:00	#N/B	1,64	1,36	0,61	0,18	0,00	0,79	#N/B	2,4	0,51	0,4	1,8	2,38	2,33	1,89	#N/B	0,18	1,53	#N/B	#N/B	2,32
10-12-05 17:00	#N/B	1,65	1,38	0,63	0,2	0,00	0,79	#N/B	2,41	0,52	0,41	1,81	2,39	2,34	1,9	#N/B	0,19	1,54	#N/B	#N/B	2,32
11-12-05 09:00	#N/B	1,67	1,39	0,59	0,15	0,00	0,77	#N/B	2,41	0,5	0,41	1,82	2,4	2,36	1,89	#N/B	0,16	1,52	#N/B	#N/B	2,32
11-12-05 17:00	#N/B	1,68	1,4	0,6	0,16	0,00	0,77	#N/B	2,4	0,51	0,41	1,81	2,41	2,37	1,9	#N/B	0,17	1,5	#N/B	#N/B	2,31
12-12-05 09:00	#N/B	1,69	1,44	0,67	0,16	0,00	0,78	#N/B	2,40	0,51	0,43	1,82	2,41	2,38	1,89	#N/B	0,16	1,52	#N/B	#N/B	2,31
12-12-05 17:00	#N/B	1,71	1,47	0,73	0,20	0,00	0,81	#N/B	2,36	0,54	0,44	1,85	2,40	2,36	1,90	#N/B	0,20	1,56	#N/B	#N/B	2,32
13-12-05 09:00	#N/B	1,72	1,46	0,68	0,22	0,00	0,82	#N/B	2,39	0,56	0,45	1,86	2,42	2,38	1,92	#N/B	0,22	1,57	#N/B	#N/B	2,33
13-12-05 17:00	#N/B	1,73	1,48	0,67	0,23	0,00	0,83	#N/B	2,40	0,58	0,46	1,87	2,43	2,39	1,94	#N/B	0,23	1,59	#N/B	#N/B	2,33
14-12-05 09:00	#N/B	1,75	1,49	0,73	0,23	0,00	0,84	#N/B	2,38	0,57	0,47	1,87	2,43	2,40	1,93	#N/B	0,23	1,59	#N/B	#N/B	2,33
14-12-05 17:00	#N/B	1,76	1,50	0,76	0,25	0,00	0,85	#N/B	2,39	0,59	0,48	1,87	2,42	2,41	1,92	#N/B	0,25	1,60	#N/B	#N/B	2,33
15-12-05 09:00	#N/B	1,78	1,51	0,71	0,26	0,00	0,85	#N/B	2,40	0,60	0,50	1,88	2,43	2,40	1,93	#N/B	0,27	1,59	#N/B	#N/B	2,32
15-12-05 17:00	#N/B	1,79	1,52	0,74	0,27	0,00	0,86	#N/B	2,41	0,60	0,51	1,88	2,44	2,42	1,94	#N/B	0,28	1,60	#N/B	#N/B	2,33
16-12-05 09:00	#N/B	1,79	1,53	0,77	0,26	0,00	0,87	#N/B	2,39	0,61	0,51	#N/B	2,46	2,43	1,96	#N/B	0,26	1,62	#N/B	#N/B	2,33
16-12-05 17:00	#N/B	#N/B	1,54	0,79	0,27	0,00	0,88	#N/B	2,40	0,61	0,52	#N/B	2,47	2,44	1,97	#N/B	0,27	1,62	#N/B	#N/B	#N/B
17-12-05 09:00	#N/B	#N/B	1,56	0,81	0,28	0,00	0,89	#N/B	2,40	0,62	0,53	#N/B	2,47	2,44	1,98	#N/B	0,28	1,63	#N/B	#N/B	#N/B
17-12-05 17:00	#N/B	#N/B	1,58	0,84	0,29	0,00	0,90	#N/B	2,39	0,63	0,53	#N/B	2,48	2,45	1,98	#N/B	0,28	1,63	#N/B	#N/B	#N/B
18-12-05 09:00	#N/B	#N/B	1,59	0,82	0,29	0,00	0,90	#N/B	2,42	0,64	0,54	#N/B	2,48	2,45	1,99	#N/B	0,29	1,64	#N/B	#N/B	#N/B
18-12-05 17:00	#N/B	#N/B	1,60	0,80	0,29	0,00	0,90	#N/B	2,41	0,65	0,55	#N/B	2,48	2,44	1,98	#N/B	0,29	1,65	#N/B	#N/B	#N/B
19-12-05 09:00	#N/B	#N/B	1,62	0,85	0,30	0,00	0,91	#N/B	2,43	0,66	0,56	#N/B	2,49	2,45	1,99	#N/B	0,30	1,66	#N/B	#N/B	#N/B
19-12-05 17:00	#N/B	#N/B	1,7	0,85	0,31	0,00	0,92	#N/B	2,41	0,67	0,57	#N/B	2,49	2,46	1,99	#N/B	0,29	1,65	#N/B	#N/B	#N/B
20-12-05 09:00	#N/B	#N/B	1,64	0,89	0,32	0,00	0,93	#N/B	2,43	0,68	0,58	#N/B	2,5	2,45	2	#N/B	0,3	1,66	#N/B	#N/B	#N/B
20-12-05 17:00	#N/B	#N/B	1,72	0,89	0,33	0,00	0,94	#N/B	2,42	0,68	0,59	#N/B	2,5	2,44	2	#N/B	0,31	1,66	#N/B	#N/B	#N/B
21-12-05 09:00	#N/B	#N/B	1,65	0,88	0,33	0,00	0,95	#N/B	2,46	0,69	0,59	#N/B	2,51	2,46	2,01	#N/B	0,32	1,67	#N/B	#N/B	#N/B
21-12-05 17:00	#N/B	#N/B	1,72	0,89	0,34	0,13	0,95	#N/B	2,44	0,7	0,6	#N/B	2,51	2,47	2,01	#N/B	0,33	1,67	#N/B	#N/B	#N/B
22-12-05 09:00	#N/B	#N/B	1,66	0,9	0,35	0,14	0,96	#N/B	2,47	0,71	0,61	#N/B	2,53	2,46	2,01	#N/B	0,35	1,67	#N/B	#N/B	#N/B
22-12-05 17:00	#N/B	#N/B	1,74	0,91	0,36	0,14	0,96	#N/B	2,46	0,72	0,62	#N/B	2,53	2,47	2,02	#N/B	0,35	1,68	#N/B	#N/B	#N/B
23-12-05 09:00	#N/B	#N/B	1,69	0,92	0,38	0,15	0,97	#N/B	2,48	0,73	0,63	#N/B	2,54	2,47	2,04	#N/B	0,37	1,68	#N/B	#N/B	#N/B
23-12-05 17:00	#N/B	#N/B	1,76	1,01	0,39	0,16	0,97	#N/B	2,48	0,74	0,64	#N/B	2,55	2,48	2,04	#N/B	0,4	1,68	#N/B	#N/B	#N/B
24-12-05 09:00	#N/B	#N/B	1,71	0,93	0,38	0,16	0,98	#N/B	2,5	0,74	0,64	#N/B	2,54	2,47	2,04	#N/B	0,42	#N/B	#N/B	#N/B	#N/B
24-12-05 17:00	#N/B	#N/B	1,79	1,02	0,4	0,17	0,98	#N/B	2,49	0,75	0,65	#N/B	2,55	2,48	2,05	#N/B	0,43	#N/B	#N/B	#N/B	#N/B
25-12-05 09:00	#N/B	#N/B	1,74	0,96	0,38	0,17	0,99	#N/B	2,52	0,75	0,65	#N/B	2,55	2,49	2,05	#N/B	0,43	#N/B	#N/B	#N/B	#N/B
25-12-05 17:00	#N/B	#N/B	1,8	1,04	0,4	0,18	1	#N/B	2,54	0,76	0,65	#N/B	2,56	2,5	2,06	#N/B	0,44	#N/B	#N/B	#N/B	#N/B
26-12-05 09:00	#N/B	#N/B	1,76	0,96	0,39	0,19	1,01	#N/B	2,55	0,77	0,66	#N/B	2,56	2,51	2,06	#N/B	0,44	#N/B	#N/B	#N/B	#N/B
26-12-05 17:00	#N/B	#N/B	1,85	1,1	0,4	0,2	1,02	#N/B	2,57	0,77	0,67	#N/B	2,57	2,52	2,07	#N/B	0,45	#N/B	#N/B	#N/B	#N/B
27-12-05 09:00	#N/B	#N/B	1,78	1,02	0,4	0,2	1,02	#N/B	2,55	0,78	0,68	#N/B	2,56	2,51	2,07	#N/B	0,45	#N/B	#N/B	#N/B	#N/B
27-12-05 17:00	#N/B	#N/B	1,86	1,1	0,41	0,21	1,03	#N/B	2,56	0,79	0,69	#N/B	2,56	2,5	2,06	#N/B	0,44	#N/B	#N/B	#N/B	#N/B
28-12-05 09:00	#N/B	#N/B	1,79	1,01	0,42	0,22	1,04	#N/B	2,57	0,8	0,7	#N/B	2,57	2,52	2,07	#N/B	0,45	#N/B	#N/B	#N/B	#N/B
28-12-05 17:00	#N/B	#N/B	1,87	1,09	0,43	0,23	1,04	#N/B	2,57	0,81	0,71	#N/B	2,57	2,52	2,08	#N/B	0,46	#N/B	#N/B	#N/B	#N/B
29-12-05 09:00	#N/B	#N/B	1,81	1,03	0,44	0,24	1,05	#N/B	2,58	0,82	0,72	#N/B	2,58	2,54	2,09	#N/B	0,47	#N/B	#N/B	#N/B	#N/B
29-12-05 17:00	#N/B	#N/B	1,89	1,1	0,45	0,25	1,05	#N/B	2,58	0,82	0,73	#N/B	2,58	2,55	2,09	#N/B	0,48	#N/B	#N/B	#N/B	#N/B
30-12-05 09:00	#N/B	#N/B	1,82	1,06	0,46	0,26	1,06	#N/B	2,59	0,83	0,74	#N/B	2,59	2,56	2,1	#N/B	0,49	#N/B	#N/B	#N/B	#N/B
30-12-05 17:00	#N/B	#N/B	1,9	1,12	0,47	0,27	1,06	#N/B	2,6	0,84	0,74	#N/B	2,6	2,57	2,11	#N/B	0,5	#N/B	#N/B	#N/B	#N/B
31-12-05 09:00	#N/B	#N/B	1,85	1,1	0,46	0,27	1,07	#N/B	2,61	0,84	0,74	#N/B	2,6	2,56	2,1	#N/B	0,49	#N/B	#N/B	#N/B	#N/B
31-12-05 17:00	#N/B	#N/B	1,9	1,15	0,46	0,28	1,07	#N/B	2,62	0,85	0,75	#N/B	2,62	2,58	2,12	#N/B	0,51	#N/B	#N/B	#N/B	#N/B
01-01-06 00:00	#N/B	#N/B	#N/B	1,12	0,44	0,25	1,07	#N/B	2,61	0,83	0,72	#N/B	2,6	2,54	2,09	#N/B	0,43	#N/B	#N/B	#N/B	#N/B
02-01-06 00:00	#N/B	#N/B	#N/B	1,09	0,46	0,27	1,08	#N/B	2,62	0,84	0,73	#N/B	2,61	2,55	2,1	#N/B	0,44	#N/B	#N/B	#N/B	#N/B
03-01-06 00:00	#N/B	#N/B	#N/B	1,05	0,46	0,27	1,09	#N/B	2,63	0,84	0,74	#N/B	2,6	2,54	2,09	#N/B	0,42	#N/B	#N/B	#N/B	#N/B

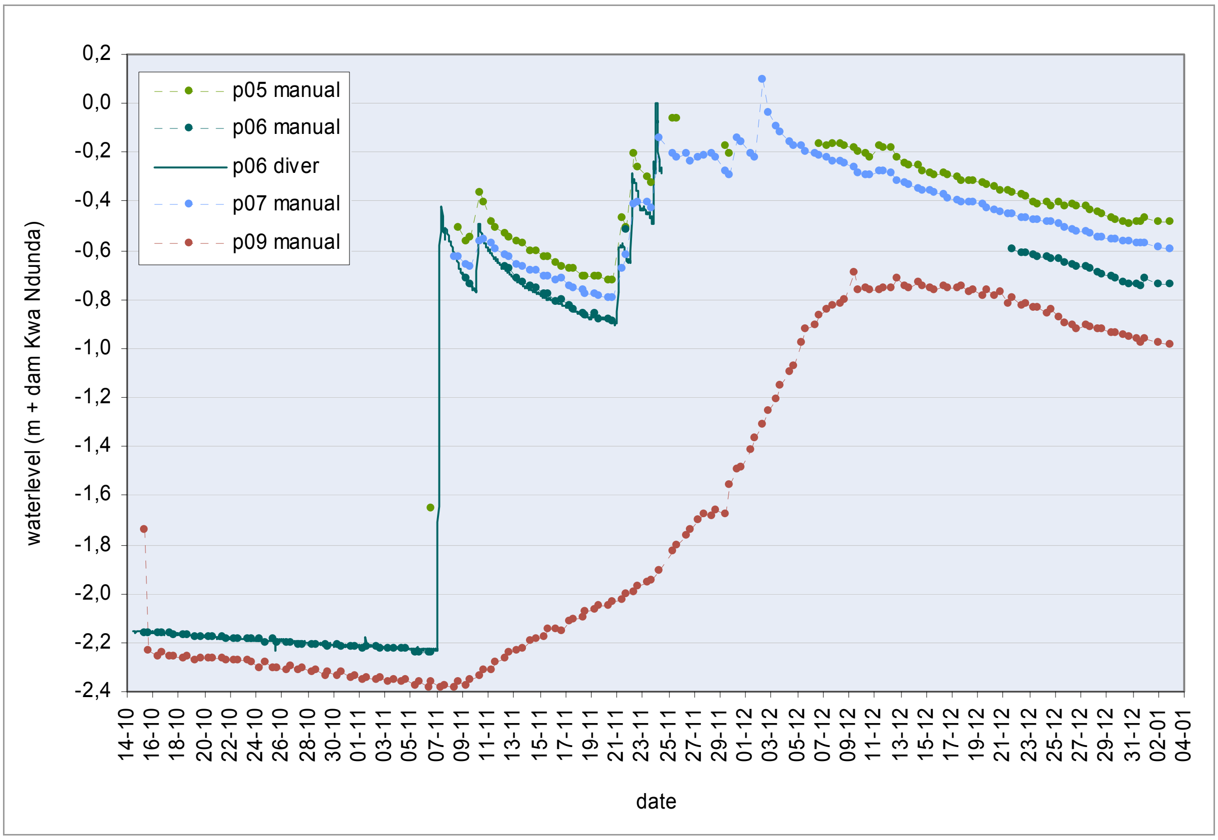
All measurements are relative to the top of the piezometer

#N/B No value (watertable below bottom piezometer) or not measured (not able to reach piezometer)
Piezometer full
Measurements just after pumping or just after augering (filled with water for augering)
Probably readings incorrect. Data adjusted

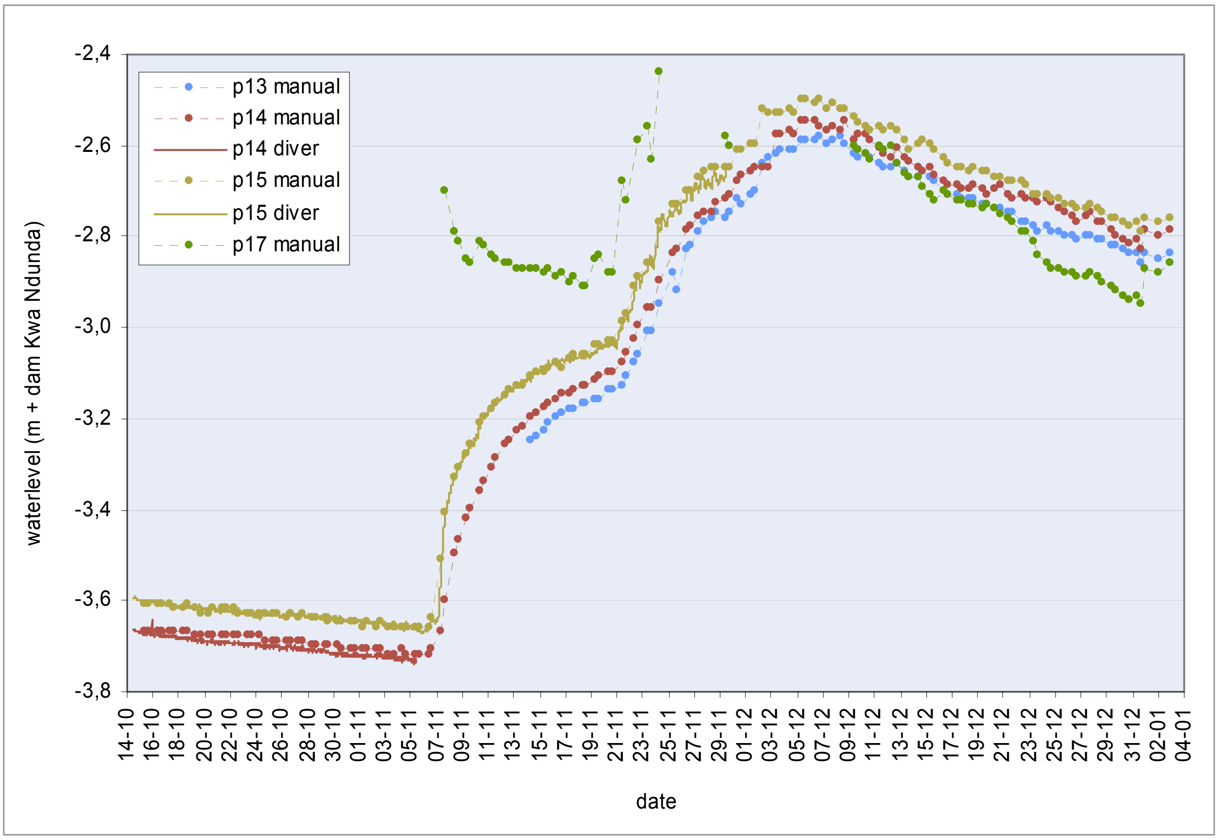
Appendix J Waterlevels (graphs)



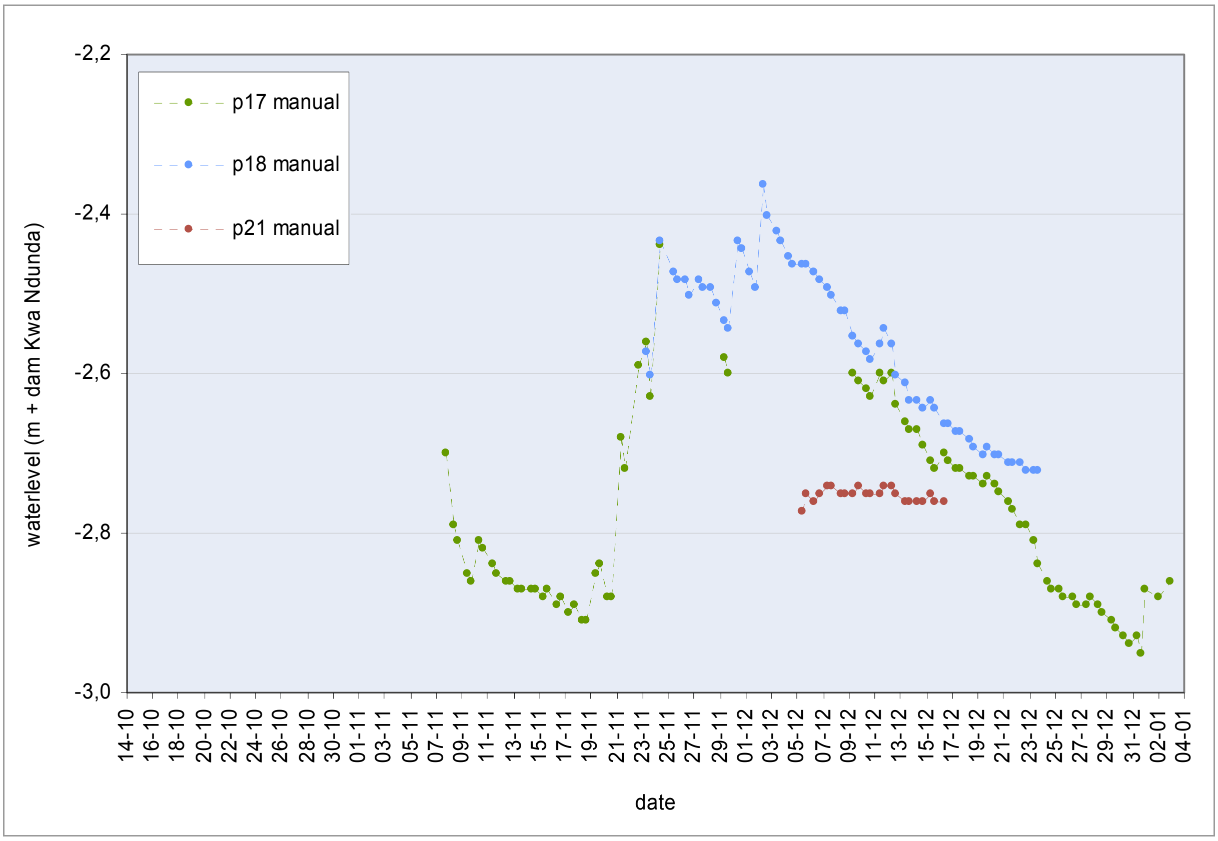
Cross-section North of dam Kwa Ndunda, Western part



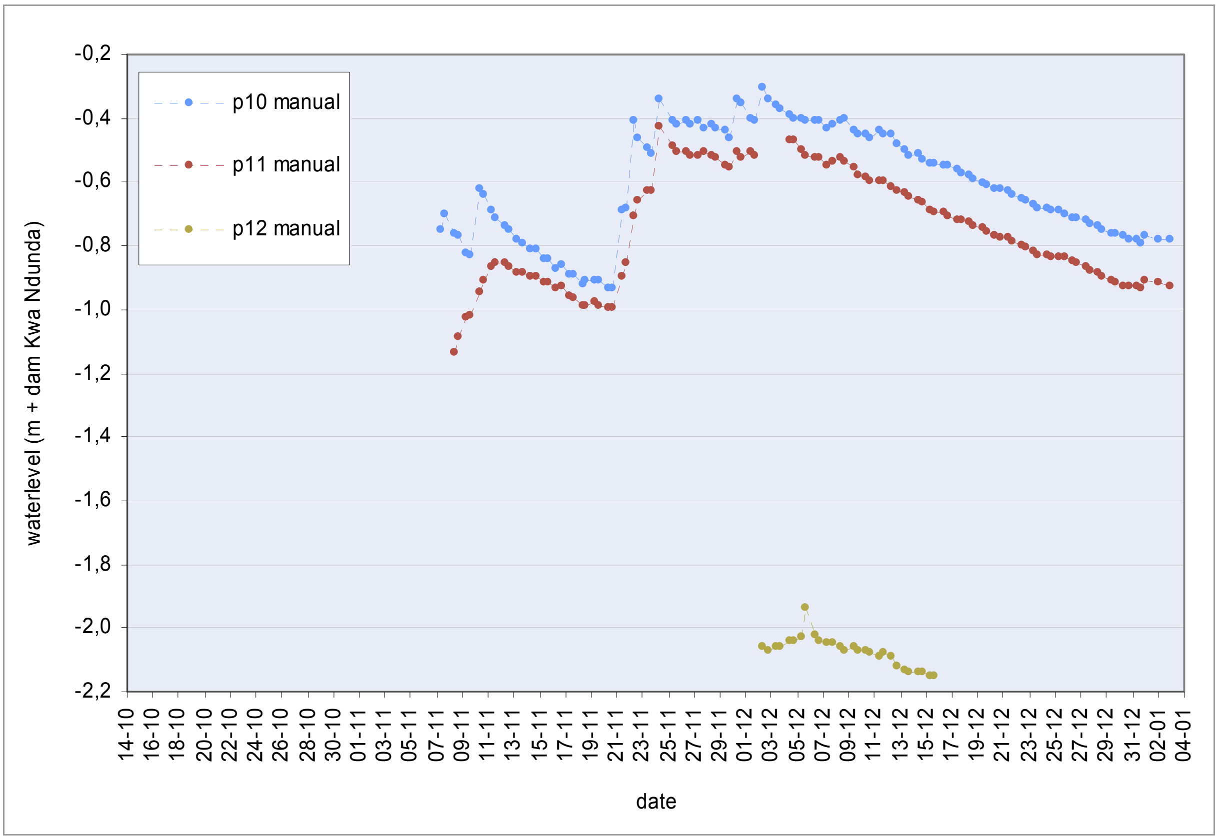
Cross-section North of dam Kwa Ndunda, Eastern part



Cross-section South of dam Kwa Ndunda, Western part



Cross-section South of dam Kwa Ndunda, Eastern part



Piezometers next to dam Kwa Ndunda

Appendix K Waterbalances

Water available in system

		March - November	November - March	Per year
	Catchment size			
W_c	Width catchment between the dams	1750 m^1	1750 m^1	
L	Length of the catchment and river	660 m^1	660 m^1	
A	Area of catchment	1,2 km^2	1,2 km^2	
	River			
W_r	width of the river	10,1 m^1	10,1 m^1	
D_r	thickness alluvium in riverbed	1,65 m^1	1,65 m^1	
n_r	porosity sand	35 %	35 %	
S_{yr}	Specific yield in riverbed	27 %	27 %	
Gr	Recharge to groundwater from riverbed	70 mm	30 mm	100 mm
	Banks			
s	Slopes	8 %	8 %	
W_b	width of influence	20,7 m^1	20,7 m^1	
Clay/silt				
E_{dc}	Effective depth banks - clay/silt at riverside	1,00 m^1	1,00 m^1	
S_{ybc}	Specific yield in river banks - silt/clay	5 %	5 %	
A_{bc}	Area crossection of layer, 1 side	6,3 m^2	6,3 m^2	
Weathered rock				
E_{dr}	Effective depth banks- weathered rock	0,65 m^1	0,65 m^1	
n_{br}	porosity weathered rock	30 %	30 %	
S_{ybr}	Specific yield in river banks - w.rock	10 %	10 %	
A_{br}	Area crossection of layer, 1 side	10,8 m^2	10,8 m^2	
	Climatic influences Nov - March			
P	Precipitation	357 mm/8 mnd	563 mm/4 mnd	920 mm/yr
E_s	Evaporation from riverbed, potential	1089 mm/8 mnd	463 mm/4 mnd	1552 mm/yr
rc	runoff coefficient to river	50 %	30 %	
d	Total days	256 days	109 days	365 days
	Evap from sand	30 %	30 %	
	Recharge and baseflow	0,25 %	0,25 %	
	Calculations			
Input				
P	Precipitation	412.335 m^3/8 mnd	650.265 m^3/4 mnd	
Q_{in}	inflow river	0 m^3/8 mnd	0 m^3/4 mnd	
L_{in}	leakage inflow	L_{out}	L_{out}	
Fluxes within system				
R	Runoff	206.168 m^3/8 mnd	195.080 m^3/4 mnd	
B_s	lateral baseflow within slopes	515 m^3/8 mnd	1.138 m^3/4 mnd	
Outputs				
E	Total evaporation from riverbed	762 m^3/8 mnd	324 m^3/4 mnd	
ET	Evapotranspiration from hillslopes	205.652 m^3/8 mnd	454.048 m^3/4 mnd	
		178 mm	393 mm	
G_r	Recharge to bm aq. from riverbed and banks	1.424 m^3/8 mnd	606 m^3/4 mnd	
Q_{out}	Riverdischarge	201.351 m^3/8 mnd	190.263 m^3/4 mnd	
	Retained behind the ssd	2,3 %	2,5 %	
Y_r	Potential yield from river bed	2.976 m^3/8 mnd	2.976 m^3/4 mnd	
Y_{br}	Potential yield from river bank, weathered rock	1.425 m^3/8 mnd	1.425 m^3/4 mnd	
Y_{bc}	Potential yield from river bank, caly/silt	416 m^3/8 mnd	416 m^3/4 mnd	
Y_b	Potential yield from banks, total	1.841 m^3/8 mnd	1.841 m^3/4 mnd	
Y	Potential yield total	4.817 m^3/8 mnd	4.817 m^3/4 mnd	
U_p	**Potential use**	**3.146 m^3/8 mnd**	**5.024 m^3/4 mnd**	
	Potential use per day	**12,3 m^3/day**	**46,1 m^3/day**	

Water use by local people

(Rhebergen and De Bruijn, 2006)

Usage		
housholds irrigating land	70	%
housholds with no irrigation	30	%
usage per houshold with irrigation	450	l/day
usage per houshold with no irrigation	91	l/day
people per houshold	7	people
population using dam	150	people
cattle per household	2	cattle
amount of cattle	43	cattle
cattle usage	6	l/day
goats per household	5	goats
amount of goats	107	goats
goats usage	3	l/day
Calculations		
irrigation water	5,4	m^3/day
goat usage	0,3	m^3/day
other usage	2,0	m^3/day
total	7,7	
total usage March - November	**1960**	m^3/8 mnd
total usage November - March	**835**	m^3/4 mnd