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Exploring the influence of sand storage dams on hydrology and water use

A case study in the Kiindu catchment in Kitui, Kenya



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By

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in partial fulfilment of the requirements for the degree of

Master of Science

in Civil Engineering

at the Delft University of Technology,

to be defended publicly on Wednesday April 20, 2016 at 16:00 PM.

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Preface

This Master thesis marks the end of my master study in civil engineering at the TU Delft. I started studying civil engineering at the University of Wismar, to participate in the development of infrastructure and more general of the physical environment we live in. After switching to the university of applied science in Muenster I discovered my interest in water management. The challenge to 'manage' the natural resource water – one of the basic human needs – and fundamental element of our environment fascinated me. I, like many others in rather rich water developed countries took the provision of clean drinking water, the safety for flood hazards and all the other services related to the water for granted. Now I discovered how much effort had to be given to provide these basic service for the public.

I graduated in Münster with the thesis about the restoration of the river Vechte (dutch: Overijsselse Vecht). After two years work experience in the Netherlands I followed the advice of one of my professors in Muenster study the master programme in civil engineering at the TU Delft. During my study I enjoyed learning the academic background I missed in my first study. Especially I enjoyed the various courses in the field of hydrology in general and the courses that link hydrology to society in particular. When I got the chance to study the effects of the sand storage dams, it was not only a topic I already considered to study in Münster but also the opportunity to combine groundwater modelling with water use and human interaction.

This study would not have been possible without support of Maurits Ertsen, who proposed the topic and lay the connection to Kenya. Furthermore I would like to thank him, Abby Onencan, Mark Bakker and Nick van de Giesen for their guidance and valuable feedback. The fieldtrip was made possible by the NGO Sasol. I would like to thank the CEO Mutinda Munguti and Harriet Kalunde and all the Sasol staff that helped me to organize the fieldtrip and supported me during my time in Kenya. I also would like to thank Theophilus Musimi who not only translated conversations when needed but introduced my into everyday live in Kitui, which made the fieldtrip such a inspiring experience. Furthermore I want to thank Mr. Mutoka, Mr. Kyende, Mr. Muimi, Mr. Wambua and Mr. Mutunga who took the time to show me around in the catchment and all the other interviewees that participated in this study.

Last but not least I want to thank girlfriend Mascha van Dort and my two children Luca and Jessie, for their love and support during the study.

Paul Strohschein

The Hague, April 2016

Abstract

Since the 1990th Sasol, a local Non-Governmental-Organization (NGO), builds sand storage dams, to mitigate the consequences of droughts in the semi-arid county of Kitui, Kenya. Sand storage dams are dams constructed in ephemeral rivers which increase the storage capacity of the riverbeds.

The water stored by sand storage dams enables local people to generate income through irrigated agriculture and brick making. By exploiting the stored water people also influence the groundwater flows and tables through water extraction and evapotranspiration, runoff and infiltration through the cultivation of land. This two way feedback between society and water system is further influenced by local circumstances like water quality, slopes and local initiatives.

In this study the long term effects of sand storage dams on hydrology and water use were assessed in the Kiindu catchment near Kitui town. It combines observed human agency and simulated effects of sand storage dams on groundwater levels to depicture what is called in socio-hydrology the co-evolution of society and water system after the construction of sand storage dams.

During a fieldtrip the study area, the local circumstances and the exploitation of water sources were assessed by means of trans-sectional walks and semi-structured interviews. The results show the interaction of local circumstances, society and water system led to different local developments even in a small catchment like the Kiindu catchment. How water is extracted and used depends on catchment properties. If the riverbanks are broad and lots of water from the riverbed can be extracted like in the downstream of the study area, people do irrigated agriculture on the riverbanks. But in such areas it is hard to find locations where sand dams can be founded on rock. Therefore sand dams are endangered by erosion of the riverbanks. In areas with steeper slopes and narrow and thin riverbeds, irrigated agriculture cannot be applied in the vicinity. Here people need to invest in equipment to utilize the water stored by the sand dams. But in these areas there are more locations where sand dams can be founded on rocks. Therefore the sand dams are more robust. Other factors that influence the utilization of water from the catchment are water quality and the availability of alternative water sources.

To investigate how the effects of the sand storage dams on the groundwater tables may influence the availability of water and therefore the water use, a groundwater model was developed. With the 'pmwin' groundwater model, which is based on the finite-difference groundwater model MODFLOW, the influence of local catchment properties on the performance of the sand dams were assessed and changes in flow directions around sand dams analysed. The simulations show that the slopes of the stream and the thickness of the riverbed have a major impact on the amount of water stored by the sand dams. Because the sand dams which store the largest amount of water lie in the area where most of the irrigated fields are located, the modelling results give a possible explanation for the observed development.

The study shows that the sand dams in general lead to larger amounts of water available in the catchment. Therefore they improve living conditions of the local communities. However the effects of the sand dams differ between the areas. In some areas they only help the communities to satisfy their domestic water demand, while in other areas people have sufficient water to generate income through irrigated agriculture. But sand storage dams may also fail and their effect abate afterwards. Thus the study shows that there is not 'The Effect' of the sand storage dams on the development of a catchment. To understand why sand storage dams have a certain effect it is important to take the local circumstances into account by assessing their effects. One should also be cautious and choose a flexible implementation and operation approach that takes the local circumstances into account if the experience with sand storage dams is transferred from one area to another.

Finally, if there is not 'The Effect' of sand storage dams, how do developments of catchments look like after the construction of sand storage dams? Based on the information obtained in the field, hypothetical socio-hydrological narratives for small sub areas in catchment, which need to be proved in further research, are formulated to show how these sub-catchments may have developed.

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1 Introduction

Large areas in Africa suffer from water scarcity during dry periods. Since ‘water is the key to development in arid and semi-arid lands’ (Sasol, 1999), mitigating the consequences of droughts through ensuring water supply in arid and semi arid areas is necessary to sustain the development in these often underdeveloped regions.

Since precipitation in most developing countries is seasonal, ensuring the water supply can be achieved by storing water from rainy seasons to dry seasons (Nilsson, 1988). To mitigate the adverse consequences of climate change, options to store water across the landscape need to be considered (World Bank, 2010). A ‘promising option for the improvement of sustainable integrated water resource management’ is to use the storage capacity of the subsurface through the Management of the Aquifer Recharge (MAR) (Tuinhof et al., 2002). MAR is often the cheapest form of safe water supply for communities (Dillon, 2005). But due to a lack of understanding of hydrology and/or knowledge of MAR, expansion of these concepts has been limited (Dillon, 2005).

One of the ‘environmentally sound solutions’ that makes use of the storage capacity of the subsurface are subsurface and sand storage dams (Steenbergen et al., 2009). The technique of these dams is rather simple and applied in various regions almost all over the world (see Figure 1).

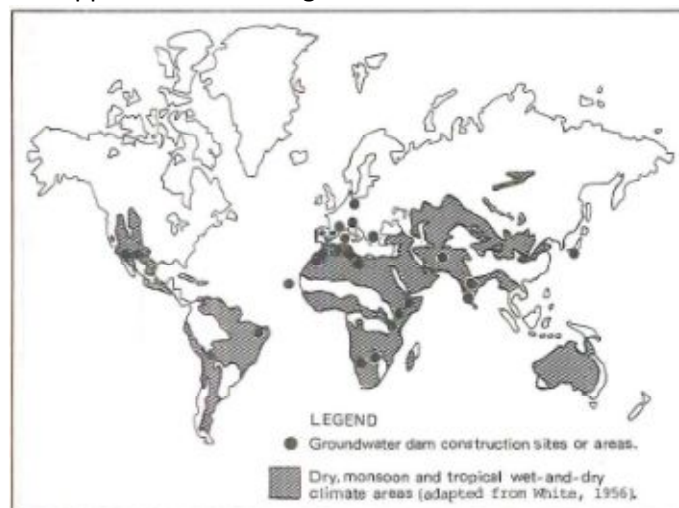


Figure 1 Groundwater dam construction sites (source: Nilsson, 1988)

Subsurface dams are built in the riverbed of ephemeral rivers. If the crest of the dams is raised above riverbed level, to increase the storage volume upstream, the dams are called sand storage dams. The name refers to the sand that accumulates upstream after the construction of the dams. During the wet season sand storage dams store water in the riverbed upstream and increase groundwater levels in their vicinity. During the dry season the sand storage dams impound water that flows in the riverbed.

In Kitui, Kenya, communities, supported by the non-governmental organization Sahelian Solutions (Sasol), started in 1990 to build sand storage dams to insure their water supply during dry periods.

Sasol aimed to built a network of water supply facilities, composed of sand storage dams, shallow wells and rainwater harvesting tanks that reduces walking distances to less than two kilometers (Sasol, 1999). Through the increased storage capacity, sand storage dams have an effect on groundwater levels and on the socio-economic development, if local communities utilize the additional stored water. In an assessment of the effects of the sand dams in Kitui, Pauw et al. (2008) distinguish primary and secondary benefits. Primary benefits are the additional water stored in the catchment while the secondary benefits comprise education through school attendance, increased agricultural activity and yield, ownership and income. Lasage et al. (2008) estimated that the income of community members adjacent to sand dams in Kitui rose by 60%.

1.1 Hypothesis and research question

Traditionally the science of hydrology focused on the natural processes of the hydrological cycle in pristine catchments. But since 'pristine catchments are the exception rather than the norm' (Troy et al., 2015) the human factor needs to be taken into account in order to be able to understand current and predict future developments. Till recently human agency was considered an external force which could be treated in a scenario based approach based on assumed 'quasi-stationarity' (Sivapalan et al., 2015). However, hydrology also influences society. The consideration of a two way feedback between societal and hydrological development led to the hypothesis of co-evolution of society and water system. The new discipline of socio-hydrology, wherein human agency is treated as endogenous that interacts with the water system, was established. (Sivapalan et al., 2012). In 2013 the International Society of Hydrological Sciences (ISHS) proclaimed the new scientific decade 'Panta Rhei – everything flows – change in hydrology and society'. (Montanari et al., 2013)

The construction of sand storage dams is one example how local communities intervene in hydrological processes in order to improve their water supply. Sand storage dams influence groundwater flow, which as a result lead to an increased amount of water available in the catchment. The additional water if utilized lead to an improved water supply and enables socio-economic development. Pauw et al. (2008) called the additional water available and its implications for society primary and secondary benefit respectively. But the socio-hydrological development or evolution does not stop at this point. The development and an increased water use (especially in irrigated agriculture) influences the hydrology of the catchment which in turn has implications on the local communities. The consideration of the co-evolution of water system and society stirred by sand storage dams is summarized in the following hypothesis:

Sand storage dams stimulate 'the co-evolution of hydrology and society' on catchment scale and influences the development of the catchment.

Some research about sand storage dams and their effect on hydrology as well as on the socio-economic development has been done (see subchapter 2.1.1). However often studies focus either on the effect of the sand storage dams on the hydrology in general (Borst et al., 2006), on groundwater levels in particular (Hoogmoed, 2007, Hut et al., 2008 and Orient Quilis et al., 2009) or on the effect on the community (Ertsen et al., 2005). Furthermore most hydrological studies are restricted to a limited number of sand dams while studies about their effect on the socio-economic developments averaging their effect on the socio-economic development, which diffuses the link between hydrology and society. The scope of this study is broader. It focuses on the effects of the sand dams on the hydrology (basically groundwater level) as well as on water use and its implication for the catchment as well as for the communities. The study focuses on a single catchment with multiple sand dams built about 18 years ago to gain understanding how hydrology and society influence each other on catchment scale.

The study centers around the following two research questions

1. How does the 'coupled human-water system' in a catchment develop after the construction of sand storage dams?
2. *What are the main factors and processes that lead to these developments and how are they related to the sand storage dams?*

1.2 Outline

In chapter 2, the technology of sand storage dams is described in more detail, and available literature about sand storage dams is summarized. Furthermore the chapter gives some background information about the research area.

The catchment and human water use were assessed during a fieldtrip through trans-sectional walks and semi-structured interviews. The basic concepts and findings are described in chapter 3. At the end of the chapter relations between the different findings are proposed.

The effect of the sand storage dams on the groundwater levels in the research area were assessed through a ground water model. In chapter 4, the model is described and the results are presented and discussed.

The schematization of the catchment is based on limited data and could not be calibrated since there are no long term groundwater records. A discussion whether the modeling results reproduce observations during the fieldtrip, how they may explain these observation and what they imply for the development of the catchment is described in chapter 5.

In chapter 6, conclusions from the fieldtrip and the modeling exercise are drawn. At the end the consequences of the conclusions are described.

In chapter 7, areas for further research are suggested which is necessary to describe the development in the catchment more comprehensively.

In the frame of the study the development of the catchment cannot be described ultimately. However based on the information gained during the fieldtrip possible hypothetical socio-hydrological narratives are proposed in chapter 8, to show how such narrative may look like and how divers they may be.

2 Background

2.1 Sand storage dams

In arid or semi-arid catchments many streams are ephemeral, thus rivers discharge water only during the rainy season. In the dry season the river dries up. If the river is dry, water is still - via wells - available as groundwater. Traditionally people dig holes - so called scoop holes - in the riverbed to fetch water. Due to water use, groundwater flow and evaporation, the groundwater tables in the riverbed decline during the dry season. To prevent the water from draining downstream, dams are built in the riverbed perpendicular to the flow direction. These dams are called subsurface dams if the dam does not stick out of the riverbed.

To increase the storage volume and improve the water supply further, the crest of the dam can be increased above the surface of the riverbed. During the rainy season sediments accumulate upstream of the dam and the riverbed rises. When the storage volume is filled with sediments the dam is called matured. These dams are called sand storage dams or sand dams.

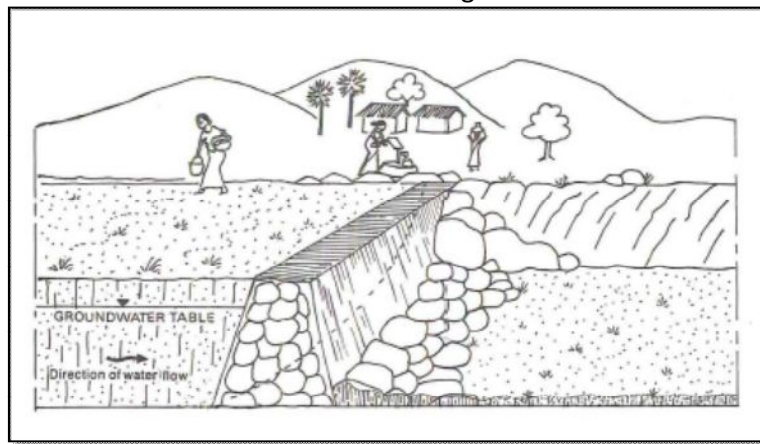


Figure 2 General principle of sand storage dams (Source: Nilsson, 1988)

The sedimentation which is a problem for surface dams is part of the principle of the sand dams, where the water is stored in the soil. The crest of the sand dams should be increased in stages so that coarse sediment can settle upstream of the dam while finer sediment will be transported during floods further downstream. For sand dams it is important that the sediment is not too fine. Because then the pore volume of the storage and therefore the storage capacity, decreases. Furthermore with finer sediments water extraction becomes difficult because of lower hydraulic conductivities.

Advantages and Disadvantages

By applying the technology of sand storage dams, water is stored in the soil under the surface. This offers four main advantages compared with surface dams:

- No land is inundated. Thus the land above the storage can still be used.
- Decreased evaporation losses. The soil above the water table protects the water against solar radiation and decreases evaporation losses, which are high in arid and semi-arid areas.
- Good water quality. Because the stored water comes not into direct contact with droppings from cattle and other animals the water quality remains well throughout the dry period.
- No parasites. The soil on top of the water table also prevents parasites like mosquitoes to breed in the water.

The disadvantages of sand storage dams compared to surface dams are

- Less water is stored. Water is only stored in the space (pores) between the soil particles which decreases the volume of water stored in the reservoir.

- No direct water extraction. Extracting water is only possible from scoop holes and wells and not directly from the water surface.

2.1.1 Literature research and scientific context

Sand storage dams and their effects on hydrology and socio-economic development have been the subject of several studies. Most literature focuses mainly on one of the following aspects; (1) the planning and implementation aspects, (2) the structure and its construction itself, (3) their effects on the hydrology in general and groundwater levels in particular or (4) the utilization of the stored water and its effect on income, education and agricultural practice. Some studies include also the (5) implication of water use on groundwater levels and other basic feedback mechanisms. Below the a short overview about the available literature according to the mentioned aspects if given. What needs to be studied further is how these aspects relates to each other. How they evolve over time and how they influence the development of a catchment. This study focuses on the interaction between hydrological effect and water use and its influence of the development of a catchment.

1. Planning and implementation

To achieve better living conditions through an ensured and increased water supply, Sasol took the initiative and provided funding and skills for the construction of sand storage dams.

The approach followed by the local NGO Sasol to implement sand storage dams in Kitui county is described in Sasol et al. (1999). Ertsen et al. (2005) argue that the construction of sand storage dams have not resulted in stronger organizational structures. Furthermore they found that after the construction process little communal activities take place. This may be caused by the 'highly predefined implementation approach'. A study by Ertsen et al. (2009) focuses on the planning aspects like community involvement, decision making and incentives of the different stakeholders followed by Sasol. They highlight the power relations between the NGO and the local community.

Forzieri et al. (2008) developed a method to select suitable sites for the construction of surface as well as subsurface dams by using remote sensing data.

2. The structure, construction process and maintenance

The sand dam as structure itself and the construction process in general is described by Nilsson (1988) and Nissen-Petersen (2006). Moreover there is some research done to improve the design as well as the maintenance of the sand dams. (Beimers et al., 2001a and Beimers et al., 2001b). Sasol enhanced the design of the sand storage dams. The principles for construction and operation are summarized by Munyao et al. (2004).

3. The effect of sand storage dams on hydrology

In 2006 and 2007 several master theses from the VU Amsterdam were written about the effect of the sand dams on the hydrology of the catchment (Borst et al., 2006, Hoogmoed, 2007, Gijbertsen, 2007 and Janssen, 2007). Hoogmoed (2007) and Orient Quilis (2007) studied the effect of the sand storage dams on the groundwater levels in the vicinity of the dams. Hoogmoed (2007) focused on the short time response of the groundwater tables after rainfall events. For the model she used rainfall as well as groundwater levels measured during a field campaign. Orient Quilis (2007) focused on the long term effect of the sand dams over a period of decades. She built a simplified idealized groundwater model. An important parameter that determines the effect of a network of sand storage dams is the distance between the single sand dams. (Orient Quilis et al., 2009)

The effect of the sand dams on environmental flow downstream is analyzed by Lasage et al (2013) for different climate scenarios and numbers of sand dams in a catchment in Ethiopia. They conclude that sand dams increase the number of month with low flows downstream. However, due to their positive effect on the (drinking) water supply of rural communities, the impact on the downstream is considered acceptable. Borst et al. (2006) estimated the downstream effect of the sand dams as 'very insignificant'.

4. Water use around sand storage dam and the impact on the adjacent communities

The increased storage capacity lead to increased water use and to improved living conditions. Hussy (2007) describes how water can be extracted from sandy rivers. How living conditions changed after the construction of the sand storage dams is assessed by Pauw et al. (2008). In this study the authors distinguish the benefits of sand storage dams into primary and secondary benefits. Primary benefits are stored water in the catchment. Secondary benefits can be found in the field of education through school attendance, increased agricultural activity and yield, ownership and income which also includes health. Lasage et al. (2008) found out that the sand dams built in Kitui have a big impact on communities and that the income of the members of communities rose by 60%.

5. Feedback of water use and socio-economic development on hydrology

Depending on agricultural practices, the cultivation of agricultural land may increase land degradation as shown by Tesmegen et al. (2008). But it may also increase the infiltration if water conservation techniques are applied like infiltration trenches with bunches as described by Mukurira et al. (2009). The influence of different tillage techniques on infiltration is assessed by Moroke et al. (2009).

Feedback loops due to the construction of sand storage dams have not been explicitly subject to intensive research. However in the hydrological studies of Orient Quilis (2007) and Hut et al. (2008) the effect of different water uses on groundwater tables are simulated in few scenarios. Pauw et al. (2008), in their assessment of sand storage dams, studied effects on the living conditions which in turn affect the land cover.

2.2 Study area

The study area is the Kiindu catchment in Kitui county in Kenya. Kitui county is one of 48 counties in Kenya. It lies 150 km east of Kenyas capital Nairobi. The capital of Kitui County in Kitui town (UTM zone 39 390116 East, 9849074 North) The research area is about 12 km south of Kitui town. The spring of the Kiindu is south of the village of Wikilyle. The general drain direction is south. In the south the Kiindu flows into the Nzeeu river which is part of the bigger Tana catchment which discharges into the Indian Ocean.

Kiindu catchment

The Kiindu itself has several tributaries. The two biggest are the Muasya and the Nduni. Upstream of the junction of the Muasya the local people call the main river Kivuna. Downstream of this junction the people call the stream Kiindu. Due to the limited time the study focuses on the area upstream of the junction Kiindu/Nduni. In the course of the report the names Kivuna, Muasya, Nduni and Kiindu will be used to point to the corresponding reaches.

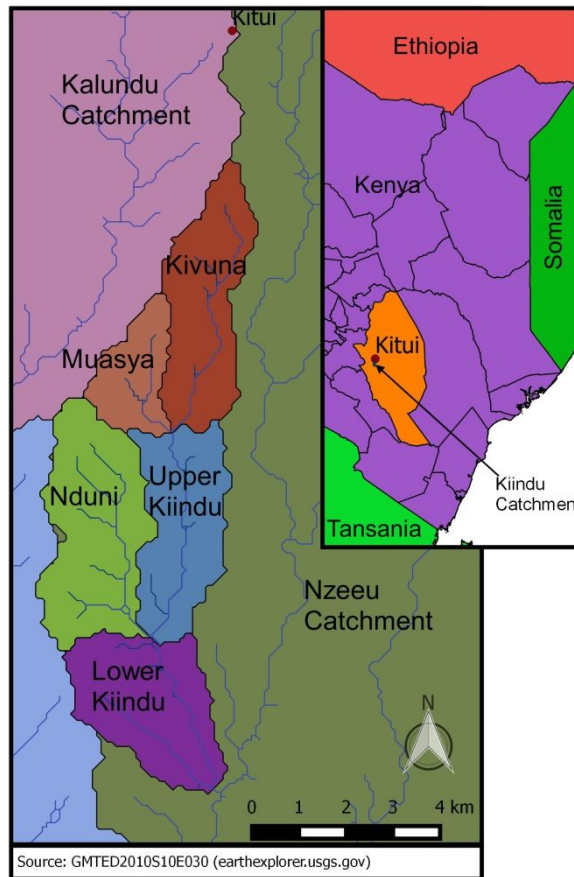


Figure 3 Overview study area

The topography ranges from about 1100 m above sea level in the north to about 950 m above sea level in the south of the catchment. The underlying rock formations consist of gneisses. The surface of the gneiss is weathered. The degree and the thickness of the weathered layer varies throughout the catchment. A clay layer has been build up on top of the weathered rock layer. The thickness of the riverbed varies from few centimeters to more than two meters (Borst et al., 2006).

The climate in the study area is semi-arid. The annual rainfall is about 800 mm, but fluctuates from year to year. Most of the rain falls during two rainy seasons in December/January (short rains) and March/April (long rains). However these rainy season tend to fail regularly coursing regular famines. According to local lore rain fails completely at least every four year (Sasol, 1999). The annual potential evaporation is about 1800 mm (Borst et al., 2006).

The population in the study area as in whole Kitui county belongs to the Kamba tribe. The landscape is dominated by scattered homesteads on irregular plots of cropland between natural vegetation. The Acacia and thorny bushes are the common vegetation in the catchment, that 'response rapidly' to rainfall (Borst et al., 2006). Several homesteads form villages that elect an village elder which acts as a spokeswoman/spokesman who represents the village. Most of the cropland is used to do rain fed agriculture with subsistence crops such as maize, beans and peas. Few people irrigate small plots on the riverbanks. The majority of young people seek work outside the district to support their families through money sent home (Sasol, 1999).

3 Fieldwork

3.1 Methods

The developments in the study area were assessed during a fieldtrip from 21 July to 27 September. The assessment consisted of semi-structured interviews and trans-sectional walks. Both, the trans-sectional walks and the semi-structured interviews were conducted together with Theophilus Musyimi, a local student, who helped to put the obtained information into the cultural context and translated the interviews when needed.

After arriving in a new area in the catchment the village elder was visited to inform him or her about the fieldwork and to make appointments for semi-structured interviews (if required). Afterwards first a trans-sectional walk was conducted to assess the catchment. During the trans-sectional walks the first semi-structured interviews were conducted, if local people were met. The following days additional semi-structured interviews along the riverbed and at homesteads, at some distance of the river were conducted to get a more comprehensive picture. During the semi-structured interviews the participants illustrated their experiences by showing the location of water use and/or extraction. Rough concepts of semi-structured interview and trans-sectional walk were prepared beforehand. Initially the interviews contained very detailed questions about the water use and the societal background (see Appendix B). It turned out that this initial concept was too specific and the interviews took too long. Participants of community meetings had to wait, because the questions were much too detailed. To be able to speak to more people the concept was shortened with only eight main questions to address the topics mentioned below. (see Appendix B) The conversation could go into more detail with more specific questions, if interviewees had additional experience. Moreover the setting of the semi-structured interviews were revised from community meetings to a more spontaneous procedure, where people were interviewed during their daily life, because the community meetings were probably attended mainly by people which had complains about the shortage of water. People who had sufficient water probably stayed on their farms and continued with their work. Furthermore the community meetings could have lead to disappointments, because they potentially could raise the expectation by the participants that their water supply will be improved by activities related to the interviews. The new procedure also had the advantage that the location, technique and purpose of water extraction could be assessed immediately. To get a more representative sample of interviewees people, who may have more difficulties to get water and/or use alternative water sources were visited on their plots.

During the **semi-structured interviews** three main topics were addressed:

- Current and former water use and water sources. An indication of the effects of the sand dams may be the degree of the water use as well as the shift from water sources from distant to water sources near the dams or homesteads.
- Observed changes in landscape, vegetation and groundwater levels. In theory sand dams lead to higher groundwater tables which may change vegetation and land use. Higher groundwater tables may also be visible in wells.
- Social environment. Also society may have changed in the last years. This may be an alternative reason behind the water and land use that may not be linked to the hydrology.

The **trans-sectional walks** were conducted to obtain information about

- General characteristics of the stream and catchment. The locations of tributaries, rock outcrops and the levels of the riverbed and bank were noted as well as the width and the thickness of the riverbed.
- Human water use. The locations of sand dams, public as well as private shallow wells and irrigated fields were assessed.
- Vegetation. Due to changes in the hydrology the vegetation could have changed over the last 18 years.

3.2 Findings

The results of the fieldtrip are illustrated in the field rapport in Appendix A. During the fieldwork different components (like landscape, water sources, water use etc.) that influenced or were influenced by the development of the catchment were assessed. The results show that the characteristics of these components are not uniform throughout the catchment but differ between the different subareas. In Figure 4 the local characteristics of these components are illustrated for the Kivuna/Kiindu stream. Below a short description of these components and their local features is given that also comprises the Muasya and Nduni tributary.

Landscape

Under the heady 'landscape' in Figure 4, the shape of the valley and the dimensions of the riverbed are summarized. The general rough trend of these characteristics is that the valley widens in downstream direction and the riverbed becomes broader and thicker in downstream direction. Locally the valley can be quite narrow and the width of the riverbed may be larger or smaller depending on local circumstances.

Riverbed

The riverbed as observed during the fieldtrip is locally influenced by the sand dams. Upstream of the sand dams the riverbed is much thicker due to the accumulated sand, while downstream often the riverbed is washed away and the underlying rock is exposed. Rock bars are present upstream of the two steeper sections between sand dam 6 and 7 and between sand dam 20 and 21. In the steep sections the river does not form a defined riverbed. In this rocky sections sediments only settle between rocks.

Land cover

On steep slopes, especially in the upstream, the land is covered by natural vegetation. On milder slopes people do rain fed agriculture. In downstream direction the natural vegetation is reduced to a small strip along the river. Riverbanks and hill slopes are used for agriculture. In areas where people do irrigated agriculture people on the riverbanks natural vegetation almost vanished.

For a much more detailed description see Appendix A.

(Riverbank) Erosion

The erosion of the riverbanks takes place in the whole catchment. In the upstream catchments of the Kivuna, Muasya and Nduni it is limited to the vicinity of the sand dam. Along the Kiindu especially downstream of sand dam 16 the tenth of meters are effected by erosion. Irrigated plots on the riverbanks are washed away.

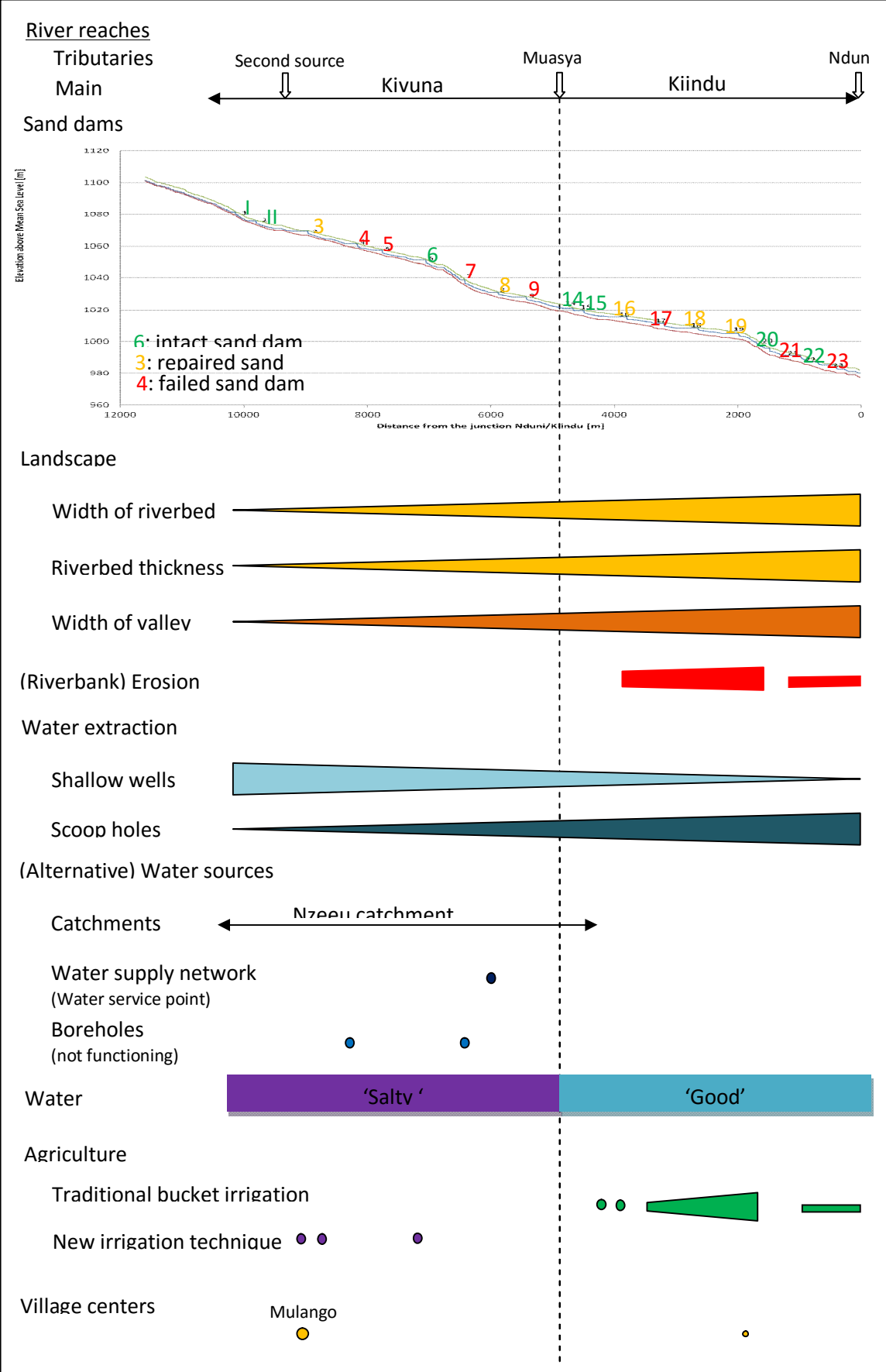


Figure 4 Findings along the Kivuna/Kiindu reach

Sand dams

Failures

The observation about the condition of the sand dams show that about half of the sand dams (14 out of 27 sand dams built by Sasol) broke initially. From the visited sand dams the most upstream sand dams are still intact. The two sand dams in one of the two main sources of the Kivuna stream, all sand dams in the Muasya tributary and the three sand dams most upstream in the Nduni tributary never failed. Furthermore the two sand dams 6 and 20 (which was built in the colonial area) located upstream of a steeper section have not failed. Of the nine sand dams built by Sasol in the Kiindu stream only the two most upstream sand dams (14 and 15) and sand dam 22 have never failed. The sand dams built by other organization or persons in the Nduni tributary all failed initially.

Repairs

In the Kivuna stream between the junction of the two sources and the junction with the Muasya 6 of the 7 sand dams broke initially. Only sand dam 6 has been intact all the time. Of the three sand dams upstream of sand dam 6 only sand dam 3 was (successfully) repaired. Downstream of sand dam 6, sand dam 7 has not been repaired, sand dam 8 has been successfully repaired while sand dam 9 broke again after its repair.

In the Kiindu catchment upstream of sand dam 20, three of the initially four broken sand dams have been successfully repaired. Only sand dam 17, which broke recently, has not been repaired. The two broken sand dams downstream of sand dam 20 have not been repaired.

In the Nduni catchment the two broken sand dams in the downstream have been repaired while the two sand dams upstream have not been repaired (see Appendix A).

Water Extraction

Most of the shallow wells built by Sasol do not deliver water anymore. They are either filled with branches and sediments or washed away during floods. Highly used public shallow wells are sited next to sand dam II, 14, 20 and 25. Since the donated shallow wells in most cases are out of use, most people extract water from scoop holes again.

The observations during the fieldtrip suggest that the general water extraction pattern differs between upstream and downstream. In the most upstream parts (private) shallow wells are much more used than in the downstream part

Further downstream more water is extracted from the riverbed via scoop holes. These shallow wells are public so that everybody is allowed to use them. Further downstream people dig 'private' scoop holes to water their goats or to fetch water for irrigation. Scoop holes for domestic water extraction are public in general. Shallow wells are less applied.

(Alternative) Water sources

People in the Kivuna and Muasya catchment are less dependent on water from the catchment. They have alternative water sources with rather high quality water. They can use the water from the water supply network of Kitui or the Nzeeu catchment.

In the Kivuna catchment there are also two boreholes that potentially could supply the local communities with water of 'good quality' from deeper aquifers. However the borehole next to sand dam 4 is filled with stones and therefore not restorable anymore. To rehabilitate the borehole next to sand dam 7, the repair of the pipe network needs to be funded and the operation of the borehole needs to be organized

Downstream of sand dam 14/15 people rely on water from the Kiindu catchment, which is less salty. The people in the Nduni catchment have the Kalundu catchment as alternative water source. But people report that they avoid using the water for consumption since the Kalundu is highly polluted with waste water from Kitui town. Therefore they have a strong preference for the water from the Nduni catchment.

Water quality (and water use)

The water from the riverbed in the Kivuna river is considered salty. Whether it is suitable for agriculture purposes is considered controversial in the communities. It is mainly used for washing, watering goats and brick making. For domestic use people use water from the Nzeeu catchment and the water supply network. Water from shallow wells is less salty. The owners use it for every purpose.

In the Kiindu the water quality is considered to be good. Therefore people use water from the riverbed for domestic use as well as for irrigation in areas where enough water is available.

In the Musya and Nduni tributary the water quality is considered good, but the amount of water available is not enough for more than domestic use.

Agriculture

Throughout the catchment people mainly do rain fed agriculture on mildly sloped hills. If enough water is available people start to do irrigated agriculture to diversify their diet and generate income.

In the Kivuna catchment and the upper parts of the Kiindu catchment few small plots of about 10 m² along the stream are irrigated. At some distance from the stream three people invested in shallow wells, pumps and storage tanks to apply larger scale irrigation on their plots.

In the Kiindu catchment people irrigate plots on the riverbanks with water from scoop holes. Upstream of sand dam 16 there are only 2 bigger irrigated fields. Downstream of sand dam 16 the technique becomes more and more applied. Between sand dam 18 and 20 the riverbanks of whole reaches are covered by irrigated fields. Below the steeper section downstream of sand dam 20 several plots on the riverbanks are used to do irrigated agriculture.

Village centers (and infrastructure)

On the borders east of the catchment more or less parallel to the Kivuna-Kiindu stream the road connects Wikkilily in the North with the South of Kitui county. The commercial center of the region is Kitui town, about 5 km north of the catchment. Throughout the study area there are several shops that supply the rural communities with basic needs. Next to the Mulango Mission Center a small community center is located which comprises next to specialized shops like butchers also an old secondary school. Mulango which is the biggest center in the study area offers the opportunity to generate income apart from agriculture. Further south another smaller center is located which comprises the office of the local chief for the southern part of the study area.

3.3 Discussion

After identifying the local differences of the various components, the cause and consequences of these differences are analyzed. The information suggests relations between landscape, sand dams, water cycle, water use and human agency. Figure 5 illustrate probable relations between the single components. The relations are divided in 4 groups indicated in Figure 5 by different colors.

The first group of relations show the influence of the catchment properties on water use through (a) the suitability of the catchment for irrigated agriculture, (b) the stability of sand dams, (c) water extraction techniques and (d) water quality.

The second group of relations shows the influence of human agency (through water and land use) on (a) the catchment properties (land cover) and (b) (the stability of) sand dams.

The third group shows that Who benefits (a) depends on the extraction technique and the ability to invest, (b) influences the development through (i) the degree of water use and (ii) the maintenance of the sand dams.

The fourth relation is found in the literature. The study by Borst et al. (2006) probably shows that sand dams effect the groundwater quality. But this relation needs to be analyzed in further research. Below the probable relations are described in more detail.

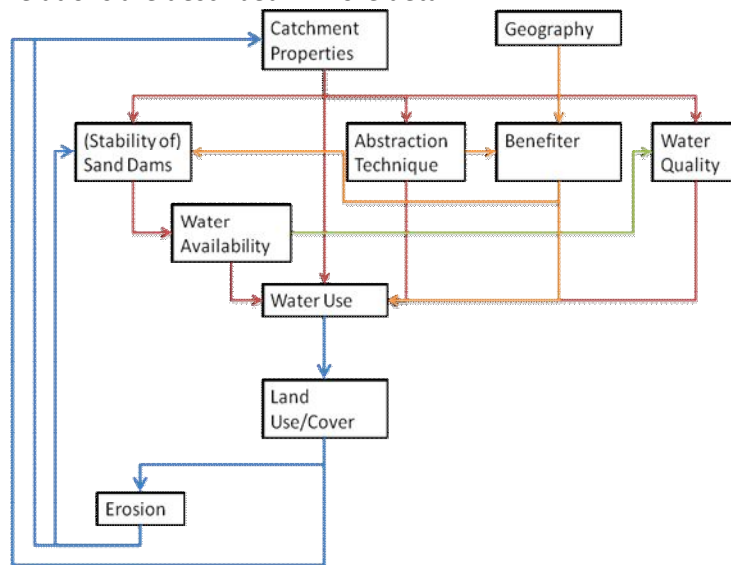


Figure 5 Proposed dependencies

1. Red arrows: The influence of catchment properties on water use through ...

a. ... suitability for irrigated agriculture.

In order to do irrigated agriculture, fields need to be only slightly sloped. In the upstream parts of the catchment the slopes are in general steeper and terraces need to be dug first, before irrigated agriculture can be applied. Furthermore areas which are suitable for digging terraces are at some distance from the stream. Further downstream the valley is wider. The riverbanks are only slightly sloped and therefore suitable for irrigation without extensive preparation. Since the riverbed is also wider and thicker than upstream, more water is available via scoop holes (see also section 4.2.1). Furthermore the distance to the riverbed decreases and ensures a simple water supply.

Thus the effort to develop larger scale irrigated agriculture decreases in downstream direction.

b. ... (the stability of) sand dams.

Considering the local difference described in section 3.2, the properties of the catchment have likely influence the stability of the sand dams.

Section 3.2 shows that sand dams fail less often in the upstream parts. In the upstream parts the valley is narrow and the riverbanks relatively thin. In these areas the sand dams can be constructed

on the rock beneath the sandy riverbed and in the riverbanks. Also the sand dams 6 and 20 (and to a lesser degree 14 and 15) are founded on rock outcrops upstream of a steep river section. With the foundation on rocks the erosion of the sides of the sand dams can be avoided or minimized.

In the Kiindu catchment the valley is wide and the riverbed broad. Most sand dams could not be built on rock. Therefore all but one (sand dam 22) sand dams failed and needed to be repaired in the course of the years (see Figure 4).

Thus the stability of the sand dams decreases in downstream direction.

c. ... water extraction techniques.

While the relatively thin and narrow riverbed makes it easy to find the sand dams on rock, water extraction becomes more complex. Because of the thin and narrow riverbed, water cannot be extracted directly from scoop holes in the most upstream parts of the catchment. Therefore here only few scoop holes could be found in the riverbed. Instead several interviewees showed us their private shallow wells, which they had dug into the weathered rock to satisfy their water demand. Along the river the number of scoop holes increases in downstream direction, while the number of shallow wells decreases. Between sand dam 17 and 20, scoop holes are dug next to each other to fetch water for irrigating fields on the riverbanks.

d. ... water quality.

Another factor that influences the water use is the (considered) water quality. In the Kivuna catchment people report that water from the riverbed is salty and therefore hardly usable for domestic purposes. Whether the water is suitable for irrigated agriculture is considered controversial within the community. People evade the usage of the water from this reach and fetch water from the neighboring Nzeeu catchment. Therefore people use less water from the catchment if water quality is considered poor and alternative water sources are available.

2. Blue arrows: The influence of human agency (through water and land use) on ...

a. the catchment properties

When people start to do agriculture they start to change the land cover which in turn influences hydrological processes like interception, infiltration, etc. Traditional agriculture in Kitui consists of rain fed crops, like beans and peas. However when water becomes available, due to the construction of sand dams, people start to develop irrigated agriculture. The most obvious locations for irrigated agriculture are the riverbanks because they are rather flat and close to the scoop holes. In order to cultivate the land, people clear the riverbanks from natural vegetation.

Another purpose of the extracted water is brick making. Especially on slopes which are less suitable for irrigation people use water to form bricks. Therefore they clear the location from natural vegetation and cut trees to produce charcoal to burn the bricks.

Both water uses, irrigated agriculture and brick making, lead to less natural vegetation and therefore influence infiltration, interception and runoff. Moreover it may lead to land degradation as described in Appendix A. During the fieldtrip it could be observed that the sections with the highest water use are also the area with the largest erosion.

b. ... (the stability of) sand dams

The erosion, if it reaches the vicinity of the sand dam, at the end may influence the stability of the sand dams that are founded in the riverbanks. This would explain why all sand dams in the area with the most irrigated plots were broken initially.

On the other hand people may have also the largest incentive to repair sand dams. This would explain why most of initially broken sand dams in these areas were repaired afterwards. If the results (described in section 3.2) are considered in more detail it can be noted that

- three out of four sand dams in the Kiindu catchment upstream of sand dam 20 (which is the area with the largest area of irrigated agriculture) are successfully repaired

- only two out of six sand dams in the Kivuna catchment were successfully repaired. Here the functioning sand dams have a much less obvious effect than downstream.

Since it could not be clarified why and how sand dams were repaired, the link between the utilization of stored water and repair and maintenance of the sand storage dams is speculations. However the results of the fieldtrip suggest that the probability that sand dams get repaired increases with their potential to store water.

3. Orange arrows: Who benefits ...

Another factor in the development in the catchment is who benefits, how he/she benefits and why he/she benefits. To assess these considerations comprehensively a study about organizational structures needs to be conducted, which is out of scope of this study. However during the fieldwork several observations could be made which suggest links between catchment properties, water use and the capacity of people to invest.

a. ... depends on the extraction technique and the ability to invest

The utilization of the water sources in general is influenced by the location of the particular water source in the catchment. Even in small catchments, like the Kiindu catchment, there are some differences in infrastructure throughout the catchment. In the Kivuna catchment the center of Mulango is located, which provides the best opportunities to generate income apart from agriculture. In the area people live who have additional income and therefore the financial background to invest in shallow wells, pumps and tanks. These facilities are essential to extract larger amounts of water from the shallow aquifer and develop irrigated agriculture. Other people in the area (probably without these resources) do not use large amounts of water and try to generate income through (casual) work.

In other areas people have less job opportunities. In these areas people basically rely on agriculture. Because water can be extracted from the riverbed there is no need to invest in wells, pumps and tanks to develop irrigated agriculture. Here the distance to the stream is critical for the development of irrigated agriculture.

b. ... influences the development through ...

i. ... the degree of water use

In the upper parts of the catchment, where shallow wells, pumps and tanks are the requirements to develop irrigated agriculture, only few farmers (had the capacity to) invest. Therefore water use is limited to domestic purposes and brick making.

In the downstream parts, investments are not needed to irrigate plots on riverbanks by buckets. Furthermore the alternatives to generate income are limited. Therefore irrigated agriculture is probably be more attractive and therefore water use (much) larger in the downstream parts than it the upstream parts.

ii. ... the maintenance of the sand dams

Only little information about the maintenance and repair of sand dams could be obtained during the fieldtrip. Sand dam 3 was repaired on the initiative of one individual farmer. He is by far the biggest benefiter of the sand dams since he could invest in the equipment necessary to utilize the stored water. Therefore and because of his capacity to invest other community members refused to participate.

How most of the sand dams further downstream are maintained and repaired and who took the initiative could not be discovered. However the community around sand dam 23 made some effort to start repairing the damaged sand dam. But the community was neither able or willing to organize the effort or to manage help from outside the catchment, as was done in the case of sand dam 3.

These cases suggest that when people have to invest in the equipment to utilize the water source, they also have the incentive and the possibilities to maintain the sand dams. In areas where many

people benefit from sand dams and can exploit the water resource without prior investment, people need to organize collective action.

4. Green Arrow: Does sand dams effect the groundwater quality?

Initially this study focused on the quantitative effects of sand dams. However during the fieldtrip the issue of saline groundwater became apparent. In the Kivuna catchment the salinity of the groundwater limits its usefulness for human consumption and agriculture. Borst et al. (2006) identified saline rock in the catchment as the source of the salinity. Furthermore they conducted several Electric Conductivity (EC) measurements in one reach of the stream. They found that at the end of the dry season the groundwater downstream of the sand dam was more saline than upstream. Since no EC-measurements were conducted in this study these observation could not be tested. However we will return to the question how the sand dams probably influence water quality in the discussion of the modeling results in section 5.2.2.

4 Model

After assessing the different components like landscape and water use, whose interplay influences the socio-economic development as well as hydrology, the effects of the sand storage dams on groundwater levels are analyzed in more detail. To analyze the effect of the sand storage dams on the groundwater levels, a groundwater model with the modeling software PMWIN is developed

4.1 Schematization

4.1.1 Model lay-out

4.1.1.1 Cell size

The freeware version of PMWIN limits the number of grid cells to 200,000. Therefore the grid is rather rough and ranges from 50m x 50m at the edge of the catchment to 10m x 5m in the vicinity of the river. Most of the larger cells became no-flow cells after the determination of the model extent. The model comprises 670 rows and 327 columns.

4.1.1.2 Model extent

The single layer in the groundwater model comprises the whole catchment. In the catchment water from the shallow aquifer can be extracted from the coarse sand of the riverbed, the loamy/clayey riverbanks or weathered rock below the clayey top layer of the hill slopes. The location of the riverbed is determined based on the Digital Elevation Map (DEM). From the elevations of the riverbed cells a longitudinal profile was created. Afterwards the slope of the longitudinal profile was smoothed manually.

Whether a cell is assigned to the loamy/clayey or the weathered rock aquifer depends on the height of the cell above the riverbed in the particular cross-section. If the elevation of the cell (according to the DEM) is less than 3 meter higher than the elevation of the riverbed cell, it represents the clayey/loamy riverbank. If the elevation is between 3 and 10 meters higher than the riverbed, the cell represents weathered rock. If the elevation is more than 10 meter higher than the riverbed cell in the cross-section the cell is a no-flow cell. With the developed approach also the extent of the model is restricted to the area less than 10 meter higher than the center of the valley.

Figure 6 illustrates how the aquifer is schematized based on the elevation from the DEM.

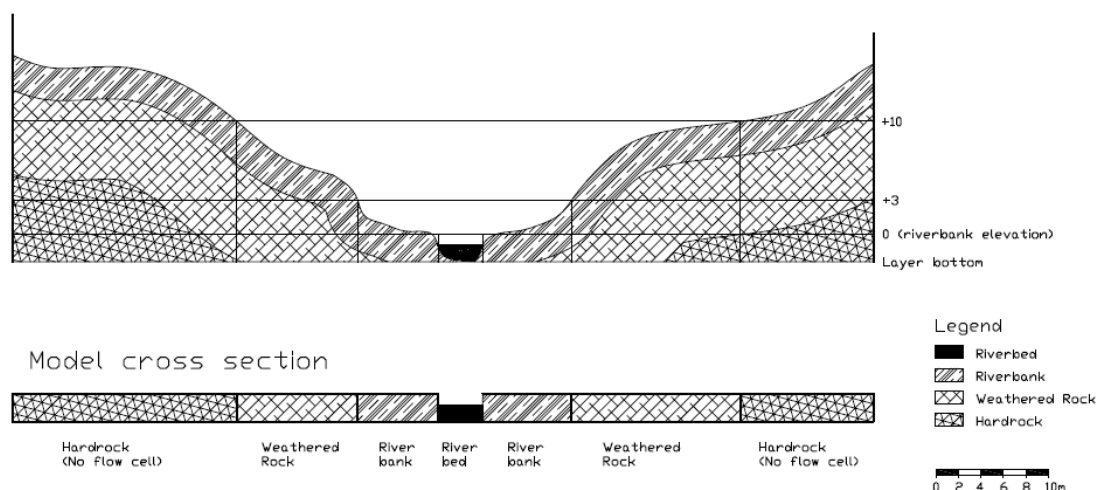


Figure 6 Schematization of the aquifer

The thickness of riverbed is 0.5 m in the upstream part and gradually increases to 2.5 m at the junction with the Nduni. The surface of the riverbank is 2 m above the riverbed in the whole catchment.

The approach is described in more detail in Appendix E.

4.1.1.3 Boundary conditions

The boundaries in the north, west and east of the stream are no-flow boundaries. The exact location of the boundary is determined according to the procedure described above (see also Appendix E). In the south at the downstream edge of the model a general head boundary is applied (see Figure 8).

Flow through a general head boundary cell is calculated by:

$$Q_{\ell} = c_{\ell}(h_{\ell} - h)$$

To define the general head boundary two values need to be determined (Weng-Hsing, 2005), the conductance (c) and the level of the bottom of the cell (h). The bottom level of the aquifer is based on the DEM (see section 4.1.1.2 above). The conductance is determined by

$$c = k \cdot \frac{dh_{\ell}}{dx} \cdot w$$

With

$$k = \text{hydraulic conductivity } \left[\frac{m}{d}\right]$$

$$\frac{dh_{\ell}}{dx} = \text{head gradient } [-]$$

$$w = \text{cell width } [m]$$

The hydraulic conductivity of the cell depends on the aquifer type (see section 4.1.1.4 below). The head gradient is approximated as equal to the determined gradient of the layer bottom. Therefore the water table rises and falls parallel to the slope of the bottom of the layer.

4.1.1.4 Parameters

As described above the model consists of one layer. This layer contains three different types of aquifers. The hydraulic conductivity is determined through double ring infiltration, sludge and Auger hole measurements which are described in Appendix C. The other parameters are taken from literature. The parameters used for the three different aquifer types are given in Table 1.

Table 1 Parameters of the different aquifer types

	Riverbed	Riverbank	Weathered rock	Source
Conductivity [m/d]	60	2	0.1	Measurements, Borst et al. (2006)
Transmissivity [m ² /d]	Transmissivities are calculated by multiplying the conductivity and the thickness of the layer			
Effective porosity [-]	0.42	0.32	0.1	Borst et al. (2006)
Specific yield [-]	0.28	0.08	0.02	Borst et al. (2006)

In order to avoid convergence problems during the simulations the transmissivity of the aquifer is set constant throughout the simulation.

4.1.2 Stress periods

The time step in the simulations is set to 5 days. The weather can be simplified in alternating wet and dry seasons. Two climatic scenarios are simulated.

- A **regular dry year** consist of two wet and two dry seasons. The first rainy season lasts 2 month (60 days) followed by a dry season of the same duration. The second rainy season lasts for 3 month (90 days) succeeded by a 5 months long dry period.

- The simulation of an **subsequent dry year** starts with the hydraulic heads calculated for the end of a regular dry year. The first two wet seasons (the stress periods 1 and 3) of the model run are replaced by dry seasons.

The simulations for a regular dry year are repeated until the head difference between two succeeding years at the end of the second dry period is smaller than $\pm 0.01\text{m}$ for all cells.

4.1.2.1 Wet season

Recharge via percolation

The recharge can be included into the model by using the recharge package. For this, only the recharge rate needed to be determined for the rainy seasons. The recharge rate used in the model is derived from estimates made by Hoogmoed (2007). She determined that about 2% of the rain infiltrates. Assuming that the yearly rainfall is 800 mm and falls in the 150 days of the two rainy seasons, the recharge rate is 0.1 mm/day.

Recharge via riverbank infiltration

The assumption that the riverbed is saturated during the rainy season can be included into the model by imposing a general head boundary on the cells of the riverbed during the rainy season. By using a very high conductance the water level can be kept constant (Weng-Hsing, 2005). The conductance is set to $3000 \text{ m}^2/\text{d}^2$ which keeps the head constant.

4.1.2.2 Dry season

Evaporation and transpiration.

Water consumption by plants on the riverbanks and soil evaporation from the coarse sand off the riverbed can be simulated by the evapotranspiration package. In the package three parameter need to be defined.

- the maximum evaporation (or transpiration) rate
- the elevation when maximum evaporation occurs (assumed to be the surface level of the grid cell)
- and to which depth the evaporation takes place

The evapotranspiration will be reduced linearly from the maximum amount at the ET surface to zero at the defined depth. For the two processes, (1) soil evaporation (from the riverbed) and (2) transpiration by plants (from the loam/clay soil), different parameters are used.

1. For soil evaporation from the riverbed the values mentioned by Borst et al. (2006) are used. The maximum evaporation rate that occurs at the surface of the riverbed is 8 mm/d. The maximum depth to which evaporation takes place is 60 cm. (see Figure 7)
2. For the transpiration from the riverbed the following setting is estimated. The maximum transpiration rate at the surface of the riverbank is 2 mm per day the maximum depth to which transpiration occurs is 3 m. (see Figure 7)

The surface elevation of the cells, which are determined to be part of the weathered rock aquifer, are more than 3 m above the riverbed level. Therefore water levels in the aquifer are too low (with respect to surface level) for the roots of the plants to suck water out of the aquifer. Therefore it is assumed that from this section of the aquifer no water is transpired.

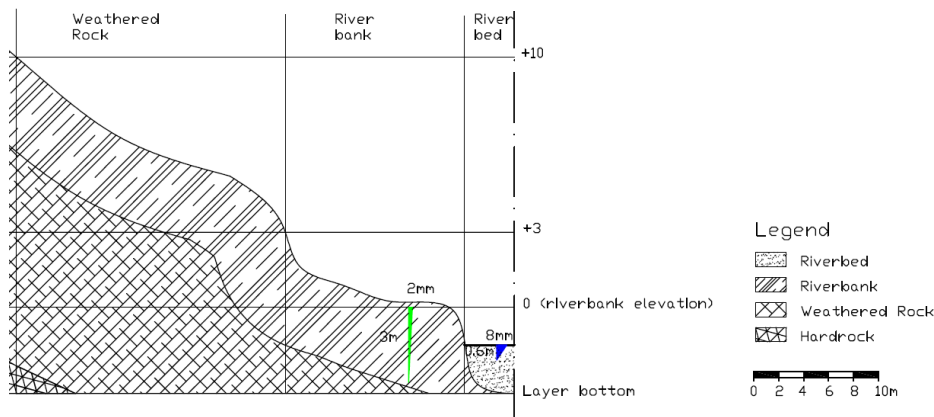


Figure 7 Assumed evaporation and transpiration profiles

4.1.3 Sand Dams

All sand dam in the Kivuna and Kiindu reach are included in the model. The sand dams in the Muasya tributary are also included but since the tributaries are not separately schematized the analysis will be focused on the sand dams in the Kiindu and Kivuna stream.

4.1.3.1 Location

The sand dams can be schematized by applying a Horizontal Flow Barrier at the locations of the dams perpendicular to the riverbed. The locations of the sand dams are based on the GPS coordinates noted in the field study (see Appendix A). The hydraulic conductivity of the Horizontal Flow Barrier is set to 0.00001 m/d to simulate a almost water tight sand dam.

4.1.3.2 Dimensions

Height

All sand dams are approximated to be 1.5m high with respect to the original riverbed.

Storage

The riverbed upstream of the sand dams is horizontal and equal to the crest level of the sand dam. This is a conservative assumption. In reality the riverbed upstream of the sand dams has a slope which is between the original slope and the used horizontal slope.

4.1.3.3 Implications for the hydrological processes

Recharge during wet season

The riverbed is approximated as saturated during the wet period. Since the riverbed upstream of the sand dam rose, also the groundwater tables upstream of the sand dams rise in the wet season. Therefore the height of the General Head Boundary which is used to simulate the saturated riverbed also needs to be increased to crest level upstream of the sand dams.

Evaporation during the dry period

Since the riverbed upstream of the sand dams rises, also the elevation of maximum soil evaporation during the dry season rises. The maximum evaporation rate as well as the maximum evaporation depth do not change. The parameters to simulate the transpiration do not change.

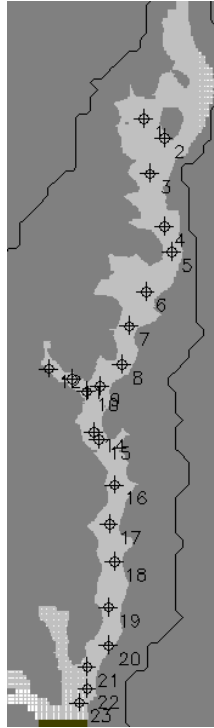


Figure 8 Location of the sand dams (dark gray: no-flow cells, light grey: aquifer, line catchment boundary)

4.1.4 Water use

In the First model runs, the effect of the sand dams are simulated without water use. To analyze the effects of (increased) water use, water use patterns for the year 1990 and 2014 are estimated and simulated separately. The determination of the water use patterns for the years 1990 and 2014 are basically based on rough estimates of population growth and their water demand. The considerations that led to these water use patterns are described in Appendix F . The water use per sand dams is given in Table 2 .

Table 2 Estimated water use patterns per sand dam

Water Use 1990			Water Use 2014		
	Water Extraction			Water Extraction	
	Each	Sum		Each	Sum
	[m ³ /d]	[m ³ /d]		[m ³ /d]	[m ³ /d]
2 Public scoop holes	1	2	2 Public scoop holes	2	4
			1 Public shallow well	1	2
2 Private shallow wells	0.2	0.4	4 Private shallow wells	0.2	0.8
	Total	2.4		Total	6.8

4.1.5 The influence of different sets of hydraulic conductivities

The model is based on a rather rough digital elevation map and a limited number of measurements. Missing parameters had to be taken from literature. The used parameters are therefore only best estimates. One important soil parameter is the hydraulic conductivity. The range measured is reported in Appendix C . In four simulations, the effect of the choice of the conductivities are simulated. First a reference scenario is simulated, in the second, third and fourth model run the conductivity of one of the three aquifer types is changed. In Table 3 the different setting of the hydraulic conductivities used in the four model runs are summarized.

Table 3 Combinations of hydraulic conductivity used in the scenarios

	Coarse sand (Riverbed)	Clay (Riverbank)	Weathered Rock (Hill Slopes)
Scenario 3.0 (Reference)	60 m/d	2 m/d	0.1 m/d
Scenario 3.1	30 m/d	2 m/d	0.1 m/d
Scenario 3.2	60 m/d	4 m/d	0.1 m/d
Scenario 3.3	60 m/d	2 m/d	0.5 m/d

4.2 Results and discussion

The discussion of the results focuses on the Kivuna/Kiindu stream. The two large tributaries Muasya and Nduni, where also sand dams are built are not analyzed since the schematization is based on the elevation of the main stream (see section 4.1.1.).

The results of the simulations are analyzed in order to answer the following six main questions.

1. How do groundwater levels change in the catchment due to of sand dams?
 - a. How much do the single sand dams effect groundwater levels?
 - b. Which are the local features that cause the different performance of the sand dams?
2. How do groundwater levels change in the vicinity of a sand dam?
 - a. What are the implications of groundwater flow around sand dams?
3. How does the water leave the catchment?
 - a. What does it imply for the catchment?
4. Do multiple sand dams have a 'network effect'?
5. How do water levels change due to estimated water use patterns?
 - a. Do the sand dams store enough water to supply the communities?
6. How does the conductivity influence the effect of the sand dams?

4.2.1 How do groundwater levels change in the catchment due to the sand dams?

Along the Kivuna/Kiindu 19 sand dams are constructed. All of these sand dams influence groundwater levels in their vicinities. In the figures in Appendix G1, the influence of the sand dams on groundwater levels at the end of

- the wet season,
- the dry season and
- an subsequent dry year

are illustrated, respectively. The extent of the effect differs between the sand dams and between the different points in time. At the end of the wet period, the effect of the sand dams is largest and the effect of two neighboring sand dams often overlap. With proceeding drought the positive effects of the sand dams decrease in most cases and the sand dams start to cause lower groundwater levels downstream.

In order to distinguish the effects of the sand dams from each other the simulations were repeated with two additional models. In the first model the sand dams with odd numbers are included while the second model includes the sand dams with even numbers.

In these models only the areas affected by sand dam 1 and 3 still overlap. The effect of the other single sand dam can be determined. The effects of sand dams 1 and 3 is separated along the line of smallest effect between the two sand dams.

By multiplying the rise of the water table with the area and the porosity of each cell, the effect can be expressed in terms of additional water stored.

Figure 9, Figure 10 and Figure 11 show the positive, negative and net effects of the sand dams in terms of additional/fewer water stored at the end of the wet season, dry season and an ensuing dry.

4.2.1.1 How much do the single sand dams effect groundwater levels?

At the end of the wet season (blue bar in Figure 9 and Figure 11)

At the end of the wet season the effect of the sand dams are purely positive. Sand dam 1 and 3 in the upstream have the largest positive effects in terms of surplus water. The positive effects of the other sand dams in the Kivuna (sand dam 1-9) and the first two sand dams in the Kiindu range between 2500 and 5000 m³. Only sand dam 7 has an positive effect which is smaller than 2000 m³. The following four sand dams (sand dam 16-19) all have a positive effect that exceeds 4000m³. Three of them have even an effect which exceeds 7000m³. The effects of the sand dams further downstream vary between 1500 m³ to 6500m³.

At the end of a regular dry season (red bar in Figure 9, Figure 10 and Figure 11)

During a regular dry season the positive effects of the sand dams decrease in 16 of the 19 cases. Only the positive effects of the sand dams 20, 22 and 23 increase. During the dry season, sand dams effect the water levels downstream negatively. This negative effect does not exceed 500 m³ in most cases. In the Kivuna reach only sand dam 7 has a negative effect that exceed the mark of 500 m³. Further downstream the sand dams 19 -23 have higher negative effects between 1700m³ and 4400m³. At the end of the dry period the negative effect does not exceed the positive effect in all cases. Therefore the net effect of all sand dams stays positive.

At the end of a subsequent dry year (green bar in Figure 9, Figure 10 and Figure 11)

At the end of an subsequent dry year the positive effects of the sand dams reduce further in most cases. In the cases of sand dam 7, 17 and 19 the positive effect during the ensuing dry year rises again after they shrank during a regular dry period. The positive effect of sand dam 20 increases further, while it consolidates in the cases of sand dam 22 and 23.

The negative effects of the sand dams also increase during a subsequent dry year. Now the negative effect of four of the first 14 sand dams exceeds 1000m³. The negative effect of the last five sand dams is more than 2000 m³ each.

In four of the 19 cases the negative effects exceed the positive effects. Thus there is less water available around the particular sand dams than there was before. Only around sand dam 1, 6 and 17 more than 2000 m³ water is additionally available at the end of an ensuing dry year.

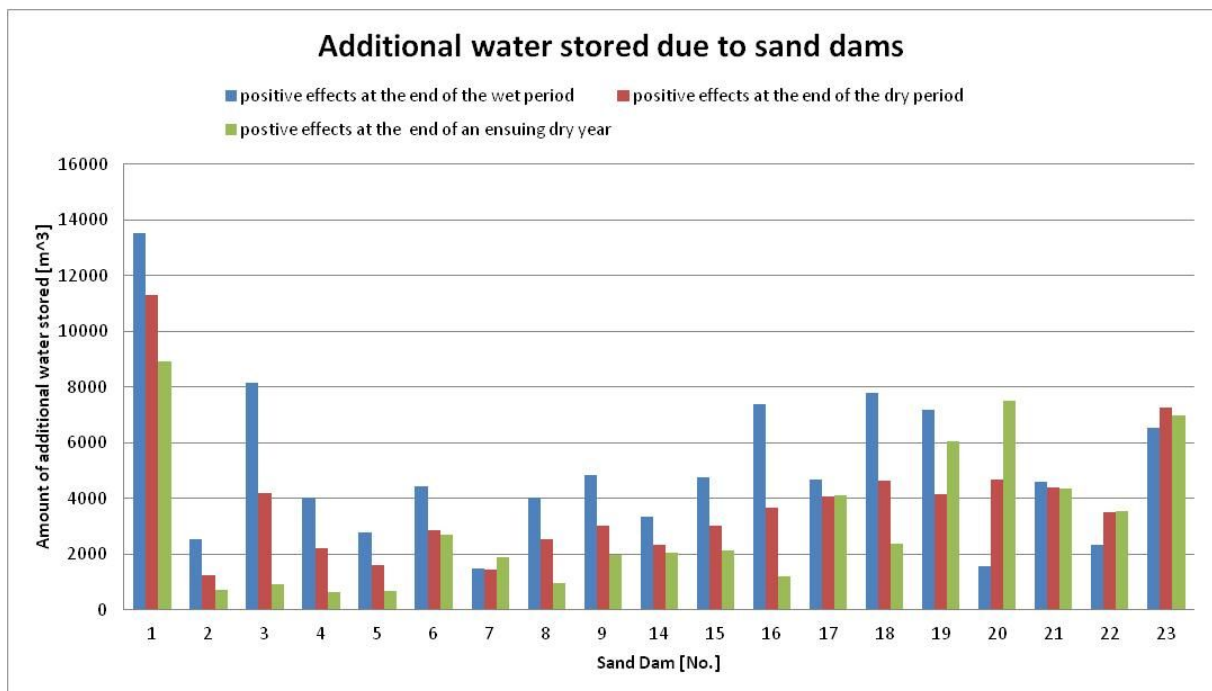


Figure 9 Positive effect of the single sand dams in m³

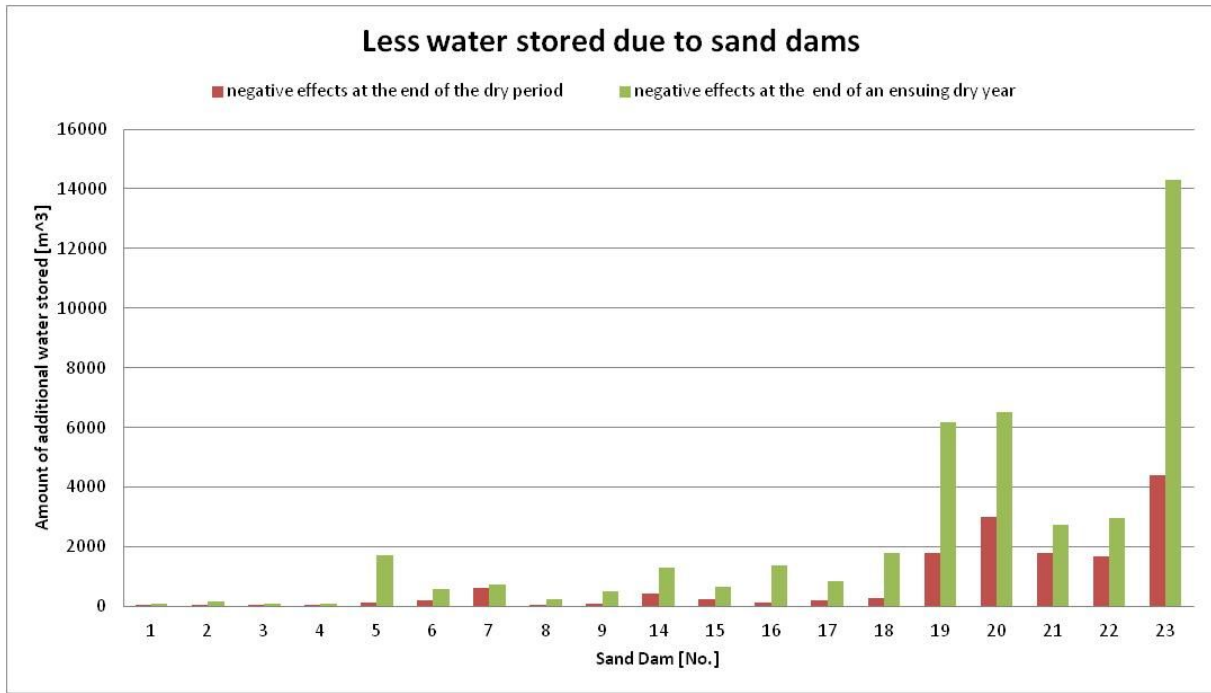


Figure 10 Negative effect of the single sand dams in m³

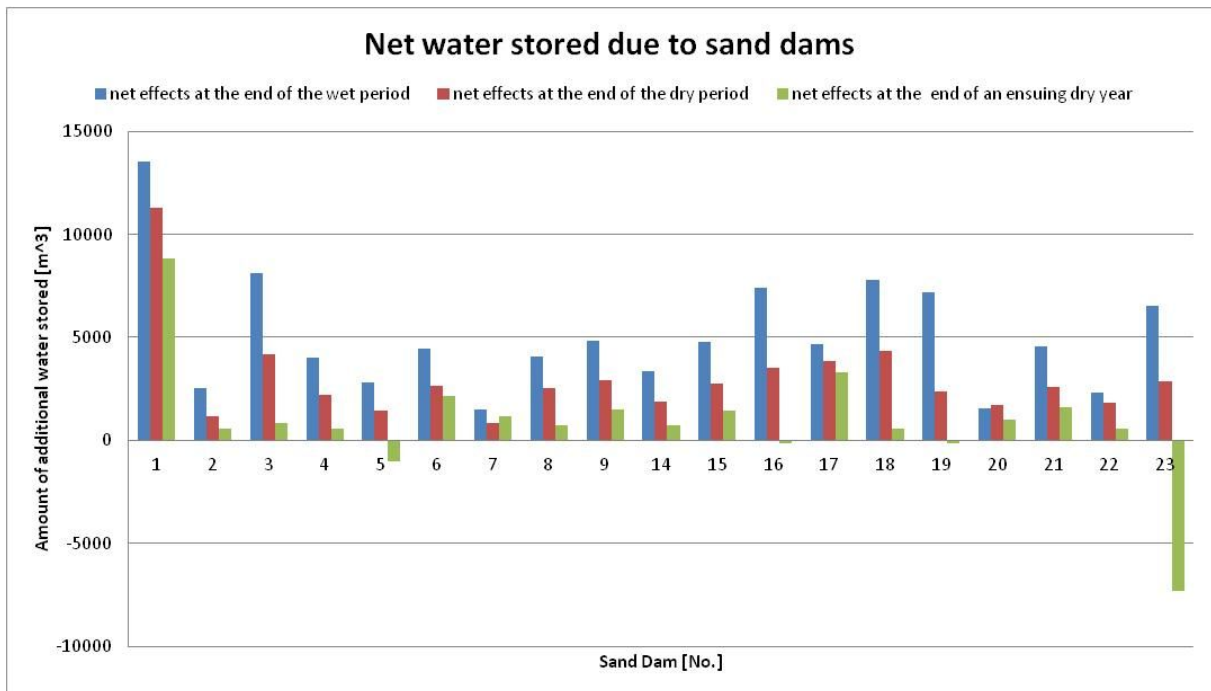


Figure 11 Net effect of the single sand dams in m³

4.2.1.2 Which arête local features that cause the different performance of the sand dams?

After the positive as well as the negative effects are quantified, the causes of the different performance of the sand dams is analyzed. Specific local circumstances, that vary between the location of the sand dams, and influence the effects of the sand dams are the slopes, the thickness of the riverbed as well as the composition of the cross-section. The specific circumstances of the location of the single sand dams are summarized in Table 4. The slopes upstream and downstream in Table 4 are the average slopes of the first 100 meter upstream and downstream of the sand dam.

The width of the riverbed is the width assumed during the schematization. The width of the riverbank and the weathered rock are the approximated distances perpendicular to the stream. Other circumstances, which may influence the performance of the sand dams that cannot be quantified, are the shape of the catchment and the position of the tributaries.

Table 4 Properties of the locations of the sand dams

Dam No.	Stream	Layer Thickness	Bottom Slope		Width of			
			upstream	downstream	Riverbed	Riverbank	Hillslopes	total
1	Kivuna	0,88	0,0000	0,0131	5	268	398	671
2	Kivuna	0,95	0,0091	0,0222	5	118	488	611
3	Kivuna	1,07	0,0000	0,0118	5	265	286	556
4	Kivuna	1,25	0,0096	0,0117	5	174	279	458
5	Kivuna	1,34	0,0117	0,0110	5	0	254	259
6	Kivuna	1,47	0,0085	0,0162	5	407	259	671
7	Kivuna	1,64	0,0271	0,0209	10	123	191	324
8	Kivuna	1,85	0,0105	0,0067	10	78	200	288
9	Kivuna	1,97	0,0070	0,0070	10	40	272	321
14	Kiindu	2,08	0,0103	0,0079	15	124	201	340
15	Kiindu	2,10	0,0070	0,0115	15	121	279	415
16	Kiindu	2,18	0,0052	0,0052	15	194	260	469
17	Kiindu	2,26	0,0065	0,0059	15	126	297	438
18	Kiindu	2,33	0,0052	0,0059	15	136	158	309
19	Kiindu	2,42	0,0058	0,0058	15	145	144	304
20	Kiindu	2,50	0,0229	0,0092	15	0	381	396
21	Kiindu	2,50	0,0078	0,0130	20	130	137	286
22	Kiindu	2,50	0,0130	0,0130	20	224	224	468
23	Kiindu	2,50	0,0064	0,0109	20	195	179	394

A statistical analysis is conducted to determine if these parameters are linearly correlated to the effects at the end of a regular wet period, a regular dry period and an ensuing dry year. The sand dams 1-3 are located in the upstream parts, where the shape of the catchment is different to the rest of the catchment and the tributaries may have a bigger impact on the performance of the sand dams. Therefore they are excluded from the analysis. Sand dam 23 is included in the statistical analysis even if its location just downstream of a large tributary close to the downstream boundary may have influenced its effects.

For a sample size of 16, the Pearson correlation coefficient is significantly correlated with a two tailed probability of more than 0.95, if its absolute value is greater than 0.5. The green numbers in Table 5, Table 6 and Table 7 indicate whether the correlation is statistically significant.

Table 5 Correlation coefficient of the correlation between location properties and the effects of the sand dams at the end of the wet period

r	correlation	Layer Thickness	Bottom Slope		Width of			
			upstream	downstream	Riverbed	Riverbank	Hillslopes	total
Additional water stored	positive	0,31	-0,82	-0,58	0,25	0,27	-0,41	0,00

Table 6 Correlation coefficient of the correlation between location properties and the effects of the sand dams at the end of a regular dry period

r	correlation	Layer Thickness	Bottom Slope		Width of			
			upstream	downstream	Riverbed	Riverbank	Hillslopes	total
Additional water stored	positive	0,76	-0,34	-0,31	0,70	0,12	-0,16	0,05
	negative	0,62	0,16	0,09	0,62	-0,01	-0,12	-0,05
	net	0,34	-0,77	-0,63	0,25	0,20	-0,08	0,15

Table 7 Correlation coefficient of the correlation between location properties and the effects of the sand dams at the end of an ensuing dry year

r	correlation	Layer Thickness	Bottom Slope		Width of			
			upstream	downstream	Riverbed	Riverbank	Hillslopes	total
Additional water stored								
	positive	0,72	0,10	-0,07	0,61	-0,01	0,01	0,03
	negative	0,55	-0,03	-0,06	0,53	0,01	-0,18	-0,08
	net	-0,18	0,14	0,02	-0,26	-0,02	0,29	0,15

Analysis

Sand dams store water through two mechanisms. First they increase the storage volume upstream, and they impound water. After the wet season the effect is purely positive because the storage volume increased while it is assumed that downstream water levels in the riverbed do not change. Since the storage volume increase with decreasing slopes, the positive effect at the end of the wet season is negatively correlated with the bottom slopes.

With proceeding drought the amount of water stored upstream of the dams decreases through evaporation and groundwater flow around the dams. The fact that the storage volume increases, after construction of the sand dams, becomes less important with proceeding drought. At the end of a regular dry period, positive as well as negative effects of the sand dams are not correlated with the slopes anymore. The net effect of the sand dams stays correlated until the end of a regular dry period, because the positive effect of the increased storage volume upstream has not vanished completely and the negative effect downstream increases with increasing slopes. Even if both relations are not statistically significant on their own, in combination they are. At the end of a subsequent dry year the net effect is not correlated with the bottom slope.

With proceeding drought the impounding effect of the sand dams becomes more important. In broader thicker riverbeds more water in the riverbed flows downstream. In these riverbeds a dam impounds more water. Therefore the positive effect of the sand dams is positively related to the thickness and width of the riverbed. Since the impounded water upstream of the dams lacks downstream, also the negative effect of the sand dams is positively correlated with the thickness and width of the riverbed.

4.2.2 How do groundwater levels change in the vicinity of a sand dam?

How the water levels evolve in the vicinity of the sand dams over time is illustrated in more detail using the example of sand dam 19. Sand dam 19 is located in the area, where farmers started to use water intensively for irrigating their vegetables on the riverbanks. Figure 9 shows that at the end of the dry period, sand dam 19 has a large positive effect upstream and a large negative effect downstream.

In Figure 12 the water levels at the end of the wet period after 50 and 100 dry days and at the end of a regular dry period, with and without sand dams are illustrated in the longitudinal of the reach of sand dam 19. The water levels in the cross sections A-A and B-B for these points in time are shown in Figure 13 and Figure 14.

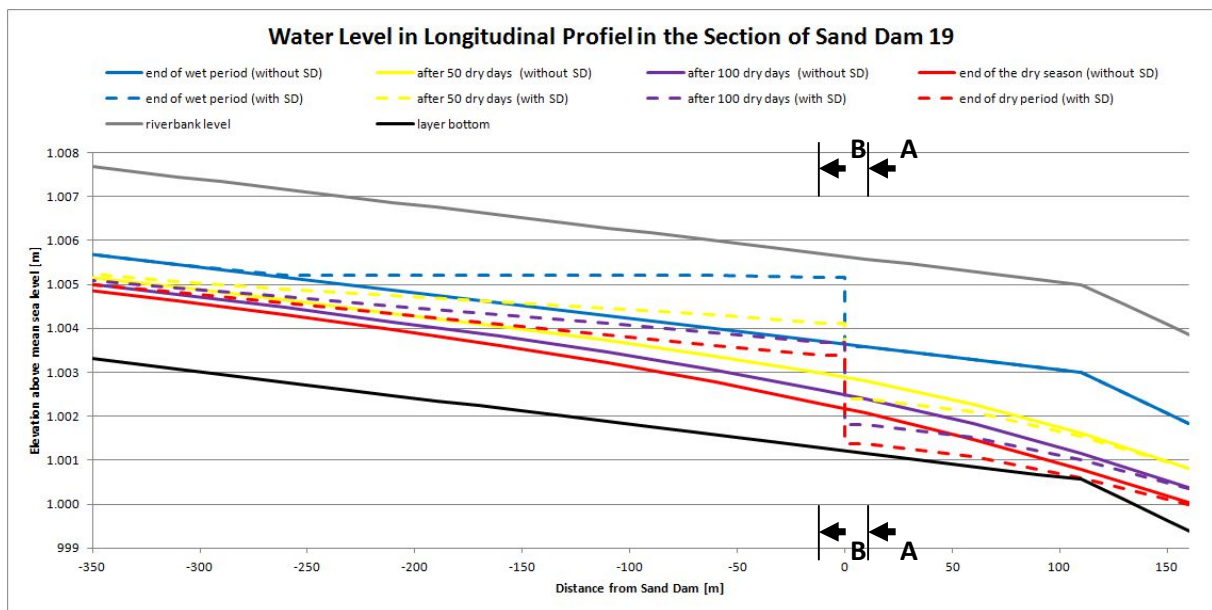


Figure 12 Water levels around sand dam 19 along the riverbed

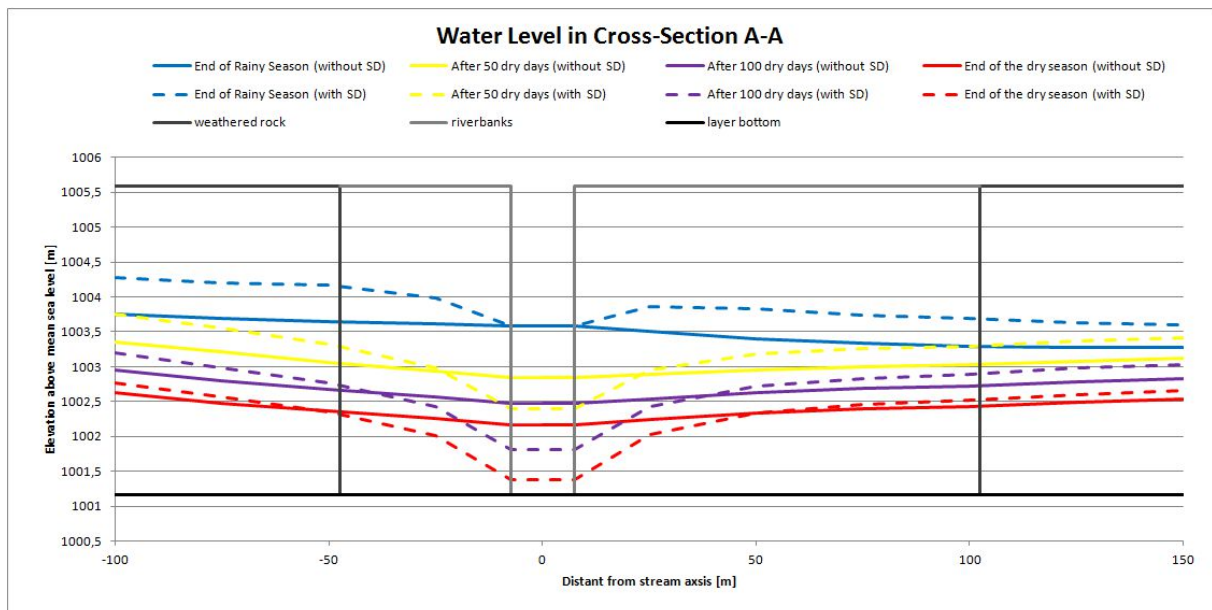


Figure 13 Water levels in cross section A-A during a regular dry period

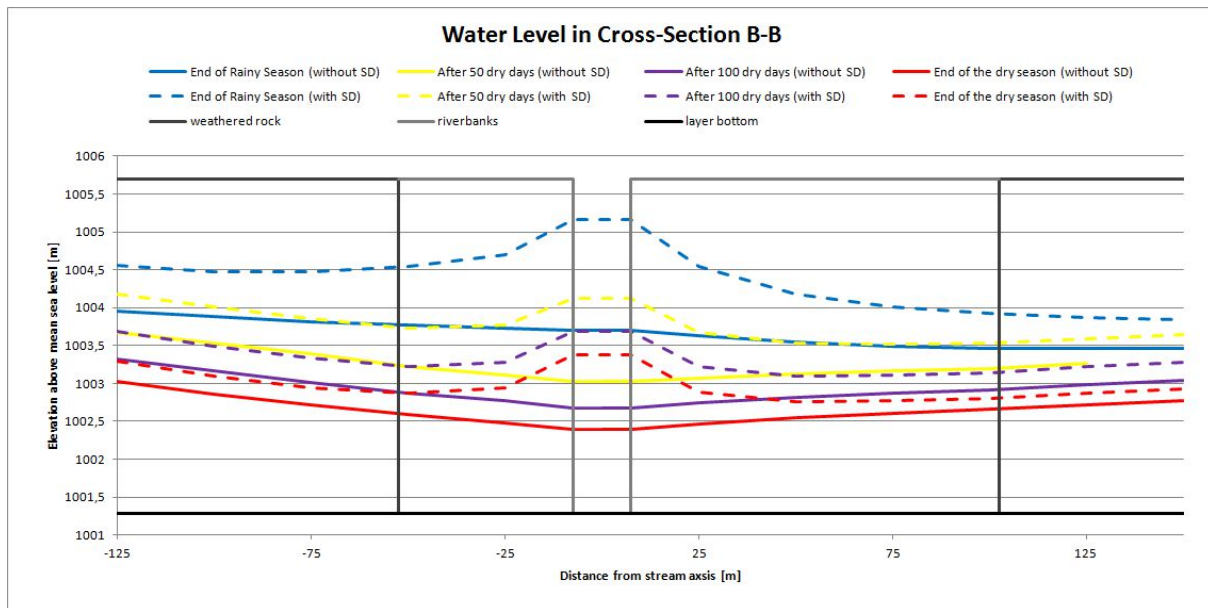


Figure 14 Water levels in cross section B-B during a regular dry period

4.2.2.1 What are the implications of groundwater flow around sand dams?

First and foremost the figures show that during a regular dry period groundwater levels in the riverbed decline more than water levels in the riverbanks and weathered rock sections of the aquifer. The decline has basically two causes. First, the hydraulic conductivity of the riverbed is much higher than the conductivities of the riverbank and the weathered rock. Water therefore can flow more easily downstream in the riverbed. Second, the elevation of maximum (soil) evaporation is on surface level (= groundwater level) at the end of the wet season. Furthermore the maximum soil evaporation rate is higher than the maximum transpiration rate assumed for the riverbanks. Finally it is assumed that there is no evaporation from the weathered rock section. The decline of about 0.2 m of the hill slopes during a regular dry period therefore corresponds to the total recharge during the wet seasons.

Figure 12 shows that the sand dam is located about 120m upstream of a steeper section. Due to the steeper section water levels decline faster. This faster decline propagates in upstream direction in the riverbed. Through the construction of the sand dams the effect of the steeper section cannot propagate further upstream. Therefore the sand dam has a relatively large effect. The drawback of the sand dam is that it also causes rather large negative effects, since water levels in the steeper section keep declining fast.

Figure 13 shows that, due to the blockage of water by the dams, water in the riverbed does not flow downstream in the riverbed. The increased leakage of water via both sides of the riverbanks does not compensate for the decreased discharge via the riverbed. Therefore the water level in the downstream declines faster. Since downstream groundwater levels after the construction do not change at the end wet season, water levels decline in absolute terms. Thus they form the negative effects mentioned above.

Originally water levels declined rather uniformly in the cross-section and the head differences during the dry season were small. After the construction, at the end of the wet season water levels in the riverbanks are higher due to increased riverbank infiltration upstream of the sand dams. The faster decline of groundwater levels in the riverbed propagates into the riverbanks in the course of the dry period. The higher groundwater levels in the riverbank upstream of the sand dams and the faster decline of water levels in the riverbed downstream lead to larger head differences between up- and

downstream of the sand dam and also to an increased amount of water bypassing the sand dam. However the additional water bypassing the sand dams, does not compensate the missing water flow in the riverbed.

Originally water infiltrated into the riverbed during the wet season until water levels in the cross-section was almost constant. With the start of the dry season water levels in the riverbed declined faster and water in the riverbanks flowed towards the stream. After the construction already in the course of the wet season, water levels in the riverbanks start to exceed the water levels in the riverbed due to water bypassing the dam. Therefore the flow direction of the groundwater is already reversed in the wet season.

Figure 14 shows that upstream of the sand storage dam the water levels decline much faster than before the construction of the dams. In contrast to the original situation water levels in the riverbed exceed the water levels in the riverbanks throughout the year and water constantly infiltrates into the riverbank. Since the dams lead to increased water levels in the riverbed upstream the head difference between riverbed and riverbanks in the upstream also increases. Due to larger head differences, more water infiltrates into the riverbanks and flows around the sand storage dams. Therefore water levels upstream decline faster after the construction of the sand dams. However water levels stay higher in absolute terms throughout the dry period. This positive effect propagates into the riverbanks and the weathered rock.

Since it is assumed that water levels at the end of the wet period are riverbed level, larger drawdown's are equal to increased effort to dig scoop holes. Therefore areas a few meters upstream of the sand dams that experience smaller drawdown's may be favorable for digging scoop holes. Since the riverbank levels do not change the effort to fetch water from shallow wells, which are dug into the riverbank or weathered rock, decrease due to the sand dams.

4.2.3 How does the water leave the catchment?

Table 8 gives the (accumulated) amount of water leaving the model by flowing downstream and through evaporation and transpiration during a regular dry period.

Table 8 Cumulative amount of water evaporated and drained through model boundary during a regular dry year

		During a regular dry period		
		Model without dams	Model with dams	Δ
Evaporation and transpiration	[m ³ per dry period]	179572	200189	20617
Outflow at the downstream model boundary	[m ³ per dry period]	18389	18332	-57
Sum	[m ³ per dry period]	197961	218521	20560

The values in Table 8 show that during a regular dry period most of the water leaving the catchment evaporates. After the construction of the sand dams the amount of water that evaporates increases, while the water that leaves the model at the downstream boundary only slightly decreases.

Sand dams thus do not impound a lot of water and effect the downstream during the dry only slightly. The sand dams increase the amount of water available in the area through increasing the storage capacity. Therefore subsurface dams that do not increase the storage capacity would not improve the water supply in the catchment.

4.2.3.1 What does it imply for the catchment?

Sand dams lead to higher groundwater levels upstream during the wet season. Higher groundwater levels lead to increased evaporation, which decreases the additional water available in the course of dry periods. Upstream of the sand dams not only groundwater tables increase, but also the riverbed which protects the groundwater from radiation and therefore evaporation. The model does not

distinguish between soil evaporation from the riverbed and transpiration from the riverbank. But since water levels in general decrease faster in the riverbed (see section 4.2.2) after the construction of the sand dams, most of the additional evaporated water is transpired by plants on the riverbanks. Thus the model simulates higher water consumption by plants and therefore higher vegetation densities.

4.2.4 Do multiple sand dams have a 'network effect'?

Whether or not the sand dams constructed as a cascade in a row along a river have a network effect (meaning that sand dams influence the effect of their neighboring sand dams) is analyzed by testing the following hypothesis

A sand dams have a network effect, if the sum of the effects of the single sand dams do not equal the effect of the cascade of sand dams.

To distinguish the effects of the sand dams two additional model were run (see section 4.2.1.1). One contains all sand dams with even numbers while the other contains the sand dams with odd numbers. By using these simulations the hypothesis becomes

$$\text{if } Effect_{\text{cascade}} \neq \sum Effect_{\text{OddSandDams}} + \sum Effect_{\text{EvenSandDams}} \rightarrow \text{network effect}$$

The figures in Appendix G2 show that there is no network effect for most areas in the catchment. Only in the most downstream sand dams develop a network effect in the course of droughts. Since the sand dams in a cascade store more water than the single sand dams together this network effect is positive. However since this network effect propagates from the downstream boundary upstream the influence of the boundary conditions on this network effect needs to be analyzed in future studies.

4.2.5 How do water levels change due to the estimated water use patterns?

The results of the simulations show that for most areas water levels do not decline due to both estimated water use patterns except of the very vicinity of the wells (see Appendix G3). In the simulation with the water use pattern estimated for the year 1990 only around the sand dams 4/5 and 9, the water levels decline more than 0.1 m. If people use water like assumed in scenario 'WU2014', water levels in the vicinity of the water extraction are up to about 0.3m lower around wells and scoop holes than without any water use.

The effectiveness of the sand dams does not change due the 1990 water use pattern. This is also true for the water use pattern of 2014 for most sand dams. Here only locally the sand dams become less effective, because the sand dams prevent that the drawdown (due to the extraction) propagates further downstream.

4.2.5.1 Do the sand dams store enough water to supply the communities?

Finally the results also show, that after the construction of the sand dams there is more water available upstream even if the water use is increased (see Appendix G3). Only in the area around sand dam 4/5 the positive effect of the sand dams is partly vanished by the human water use and water levels are lower than in the original situation.

4.2.6 How does the conductivity influence the effect of the sand dams?

The results of the simulations with different sets of hydraulic conductivities are presented in Appendix G3 . The simulations show that a change of the hydraulic conductivity influences the effects of the sand dams.

A lower conductivity of the riverbed slows down the groundwater flow and water levels in the source areas stay higher. But water from upstream replenishes the storage volume of the sand dams, if the conductivity of the riverbed is higher. However higher conductivity of the riverbed also lead to higher

discharges downstream which cannot be replenished by water from the upstream due to the dams. Therefore an increased hydraulic conductivity of the riverbed increases the positive as well as the negative effect of the sand dams.

A higher hydraulic conductivity of the riverbanks leads to an accelerated drainage of the riverbanks and weathered rock. Due to the higher permeability of the riverbanks water can bypass the sand dams more easily and the effect of a sand dam decreases.

An increased hydraulic conductivity of the weathered rock leads to faster drainage of the weathered rock and lower water levels in these parts of the aquifer. In general the effect of the sand dams is not influenced by the conductivity of the weathered rock except for the sections where the weathered rock reaches to the riverbed. If the weathered rock reaches the riverbed water can bypass the sand dams more easily if the conductivity is higher. Therefore the sand dams are less effective.

Around Sand dam 20

The results show that the area around sand dam 20 is sensitive to the hydraulic conductivity of all three sections of the aquifer. The reason for the sensitivity is that according to the schematization process, the cross-section consists only of riverbed and weathered rock. Due to the composition of the cross-section, the flow of water bypassing the sand dam is reduced. At such a location a lower conductivity of the riverbed or weathered rock leads to a bigger effect because the flow through the cross section is slowed down. Also an increased hydraulic conductivity of the riverbank increases the effect of the sand dam 20. In this case water from upstream parts flows faster into the storage of the sand dam where the permeability of the aquifer has not changed.

5 Discussion of similarities between observation and simulation

In chapter 4.2 the results of the simulation are discussed and relation between catchment properties, groundwater flow and sand dams are drawn assessed. However the model, which is only based on conductivity measurements conducted during the fieldtrip and a DEM of the study area, cannot be calibrated because of missing groundwater records. In chapter 5.1, it will be analyzed how the modeling results fit the quantitative observations of the fieldwork. The question if the simulation results support the proposed relationships and if there are additional relationships is analyzed in section 5.2.

5.1 Comparison Observation –Simulation

Four observations could be linked directly to groundwater level and seasonal fluctuations as well as to the effects of sand dams. These observations are compared with modeling results discussed in section 4.2.

1. During the fieldtrip, the general groundwater levels in the riverbed were about 0.5m below the surface. This is also the magnitude that is simulated for this time of the year (see section 4.2.2). However during the fieldtrip it was found that locally the decline can be much higher or lower. These local differences cannot be reproduced by a model that is built with a schematic approach based on a digital elevation map like in this study.
2. During the fieldwork people claimed that during the dry season groundwater was flowing from hill slopes towards their shallow wells. This is also the case in the model (see section 4.2.2). Their assumption that sand storage dams are therefore not helpful to increase water levels in their shallow wells does not hold according to the model result. As shown in the discussion in section 4.2.2 sand storage dams increase water levels even in the weathered rock section on the hill slopes.
3. Mr. Mutoka claimed that water levels increased in his shallow wells after the repair of sand dam 3. According to the simulation results, the construction of sand storage dam 3 indeed leads to increased water levels in the area where his shallow well is located.
4. An interviewee next to sand dam 18 complained that the sand storage dams does not only have positive effects. He argued that after the construction people just upstream and downstream of the sand dams have less water while people in between the sand dams have more water. The argument that people downstream of the sand dams have less water is supported by the model. The claim by the interviewee, that even just upstream of the sand dams there is less water may be explained by the fact that groundwater levels decline faster just upstream of sand dams (see section 4.2.2) than at some distance, according to the simulation results.

The comparison suggests that the model simulate groundwater flow similar to the discussed observations. There are some facts that are not in line with the simulation results. For example, in several shallow wells water levels decline much more than the 0.2 m that are simulated during the dry season. But in order to reproduce these drawdown the amount of water extracted from the well needs to be recorded.

5.2 Links between simulated groundwater levels and human agency

In chapter 3.3 several relationships and dependencies between the catchment properties, sand dams, hydrology, water use and human agency were proposed. In order to test the relations, observed developments need to be expressed (at least qualitatively) in groundwater heads and amounts of water. Therefore most of the proposed relations cannot be tested by groundwater models. Groundwater models cannot predict the stability of sand dams, but larger effects of the sand dams may increase the incentive to maintain and repair sand dams. Furthermore groundwater models cannot predict the purpose of water extraction. But larger amounts of water available created the requirements for increased water use. Thus the results of the groundwater model do not prove these relationships but indicate whether relationships are possible or reasonable.

Below three possible implications of the modeling results are discussed. First it is analyzed if the sand dams in the area of most irrigated agriculture are also most effective and therefore sustain the development. Second, possible implications of changed flow directions around sand storage dams on the water quality are discussed. Third, the relation between groundwater levels and evaporation will be addressed.

5.2.1 The relation between effect of the sand dams and irrigated agriculture

The simulation results are basically groundwater heads. By comparing the calculated groundwater heads of the simulation without sand dams with the groundwater heads of the simulations with sand dams the amount of water stored by the sand dams are calculated in section 4.2.1. During the fieldtrip it was observed that irrigated agriculture is not distributed evenly over the whole catchment. Most of the irrigated fields lie between sand dam 17 and 20. In this area also most of the sand dams were repaired after their break down. In other areas with less or no irrigated agriculture relatively less sand dams were repaired. Therefore the following relationship or hypothesis is proposed.

- *Sand storage dams have a higher probability to be repaired in areas where water use is largest, which is where sand storage dams store the most water.*

This hypothesis could not be tested based on the observations during the fieldtrip because the amount of water stored by the sand dams could not be estimated by observations only. After the simulations the hypothesis can be tested with the amount of water stored by the sand dams derived from the modeling results.

The upper Kivuna

Sand dams 1 has the biggest effect of all sand dams, while sand dam 2 has a rather small effect. Despite the fact that sand dam 1 has the largest effect in terms of stored water, no irrigated agriculture could be found. Since both sand dams were never broke, no conclusions could be drawn about the probability of repair.

Sand dam 3 and 4 both broke. However sand dam 3 has one of the biggest effect of all sand dams while sand dam 4 stores relatively little water. Irrigated agriculture in this area is restricted to two farms, where shallow wells are used to extract water. One farm is located upstream of sand storage dam 3. The farmer took the imitative to restore the dam. The other farm is located next to sand dam 4. Here the owner invest in several wells which he deepens to the depth required to satisfy his water demand.

The lower Kivuna

In the lower Kivuna four of the five sand dams failed. Only sand dam 6 is still intact. While the sand dams 8 and 9 have been repaired, the sand dams 5 and 7 were never repaired. The sand dams 5 and 7 are amongst the sand dams with the smallest effects. However sand dam 7 has a relatively large effect at the end of a prolonged dry period. The sand dams 8 and 9 have a much bigger effect during

a regular dry period. After its repair, sand dam 9 failed again, while sand dam 8 stayed intact. The only larger irrigated field in this area is located in the area positively affected by sand dam 6, which keeps also the largest net effect during a regular and prolonged dry period.

The upper Kiindu

The sand dams 14 and 15 are still intact. Sand dam 16, which stores the largest amount of water failed, but was repaired multiple times. At the time of the fieldtrip the sand dam functioned even if much water leaks through the repaired part. A small field is irrigated upstream of sand dam 14. Two larger fields are irrigated between sand dam 15 and directly upstream of sand dam 16.

The middle Kiindu

In the middle Kiindu all three sand dams constructed by Sasol in the 1990-ies failed. All three sand dams are amongst the most effective sand dams in the catchment. Sand dam 18 and 19 are repaired and functioned at the time of the fieldtrip. Sand dam 17 failed recently and was not repaired yet. Only the older sand dam 20 built during colonial times never failed. This is the area with most of the irrigated fields. In several reaches irrigation takes place on both riverbanks.

The lower Kiindu

Two of the three sand dams in this area failed. Only sand dam 22 is still intact. In general the effect of the sand dams is smaller than the effects of the dams in the middle Kiindu. Despite the failure of the sand dams people have enough water to irrigate some plots on the riverbanks.

Evaluation

The simulation results support the hypothesis that the probability for reparation of sand dams increases when the amount of water stored by the sand dams increases. Furthermore most irrigated plots are in the area of the sand storage dams which store the most water. However the amount of water stored is only an indication. The suitability of the construction site also determines if a sand storage dam can successfully be repaired. Furthermore the suitability of the landscape determines whether or not irrigated agriculture is practiced (see section 3.3). Where the landscape is suitable for irrigated agriculture additional water due to sand dams may be more valuable. Finally it needs be kept in mind that in some cases the sand dams may have failed before they were matured. Therefore the people may not be aware of the actual effect of the sand dams.

5.2.2 Implication of changed flow patterns on water quality.

Even if the study focuses on quantitative effect of sand storage dams, water quality plays a role in the choice of the water source, the amount of water extracted and therefore in the usefulness of the stored water and the sand dams (see chapter 3.3). During the fieldtrip numerous people reported that water was saline in the Kivuna reach. Whether saline water is suitable for agriculture was considered controversial. During the fieldtrip no electric conductivity measurements were conducted. Borst et al. (2006) measured the EC several times in the riverbed around sand dam 16. He found that 'The highest EC's are generally observed in scoop holes just South [which is downstream] of dam Kwa Ndunda, ... '. Furthermore he observed that the EC decreased rapidly after the first rains. The source of the salinity is likely saline rock that was found in parts of the catchment. (Borst et al., 2006)

The discussion in chapter 4.2.2 may explain the phenomenon that water is more saline downstream of the sand dam. If we assume that water becomes saline when it comes in contact with saline rock, which is (assumed to be) located in the riverbanks, the water stays longer fresh if water flows from the riverbed into the riverbank instead in opposite direction. Figure 14 shows that water levels in the riverbed upstream of the sand dams are higher than in the riverbanks throughout the year. Thus saline water from the riverbanks cannot enter the riverbed. Downstream of the sand dams the opposite is true (see Figure 13). After the construction of the sand dams groundwater levels in the

riverbanks stay higher than in the riverbed throughout the year. Thus saline water from the riverbanks enters the riverbed.

Evaluation

Whether or not the sand storage dams lead to less saline water upstream needs to be analyzed in future research. However if this is the case, through the suggested mechanism or some other processes, this would be an additional advantage of sand storage dams and increase their value for the local communities.

5.2.3 Relation between water levels and vegetation density

The simulation not only indicates proposed relations but also implicates a new relation. Due to higher groundwater tables, caused by the sand dams, water leaves the model through evapotranspiration. Since the accumulated sand upstream of the sand dams protects groundwater in the riverbanks, most if not all additional evapo-transpired water will be consumed by plants on the riverbanks. Higher water consumption by plants implicitly means that the vegetation density increases. People report that around a private sand dams in a tributary of the Nduni the vegetation flourished after its construction and vanished after its break down. This observation about the relationship between sand dams and vegetation densities is simulated in the model through higher transpiration. However in the rest of the catchment vegetation density are not considerable higher. Also people report that vegetation has not flourished after the construction of the sand dams.

Evaluation

This may have two reasons. First, groundwater tables stay too far below the surface, so that the roots of shrubs and bushes cannot reach the groundwater. And secondly, people clear the natural vegetation on the riverbanks. In the upstream, trees (whose roots may reach even low groundwater tables) are cut to produce charcoal. In the downstream part of the catchment the riverbanks are cleared completely from vegetation in order to cultivate land for agriculture. Which of these two possible reasons explains the absence of higher vegetation densities needs to be analyzed in further research. If too low groundwater levels are the cause, it can be integrated rather easily in the model by changing the parameters that determine the transpiration. If the cutting of trees and the clearing of the riverbanks are the cause, this issue should be integrated into a future study about the relation between groundwater levels, water use and human interference.

6 Conclusions

6.1 From fieldwork

The fieldwork shows that the different sub-catchments did develop differently after the construction of the sand dams. The socio-economic development of these areas are influenced by the interaction between factors like local catchment characteristics, water availability and human agency. The water supply can be increased locally through the construction of sand storage dams. An increased water supply potentially reduces walking distances to the water source, enables local people to develop irrigated agriculture and therefore supports and stimulates the development of the catchment. How the catchment develops after the construction of the sand dams and how sand storage dams improve the living conditions of the people depends also on other factors. Local catchment characteristics, water quality, the capacity to invest as well as private initiatives influence the possibility to utilize the water and may generate additional income. To outline the relations of the various factors, three different area which experience different types of developments are shortly described:

- In the Kiindu catchment, where the valley is wider and the riverbed broader, people can extract water directly from the riverbed and use it to develop irrigated agriculture on the riverbanks. People who do not own plots in the vicinity of the stream, at most benefit through shorter walking distances to the water source.
- In the upstream parts of the Kivuna and Nduni and in the Muasya tributary, where the river is narrow and the riverbed thin, less water can be abstracted from the riverbed. Therefore people increasingly use shallow wells to satisfy their domestic water demand. The few public shallow wells and scoop holes do not supply enough water throughout the dry period to develop irrigated agriculture. Therefore people use water only sporadically, to produce bricks to generate income. However, the main benefit is the ensured water supply for most of the dry period within the catchment.
- The Kivuna catchment is more developed. The village center of Mulago with several shops and a secondary school for girls is located here. Therefore people have the opportunity to generate additional income. Furthermore, people are less dependent on water from the catchment since Mulango is connected to the water supply network of Kitui and the Nzeeu river is within walking distance. Since the water is considered salty as well and alternative water sources are available, people are less eager to extent water extraction from the catchment. Only few people invested in shallow wells, pumps and tanks, which are required to develop irrigated agriculture on a larger scale.

How water is used may influence the appearance of the catchment. In areas where riverbanks are cleared from natural vegetation and extensively used for irrigated agriculture, these riverbanks are increasingly prone to erosion during floods. In areas where people produce bricks, people cut the few large trees to produce charcoal to burn the bricks. Therefore natural vegetation declines in the areas where water use is largest, even if groundwater tables rise.

The fieldtrip showed that the sand dams are less stable than commonly assumed. 18 years after the construction of most of the sand dams, the majority of them have failed at least once. In addition, it appears that the stability of the sand dams decreases in downstream direction. Sand dams in narrow streams with thin riverbeds, in the upstream of the Kivuna and Nduni and the Muasya tributary, are more robust and often did not fail. In the Kiindu reach, where sand dams are wider and often could not be founded on rocks in both riverbanks, sand dams often fail. If the sand dams are not repaired, the development stimulated by the sand dams abate. The broken dams are the remains of the attempt to improve the water supply.

An explanation why certain sand dams are repaired while others are not, could not be found during the fieldtrip. However the observations suggest that the chance that a sand dam is repaired may be related to the degree of water use in the vicinity of a sand dam.

6.2 From modeling

The modeling exercise provides insight into the effect of the sand dams on groundwater heads and groundwater flow. In particular the following conclusions can be drawn.

Firstly, the spatial extent as well as the magnitude of the effects each individual sand dam differs. Furthermore, sand dams may cause lower heads downstream of the sand dam. This negative effect increases and the positive effect decreases with prolonged droughts. Both positive and negative effects evolve differently for individual sand dams. Some sand dams have large positive effects which become smaller rather rapidly, while the positive effects of other sand dams stay relatively constant (see section 4.2.1).

Secondly, the net effects of the sand dams during a regular dry period increases if the bottom slope decreases, because of two reasons. Mild slopes upstream increase the storage volume and higher slopes downstream lead to accelerated drainage and larger negative effects downstream (see section 4.2.1). The effect of a larger downstream slope is illustrated in section 4.2.2. The example showed how sand dams upstream of steeper sections cause large effects downstream, and therefore illustrate the positive correlation between negative effect and downstream slope.

Thirdly, positive and negative effects of the sand dams are positively correlated with width and thickness of the riverbed. Broader and higher dams are a larger barrier for the flow and therefore store more water upstream. However, they do not only store water but they also hinder more water to flow downstream and therefore cause larger negative effects downstream (see section 4.2.2).

Fourthly, sand storage dams influence the direction of groundwater flow in the aquifer during a regular dry year. Since water levels upstream are kept high by the sand dams, water throughout the year infiltrates from the riverbed into the riverbanks. Downstream water levels in the riverbanks increase because of water bypassing the sand storage dams. Here the water in the riverbanks starts to flow towards the riverbed already during the wet season (see section 4.2.2). This change of flow pattern may have implications for the water quality (upstream and downstream) in the case of saline rock in the riverbank as discussed in section 5.2.2.

Fifthly, section 4.2.3 shows that most of the water leaving the catchment during dry periods evaporates and transpires. Only a small fraction of water is drained downstream. Therefore, the storage effect of sand storage dams is much more important than their blockage effect. Subsurface dams that do not increase the storage in the catchment therefore will not increase the amount of water available during dry seasons (see section 4.2.3).

Sixthly, most of sand storage dams in this study do not have network effects on the hydrology during a regular dry season, in general. The effect of one single sand dam does not influence the effect of a neighboring sand dam in a regular dry season. If the effects of two sand dams spatially overlap, the effects basically add up (see section 4.2.4).

Seventhly, the assumed (domestic) water use pattern influence groundwater levels only in the vicinity of the water extraction. In general, sand dams store enough water to satisfy the water demand for domestic purposes and small scale commercial water use. Even if water use rises, water levels upstream of the sand dams are higher than without sand dams and water use (see section 4.2.5).

Eighthly, the hydraulic conductivity of the different aquifer types influence the drainage of the catchment and the effectiveness of the sand dams. In most cases a higher conductivity of the riverbed lead to bigger effects of the sand dams. Also lower conductivity of the riverbank and weathered rock, lead to a larger effect of the sand dams. In general, the hydraulic conductivity of the riverbed and the adjoining riverbed have a larger effect than the conductivity of the weathered rock (see section 4.2.6).

Ninthly, through the parameterization of the transpiration on the riverbanks the model simulates higher transpiration rates and therefore higher vegetation densities if groundwater levels rise. This relation needs to be analyzed in further research in more depth (see section 5.2.3).

6.3 Overall conclusions

The observations that developments differ within the catchment and the analysis of the impact of the various sand storage dams on groundwater level differs show that *'The Effect'* of sand storage dams on the development of a catchment does not exist.

The modeling exercise shows that water storage upstream also cause negative effects downstream, depending on the local characteristics of the catchment. How the stored water is utilized depends on (1) the amount of water available, (2) the effort (and capital) needed to extract water, (3) the possibility to generate additional income (mainly by developing irrigated agriculture nearby), (4) water quality and (5) the availability of alternative water sources.

The interaction of all these factors lead to individual developments in the different sub areas. Therefore it is important to take these factors into account in the assessment of (the effect of) sand storage dams in a particular area.

The conclusion that there is no 'The Effect' of sand storage dams shows that it is important to consider sand storage dams in the societal context or like in socio-hydrology as part of the co-evolution of water system and society. Furthermore it makes clear that the conclusions of an assessment of the effect of sand storage dams, may depends greatly on the level of the assessment.

An assessment of the whole Kiindu catchment would have averaged the effects of sand storage dams and would have led to the conclusion that (1) about 50% of the sand dams failed and (2) about 50% of the failed sand dams have been repaired, (3) around sand storage dams about two plots on the riverbanks would be irrigated and (4) walking distances would be reduced by 1h. However with this assessment the development of the several sub location and the reasons for success or failure cannot be understood. This conclusion makes it hard to refine the technology in following projects.

Furthermore the different developments in the different sub areas show that one needs to be cautious to transfer the experience gained in one catchment to other catchments. Even in a small catchment like the Kiindu catchment the conclusions drawn in the Muasya sub-catchment do not explain the development in the neighboring Kivuna catchment. Up-scaling the technology, which is the aim of several studies, therefore needs to follow a flexible approach that can be adapted to the local circumstances during implementation and operation.

'The Effect' of the storage dams may not exist, but what are the developments in the sub areas? During the fieldtrip not enough information about the development in the sub-catchments could be obtained to describe them comprehensively. Only few people could be interviewed per sub catchment so that their reports cannot be considered as a basis of an objective description of the developments. However to show how the areas may have developed in the past 18 years, hypothetical socio-hydrological narratives are formulated in section 8 at the end of this master thesis.

7 Recommendations for further research

7.1 Additional studies

In this study of the effect of sand storage dams on the socio-hydrological development of a catchment, main factors are identified and (inter)relations between these factors proposed. These proposed (inter)relations need to be verified and analyzed in more detail to understand how sand dams influence the socio-hydrologic development of a catchment. Therefore further research about the following four aspects are proposed. Furthermore options to enhance the model in further research are suggested.

Organizational structure

In a social study the organizational structure needs to be assessed in more detail. Ertsen et al. (2005) already stated that only few communal activities take place after the construction of sand dams. The fact that the way how sand dams are maintained and repaired, could not be clarified by interviewees during the fieldtrip reveals the lack information and understanding of the organizational structure in the communities. An assessment of the organizational structure in the study area could show how organizational structures can be used to enhance the implementation approach. Probably the new implementation approach can be more bottom up and be less predefined to increase the confidence of the local communities in their capabilities, as described by Lui et al. (2007). The implementation approach could also contain a strategy to strengthen organizational structures that are capable to manage the maintenance of the sand dams.

Agriculture

In the simulation, it is assumed that transpiration by plants increases if water groundwater tables increase. The underlying idea is that with increasing water tables more plants reach the groundwater and vegetation densities increase. However if groundwater tables rise farmer may start irrigated agriculture on the riverbanks. Therefore they clear the natural vegetation and replace it by crops. In this case the assumption that higher groundwater levels lead automatically to higher transpiration rates does not hold. Furthermore, through the cultivation of land, farmers disturb the soil structure and change the infiltration rates as shown by Moroke et al, (2009).

In this study, the influence of water use and agricultural activity on groundwater tables is either neglected by simulating the effect of sand dams without agricultural activity or simplified in rough assumptions.

Further research needs to clarify the impact of land cultivation on hydrology and vice versa. The future study should also include the influence of human interference on other hydrological processes. Due to clearing of the hill slopes, interception may be decreased and surface runoff increased during the rainy season. However if fruit trees like mangos trees are planted even the opposite may be true. Also the kind of tillage influences how much water infiltrates. Several people in the catchment dug infiltration ditches to increase infiltration. This leads to higher groundwater tables. Finally several farmers spoke about planting trees to retain water and increase groundwater levels on their plots. In order to get a comprehensive picture of the influence of human agency on the hydrology, a rainfall-runoff model should be developed. This rainfall runoff model can be linked to the developed groundwater model. To discover the interdependencies and co-evolution of human activity and water system, a coupled model needs to be developed. For both options a much more detailed database including hydrological and groundwater measurements is required.

Morphology

Another process that needs to be assessed in more detail is the erosion of the riverbed and land degradation. Land degradation is an issue that is not limited to Kitui county. However, how the hydrological as well as the social developments, caused by the construction of sand storage dams, influence land degradation and riverbank erosion needs to be analyzed. As shown in this study water

use in irrigated agriculture and to make bricks lead to lower vegetation densities and may weaken the soil protection. The consequence may be increased land degradation and riverbank erosion. During the fieldtrip it was observed that erosion is largest in the reach where most irrigation takes place. In future research it needs to be clarified whether there is a causal connection between human activity triggered by the sand dams and the erosion of the riverbanks.

Water quality

Water quality was initially out of scope of this study. Nevertheless the usefulness of sand storage dams and therefore the utilization of the stored water, depends on the water quality. The water quality is influenced by two factors. First the extracted water can be contaminated by droppings from cattle next to the scoop holes. The second factor which influences water use and therefore the development in the catchment is the salinity of the water in the shallow aquifer. Borst et al. (2006) identified saline rock as the source of the salinity. Furthermore they measured the Electric Conductivity which indicates the degree of salinity along a reach of the Kiindu catchment. They found out that the salinity in the upstream is considerable higher than in the downstream at the end of the dry period. In this study it is suggested that this may be caused by the changed groundwater flow directions upstream and downstream of sand dams. This hypothesis could not be tested in this study. However since salinity is an important parameter, which restricts the usefulness of water from the shallow aquifer, it is worth to find out the exact mechanisms that lead to the salinity. If sand dams indeed lead to lower salinity in their upstream – through the suggested different flow directions or other mechanisms – it would be another argument for the construction of sand dams.

7.2 Model improvements

In this study the geo-hydrology of the catchment was analyzed by means of a groundwater model. This model can be considerable enhanced by:

- More detailed model
- Alternative schematization approach
- Research about the basic hydrological processes

A more detailed model

The study area in this study is comprised of a whole catchment to include multiple sand dams at various locations in the catchment. Therefore the model is rather rough, developed rather schematically and takes local peculiarities not into account. The extent of the aquifer as well as the type of the dominant aquifer are based on the Digital Elevation Map. The location of rock outcrops and small tributaries are not taken into account. In further research more measurements about the location and extent of the aquifer and rock outcrops and as well as tributaries can be included in a future model. This model need to be much smaller with a much smaller cell size. With it, the impact of local peculiarities could be simulated and the development in a smaller area could be traced in more detail.

Alternative Schematization approach

Based on GIS data, the shape and extent of the aquifer may be schematized differently through an alternative schematization approaches. In this research the extent of the model and type of the aquifer is based on the elevation of a cell above the riverbed in the cross section. Alternatively aquifer cells may get certain properties based on the slope according to the DEM. The outcomes of these approaches should be compared to groundwater measurements and geological profiles. With the most suitable approach, a model should be developed that can be applied to another catchment as well, where it could be a helpful tool to identify preferable construction sites, from a geo-hydrological perspective.

Detailed analysis of the hydrological processes to validate the effect of sand dams more accurately

In the model, the hydrological processes groundwater recharge, soil evaporation and transpiration are based on values from literature and rough assumptions. Because the simulations have shown that these processes have a major impact on the effect of the sand dams, these processes should be analyzed in more detailed in order to determine the effect of the sand dams more accurately.

In any case this every future model needs to be verified by groundwater measurements over a period of several years.

8 Hypothetical Socio-hydrological narratives

If there is not 'The effect' of sand storage dams, how can such divers developments look like? The semi-structured interviews conducted during the fieldtrip were too few to be representative and the assessment of the catchment was not detailed enough for a comprehensive description of the developments of last two decades. However they show trends and are used to formulate examples of possible or hypothetical socio-hydrological narratives to show how such narratives may have looked like.

8.1 The upper Kivuna: When sand dams are valued and people have resources

Initial situation

This is the source area of the Kiindu/Kivuna catchment. The people do rain fed agriculture on the hill slopes. Between the tops of the hills small streams form thin narrow sandy riverbeds. In the vicinity of the stream the slopes are steeper and are not suitable for agriculture. Therefore and because of the higher rainfall the vegetation is naturally green along the stream.

Mulango (aside of Wikililye which is on the northern edge of the catchment) is the biggest settlement with several shops. Here a secondary school is located which received water from a borehole next to the stream. People get some water from the riverbed, but most people go the Nzeeu river to fetch water.

Development

In 1995/96 four sand dams (sand dam 1, 2, 3 and 4) were constructed in the area. Due to the initiative of Mr. Kyende, Sasol built an additional sand dam (sand dam I). Sand dam 4 was constructed about 20 meter further downstream than initially planned, because the community suggested that it could improve the accessibility of the primary school, if it also served as a bridge. According to Mr. Muthoka, after the construction of the sand dams, the water levels in the area rose. Upstream of sand dam I the riverbed rose till bank full level. Downstream the riverbed was eroded. Around year 2000, sand dam 3 and 4 failed (probably also sand dam 1 and 2) and sand which was already accumulated upstream of the sand dams was washed away. The water levels in the area dropped which could be observed by the owner of a well upstream of sand dam 3, Mr. Muthoka. He had already planned to use his well more intensively. Therefore he got in touch with Sasol and tried to mobilize the community to participate in the repair of the sand dam. He also reports that most people did not recognized the value of the sand dams, and therefore refused to participate. In the end the sand dam was repaired at the expense of Mr. Muthoka, who had to pay for the stones and labor. Riverbed and water levels in his well upstream rose again.

Sand dam 4 was replaced by a road which now connects both sides of the river. Due to the initiative of Mrs. Mumo an additional sand dam (sand dam II) was constructed by Sasol between sand dam I and 3 around the year 2006. In contrast to the other sand dams, the pump upstream of sand dam II still works. The spilled water around the well indicates that it is intensively used.

Evaluation

Since the riverbed is narrow and thin only little water can be extracted directly from the riverbed. Therefore the main water source within the catchment are shallow wells. To dig these shallow wells is labor and/or capital intensive. Success of digging a well is not guaranteed. 'Ordinary' people, who cannot afford to dig a well, benefit less. Therefore for most people, the situation has not changed significantly since the construction of the dams. They still go the Nzeeu river to fetch water for everyday use

The area is probably the wealthiest and most developed one in the catchment, because the area is located near Mulango, where people have job opportunities. There are some people with regular employment, who have the resources to invest in the construction of private shallow wells and pumps and therefore have the opportunity to benefit more from the sand dams. Because of their investment and their observed benefits these persons also take care of the sand dams.

Mulango is also a place where people meet and exchange experiences. All of the farmers who invested in shallow wells, tanks and probably pumps and pipes live in the area and know each other. Therefore the individual initiatives may have stimulated each others.

8.2 The lower Kivuna: When sand dams fail and people become distracted

Initial situation

The Kivuna is winding through the hilly landscape. In the course of the river, the slopes become milder and the riverbed is more and more accessible. Along the river a strip of natural vegetation is present. People extract water from the river but the main water source is the Nzeeu river, which is less salty. Several interviewees try to generate income through casual work in the area or even in Kitui and Nairobi.

Development

In 1995/96 5 sand dams (sand dam 5, 6, 7, 8 and 9) were constructed by Sasol. After construction the riverbed rose, but until 1999 the riverbanks of 5, 7, 8 of the 9 sand dams were eroded. The water now bypasses the dams and the accumulated sand upstream of the broken dams is washed away. Only sand dam 6, which is founded on rock upstream of a steep rocky river section still functions. Sand dam 8 and 9 were repaired. However sand dam 9 failed again. The water levels around sand dam 8 are close to riverbed surface. Even downstream of dam 8 water levels are only a few centimeter below the surface, which may indicate leakage or seepage.

In this stretch people water their cattle and goats from scoop holes. The scoop holes are also used to fetch water for making bricks. Making bricks becomes more popular in this section. This is probably because the water quality is considered not suitable for irrigation or domestic water use.

Several private shallow wells could be found in the area. Some of them dry up during the dry season according to local people. Other wells have plenty of water. Some owner of these wells report that they use their wells only sparsely because they have alternative water sources or prefer the water from the water network of Kitui, which can be bought at a primary school.

In 2008 a borehole was drilled next to sand dam 7, by the initiative of a minister of the national government. After supplying the local community with water from a deeper aquifer, the supply stopped due to several reasons (see Appendix A). Now the borehole does not supply the local community with water and it is questionable when and if the borehole will serve the community in the future. As a consequence people are now focused on this borehole and do not search for other opportunities to improve their water supply, even if they suffer from water shortage.

Evaluation

Because the water is salty, the river is not the first choice of the local community as water source. Therefore people may not be (so much) interested in increasing the amount of water available in the riverbed, which decreases the incentive to repair and maintain the sand dams. Since many people consider the water as too salty for irrigation, most water is used for brick making. To produce charcoal for burning the bricks, trees are cut and the vegetation along the stream becomes less dense according to interviewees.

People in the area look for water sources alternative to the shallow aquifer since the water is too salty. But also because a borehole was drilled in the area, which supplied the communities with fresh water, water from the riverbed became less attractive. The borehole is the hope for the community for a reliable water supply. Therefore people do not search for a solution, like sand dams within the catchment, which they could implement by themselves.

8.3 Muasya/upper Kiindu: when sand dams function as intended

Initial situation

The Musaya tributary is the first larger tributary. In contrast to the Kivuna catchment the water quality of the Muasya catchment is considered to be good. According to local people the stream was narrow with a thin riverbed which dried up early in the dry season before the sand dams were constructed. They got water from the Nzeeu river, which takes up to 3 hours from this area.

Development

In this area 6 sand dams were constructed in the period 1995/96. All of the sand dams are still intact. After the construction, the sandy riverbed rose. Groundwater levels increased and the vegetation became 'more green'. The riverbed which formally dried up in August delivers water now until September/October. Together with the connection of the water supply network at a primary school the water in the riverbed satisfies basic domestic water demand now.

At a few locations there are shallow wells which enable the owners to irrigate some vegetables and fruit trees on the riverbanks. At the end of the dry period the owner of the wells also sell water to other members of the community.

In the area around sand dam 14/15 the community dug public wells, but they dry out too early to be of help for them. According to one owner there is already enough water in the area but the people are 'too lazy' to dig their own wells. People suggested the rehabilitation of existing shallow wells and the construction of new or heightening of existing sand dams to improve their water supply. However there are no initiatives to actually improve the water supply. According to one village elder collective action is less common than it was in the past.

Evaluation

The valley is narrower than in the neighboring area and the dams could be found on rocks below the riverbed as well as in the riverbanks. Since all sand dams in the area are still intact the locations for constructing sand dams seem to be well chosen.

The sand dams function as they were intended by Sasol. They increase the amount of water available in the riverbed, satisfy together with water supply network the basic water demand and reduce the waking distances to the water source. Therefore the communities value the sand dams and propose the construction of new or the increase of existing sand dams. However the amount of water stored is too little to develop noteworthy irrigated agriculture.

8.4 The middle Kiindu: When sand dams increase the water supply drastically

Initial situation

In this area the valley becomes wider and the slopes of the riverbanks milder. Most houses are uphill on the east side of the valley on the border with the Nzeeu catchment where the road to Kitui is located. It is hard to estimate how the situation was before the construction of the sand dams since the landscape is highly influenced by human activity. Also people interviewed could not give much information because most of them moved into the area after the construction of the sand dams.

Development

In this area four sand dams (sand dam 16, 17, 18 and 19) were constructed in 1995/96. All of them broke initially but three of them were repaired again. Only sand dam 17 which failed recently is not repaired yet. Downstream of the reach, sand dam 20 was constructed about 60 years ago and is still intact.

In this area the sand dams are matured and the storages of the sand dams upstream are filled with sediments. Most of the interviewees in this area moved into the catchment after the construction of the sand dams. The abundance of water in the riverbed creates the opportunity to generate income from irrigated agriculture for the owners of the plots along the stream. Landowners that found employment in cities like Nairobi and Mombasa allow brothers, sons or nephews, who stayed in the catchment, to grow vegetables on their plots and generate income. Therefore more and more plots along the river became irrigated.

To develop irrigated agriculture, people clear the riverbanks from the trees and natural vegetation. Along the riverbanks Napier grass is planted to protect the riverbanks. The Napier grass is also used as food for cows at the end of the dry season.

People explained that in recent years, floods caused mayor erosion on the riverbanks. In several cases whole irrigated plots were washed away and the river locally doubled its width. Between sand dam 18 and 19 the stream even changed its track and therefore also the water availability changed in the area. People who formerly had enough water to irrigate their plots report that they now struggle

to maintain their irrigated agriculture, while people who have their plots next to the new track started irrigation. Between sand dam 18 and 19 and upstream of sand dam 20 irrigation is applied on most of the riverbanks.

Evaluation

Here the sand dams considerably increase the amount of water which can be extracted from the riverbed. However in the area it is difficult to find appropriate sites where sand dams can be built on rocks bars. Therefore all four newly constructed sand dams failed.

The abundance of water motivates farmers to develop irrigated agriculture on the riverbanks. It therefore provides an additional opportunity to generate income for people within the catchment. Staying in the area becomes more attractive.

The development however may also have its drawbacks. Through clearing the riverbanks from the natural vegetation, people may increase the natural erosion processes. The erosion first threaten the irrigated plot. Finally when the erosion propagates, the wing walls of sand dams may be eroded, which lead to the failure of the sand dam. It might end up in the devastation of the landscape in the future. Riverbanks become bare and subject to erosion by overland flow and river discharge, while at the same time sand dams break down. However the sand dams also get repaired, which may be caused by the fact that people highly benefit from them.

8.5 The lower Kiindu: In the transition from functioning to broken

Initial situation

Downstream of sand dam 20 the slope of the riverbed is steep. Rocks cover the riverbed and finer material like sand is washed away. This area is dry. The few people who live here have to go further up- or downstream to fetch their water.

From the end of the steeper section to the junction of the Kiindu with the Nduni the slopes become milder again, but the valley is not as wide as upstream of the steep section. People live uphill on the edge of the catchment, near the road to Kitui.

Development

In 1995/96 Sasol built three sand dams downstream of the steep dry reach. After the construction, the water level in the riverbed rose and people started irrigating the riverbanks. In 2008/09 sand dam 23 and in 2013/14 and dam 21 broke. With the breakdown of the sand dams also the water levels fell again. In the course of the years several plots on the riverbanks were washed away, but there are still people who are able to irrigate their plots on the riverbanks. However most of the formally irrigated fields are abandoned.

Evaluation

This area may be the future of the reach further upstream. Also here people benefitted from the surplus water provided by the sand dams. They started irrigated agriculture on the riverbanks. But in contrast to the area upstream the sand dams have not been repaired. Therefore people stopped irrigating their fields and lost their income.

8.6 The lower Nduni: The Natural State

Initial situation

The area is very sparsely populated. According to people the riverbed rose due to the construction of sand dam 29 further downstream. Further there is no human influence visible from the stream. In general the vegetation is natural and the trees on the riverbanks protect the riverbanks against erosion. Only a few footpaths were found and at several locations bushes are planted on the riverbanks to hinder people from entering the land.

Development

People say that the area probably has not developed in the last two decades. Because of the area is sparsely populated and there are no suitable construction sites, no sand dams were constructed. Since there are no sand dams constructed, people do not move into the catchment and water supply stays unchanged.

Further upstream three sand dams (sand dam V, 24 and VI) were constructed by different organizations. Sand dam V was constructed in a tributary by a private person leading to a much greener vegetation. According to people his well had plenty of water and was allowed to be used by neighbors. After its breakdown the vegetation became drier again. The other two sand dams in the main river, built by Sasol and another donor, were repaired several times. Upstream of these sand dams people dig scoop holes into the riverbed to fetch water. These scoop holes were at the time of the fieldtrip already very deep and almost dry, so that (at most) very little water can be extracted from the riverbed. On the riverbanks several private shallow wells were dug, which donors equipped with hand pumps.

Evaluation

Till now it seems that people do not move into the areas which are originally dry and develop their own water supply. Probably the construction of sand dams would have initiated the development of the area.

Taking the area as reference for other areas, it can be seen that improvement in the water supply by sand dams, does not automatically lead to a 'greener' or 'richer' environment. Through larger amounts of water available in the riverbed, people start to develop the environment on their behalf. This led to green irrigated fields and fruit trees, but may also lead to land degradation and erosion of the riverbanks and a less dense and diverse vegetation.

The area further upstream, where sand dams were built, demonstrate that sand dams may not be a successful measure for every area. In this area, probably due to the underlying rock formations, a lot of water seems to bypass the sand dams, or percolates into deeper aquifers, so that the riverbed dries out quickly. Even deep scoop holes upstream of sand dams provide only little water. Only the private shallow wells, sponsored by donors, relieved the situation. The effect of the sand dams on the water levels in the shallow wells is unclear.

8.7 The upper Nduni: Sand dams in an unfavorable area

Situation

This area was also sparsely populated. The Nduni was a narrow river, with a thin riverbed. One woman said that, 'you could hardly call it a stream'. The riverbanks were often more than 1.5 m above riverbed level. According to interviewees there was almost no water available in the riverbed and people in the area had to travel long distances to the Kiindu catchment to fetch water from scoop holes. Another alternative water source is the Kalundu river. But since its water is contaminated with waste water from Kitui, people avoid to use it.

Development

In 1995/96 Sasol built three sand dams (sand dam 25, 26 und 27) in the area. The sandy riverbed rose up to 2 meter at several locations and the channel was filled with sediment. People reported that Sasol had problems to dig the wells at the required depth, which is here deeper than in the Kiindu catchment. Therefore they built a fourth sand dam (sand dam 28) in a small tributary.

Afterwards donors also sponsored a sand dam just downstream of sand dam 25. Since the riverbed dries out quickly these donors also helped the people to construct the missing shallow wells (or to equip existing wells with hand pump). Most of these shallow wells along the stream are private property and delivered water at the time of the fieldtrip.

Between the years 2012/13, sand dam 25 broke during the wet period. Since then the only public well built by Sasol upstream of the sand dam dries up early in the dry period.

In the last years donors sponsored again two shallow wells for the public. One well was built upstream of sand dam 25 and one was built next to sand dam 28. The former is only about 12 feet deep and delivers 2 jerry cans per hour only, while the latter is constructed at a location where the underlying hardrock could not be penetrated. Therefore the well could not be deepened enough to reach the groundwater. The potential of a the public shallow well can be seen at the private shallow well about 50 meter further downstream of sand dam 25. Here the well owned by a women delivers continuously water.

The only alternative water sources at the end of the dry period are scoop holes in the Kiindu or the Kalundu catchment. To get water from the Kiindu takes almost the entire day while the water from the Kalundu is contaminated by wastewater from Kitui.

Evaluation

In contrast to the other catchments, shallow wells are essential for people. Like in the downstream area of the Nduni, lots of water seems to bypass the sand dams. Because only little water can be extracted from scoop holes, one sand dam does not compensate for a missing shallow well in this catchment. In this area the effect of the sand dams on the water levels in the shallow wells is unclear.

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A.1 Introduction

The developments in the study area were assessed during a fieldtrip from 21 July to 27 September. The assessment consisted of semi-structured interviews and trans-sectional walks. Both, the trans-sectional walks and the semi-structured interviews were conducted together with Theophilus Musyimi, a local student, who helped to put the obtained information into the cultural context and translated the interviews when needed.

After arriving in a new area in the catchment the village elder was visited to inform him or her about the fieldwork and to make appointments for semi-structured interviews (if required). Afterwards first a trans-sectional walk was conducted to assess the catchment. During the trans-sectional walks the first semi-structured interviews were conducted, if local people were met. The following days additional semi-structured interviews along the riverbed and at homesteads, at some distance of the river were conducted to get a more comprehensive picture. During the semi-structured interviews the participants could illustrate their experiences by showing the location of water use and/or extraction.

Rough concepts of semi-structured interview and trans-sectional walk were prepared beforehand. Initially the interviews contained very detailed questions about the water use and the societal background (see Appendix B1). It turned out that this initial concept was too specific and the interviews took too long. Participants of community meetings had to wait, because the questions were much too detailed. To be able to speak to more people the concept was shortened with only eight main questions to address the topics mentioned below. (see Appendix B2) The conversation could go into more detail with more specific questions, if interviewees had additional experience.

Moreover the setting of the semi-structured interviews were revised from community meetings to a more spontaneous procedure, where people were interviewed during their daily life, because the community meetings were probably attended mainly by people which had complains about the shortage of water. People who had sufficient water probably stayed on their farms and continued with their work. Furthermore the community meetings could have lead to disappointments, because they potentially could raise the expectation by the participants that their water supply will be improved by activities related to the interviews. The new procedure also had the advantage that the location, technique and purpose of water extraction could be assessed immediately. To get a more representative sample of interviewees people, who may have more difficulties to get water and/or use alternative water sources were visited on their plots.

During the **semi-structured interviews** three main topics were addressed:

- Current and former water use and water sources. An indication of the effects of the sand dams may be the degree of the water use as well as the shift from water sources from distant to water sources near the dams or homesteads.
- Observed changes in landscape, vegetation and groundwater levels. In theory sand dams lead to higher groundwater tables which may change vegetation and land use. Higher groundwater tables may also be visible in wells.
- Social environment. Also society may have changed in the last years. This may be an alternative reason behind the water and land use that may not be linked to the hydrology.

The **trans-sectional walks** were conducted to obtain information about

- General characteristics of the stream and catchment. The locations of tributaries, rock outcrops and the levels of the riverbed and bank were noted as well as the width and the thickness of the riverbed.
- Human water use. The locations of sand dams, public as well as private shallow wells and irrigated fields were assessed.
- Vegetation. Due to changes in the hydrology the vegetation could have changed over the last 18 years.

A.2 Results

A.2.1 Structures

A.2.1.1 Sand Dams

During the fieldtrip 35 sand dams were visited. Most of the sand dams are built by Sasol between 1995-96, but there are also sand dams that are built by missionaries some decennia's ago or by private people and charities. The condition of the sand dams varies between full functioning to broken. Figure A.1 shows the location of the sand dams and their condition. Table 1 contains the main characteristics of the dams and associated shallow wells found in the literature and supplemented by findings during the field trip.

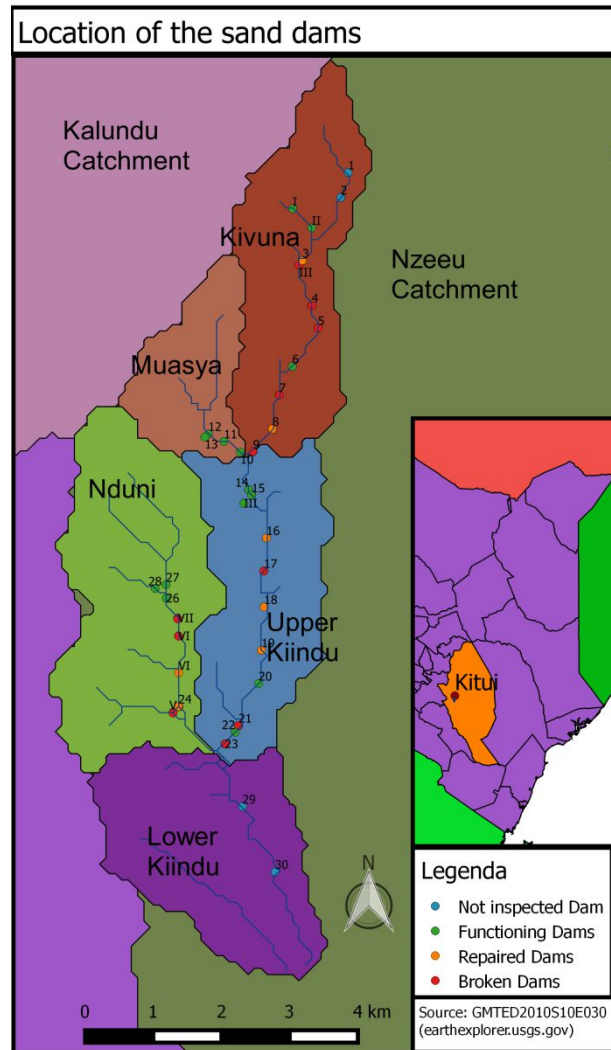


Figure A.1 Location of sand dams

Table 1 Sand dams in the Kiindu catchment¹

Dam	Name	Build	Width [m]	Height [m]	Catchment	Condition	Associated well
1	Kisenkini	Sasol '96	17	1.4	Kivuna	Not visited	Not visited

¹ Source: Sasol et al. (1999) supplemented with information about the condition of the dams and wells obtained in the field.

2	Nengry	Sasol '96	26	1.4	Kivuna	Not visited	Not visited
I	Sunzumala	Sasol '96	16	1.6	Kivuna	Intact	Dry
II	New sand dam	Sasol	12	1.6	Kivuna	Intact	Intensively used
3	Mulango	Sasol '96	26	2.3	Kivuna	Repaired	Not found
III	Ancient Sand dam	???	???	2	Kivuna	Broken	--
4	Kivuna Ndovoini	Sasol '96	30	1.3	Kivuna	Broken	Not found
5	Kwa Munzao	Sasol '96	15	2.3	Kivuna	Broken	Not found
6	Yoani	Sasol '96	19	2.4	Kivuna	Intact	Not used filled with branches
7	Kilukuya	Sasol '96	19	2.4	Kivuna	Broken	
8	Silingi ili	Sasol '96	11	3.0	Kivuna	Repaired	Damaged
9	Kwa Mwini	Sasol '96	15	2.3	Kivuna	Broken	Not found
10	Ngomano	Sasol '96	12	2.6	Muasya	Intact	Damaged
11	Kwa Mwenze	Sasol '96	12	2.6	Muasya	Intact	Damaged
12	Kitulo	Sasol '96	14	2.8	Muasya	Intact	Damaged
13	Mumbuni	Sasol '96	11	0.8	Muasya	Intact	Not found
14	Syonganga	Sasol '95	14	3.5	Kiindu	Intact	Intact
15	Kwa Kangesa	Sasol '96	19	1.8	Kiindu	Intact	Not found
IV	Cascade of sand dams	Private 1990s	3-4	1-2	Kiindu	Intact	No well constructed
16	Kwa Ndunda	Sasol '96	23	2.5	Kiindu	Repaired	Filled with branches
17	Kwa Langwa	Sasol '95	14	2.4	Kiindu	Broken	Not found
18	Kwa Mangya	Sasol '95	24	1.9	Kiindu	Repaired	Not found
19	Nzemeni	Sasol '95	18	2.4	Kiindu	Repaired	Damaged
20	Uvati	Missionaries 1950s			Kiindu	Intact	Intact
21	Kwa Mukumbe 2	Sasol '95	16	1.6	Kiindu	Broken	Not found
22	Kwa Mukumbe 1	Sasol '95	19	1.0	Kiindu	Intact	Damaged
23	Kwa Mutinga	Sasol '95	26	2.0	Kiindu	Broken	Damaged
V	???	Private			Nduni	Broken	Not found
24	Kwa Mulumbi	Sasol '96	18	2.2	Nduni	Repaired	Not found
VI	???	Donor			Nduni	intact	Not found
VII	???	Donor			Nduni	broken	Damaged
25	Kwa Kilile	Sasol '???			Nduni	broken	Dry
26	Kwa Vonza	Sasol '96	22	4.3	Nduni	intact	Not found
27	Kwa Kitoo	Sasol '96	14	3.7	Nduni	Intact	Intact (private)
28	Kwa Muthembwa	Sasol '96	16	3.2	Nduni	Intact	Dry
29	Kwa Kavoo	Sasol '95	25	-	Kiindu	Not visited	Not visited
30	Kamumbani	Sasol '95	28	2.2	Kiindu	Not visited	Not visited

A.2.1.2 *Failure mechanisms*

As illustrated in Figure A.1, 13 of the 27 sand dams built by Sasol are still working, while 15 sand dams failed initially. At the time of the fieldtrip, 8 of the sand dams built by Sasol did not function. In

most cases the wing walls in the riverbanks were washed out during floods, so that water can bypass the dams. After erosion of the sides walls some sand dams collapsed. (see Figure A.2)



Figure A.2 Failed sand dams (left: sand dam 21, right: sand dam 9)

Some sand dams are restored by building a new wing wall that is extended into the riverbank. (see Figure A.3 left) Sand dams which run the risk of breaking in the center are strengthened by an additional wall. (see Figure A.3 right) After restoration the sand dams store water in their upstream again. But high water tables downstream indicate that water leaks through the repaired sections as could be observed in the case of sand dam 8. (see Figure A.3 left)



Figure A.3 Repaired sand dams (left: sand dam 8, right sand dam VI)

A.2.1.3 *Assessment of the single sand dams*

A.2.1.3.1 **Kivuna catchment**

Sand dam 1 and sand dam 2 were not visited because they were mixed up with the sand dams I and II. According to local people they are broken.

Sand dam I was built in 1996 and is still intact. According to local people the sand dam was constructed on the initiative of the former chief assistant, who lives about 150 m upstream the sand dam. The height of the crest is almost on river bank level. Upstream of the dam, the river is filled with sand. Downstream of the sand dam the sand is washed out. The slopes of the riverbanks are steep. The associated well is dried out at the time we visited it and is filled with branches. The pump of the well is broken.



Figure A.4 Sand dam I (left) with associated well (right)

Sand dam II, which is still intact, was built between 2000 and 2006 on initiative of Janet Mumo who works in the field of development aid in Kitui and lives in this area. It has already a modified profile with a spillway to guide the water to the center of the stream. Upstream, sand has settled up to about 40 cm below the crest. The associated well still delivers water. The pump is functioning and makes water abstraction easy. Therefore the well is used intensively by the local people. On the other side of the stream another (private) well is dug into the ground which is also filled with water.



Figure A.5 Sand dam II (left) with associated well (right)

Sand dam 3, which is built in 1996, is repaired due to the initiative of Mr Muthoka , who lives about 200 m upstream. Several years after construction, the river bank on the left hand site was washed out and the sand dam collapsed. There is one well on private property upstream of the sand dams, which still contained water at the time of the visit. Whether or not the well was built by Sasol for the community could not be clarified.



Figure A.6 Sand dam 3

Sand dam III: When this 'ancient' sand dam was constructed could not be figured out. The people I spoke to could not remember the time when it functioned. It was about 2 meter high with respect to the current riverbed level.



Figure A.7 Ancient sand dam

Sand dam 4 was built 1996 south of the village of Mulango. It was intended to serve also as a bridge connecting the primary school of Mulango with the main road. Therefore the construction site was shifted several meters downstream where the river is better accessible. According to local people this was a big mistake because now the dam on the right hand site needed to be extended into the clayey riverbed instead of rocks some meters upstream. This was the main reason for a lot of erosion and the failure of the sand dam. Now the sand dam is replaced by a road which is not constructed to be water tight. The sand which accumulates upstream is regularly harvested for building purposes since access is easy. A public well which is associated to the construction of the dam is not found. However there are several private wells on plots upstream.



Figure A.8 Bridge at the original location of sand dam 4

The foundation on the right hand site of **sand dam 5** (built in 1996), was eroded during heavy floods in 1998. In the following years the riverbed was eroded even below original riverbank level. The dam still causes erosion by guiding the water along the riverbank on the right hand site. The owner of the plot on this side already tried to remove the dam to prevent further erosion. Wells that are associated to the sand dam could not be found.



Figure A.9 Sand dam 5 (left) with eroded wing wall (right)

Sand dam 6, which is constructed upstream of a steep river section and founded on top of a rock bare, is still intact. The associated well is sited about 100 m upstream on private land. According to the owner of the land (who lives further upstream) the well is not used by the local people even if it has water throughout the year and is easy accessible. Moreover he reports that some neighbors even contaminate the well with dead animals because of enviousness.



Figure A.10 Sand dam 6 (left) with associated well (right)

The riverbank on the right hand site of **sand dam 7**, which is located downstream of a steep river section, is eroded. Now water is flowing around the sand dam. The sand which had been settled upstream is washed out. A public well which was constructed together with the sand dams could not be found. According to local people, the sand dam functioned for a couple of years but erosion started short after the construction.



Figure A.11 Sand dam 7 (left) with eroded wing wall (right)

Sand dam 8 broke on the left side. However it was repaired afterwards and is now functioning again. Water tables are almost on surface level downstream of the sand dam. The storage in the upstream is completely filled with sediments. The public well is filled with branches and is dried up and therefore not used.



Figure A.12 Sand dam 8 (left) with associated shallow well (right)

Sand dam 9 is the most downstream sand dam in the Kivuna catchment. Like in the case of sand dam 7, the riverbank on the right hand side is washed out. The riverbed around the sand dams is back on original level; about 1,5 meter below the crest of the sand dam. No public well associated with the sand dam could be found in its vicinity.



Figure A.13 Sand dam 9

A.2.1.3.2 Muasya catchment

Sand dam 10 is located just upstream of big rocks. It is still intact and the storage upstream is filled with sediments. The well in the upstream associated to the sand dam is highly damaged. Even the walls of the well above the surface are washed away.



Figure A.14 Sand dam 10 (left) and well nearby (right)

Sand dam 11 is still intact. Sediments have filled the storage in the upstream till crest level. The water level in the small scoop hole just downstream is about 60 cm below the surface of the riverbed. The associated well is damaged and dry during our visit.



Figure A.15 Sand dam 11 with associated well

Sand dam 12 is still intact. There are several depressions in the riverbed upstream where sand is harvested but did not serve as scoop holes. The associated well on the right riverbank is damaged but still delivers water for making bricks.



Figure A.16 Sand dam 12

Sand dam 13 is built in a small tributary of the Muasya stream. It is still functioning but there could no indication of water abstraction be found in it its vicinity.



Figure A.17 Sand dam 13

A.2.1.3.3 Kiindu catchment

Sand dam 14 is sited about 200 m downstream of the junction of the Muasya tributary. It is still intact and the storage upstream of the sand dam is filled with sediments. The first public well was constructed on the riverbank next to the river. But the well was destroyed after the storage was filled up with sediments and water levels rose during floods. To compensate the community for the loss of the first shallow well, Sasol build a second public well further uphill. This public well is equipped with a still functioning pump. It is located on private land and only members of families, which were involved in the construction of the dam have the permission to use it. The people, which are not allowed to use the public well, have to dig scoop holes into the riverbed to fetch water.



Figure A.18 Sand dam 14 (left) with associated well (right)

Sand dam 15, which is built only about 50 m downstream of sand dam 14, is also still intact. According to people the dam was supposed to be built several hundred meter further downstream. The people suspect that corruption may be the reason for the change of the construction site. Due to the short distant to sand dam 14 the length of the storage is rather small. An associated well was not found.



Figure A.19 Sand dam 15

Cascade of three sand dams: About 100 meter downstream of sand dam 15 there are cascades of sand dams built in a small tributary. The sand dams function properly and the tributary is for large parts is filled up with sediments. The owner of the plot, which borders the tributary, worked for a land conservation authority. He built the sand dams some 20 years ago. According to him, the sand dams lead to higher groundwater levels, but he does not take advantage of them because he has several other sources of income.



Figure A.20 First (left) and third sand dam (right) of a cascade of three private sand dams in a tributary

Sand dam 16 was built in 1996 and repaired in 2001. After construction the riverbank on the left hand site was eroded and the dam lost its function. Who repaired the sand dam could not be clarified, but one person told us that the repair may be initiated by Dutch students after they finished their research. The owner of the plot on the left hand site was not present during the reparation. He improved the soil afterwards upstream of the sand dam and has a small plantation of vegetables on the former riverbed. The water table in the scoop hole just upstream of the sand dam is almost on surface level. Although the repair of the dam was successful, water leaks through the repaired section. Therefore downstream of the sand dam water stands on the riverbed.

The associate public well is located some 150 m upstream on private land. The owner of the land does not live in the area anymore and prohibited the people to enter his land and fetch water. Therefore the well is not used and children throw stones and branches in it. As compensation the local community together with Sasol build a new well for the community. The well is about 10 m downstream of the former public well. The riverbank on which the well was founded was washed out during the last rainy season. It is now restored and the walls will be rebuild at the end of the dry season.



Figure A.21 Sand dam 16 (left) with associated Well (right)

Sand dam 17 broke last rainy season. Upstream of the sand dam people had dug a scoop hole to fetch water. We found no shallow wells in the vicinity of the sand dams.



Figure A.22 Sand dam 17

Sand dam 18 is repaired several times. The storage in the upstream is not filled up with sediments. People dig scoop holes on both sides of the sand dam to fetch water. At the end of the dry season people from distant areas come to get water. The queue may become very long in those days. The public well which is usually built together with the sand dams could not be found and people did not report about it. In the future there is the risk that the river will form a new course and flow around the sand dam.



Figure A.23 Sand dam 18 (left) with repaired wing wall (right)



Figure A.24 Extension of Sand dam 18

Sand dam 19 is repaired, and sited just upstream of a larger tributary. It is found on rocks, but at the left hand side the stream eroded the riverbank. Now the sand dam is extended so that it is working again. Sand is accumulated up to crest level. The associated public well just upstream of the sand dam is destroyed by floods. Upstream of the sand dam a farmer has dug his own private scoop hole. The water level in the scoop hole is about 30 cm below the surface of the riverbed.



Figure A.25 Sand dam 19 (left) with extended wing wall (right)

Sand dam 20 is located upstream of a steep river section and founded on rocks. According to local people it was constructed in the 1950s by missionaries. Since then it functions properly. Sasol built a shallow well in the upstream which is equipped with a hand pump. The handle is removed by the local community to spare the water for the end of the dry season.



Figure A.26 Sand dam 20 (left) with associated well (right)

Sand dam 21 is located downstream of a steep river section. The foundation on the left hand side was eroded during the last years, so that the sand dam does not function anymore. About 100 meter upstream there is a single scoop hole which delivered water for an irrigated plot on the riverbanks during the last years. Since the dam broke the scoop hole dried out and even deepening the well into the weathered rock was not sufficient to recover the water source.



Figure A.27 Sand dam 21

Sand dam 22 is still intact. It stuck out of the riverbed only several centimeter. On the left riverbank a public well is located on private land. The well was maintained by the owner, but since the community is responsible for its maintenance the well is in bad condition and delivers no water anymore. (see section A.2.5.3.3)



Figure A.28 Sand dam 22 (left) with associated well (right)

Sand dam 23 is located just upstream of a big tributary. In 2009 the sand dam was damaged by a heavy flood. The attempt to restore it failed. (see section A.2.5.3.3). Now the people still fetch water from a scoop hole upstream of the sand dam. But the water table in this scoop hole dropped considerable after the failure of the sand dam. Even if the people have to deepen the public scoop hole regularly it dries not out completely and attracts people from the Nduni tributary where water is even more scarce. The well associated with the sand dam is destroyed by heavy floods.



Figure A.29 Sand dam 23 (left) with associated well (right)

A.2.1.3.4 Nduni catchment

In a rather big tributary of the Nduni stream the remains from a sand dam were found. According to local people the dam was build 10 to 15 years ago by one of the owners of the plots bordering the tributary. It was approximately 2 meter high with respect to the current riverbed. When the sand dam was matured the vegetation around the sand dam became green. However the sand dam failed after several years and the situation restored to the original state.



Figure A.30 Private sand dam in a tributary

Sand dam 24 was built by Sasol in 1996. The edges of the sand dam became a bit eroded. On the left side the outer part broke so that the water can pass the dam lower than crest level. Nevertheless the storage volume is still filled with sediments and scoop holes indicate that at least early in the dry season people can get water here. At the time of the visit the about 1,5 meter deep scoop hole was already dried up. A public well could not be found. But there are some private shallow wells in its vicinity.



Figure A.31 Sand dam 24

Upstream of sand dam 24 there are two sand dams (**sand dam V and VI**) which were sponsored by donors. Sand dam V is still intact but like sand dam 24 the sides of the sand dam are somewhat eroded and need to be maintained. Sand dam VI is broken. The few scoop holes in this area were already dried up at the time of the visit. There was no shallow well found that can be associated to sand dam V. The shallow well upstream of sand dam VI is damaged and filled with sediment. However in this area donors also sponsored several covered shallow wells on private land which are equipped with a pump. Most of these shallow wells still have water, but there is no indication of intensive use. According to some local people the donors promised that every owner of a well would get a cover and a pump for his well. Others reported that the whole well was donated.



Figure A.32 Sand dam V (Left) and Sand dam VI (Right) sponsored by a donors

The riverbank on the left hand side of **sand dam 25** is eroded and water can now flow around the sand dam. According to the people the sand dam failed two years ago. When the sand dam functioned as designed the well just upstream of the sand dam supplied the local community with sufficient water for domestic use most of the time during the dry season. Since the dam is broken the well dries up early in the dry season. Now people abstract water from a 2 meter deep scoop hole downstream of the sand dam. Hundred meter upstream of the sand dam, there is a public well which is sponsored by a donor. The community had not enough time to construct the well up to a sufficient depth in the dry season. That's why the well now is delivering only 40 liters per hour. All users of the well need to pay an amount per year for maintenance. The donors left the material required to deepen together with the instructions how to deepen the well with the community (see section A.2.5.3.3).



Figure A.33 Sand dam 25 (left) with eroded wing wall (right)

Even if water can flow around the big rocks on the right hand side, **sand dam 26** is still intact. Upstream of the sand dam some scoop holes are dug into the riverbed. Wells associated with the dam could not be found.



Figure A.34 Sand dam 26

Sand dam 27 is also still intact. In the upstream there are four 2 meter deep scoop holes dug into the riverbed that have little water. Next to the scoop holes there is a deep (private) shallow well. Its water depth is more than one meter.



Figure A.35 Sand dam 27

Sand dam 28 is a small sand dam further upstream which is still intact. According to the local people Sasol used the remaining material to built the last sand dam in the area. It is also constructed to compensate for the lack of shallow wells in the area. People reported that Sasol faced difficulties to dig the wells to the necessary depth, which is deeper than in the other steams. Therefore Sasol decided to build an additional sand dam with the residual material. Originally there was no shallow

well near the sand dam. A couple of years ago donors sponsored a well for the community. After controversial discussions the well was built next to sand dam 28. The well could not be deepened enough to reach water because of the hard rock layer.



Figure A.36 Sand dam 28

Sand dam 29 and 30 lie downstream of the study area and are therefore not researched.

A.2.2 Catchment

A.2.2.1 Stream

A.2.2.1.1 Kivuna

The most northern part of the Kiindu catchment is called Kivuna. The Kivuna has two main sources. The stream starting in the far north, where sand dam 1 and sand dam 2 are sited, is not visited. The second source is located more to the west. Here a flow channel has developed just downstream of sand dam I. Upstream of sand dam I, sand has been accumulated in the flow channel between the two hill slopes. Downstream of the sand dam, the sandy riverbed is washed away and the bare rock in the riverbed is exposed (See Figure A.37 left). The width of the riverbed is between 2 and 4 meter.



Figure A.37 Left: Eroded riverbed downstream of sand dam I; Right: Junction of the streams of the two main sources

Further downstream the sandy riverbed becomes thicker. Due to the dense vegetation the riverbed could not be assessed entirely. Between sand dam II and 3, the streams of northern and western sources unite (see Figure A.37 right). Upstream of sand dam II, 3 and 4 the thickness of the riverbed increased due to the sand dams (see Figure A.38). Upstream of sand dam 3 the process of accumulation of sediments is not completed after its repair.



Figure A.38 Left: Sand dam upstream of sand dam 3; Right: Kivuna between sand dam 3 and 4

Upstream of sand dam 4, sand is harvested for building purposes (see Figure A.39). Downstream of the sand dams 3 and 4 the sand is washed away and the underlying rock is exposed. The width of the river is about 5 meter between these two sand dams.



Figure A.39 Left: highly eroded river section downstream sand dam 4; Right: Sand harvesting upstream of sand dam 4

Downstream of sand dam 4 the riverbanks are eroded and the channel is widened (see Figure A.39 left). The riverbanks have steep slopes. The thickness of the riverbed increases gradually. Due to the irregular base rock the thickness varies considerably from a few centimeters to more than one meter. Till sand dam 6 the river winds between the riverbanks. The slopes of the riverbanks become milder. In this section only sand dam 5 disturbs the natural morphological balance. On the left hand side, the sand dam is properly founded on rock while on the right side it is washed out. Now every rainy season the right riverbank is eroded bit by bit. According to interviewees the riverbed rose after the construction of the sand dam but now it is below original level today.



Figure A.40 Kivuna stream

Just downstream of sand dam 6 a steep rocky section starts (see Figure A.41 left). Here the riverbed is more a lane on which the water flows downstream. At the downstream end of this river section the river forms a sandy riverbed again.



Figure A.41 Left: steep rocky river section downstream sand dam 6; Right: stream downstream of sand dam 7

The broken sand dam 7 downstream of the steep section also causes erosion on the riverbanks next to it. The width of the riverbed in the section ranges between 5 and 10 meters. (see Figure A.41). The sandy riverbed in most parts is thicker than 1 meter. Before the stream unites with the Musaya tributary, two larger tributaries (see Figure A.42). Till the junction with the Musaya the width of the Kivuna stream increases to more than 10 meter (see Figure A.42).



Figure A.42 Left: Small tributary; Right: Junction of the Kivuna and Musaya

A.2.2.1.2 Muasya

The Muasya tributary is visited from sand dam 12 till its mouth into the Kiindu. Upstream of sand dam 12 its riverbed is between 6 and 8 meter wide. The holes in the riverbed indicates that the people use the riverbed as a source of sand for construction sites.



Figure A.43 Riverbed upstream of sand dam 12

Upstream of sand dam 11 the riverbed becomes broader to about 12-15 meters (see Figure A.44), while at several rocky locations the width becomes smaller, like in the vicinity of sand dam 10 (see Figure A.44). The thickness of the riverbed varies, because of the irregularities of the underlying rock formations, from several centimeters in rocky sections to about 1,5 meters upstream of sand dams.



Figure A.44 Left: Riverbed upstream of sand dam 11; Right: Narrow riverbed upstream of sand dam 10

A.2.2.1.3 Kiindu

Downstream of the junction of the Muasya and Kivuna, the Kinduu (which is what the stream is called now) is more than 20 meter wide. The thickness of the riverbed is hard to estimate but in many parts larger than 1.5 meter. About 100 meter downstream of the junction sand dam 14 and 15 are sited about 100 m apart. They are founded on rocks and mark the up and downstream of a short steeper section.



Figure A.45 Left: Riverbed upstream of sand dam 14; Right: riverbed between sand dam 15 and 16

The Kiindu, downstream of sand dam 15 till the junction with the Nduni tributary, is more stretched than the Kivuna. The riverbanks are often less than 1 meter above riverbed level and therefore considerably lower than in the Kivuna. About 600 meter downstream of sand dam 15, sand dam 16 is constructed on top of rock outcrops. After its break down, the sand dam 16 was repaired. According to local people downstream of sand dam 16, heavy floods have washed away large parts of fertile riverbanks. Therefore the riverbed changed its track and became much wider. Two examples are given in Figure A.46. Here the left riverbank formally followed the line indicated in the picture. Further downstream the stream becomes narrower again.



Figure A.46 Eroded riverbanks downstream of sand dam 16

Between 100 and 200 meter upstream of sand dam 18 both riverbanks are intensively irrigated and protected by Napier grass (see Figure A.47). In the vicinity of sand dam 18 only small plots are irrigated (see Figure A.47).



Figure A.47 Left: irrigated riverbank; Right: Riverbed upstream of sand dam 18

According to people the river changed its course downstream of sand dam 18. Areas next to the former riverbed dried up, while plots along the new river bed have now enough water for irrigation (see Figure A.48). In this area the river becomes narrower again (see Figure A.48). Around sand dam 19 only a few short sections of the riverbanks are protected by Napier grass. Upstream of sand dam 20 almost riverbanks are protected by Napier grass and the riverbed is blotched with private scoop holes.



Figure A.48 Riverbed scattered with scoop holes to supply the irrigated riverbanks upstream of sand dam 19 (left) and sand dam 20 (right)

Downstream of sand dam 20 there is a steep rocky section (see Figure A.49). The riverbed is now rocky and up to 60 meter wide. Downstream of this steep section the river forms a sandy river bed again (see Figure A.49). The river now is between 20 and 30 meter wide. The thickness of the riverbed is hard to estimate but can be considered that it is for large parts to be around 2 meter.



Figure A.49 Left: Steep rocky river section; Right: Riverbed upstream of sand dam 21

The riverbanks are exposed to heavy floods, which threatens the irrigated plots on the riverbanks. Just upstream of the broken sand dam 23, a large tributary enters the stream (see Figure A.50).



Figure A.50 Left: riverbed upstream of sand dam 23; Right: Large tributary just upstream of sand dam 23

Until the junction of the Kiindu with the Nduni the river stays about 30 -50 meter wide (see Figure A.51 left). Through the measurements conducted in this area, the thickness of the riverbed could be estimated more than two meters. Downstream of the junction the Kiindu becomes about 100 meter wide (see Figure A.51 right).



Figure A.51 Left: junction of the Nduni and Kiindu; Right: Kiindu downstream of junction with the Nduni

A.2.2.1.4 Nduni

The Nduni tributary was visited from the junction with the Kiindu in upstream direction. According to local people the downstream part of the Nduni is free of human interference. Therefore it can be considered as reference area for the natural state of the catchment. Only sand dam 29 further downstream may have influenced the stream. But there are no human activities along the downstream of the Nduni. Large trees and often dense vegetation protect the river banks against erosion. (see Figure A.52). Often the riverbanks are more than one or even two meter above bed level. The stream is about 30-40 meter wide and several tributaries enter the main stream.



Figure A.52 Left: Riverbed in the downstream part of the Nduni; Right: Tributary

Further upstream Sasol built four sand dams. Upstream of the sand dams, which are higher than the sand dams in the Kiindu, the channel is filled with sediments. Level differences between the riverbed and the riverbank become smaller (see Figure A.53) and increase again in upstream direction. According to the local people the Nduni could only be called a river after their construction of the sand dams. Originally it was a narrow streamlet with a thin riverbed.



Figure A.53 Riverbed downstream of sand dam 25

Along the river people dug scoop holes into the riverbed to fetch water. Despite their depth of sometimes almost 2.5 - 3 meters most of them were already dry at the time of the fieldtrip. Downstream of sand dam 25, there is only one scoop hole which is intensively used. Until the most upstream sand dam 26 and 27 the river stays between 5 and 10 meters wide.

A.2.2.1.5 Nzeeu: A reference case

I spend one day to visit the Nzeeu river, which is an alternative water source for the upper parts of the study area (see section A.2.3). In the inspected reach no sand dams are constructed. The local people here do not report about erosion of the riverbanks. In the Nzeeu river it is the riverbed that is washed away. People told me that 30 years ago the riverbed was mainly covered by sand. Only the tops of the rocks in the riverbed could be seen. Now the riverbed is about one meter lower than 30 years ago (see Figure A.54). People are uncertain, if the riverbed of the Nzeeu will supply enough water for the neighboring communities in the future.



Figure A.54 Left: Rocky riverbed of the Nzeeu river Right: Indication of the old riverbed level

The reason for the erosion of the riverbed in the Nzeeu catchment is as unclear as the erosion of the riverbanks in the Kiindu catchment. Possible explanations for the riverbed erosion are the construction of dams in the upstream and the massive extraction of sand near Kitui for construction purposes.

A.2.2.2 *Land cover: Vegetation and Land Use*

During the fieldtrip also the land cover was assessed. In the next paragraphs the land cover is described briefly. By assessing the vegetation it needs to be kept in mind that the fieldtrip took place in the middle of the five-six month lasting dry period. People report that vegetation flourish depending on the rainfall amounts during the rainy season and the point in time during the dry period. How fast the vegetation response to the rainfall and starts to flourish is shown in Borst et al. (2006).

A.2.2.2.1 **Kivuna**

The trans-sectional walks started in the vicinity of sand dam I. Here the slopes on the hilltops are mild and used for rain fed agriculture. Closer to the stream naturally dry vegetation dominates. (see Figure A.55). Between sand dam I and sand dam 4 the slopes along the river are steep and the vegetation is 'naturally green'. Large parts of the river in this section are overgrown by vegetation and the river is partly difficult to access from the riverbanks (see Figure A.55). Mulango, a small village with shops and bars is located east of the stream. Most people on the east side have some fruit trees in their gardens but do not do extensive agriculture. On the hill slopes on the western side people grow rain fed crops like beans and peas.



Figure A.55 Left: mild sloped landscape with sparse vegetation around sand dam I; Right: naturally green vegetation along the stream

Downstream of sand dam 4 the vegetation becomes less dense. The stream is not completely overshadowed by vegetation anymore. Rain fed agriculture is now applied on both sides of the stream. Since the slopes become milder the beans and pea fields reach further to the stream. According to the people, the vegetation became less dense during the last years. Some blame the poor rain of the last years for it, while others also mentioned that people cut more trees to make charcoal for burning bricks. Next to sand dam 6, about 100 meter uphill, a farmer irrigates his garden with water from his well.



Figure A.56 Left: rain fed agriculture: beans and papaya trees

The slopes along the steep river section downstream of sand dam 6 are covered by naturally drought resistant vegetation. Due to the deep slopes the area is not used for agriculture. Further downstream a small strip on the riverbanks is covered by trees and bushes. Behind this strip people use the land for rain fed agriculture and brick making.



Figure A.57 Left: Dry resistant vegetation on the steep river section; Right: brick making site on the riverbanks

A.2.2.2.2 Muasya

More or less parallel to the Kivuna, the Muasya stream flows in southwards direction. On the hills between the two streams the landscape varies between natural vegetation and rain fed agriculture (see Figure A.58 left). The land cover in general is the same as in the Kivuna catchment. More upstream there is also a strip of natural vegetation along the river (Figure A.58 right) while more downstream, people cleared these strips and sparsely do agriculture on small plots on the riverbanks.



Figure A.58 Left: rain fed agriculture between the Kivuna and Muasya stream; Right: Muasya stream



Figure A.59 left riverbank cleared from natural vegetation; Right: irrigated vegetables on the riverbank

A.2.2.2.3 Kiindu

Downstream of the junction of the Kivuna and the Muasya the strip of natural vegetation that covers the riverbanks in the Kivuna and Muasya disappears almost completely. The area upstream of the sand dams 14 and 15 are dominated by brick making sites. The trees on the riverbanks are cut for the production of charcoal (Figure A.60 right). On the hill slopes and the riverbanks the soil is bare and not protected against erosion (Figure A.60 left).



Figure A.60 Left: Riverbank unprotected against erosion; Right: Cut trees on the riverbanks

Around sand dam 14 and 15, there are some small plots, which are protected by Napier grass. Downstream of the sand dams the mild slopes of the hill slopes and the riverbanks are covered by small bushes. Goats graze on these sparsely vegetated riverbanks.(Figure A.61 right) At a distance from the stream the land cover varies from natural trees to rain fed agriculture(Figure A.61 left).



Figure A.61 Left: Varying vegetation of the riverbanks; Right: Goats grazing on sparsely vegetated riverbanks

Till sand dam 16 several short sections of the riverbank are protected by Napier grass against erosion. Only one farmer irrigates his plot on the riverbank. Next to sand dam 16 another farmer irrigates his vegetables. Downstream of sand dam 16 the vegetation consist of trees and bushes. The Napier grass which protects the riverbanks around sand dam 17 also serves as food for the cattle at the end of the dry season (Figure A.62 left). Further downstream the plots behind the protected riverbanks are irrigated with water from scoop holes in the riverbed (Figure A.62 right).



Figure A.62 Left Napier grass next to sand dam 17; Right: Napier grass protects irrigated plots on the riverbanks

However just next to this irrigated plots the hill slopes as well as the riverbanks are cleared again like in the vicinity of sand dam 18 (see Figure A.63 left). Between sand dam 18 and 19, where the river has changed its course, people irrigate the entire riverbanks with water from their private scoop holes (Figure A.63 right).



Figure A.63 Left: dry vegetation next to sand dam 18; Right: irrigated plots

While the area along the river is very green due to irrigation the hill slopes are rather bare. Also downstream of this section, the landscape becomes dry again except for a few irrigated plots on the riverbanks (Figure A.64 left). Upstream of sand dam 20 people irrigate the area intensively again. People even use donkeys to transport water from private scope holes to areas several meters uphill.



Figure A.64 Left: small irrigated plot between dry bushes; Right: Sand dam 20 with irrigated plots next to the papaya trees

The area downstream of sand dam 20 is sparsely populated. It is dominated by steep slopes which are covered by dry trees and bushes (Figure A.65 right). On the slopes in the steep section, the people dug terraces for rain fed agriculture (Figure A.65 left).



Figure A.65 Left: Terraces on the hill slopes; Right: Bushes on higher elevations

Further downstream in the area between sand dam 21 and the junction with the Nduni tributary the slopes become milder again. The drought resistant natural vegetation remains the dominant land cover (Figure A.66 left) but further up the hill rain fed crops like beans and peas are grown. Around sand dam 23 and the junction with the Nduni, few farmers irrigate vegetables on the riverbanks again (Figure A.66 right).



Figure A.66 Right: Bushes along the riverbed; Right: irrigated plots next to sand dams 23

A.2.2.2.4 Nduni

In the downstream the Nduni is not much influenced by human interaction. According to local people the area can be considered as reference of the natural state of the Kiindu catchment, even if the sand dams further downstream in the Kiindu have lead to a thicker riverbed. The downstream area of the Nduni is sparsely populated. There is no evidence that people abstract water from the riverbed or via shallow wells on the riverbanks. The riverbanks are mostly covered by the natural vegetation which protect them from erosion (Figure A.67 left). On the land between the Kiindu and the Nduni the land owner planted vegetation which prevents cattle of entering the land. Other human activity cannot be observed from the stream.



Figure A.67 Left: Trees between the Nduni and Kiindu stream; right: Roots protecting the riverbank against erosion

Upstream of the sand dams V and 24 the area becomes more populated. Further upstream the people start to do rain fed agriculture on the hill slopes. The private land along the river is protected with bushes and Napier grass (Figure A.68). In addition to rain fed crops several people planted mango trees especially in the area around sand dam 25 (Figure A.68).



Figure A.68 Left: Protected riverbank; Right: big mango trees next to sand dam 25

Further upstream, the area around the sand dam 27 and 28 is dry again and is covered by the original vegetation.



Figure A.69 Dry vegetation

A.2.3 Water Sources

The amount of water used depends on the purpose and the location of the water source. During the interviews it became apparent that in several areas people had water sources with different water qualities, alternative to the Kiindu catchment. Water quality also varies within the catchment and influences the purpose of the water.

People throughout the catchment report that the amount of water available is dependent on the amount of rainfall. In years with high precipitation rates, people can fetch sufficient water from scoop holes and wells throughout the year. In dry years scoop holes and wells are exhausted during the dry season and people have to get water from alternative water sources. Simultaneously the vegetation stays longer green in wet years. Figure A.70 shows the different water sources and their water qualities according to local people.

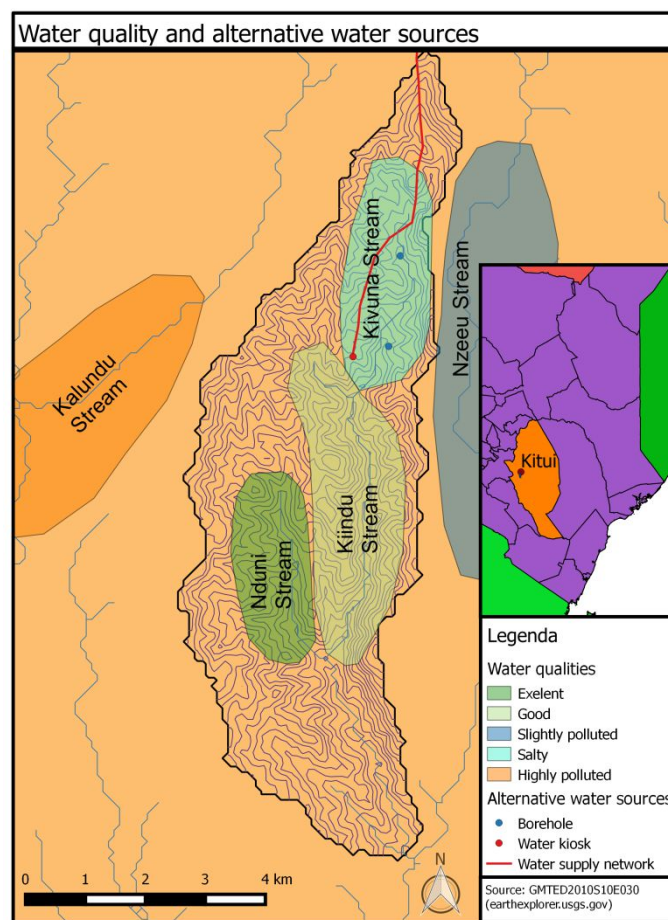


Figure A.70 Water sources with different water qualities

A.2.3.1 Shallow aquifers

In the **Kivuna** catchment the water is considered to be salty. The origin of the salt is saline rock (Borst et al., 2006) in the Kivuna catchment, which is found in many areas in Kitui county. Therefore the use of water for domestic use and agriculture is limited. People use it mainly for watering goats and donkeys or for making bricks. Whether the water is suitable for irrigation is considered controversial in the community. For domestic use the people in this area prefer water from the water supply network of Kitui and the Nzeeu catchment.

The **Nzeeu river** lies east of the Kiindu catchment and is an alternative water source for people especially in the Kivuna catchment. To get water from the Nzeeu catchment it takes 1 to 2 hours, depending on the location of their homestead. The water of the Nzeeu is slightly polluted with

drainage water from Kitui town. Nevertheless people consider it suitable for all purposes and prefer it over the salty water from the Kivuna.

The quality of the water from **Muasya** tributary, the **Nduni** tributary and the section of the **upper Kiindu** is considered good. People use it for all purposes. According to the people in the Nduni catchment, the quality of the water in the Nduni is the best in the whole area.

The **Kalundu** river in the west of the Kiindu catchment is an alternative water source for the people in the dry Nduni area. The Kalundu is the main recipient of the drainage water from Kitui town. Therefore the water is highly polluted with wastewater and of poor quality. People claim that they become sick if they have to drink it without cooking it beforehand. However in extreme dry periods they depend on it, due to a lack of alternatives.

A.2.3.2 *Deeper aquifers*

There are no comprehensive studies about the deeper aquifer in Kitui county available. Nevertheless boreholes are drilled deep into the ground and supply communities in the county. In the study area there are already two boreholes. Another is under construction. These boreholes are a potential alternative to the water from shallow aquifers. Many people see them as *the* opportunity to ensure their water supply in the future, even when the experiences with the existing boreholes are ambivalent.

Borehole next to Mulango: The destruction of assets

The first borehole was drilled next to Mulango in the nineteen fifties by missionaries under the colonial power to supply the secondary school in Mulango with water. The water from the borehole is salty like the water in the river at this location. But it was still suitable for use at school. About 10 years ago another borehole was drilled in the Nzeeu catchment closer to the secondary school. The pump and all other equipment was removed from the old borehole. The ownership of the borehole after removing the pump was not clear (at least nobody I spoke to knew it exactly). The attempt of two neighbors to cover the borehole and to conserve the borehole for the future failed. Other members of the community removed the cover, because they feared, the borehole would be claimed by these individuals. Now the borehole is filled up with stones which children have thrown into the pipe. According to one of the neighbors, now, cleaning the borehole is more expensive than drilling another one. (This history of the borehole next to Mulango was reported by Mr. Mutua during an interview on Tuesday 6 August 2014.)



Figure A.71 Borehole next to Mulango

Borehole next to sand dam 7: The challenge of cooperation

The second borehole is located next to sand dam 7, south of Mulango. The people in the area report the history of this borehole differently. Below the history of the borehole is depicted according to reports of most interviewees. However individual reports of interviewees differ in some details. Therefore the history below does not depicture the true and objective history of the borehole.

The borehole was drilled around 2006 under the initiative of a former Minister of the national government, who came from Kitui. The planning and the construction was done without involving the local communities. After completion the installation was handed over to the local community. The community founded a committee for the operation of the borehole. In the first years the borehole supplied the households in the surroundings with water of a good quality.



Figure A.72 left: Pumping Station Right: Storage tank on top of a hill

The problems started with irregularities in the book keeping, with the consequence that the diesel fuel for the pump could not be paid anymore. Also people started to withdraw water illegally and damaged the network. Therefore the service stopped and negotiation about the further operation of the borehole started. During the time of no operation people (most people point at the youth in the community) dismantled the pipe network and sold it. The community was not able to repair the network and therefore the water supply has stopped until now.

Recently 4 families from neighboring communities restored the pipe which connects the pumping station with the tank on top of the hill (see Figure A.72). Furthermore they connected their households with the storage tank. This initiative was done without the involvement of the community. Therefore the kiosk where water was sold to the community is not connected. At the moment there is a discussion on how to continue. The families which restored the network want to pump water to their homesteads as soon as possible. Most community members argue that first the whole network needs to be restored, so that it is guaranteed that the whole community benefits from the borehole. How to finance the repair is unclear, so is how the borehole will be operated and maintained afterwards. Because of the experience of the last years the community distrusts the investors while the investing families do not consider the community as capable of operating and maintaining the borehole. Therefore people do not expect a satisfactory solution in the short run.

A.2.3.3 *Water supply network*

Parts of the catchment are connected to the water supply network of Kitui, which receives its water from Masinga Dam. The water is of good quality and can be used for every purpose. Some households next to the center of Mulango are directly connected to the network. People in the rural area can buy it at a primary school for 5 KSH per jerrycan of 20 liters. According to the people it is not

reliable. Often no water is delivered for a couple of days. Furthermore they reported that it is prohibited to use it for irrigation.

A.2.3.4 *Roof water harvesting*

Roof water harvesting becomes more and more common in the area. Especially in the more developed areas, which are better connected to the road network, many houses are equipped with tanks, in which the collected rain water from the roof is stored.



Figure A.73 Roof water harvest tank

A.2.4 *Water use*

Sand dam are intended to increase the available water for the communities during the dry season. After satisfaction of the domestic water demand, water is also used as basis for other economic activities, mainly agriculture and brick making in the Kiindu catchment. The different techniques to abstract water from the shallow aquifer which are described in section A.2.4.1. The purposes are described in chapter A.2.4.2.

A.2.4.1 *Water abstraction*

Next to some properties of the catchment like the water quality and the location of the different water sources, the facilities to fetch water within the Kiindu catchment determine the amount and the purpose of abstracted water. The facilities can be categorized into shallow wells which are between 20 and 50 feet deep and scoop holes which are up to 2 meter deep pits that are dug in the riverbed. Both facilities can be distinguished further into public and private.

A.2.4.1.1 *Public shallow wells*

To simplify the abstraction of water Sasol builds shallow wells equipped with a hand pump on the riverbank upstream of the sand dams. After construction both the wells and the dams are handed over to the community involved in the construction. In theory both structures, dams and wells, need to be maintained by the community. During the fieldtrip the wells were inspected and major problems were discovered.

- **Broken wells:** Only halve of the wells were found. Most of these wells were broken or filled up with sediments, so that people cannot extract water from them anymore.
- **Broken pumps:** If the wells still contained water, in almost all cases the pump was broken. Since the water levels in the wells are often several meters below surface, getting water by pulling a bucket of water several meters becomes an exhausting exercise.
- **Public wells on private property:** Often the most appropriate locations for the wells are on private ground. Before the construction agreements are made about the usage of the wells. However these agreements do not hold in every case so that the former public wells merged into private property.

The inventory of the public shallow wells is summarized in Table 1 .

A.2.4.1.2 Private shallow wells

In the last decades private shallow wells became more popular. Especially in the upper parts of the catchment, where the stream is rather narrow and the riverbed thin, people dig their own private wells. Most of these private wells are about 20 feet deep. But several shallow wells are up to 40 to 50 feet deep. The usage of these wells ranges from highly intensive, when water is used to irrigate whole plots, to sporadic when the owner of the well has developed other sources of water and/or income. In some cases the wells may also be used by neighbors. Some well owners also sell water to other members of the community, when water becomes scarce.

The main advantages of the private wells are the clear property rights and the short distance to the location where the water is used. The biggest obstacles for the people to dig their own shallow wells are the high effort or the high costs if one is forced to hire somebody. Another main difficulty is the uncertainty where digging of a well is successful. Some people already tried to dig wells at several locations without success. In the interviews several people claimed that if there would be a guarantee that they would find water at a depth of about 20 feet, they would dig their own wells.

A.2.4.1.3 Scoop holes

Traditionally the people dig scoop holes in the riverbed until groundwater is reached and fetch water manually from these holes. This technique is still widely used when public wells are broken or people are prohibited to use them. In several areas the distance between the wells and their homestead is very large, so that people prefer to fetch water from nearer scoop holes. Another advantage of the scoop holes is that it is easier. Pulling up buckets a couple of meters at wells without function pump is too hard for some people (especially children).



Figure A.74 Public scoop hole

In the upstream parts most of the scoop holes are public and everybody can use them to fetch water or to water goats and cows. In the downstream parts (especially from the junction Kivuna/Muasya downwards), scoop holes become more applied. Here often different scoop holes are used for different purposes. Scoop holes for domestic use are in general public, while scoop holes for watering goats and cattle and irrigation are often private. These private scoop holes are protected by a fence of thorny branches which are put into the sand.



Figure A.75 Private scoop hole next to irrigated plot protected by thorny branches

A.2.4.2 Purposes

A.2.4.2.1 Domestic water use

The sand dams are intended to ensure the domestic water supply in the first place and to reduce the effort necessary to satisfy the domestic water demand. Sasol aims to reduce the walking distance to the water source. The water used for domestic purposes varies by 40 and 100 liters per household. It is highly dependent on the distance to the water source and the possibilities to transport the water. People who have to carry the water by themselves generally go twice to the water source to fetch 20 liters per time. People who make use of a donkey to carry the water generally go one time and fetch 5 jerrycans of 20 liters per jerrycan. Several families have alternative water sources (see section A.2.3), like roof water harvest tanks, private shallow wells or access to the water supply network of Kitui.

A.2.4.2.2 Agricultural water use

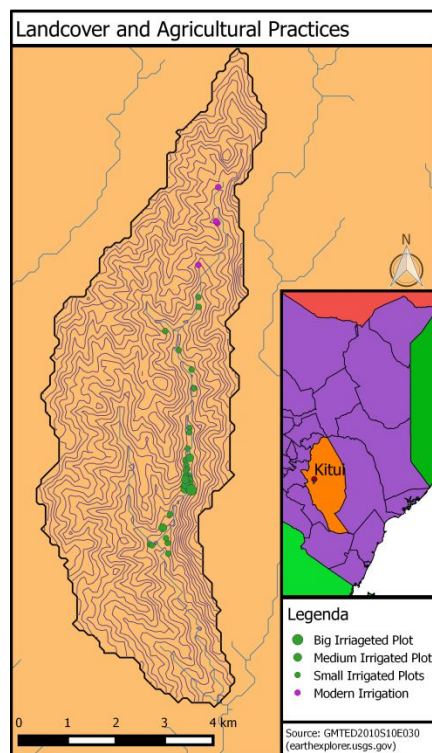


Figure A.76 Location of irrigated fields found during the fieldtrip

A.2.4.2.2.1 Traditional irrigation

The common grown crops are peas and beans which do not need irrigation. Apart from common agricultural praxis of growing rain fed crops, several people apply irrigation to grow vegetables. Most farmers who irrigate use buckets to fetch water from scoop holes and pour it in depressions next to the vegetables.



Figure A.77 Traditional irrigated vegetables

The location of the irrigated plots are indicated in Figure A.76 .

A.2.4.2.2.2 'New' irrigation techniques

Next to simple bucked irrigation some farmers, especially in the Kivuna catchment, where less water is available in the riverbed, have developed alternative irrigation methods on a bigger scale. Below four farmers and their approaches are described.

1. Drip irrigation by gravity

In the Kivuna catchment upstream of sand dam 3, Mr. Muthoka is pumping water from his well next to the stream to a tank next to his house uphill. He installed a pipe network over his whole plot to apply drip irrigation by gravity on his fields. In total he has 6 fields. Each field is divided into two subplots that are 10 broad and 30 meter long. During the fieldtrip he irrigated 2 of these plot. But he plans to irrigate all plots, which are in total 3600 m² in the future.



Figure A.78 Mr. Muthoka next to his tank (left) to irrigated his fields (right)

2. Greenhouse and Fishpond supplied by multiple wells

Next to sand dam 4 his brother Mr. Muimi invests in wells. He plans to irrigate his land after his retirement. At the moment he has two wells. One is used to pump water into a tank next to his house to supply his greenhouse with water. The diameter of the other well is too small to efficiently

pump water. Therefore people use buckets to pull water to the surface for domestic use. Now he is investing in a well with a diameter of about 5 meter which will be 58 feet deep. In the end when all wells are constructed at the calculated depth he will be able to pump approximately 78 drums (7800l) every three hour. With this well he plans to irrigate the rest of his plot. Next to agriculture he experiments with a fishpond as an alternative business.



Figure A.79 Greenhouse and Fishpond supplied by water from shallow wells

3. Irrigation by perforated bottles and harvesting surface runoff

His neighbor Mr. Mutua also has a private well, but it dries out early in the dry season since sand dam 4 failed. Therefore he lacks the water to irrigate the vegetables in his greenhouse. However he is not dependent on income from agriculture. He tries alternative measures to increase agricultural production. During the fieldtrip he started to place plastic bottles with perforated bottom into the soil next to passion fruit and papaya trees. To irrigate the trees he fills the bottles, so that water flows slowly out of the bottle and infiltrates into the root zone. Apart from the water saved, due to the decreased soil evaporation, a mayor advantage is that the chicken do not scratch the ground anymore and disturb the soil in the rooting zone. After a couple of weeks I visited him again to see if he succeeded. The plants, which had this drip irrigation, had considerable more new leaves than the ones without bottle.

To increase the water available for irrigating the trees and his vegetables in his greenhouse he tries to harvest the overland flow during the rainy season. He calculated that he would need 120 m³ to irrigate his vegetables. Therefore he started to dig a 10m x 4m large and 3 meter deep pit downhill. Afterwards he wants to put foil of a fish pond in it, to prevent infiltration. Probably he will also cover the pit against evaporation. To fill this pit he already build small dikes to guide the overland flow from his land into the pit (see Figure A.80).



Figure A.80 Left: Bottle drip irrigation; Right: Earthwork to guide overland flow towards a collection pit

4. Irrigation by gravity with a garden hose

Next to sand dam 6, Mr. Wambua invests money he earns in Nairobi in a well next to his house. He equipped the well with a pump and pumps once a week about 7m³ to a tank next to his house. From this tank his family, who takes care of the garden, irrigates vegetables and fruit trees with a garden hose. In the future he wants to extent the irrigated field and probably also construct a fishpond.



Figure A.81 Water tank (left) to irrigate vegetables by gravity with a garden hose (right)

A.2.4.2.3 Brick making

Throughout the catchment people make bricks to build new or extent old houses. Brick making is also an opportunity to generate income. For making bricks the dry soil needs to be mixed with water until the soil becomes soft. Then the soft soil is pushed into a standard form. The wet brick is removed from the form and laid in the sun to dry (Figure A.82). After drying the brick is stapled and burned (Figure A.82).



Figure A.82 Brick making site. Bricks drying (left); preparation for burning the brick (right)

From one jerrycan (20 liters of water) about 6 bricks can be made. In contrast to agricultural water use, water needs to be available for the period of brick making only. Also the water quality is considered less important than for agricultural purpose.

A major problem with making bricks is that the vegetation of the location of brick making is cleared and the soil is left behind unprotected against erosion (see Figure A.83 left). Another point of concern is that large amounts of charcoal are needed to burn the bricks. Areas where bricks are made are therefore often have fewer trees and soil erosion in these areas is stronger(see Figure A.83 right).



Figure A.83 Left: Brick making site cleared from natural vegetation; Right: cut trees for charcoal production

A.2.5 Population development and human action

Till now the physical properties of the catchment and the way people exploit the natural resources are described. However the developments within the catchment are also driven by larger scale development, like technological change and population growth. In this study these development cannot be assessed comprehensively. Nevertheless during the fieldtrip some of these developments could be observed.

A.2.5.1 Human resources

In 1999 the population growth rate in Kitui, according to Sasol et al. (1999) was about 3% per annum. Detailed data about population growth in the study area over the last two decades was not acquired in this study, but the community elders report that the number of people in their communities steadily grow. In the last two decades not only the number of inhabitants has increased but also communities and individual people who live in the catchment developed. This aspects were initially not the focus of the study. However the three aspects below appeared during the interviews several times.

A.2.5.1.1 Generational change

Therefore people who participated in the construction of the sand dams were mostly women that are aged now. Most people interviewed cannot remember the time before the sand dams were constructed. The interviewees were either children, or women who married men from the catchment. Therefore the context and the knowledge taught by Sasol during trainings are often not known by the generation which farm the catchment now.

A.2.5.1.2 Education

In 2012 the campus of the Kenya water institute in Kitui was opened. The institute offers courses in water technology and resource management to the public. Several people I met during the fieldtrip study at the Kenya Water Institute in Kitui. They come into contact with new agricultural and irrigation technologies and plan to apply them on their plots.

A.2.5.1.3 Experience

Also the men who returned from Nairobi and Mombasa come back after their retirement with knowledge about new technologies and probably capital to invest trigger the application of new technologies.

A.2.5.2 Transportation and telecommunications

Another 'external' development that will have influenced the development in the catchment is the improved transport to Kitui and new telecommunication technologies.

The connection of the catchment to Kitui through public and private transport improved drastically. Mr. Musyimi reported that even ten years ago there were only few cars and no boda-bodas, (local

motorbike taxis) in Kitui. Today businessmen have cars or motorbikes and boda-bodas can be found on every crossroad in Kitui. Even in Mulango often one or two motorbikes are available. The improved transport not only gives the opportunity to bring the crops to the market and earn money but also makes it easier to maintain business relations. These business also can be more easily maintained by ICT and mobile phones.

A.2.5.3 *Cooperation and initiatives*

The assessment of cooperation and (private) initiatives of the community members were not the focus of the study. However since (according the interviewees) the sand dam committees disappeared shortly after finishing the construction, the water resources in the catchment need to be utilized by private initiatives and cooperation. As described by Sasol (1999) it is important to involve the people in development projects, support them by defining the most urgent problems and find their own solutions. Further it is assessed what the obstacles for the people are to come into action and implement their ideas.

The answers given in the interviews are personal experiences of individuals and not representative for entire communities. Therefore some general comments that were often mentioned during the interviews will be repeated. Furthermore the utilization of water and the effort to maintain structures through private initiative or cooperation is shown in examples.

A.2.5.3.1 Private initiative

The majority of the interviewees do not think that they can improve their water supply by themselves. Several interviewees claim that they need help from outside to make progress in developing the local water resources. Most interviewed people claim that they are ready to participate, if the government, NGOs or donors would take the initiative. A quote often heard was; 'waiting for donors became a culture'. Some participants argued that the people have not the confidence to *be able* to improve their situation themselves. Several people that are better off thinking that the cause of the passiveness is reluctance.

There are however people that take the initiative by themselves. These initiative are highly divers. They range from repairing damaged or broken dams, building new sand dams in smaller tributaries, digging shallow wells, investment in pumps, development of irrigated agriculture, planting trees and experimenting in water saving techniques in agriculture (see section A.2.4.2).

A.2.5.3.2 Cooperation

During the interviews the people described their experience with cooperation within the communities. Within the local villages members form groups that start small projects. The degree of activities of the groups are divers. Some groups are a solidly collective which support each other with labor and money in difficult times. Other groups start to grow crops together or make baskets to gain income to pay the school fee for the children. A few groups maintain tracks in the villages. These activities are considered helpful and may create a form solidarity amongst them. However most interviewees consider the villages and local groups as not to be capable to improve the water supply of the communities.



Figure A.84 Left: Dress of a self help group; Right: Baskets produced by a group to generate income

A.2.5.3.3 Examples of private initiatives and the difficulties of cooperation

Below there are some examples of people that took the initiative and the difficulties of cooperation. The examples are based on the stories told during the interviews. The correctness and integrity of the examples could not be double-checked.

Example 1: The repair of sand dam 3

Mr. Muthoka, a retired teacher told me his story, how sand dam 3 was repaired. He owns a butchery in Mulango and his wife has a small business in Kitui, which makes them less dependent on agriculture. Aside from these activities he is busy to prepare irrigated agriculture on his plot in the vicinity of Mulango. For this purpose he invested in a well next to river, built a tank next to his house and brought a pump which pumps water from the well into the tank. A pipe network is already installed which connects the different sections of his plots with the tank. (see also A.2.4.2) When sand dam 3 downstream of his plot broke, the water table in his well dropped considerably. Therefore the well could not provide sufficient water to irrigate his plots any longer. Therefore he tried to mobilize the community to take action in order to repair the sand dam. This initiative failed because of the reluctance of the community. Finally the sand dam was repaired with the support of Sasol on his expense. He had to pay for the rocks and the labor which according to the policy of Sasol needed to be contributed by the community.

Now he takes the responsibility to take care of the dam. According to him, this story is typically for the ability to cooperate within the community. He reported on two other examples. Apart from the sand dam he also has to maintain the road next to his fields, which is also used by the community. And when Mulango was connected to the water supply network, only few people participated, so that now only few households are connected to the network.

Example 2: The maintenance of a shallow well I

A village elder told me the story about a well in the area around sand dam 14, built by Sasol. Sediments and breaches entered the shallow well and the pump broke. After a couple of years, Sasol came back to evaluate the activities in the area. They found the well in bad condition and asked the local community to remove the sediments and branches from the well and promised to deepen the well and equip it again with a pump. Every household of the community was asked to provide labor in order to clean the well. The families sent their children to clean the well, for whom the work was too hard. When Sasol came to deepen the well and to equip it with a pump they found the well still filled with sediments and left the area without restoring it.

Example 3: The maintenance of a shallow well II

At sand dam 22 people told me the story about a public well next to the sand dam, which supplied the local community with water. The well was constructed on private property. The owner of the plot was the one who benefited most of the well. He irrigated the riverbanks next to the well and therefore also maintained it. During a severe flood the plot was washed away and the owner gave up irrigating his plot. Therefore he stopped to maintain the well. It was now up to the local community to maintain the well. But they failed to maintain the well so that now they rely on the water from scoop holes next to the sand dam again.

Example 4: The maintenance of a sand dam

During a severe flood in 2009, sand dam 23 was damaged and it was obvious to the local people that the sand dam would fail in the following years. Mr. Mutunga told me how he tried to mobilize the young people of the community to collect rocks. During the first day they collected stones and stapled them next to the sand dam. The next day no one showed up and the initiative ended. Mr. Mutunga returned to Nairobi for work and during the next year the collected stones were washed away. Another year later, the sand dam finally failed.

Example 5: Restoring a sand dam

In the Nduni catchment upstream of sand dam 25, people which were waiting for their turn to pump water told me the story about the construction of the well and why it delivers only two jerry cans per hour now.

Donors sponsored a well equipped with a hand pump to the local community. They provided all materials and paid the community members who built the well. Because the time was too short, the well could not be deepened to the required depth of about 20 feet. After 12 feet they had to stop and they constructed the walls and covered the well. The donors left the materials and the instruction how to deepen the well to the community. Today, after two years, the wells is still 12 feet deep. At the day of the visit the well delivered about two jerrycans every hour, so that the people had to wait for several hours in a queue. People regularly go home without having been served. Nevertheless no one takes the initiative to deepen the well and to improve the water supply for the whole community. At least the community maintains the well and people have to pay 200KSH per year if they want to use the well.

The potential of the well can be estimated using the example 100m further downstream. Here a woman has invested in a well with a diameter of about 2 meters and a depth of about 30 feet. The owner of the well sells water to people from a larger area to a price of 5 KSH per jerry can. The well delivers water continuously. The income of the owner is up to 1000 KSH per day. Thus 200 jerrycans can be withdrawn from the well per day even in dry times.

B. Concepts of the semi-structured interviews

B.1 Initial concept of the semi-structured interviews

Evaluation form for semi-structured interviews	
General	
Date	
Number	
Community	
Number of households	
Number of community members	
Dam used as water source (general)	
Family data	
Name of the family	
Number of family members	
Location of their house	
Main source of income	
Domestic water use	
Location of drinking water source	
Amount of water used for domestic purposes	
Agricultural water use	
Sort of crop	
Period of growth	
Water use in irrigation	
Location of their fields	
Location of the water source	
Transport of water	
Livestock	
number of cattle	
Number of goats	
Location of the water place	
Brick production	
Amount of bricks produced	
Location of brick production	
Location of water source	
General comments on water use	
Comments on personal changes (change of: location of water source, agricultural practice, family and welfare)	
Comments on the observed changes in the landscape: (changes of: vegetation Water availability, mosquito's)	
Comment on future plans	

B.2 Revised concept of the semi-structured interviews

General Data	Dam	Community	Name	Phone	Children	Income	Age	Per./HH	Loc. of HH
Water Use	Agric.	Size of Field	Irrigation	Bricks	Goats	Cows	hens	donkey	
Crops	Maize	Beans	Peas	Pigeon peas	Cow peas	Green gr.	Veg.	Banana	Mangos
Water source	Amount	type	transp. by	Effort					
Organization of the community	?								
Opinion/experience with Sand Dams									
Changes in community									
Changes in landscape									
Suggestion for the improvement of water supply									
Thing that needs to be improved most urgently									
Plans for the future									
Others									

C. Measurements

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C.1 Introduction

During the fieldtrip the hydrological conductivity of different water bearing layers was measured, because is an important parameter in the groundwater model. The conductivities of the coarse sand of the riverbed and clayey/loamy soils of the fields were determined with double ring infiltration tests. The conductivity of the soil under the riverbanks below the water tables were determined with the Auger Hole method. The conductivity of the weathered rock was determined by slug tests in private shallow wells. The methods as well as practical considerations are described in the corresponding chapters. The location of the measurement sites in indicated in Figure C.1.

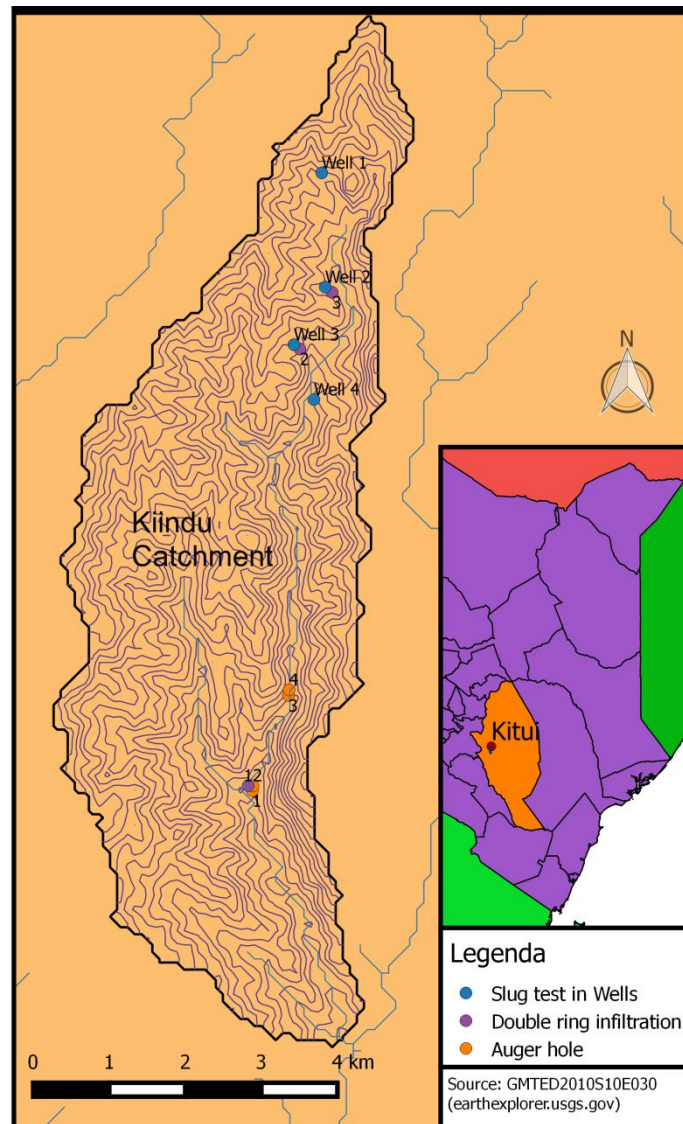


Figure C.1 Measurement locations

C.2 Auger Hole method

The Auger hole method was conducted according the procedure described by Van Beers (1983). With the Auger hole method the hydraulic conductivity can be simple and rapidly determined. This method consists of three steps plus the determination of the hydraulic conductivity.

1. Drilling of the hole

According to Van Beers (1983) 60-70cm below the water table is a practical drilling depth if the soil is homogeneous.

2. Removal of the water from the hole

Secondly the groundwater needs to be removed from the hole so that the water table declines between 20 and 40 cm. Van Beers suggested a bailer to remove the water as fast as possible. Due to practical reasons an open cup on a stick was used.

3. Measurement of the rate of rise.

Directly after the removal of the water the measurements starts. In regular time steps the water level in the hole is recorded with a diver.



Figure C.2 Execution steps of the Auger hole method

C.2.1 Determination of the hydraulic conductivity

The hydraulic conductivity is determined with formula (1) according to the procedure described in Van Beers (1983).

$$K = \frac{4000 r^2}{(H + 20r) \left(2 - \frac{y}{H}\right) y} \frac{\Delta y}{\Delta t}$$

K = hydraulic conductivity

H = depth of hole below the groundwater table.

y = distance between groundwater level and the average level of the water in the hole for the time interval Δt .

r = radius of the auger-hole

S = depth of the impermeable layer below the bottom of the hole.

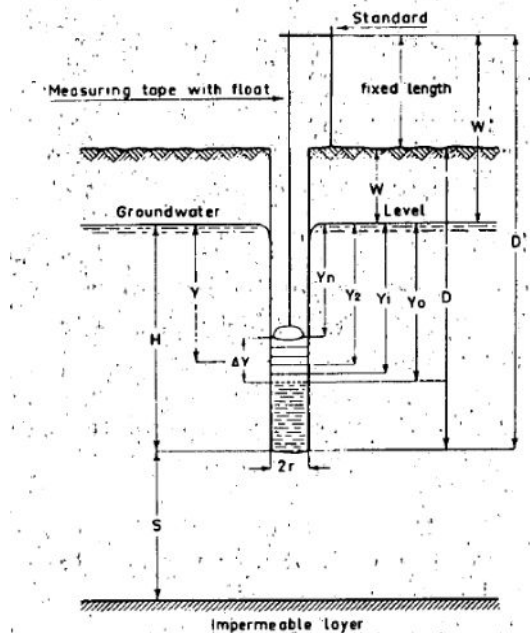


Figure C.3 Measurement settings according to the auger hole method (source: Van Beers, 1983)

According to Van Beers (1983) the maximum error is 20% if the following conditions are met:

- $5 \text{ cm} < r < 7 \text{ cm}$
- $20 \text{ cm} < H < 200 \text{ cm}$
- $y > 0.2 H$
- $S > H$

C.2.2 Site and site selection

Based on practical considerations the criteria for the selection of the measurement sites were

- High groundwater tables.
- Stable soil
- Permission of the land owner

Four suitable sites were selected.

Site 1

The first site is located downstream of sand dam 23 on the riverbanks on a formally irrigated plot. In order to be able to drill a borehole, first a 1.6 m deep pit had to be dug. At the bottom of the pit the borehole was drilled. Because of the sandy soil the borehole had to be stabilized by a perforated pipe to prevent the collapse of the borehole. The measurement was 4 times repeated in the same borehole.

Site 2

The second site is located 150 m further upstream of the first site. Here floods in the last years have eroded the riverbank so that it had the same elevation as the riverbed. Since the water table was lower than expected also here first a 1.8 m deep pit had to be dug. And the borehole which was drilled in the bottom also had to be stabilized with by the perforated pipe. The measurements was three times repeated.

Site 3 and 4

The third and fourth site is located upstream of sand dam 20. Here we found two private scoop-holes in the riverbed. At this location the water table lay in a sandy clay soil below the riverbed. Direct next to the water surface, a small flat area was carved to reach the water and fetch it. The owner of the scoop holes allowed us to drill a bore hole and to do our measurements. Also these boreholes needed to be stabilized by the perforated pipe. In total we conducted 6 measurements; 3 in the first and 3 in the second scoop hole. Only during three of the six measurements the divers recorded a recovery curve. During the other measurements the pressure fluctuated and became constant afterwards.



Figure C.4 Measurement site 1 (left) and site 3 (right)

C.2.3 Practical considerations

During the execution of the measurements we faced several difficulties that influenced and likely reduce the accuracy of the measurement.

- The depth of the impermeable layer S could not be determined.
- The auger-hole was not stable and needed to be stabilized with a perforated pipe.
- The water could not be withdrawn as fast as described by Van Beers.
- The water table recovered that fast that in several cases the water level could not lowered sufficiently to meet the requirement $\gamma > 0.2H$.
- The chosen measuring interval of the diver was too long at the first two sites to conduct a reliable measurement
- The boreholes were placed next to a scoop holes at the third and fourth site.

C.2.4 Results

Site 1

At the first site the measurement was repeated 4 times. The recovery curve of the measurements are presented below. The calculated hydraulic conductivities ranges between 3 and 23 m/d. The hydraulic conductivities for the single measurements are presented in table below .

Site 2

At the second site the measurement was repeated 3 times. The recovery curve of the measurements are presented below. The calculated hydraulic conductivities ranges between 4 and 24 m/d. The hydraulic conductivities for the single measurements are presented in the table below.

Site 3

At the third site the measurement was repeated 3 times. Two times the measurements failed. The recovery curve of the successful measurement is 24 m/d.

Site 4

At the fourth site the measurement was repeated 3 times. The first measurement failed. The recovery curve of the second and third measurement is presented in the Appendix D. The calculated hydraulic conductivities are 23 and 33 m/d.

Table 1 Results of the Auger hole method

site	measurement	conductivity m/d
1	1	8
1	2	3
1	3	6
1	4	23
2	1	4
2	2	24
2	3	13
3	1	failed
3	2	failed
3	3	24
4	1	failed
4	2	23
4	3	33

C.3 Slug test

The hydraulic conductivity of the weathered rock layer is determined with the slug test. The measurement is similar to the measurement conducted with the Auger hole method. In contrast to the Auger hole method, the measurements were conducted in shallow wells and not in drilled boreholes. For the measurements water from these wells is abstracted by hand (in the case of well 1 and 4) or by a pump (in the case of well 2 and 3). Afterwards a diver measures the water levels in the wells every 30 seconds. In addition to the slug test the measurement is also evaluated according to the Auger hole method described above.

C.3.1 Determination of the hydraulic conductivity

According to the slug test the hydraulic conductivity can be determined via the equation:

$$K = \frac{r_c^2 \ln\left(\frac{R_e}{r_w}\right)}{2L} \frac{1}{t} \ln \frac{y_0}{y_t} \quad (1)$$

- K = hydraulic conductivity
- L = Height of the portion of the well through which water enters
- y = distance between groundwater level and the average level of the water in the hole for the time interval Δt .
- r_c = radius of the well
- r_w = horizontal distance from well center to original aquifer
- R_e = effective radius over which y is dissipated.

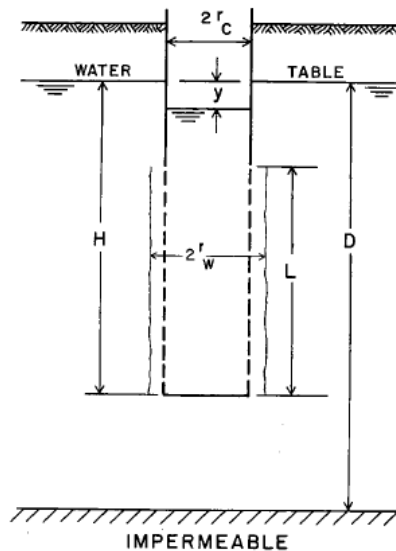


Figure C.5 Geometry and Symbols used to evaluate slug test (source Brouwer et al., 1976)

Assumptions:

Because the method is developed for boreholes and not all the necessary parameters in the equation could be determined several assumptions had to be made

- The well is permeable over the whole height below the water groundwater table. ($L=H$)
- There are no gravel envelopes or developed zones that are higher permeable around the wells ($r_w = r_c$).
- The thickness of the aquifer is equal to the two times the depth of the well below the water table. ($D=2H$)
- The term $\ln(R_e/r_w)$ is determined according the procedure described by Bouwer et all (1974)

C.3.2 Site and site selection

For the measurements I made appointments with owners of shallow wells in the morning before they wanted to extract water from their well. Before the extraction a diver was installed in the well. This diver were left in the well for about 24 hours to measure the recovery of the water table every 30 seconds. The farmers told me that there was no intensive use of the well the day before and that, at least for the rest of the day, no water will be extracted from the well, so that the measurement will not be disturbed. To be able to compensate for atmospheric pressure variations, a second diver was placed in the houses of the well owner.

During the field trip four wells in the Kivuna catchment (where shallow wells are more often applied) could be identified. In two cases the water was removed by hand through pulling buckets out of the well. In the other two cases the water was pumped out of the well.



Figure C.6 Water abstraction by hand (left) and by pump (right)

C.3.3 Practical considerations

During the measurements there are some aspects that may decrease the accuracy of the determined hydraulic conductivity.

- **Local conditions.** Most owners of private shallow wells claim that there are water veins in the rock. If this is true, the hydraulic conductivity may vary considerably throughout the area. Furthermore the thickness of the aquifer is not known.
- **Well dimensions.** The dimensions of the wells are not regular. They are only roughly round and the bottom is not totally flat. The dimensions used are thus only the best estimates.
- **Water abstraction.** In two of the four measurements the water had to be abstracted by hand. Therefore the water level was lowered slowly and only a couple of centimeters, which is very little compared to the diameter of the well.
- **Interference.** The measurement took about one day. Therefore the diver was left in the well. For the wells 3 and 4 it cannot be guaranteed that other people abstracted water during the measurement.

C.3.4 Result

The determined hydraulic conductivities of the weathered rock layer, based on the recovery of the water tables in the wells are given in below. Because the y-t relationship does not follow a straight line for well 1 and 3, when the y-axis is plotted on a logarithmic scale all measurements are also evaluated according to the Auger hole method. It needs to be remarked that the Auger hole method is most appropriate for boreholes with much smaller diameters.

Table 2 Hydraulic conductivities of the weathered rock

Well No.	Conductivity (m/d)	
	Auger hole method	Sludge test
1	0,08	-
2	0,21	0,12
3	0,04	0,52
4	0,27	0,11

C.4 Double Ring infiltration test

A standard method to measure the infiltration rate is the double ring infiltration test. For this test two rings of different sizes need to be penetrated about 2 cm into the soil. After filling the rings the drop of the water surface in the inner ring is measured in regular time intervals. There are two things that need to be maintained during the measurement.

- To ensure vertical infiltration, the water level should be as low as possible but the rings should never get dry. Thus the rings need to be refilled after a certain time.
- The water level of inner and outer ring need to be kept at a similar level to ensure that the water of the inner ring will infiltrate as vertical as possible.

C.4.1 Determination of the nearly saturated vertical hydraulic conductivity

With a double ring infiltrometer the infiltration rate in millimeter per second is. Over time the infiltration rate decreases until it becomes constant due to the saturation of the soil. The measurement ends when the infiltration rate becomes constant. This constant infiltration rate is also called the vertical nearly saturated hydraulic conductivity (mm/h or mm/d).

C.4.2 Site and site selection

The double ring infiltration test were conducted at different locations with different soil types, which are characteristic for the catchment. The most important criteria for the site selection was the availability of water. Therefore the infiltration measurement in the riverbed and the riverbank were

conducted downstream of sand dam 23, where an owner of a private scoop hole allowed us to use his water and provided the equipment to fetch and store water next to the measurement site. The measurements on the loam/clay soil on fields were conducted next to wells where we had the permission of the owners to use water from their wells. The locations are indicated in Figure C.1 .



Figure C.7 Execution of the double ring infiltration test

C.4.3 Practical considerations

In order to conduct the measurements the equipment needed to be improvised. The metal ring were made by a tinsmith. In order to measure the drop a plank with a small hole was put on top of the rings. A straw fitted exactly into the small hole and guaranteed that a bristle of a broom could move freely up and down. The bristle was fixed on a top of a bottle that swam on the water in the inner ring. The drop in water level was measured at the upper end of the bristle.

There are some circumstances, that may have influenced the measurements

- The accuracy due to the equipment was about $\pm 1\text{mm}$
- The used water contained fine particles that settled on the surface
- Filling the rings might have disturbed the soil surface.
- The soil profile in the riverbed where not homogeneous but consisted of different sand layers.
- In the soil of the fields roods can be expected that build preferential flow paths.
- The surface of the fields was covered by small drought cracks that form preferential flow paths.

C.4.4 Results

Infiltration in coarse sand of the riverbed

Two measurements were conducted in the center of the river where the riverbed consists of coarse sand. Both measurements were conducted for 1.5 minutes only, because of the high infiltration rate and the shortage of water. The results are:

- $2.7\text{ cm}/30\text{sec} = 54\text{ mm}/\text{min} = 3240\text{ mm}/\text{h}$ (78 m/d)
- $2.9\text{ cm}/30\text{sec} = 58\text{ mm}/\text{min} = 3480\text{ mm}/\text{h}$ (84 m/d)

The results cannot be considered as accurate because of the limited number and the short duration. However they confirm the rather high hydraulic conductivity found in the literature.

Infiltration the fine sand of the riverbed

The sand at the edge of the riverbed was considerable finer. Here two measurements were conducted. The constant invitation rate, thus the nearly saturated infiltration rate is

- about 60 mm/h (1.4 m/d) in the first measurement.
- about 80 mm/h (1.9 m/d) in the second measurement.

The infiltration curves of the measurements are presented below.

Infiltration on the hill slopes

The measurements were conducted in the upstream part of the catchment where farmers allowed us to conduct the measurements on their fields next to their wells.

The first site is located at about 100 m from sand dam 6. Here two measurements were conducted. The constant infiltration rate, thus the nearly saturated infiltration rate is

- about 300 mm/h (7.2 m/d) in the first measurement.
- about 200 mm/h (4.8 m/d) in the second measurement.

The second site is located about 100 m away from sand dam 4. Here three measurements were conducted. The constant infiltration rate, thus the nearly saturated infiltration rate is

- about 80 mm/h (1.9 m/d) in the first measurement.
- about 50 mm/h (1.2 m/d) in the second measurement.
- about 60 mm/h (1.4 m/d) in the third measurement.

Table 3 Hydraulic conductivities determined with the double ring infiltrometer

Soil and location	Measurement	Hydraulic Conductivity [m/d]
Coarse sand of the riverbed	Measurement 1	78
	Measurement 2	86
Fine sand of the riverbed	Measurement 1	1,4
	Measurement 2	1.9
Clay of the Fields (Location 1)	Measurement 1	7.2
	Measurement 2	4.8
Clay of the Fields (Location 2)	Measurement 1	1.9
	Measurement 2	1.2
	Measurement 3	1.4

C.5 Evaluation

The purpose of the measurements was to gain information about the hydraulic conductivity of the water bearing layers in the catchment. The number of measurements are limited and the locations of the measurements were chosen on practical considerations and are therefore not representative for the whole catchment. However the measurements indicate a range of the hydraulic conductivities of the different soil types. Below the measured values are compared with the values derived by Hoogmoed (2007) to found the groundwater model developed afterwards on a broader data basis.

The riverbed

For the coarse sand in the riverbed, only the initial infiltration rate could be approximated. The measured initial infiltration rate of about 80 m/d is in line with the hydraulic conductivity of 56 m/d determined Hoogmoed (2007). The hydraulic conductivity of the finer sand of lower layers in the riverbed, determined with the auger hole method, ranges between 23 and 32 m/d, which is slightly lower than the 35 m/d determined by Hoogmoed (2007).

Riverbanks and fields on the hill slopes

The soil types on the riverbanks consist of fine sand, clay and silt. The composition varies from location to location. The tests with the double ring infiltrometer show that the conductivity of the fine sand is in the range of 1 – 2 m/d. The results of the Auger hole method show that the hydraulic conductivity of the clay/silt on the riverbanks vary between 3 and 24 m/d, which is approximately the range determined by Hoogmoed (2007).

The hydraulic conductivity of the loamy soil of the field on the hill slopes varies roughly in the range of 1m/d to 10 m/d, depending on the location.

Weathered rock

The hydraulic conductivity of the underlying weathered rock measured in the wells ranges from 0.04 m/d to 0.27 m/d, and are therefore much lower than the values of 10 m/d determined by Hoogmoed (2007). The conductivities derived from the measurements in the two wells more upstream are lower than those from the wells in the further downstream. The high conductivities obtained by Hoogmoed (2007) are measured even further downstream.

Summary

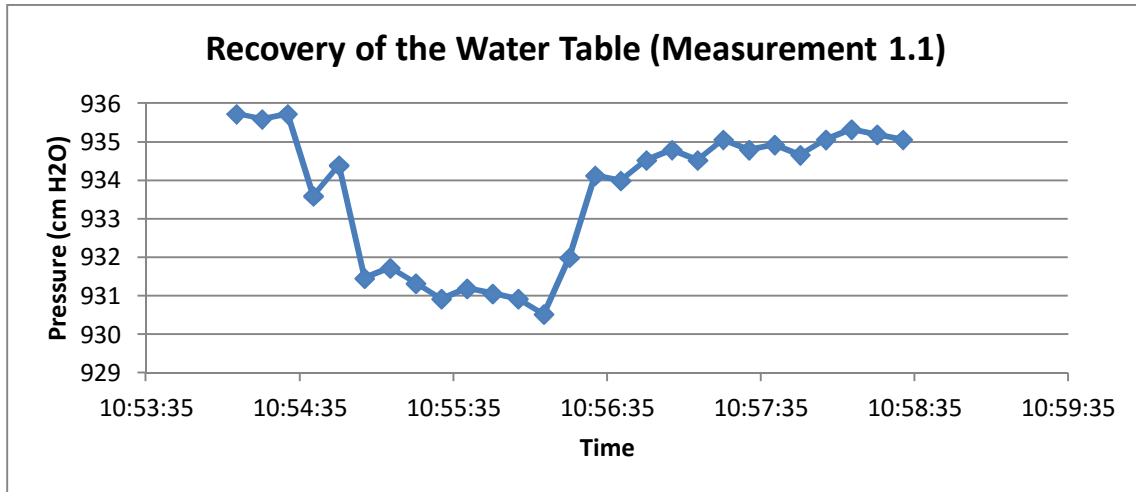
During the execution of every single measurement things needed to be improvised. To conduct the double ring infiltration test the equipment had to be produced by myself. To prevent the collapse of the boreholes, self-made perforated pipe had to be used. In order to determine the hydraulic conductivities of the weathered rock, measurements in private shallow wells were conducted with all the mentioned practical difficulties. All these difficulties can be seen at the graphs in Appendices. However the comparison with the values derived by Hoogmoed (2007) show that the determined values lie in a reasonable range.

D. Infiltration and recovery curves

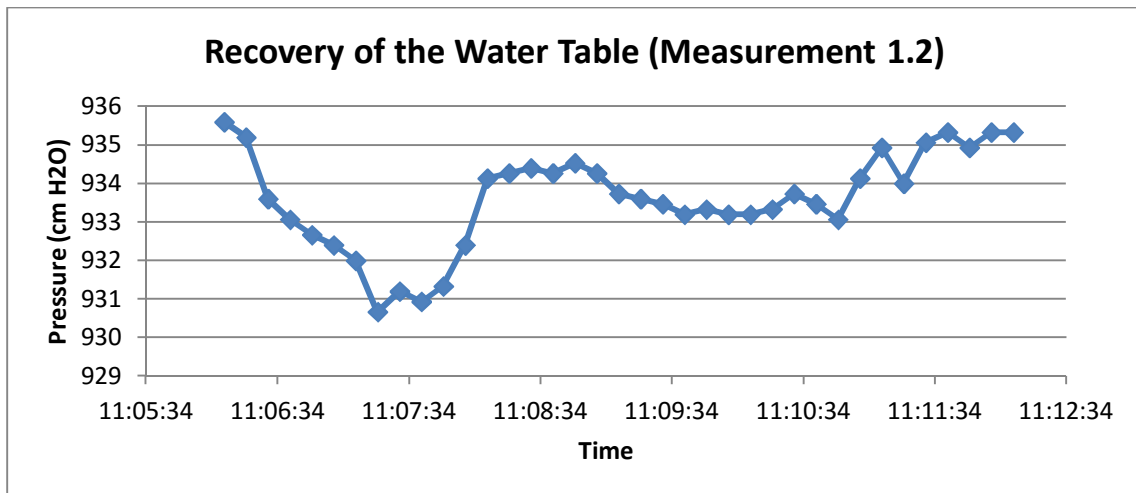
D.1 Recovery curves of boreholes

Site 1

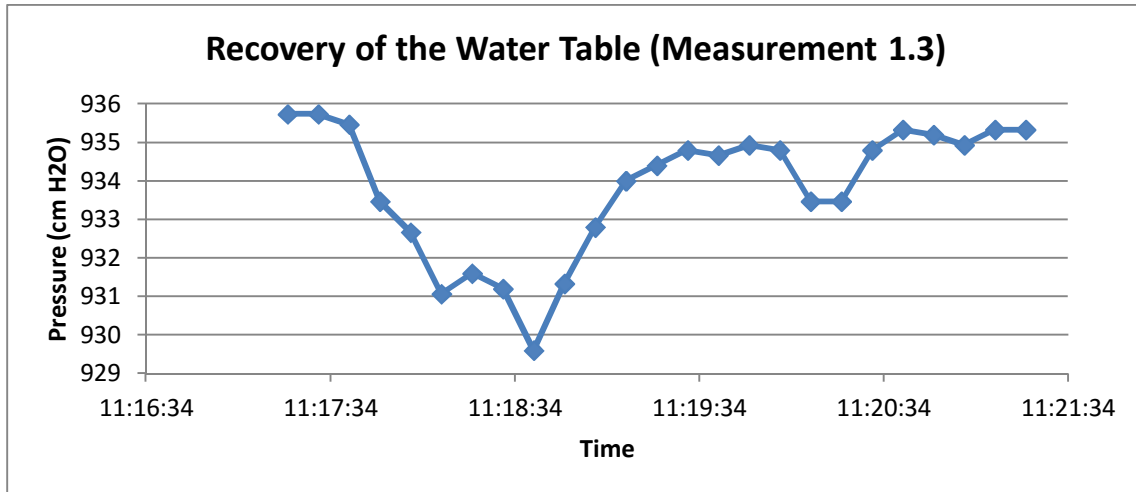
Measurement 1



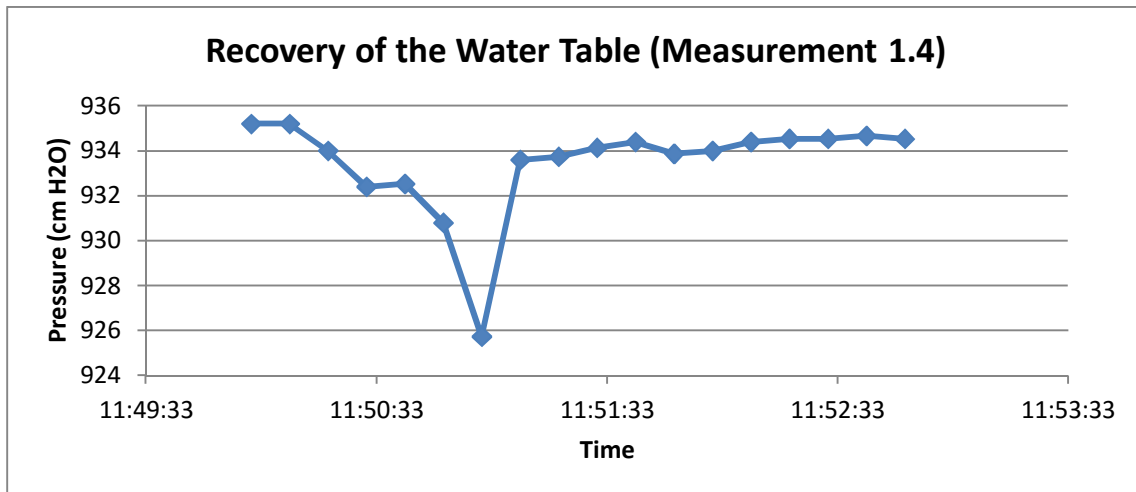
Measurement 2



Measurement 3

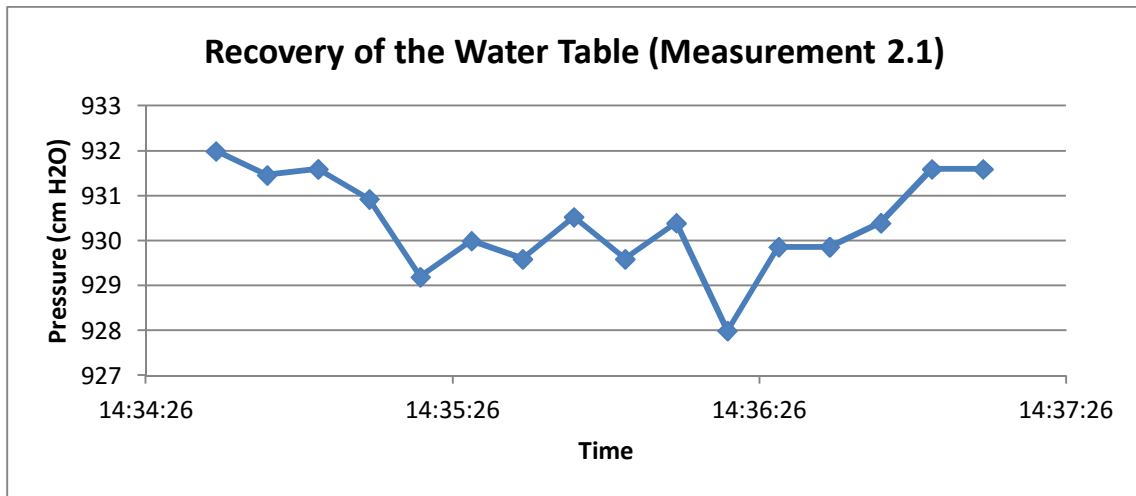


Measurement 4

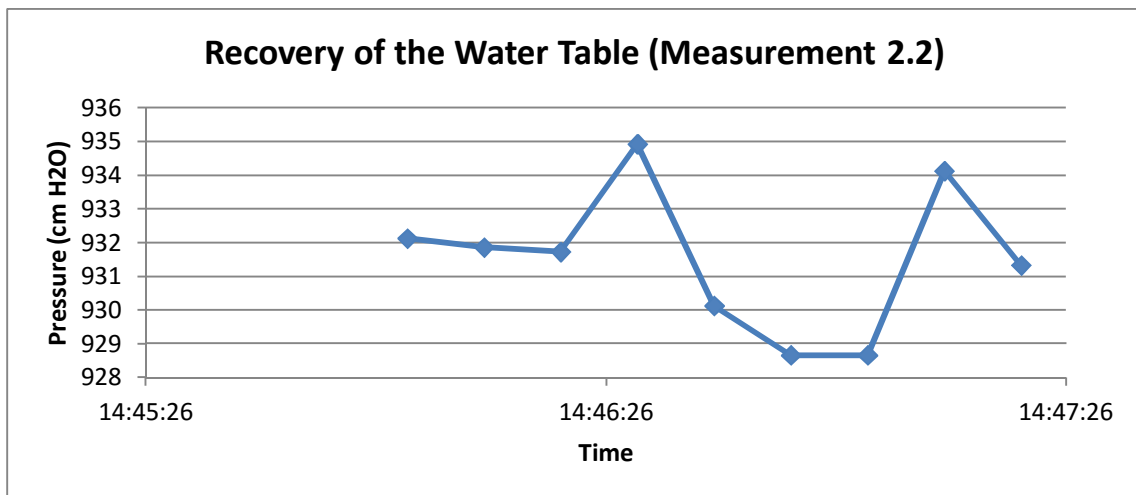


Site 2

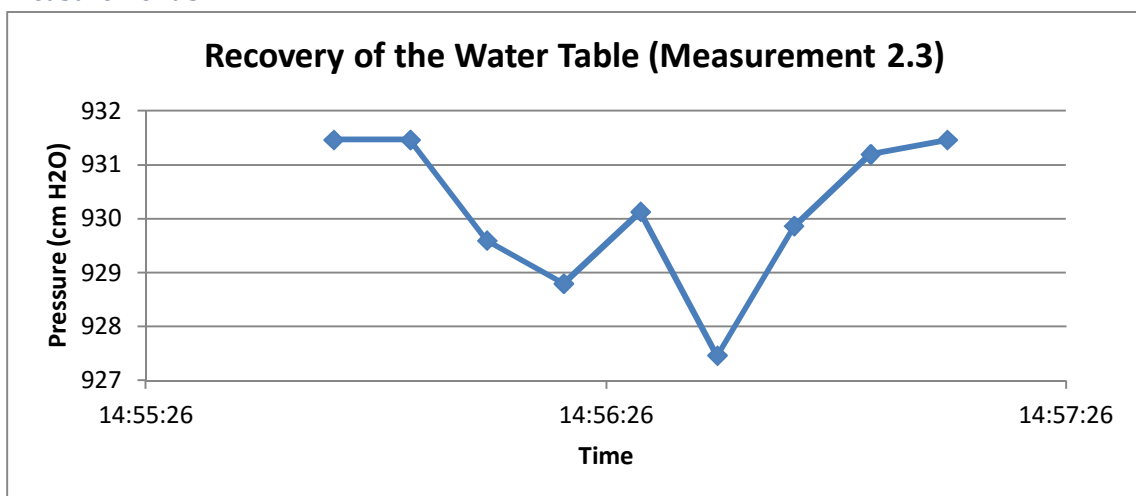
Measurement 1



Measurement 2

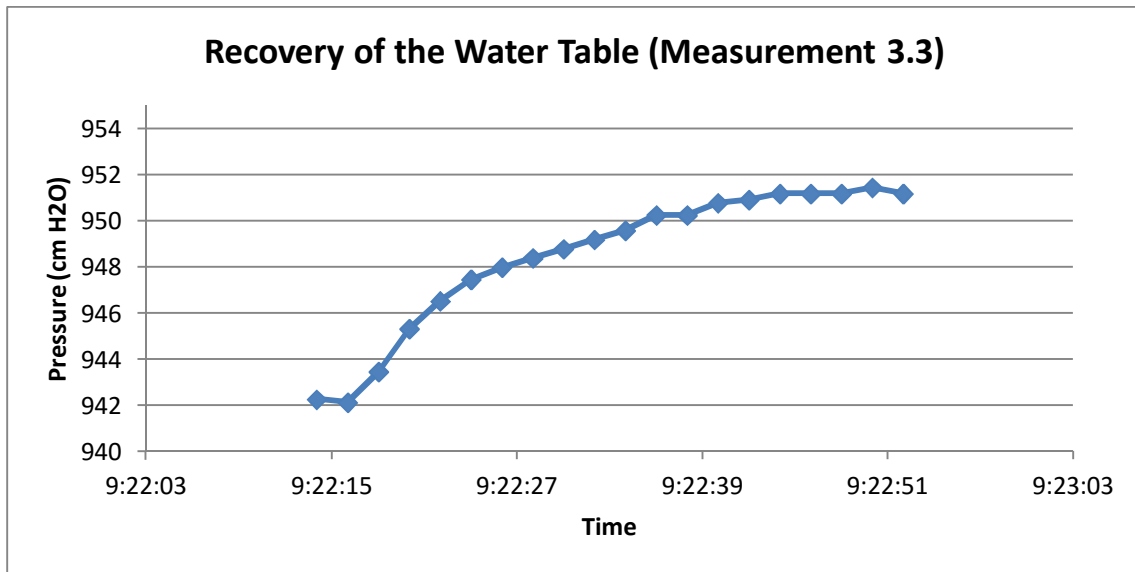


Measurement 3



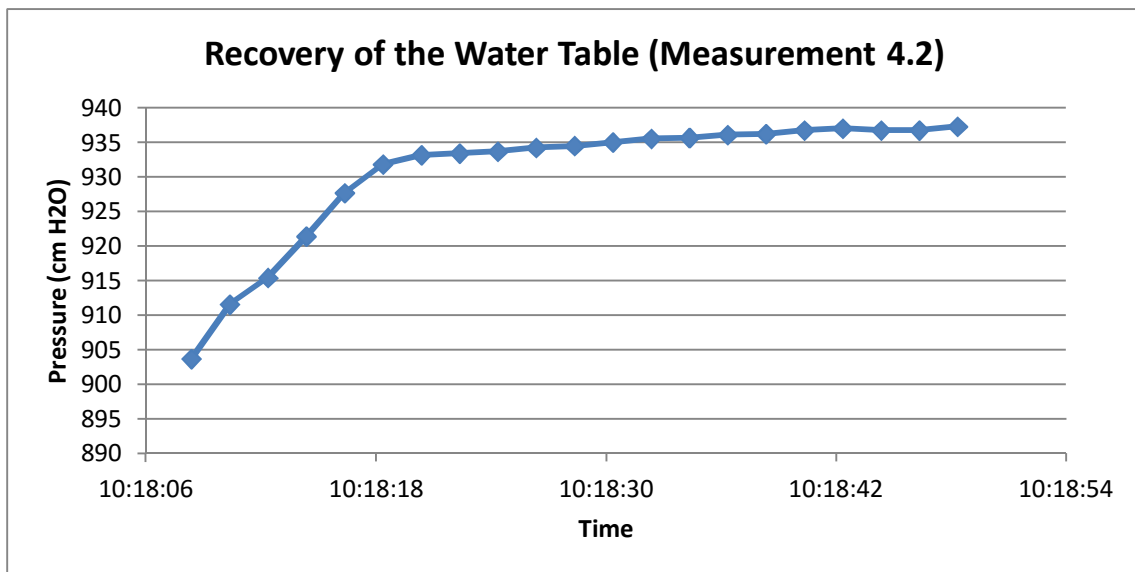
Site 3

Measurement 3

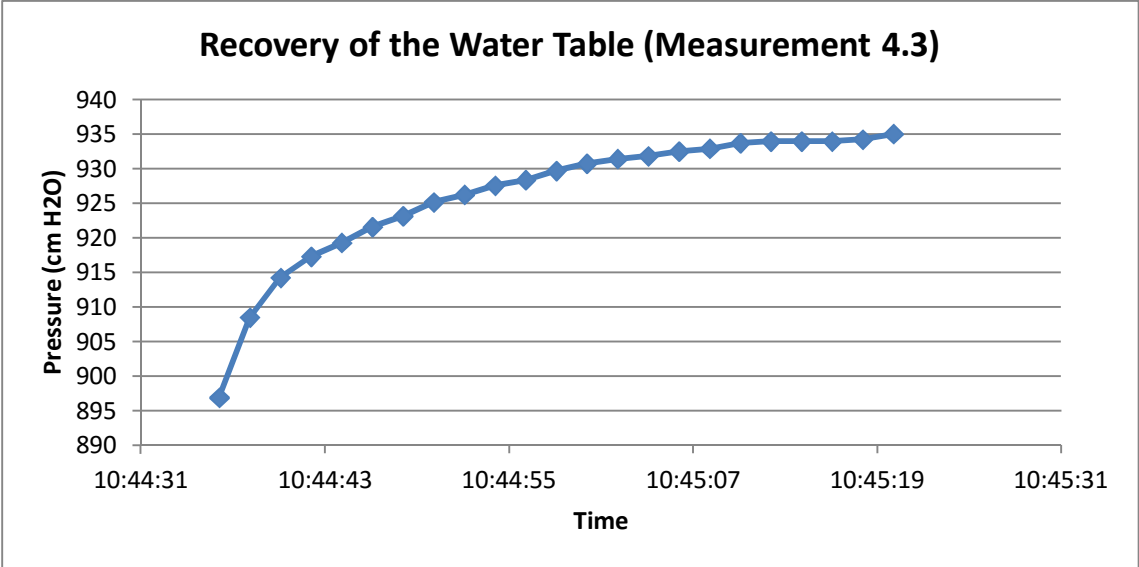


Site 4

Measurement 2

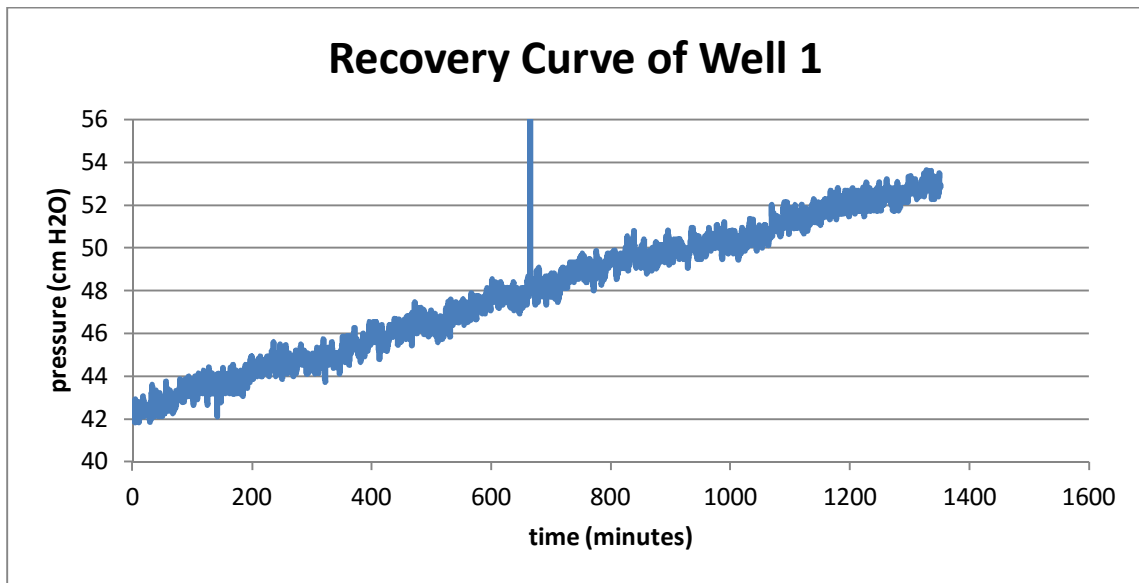


Measurement 3

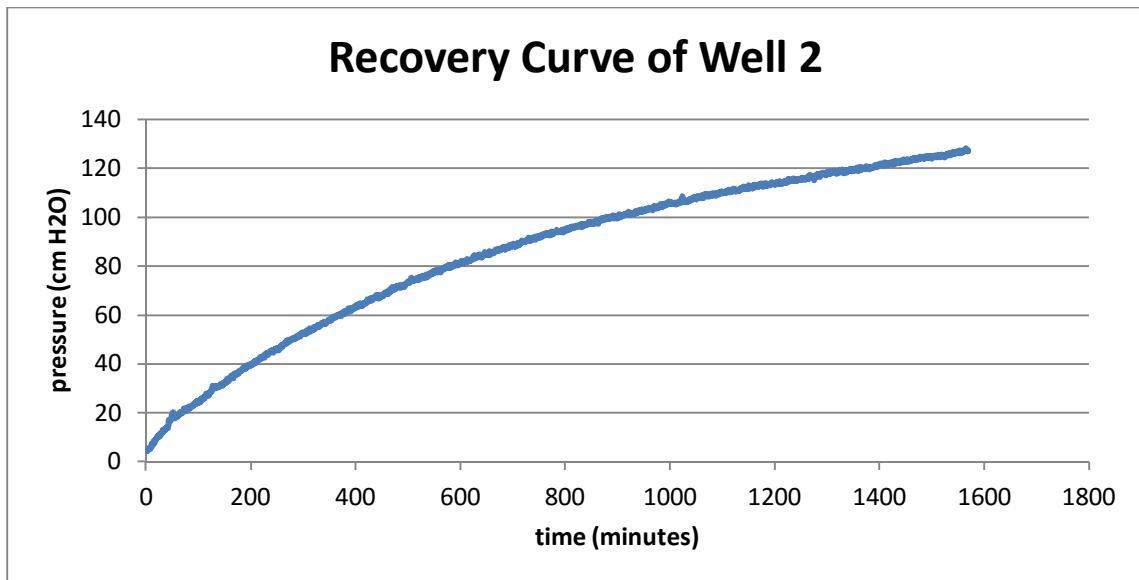


D.2 Recovery curves of shallow wells

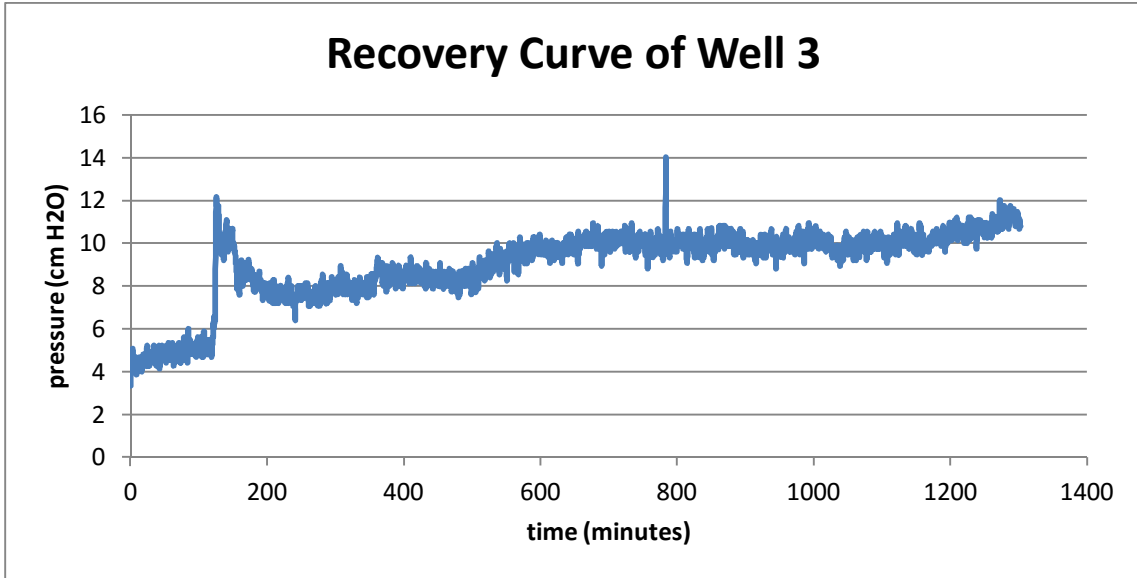
Well 1



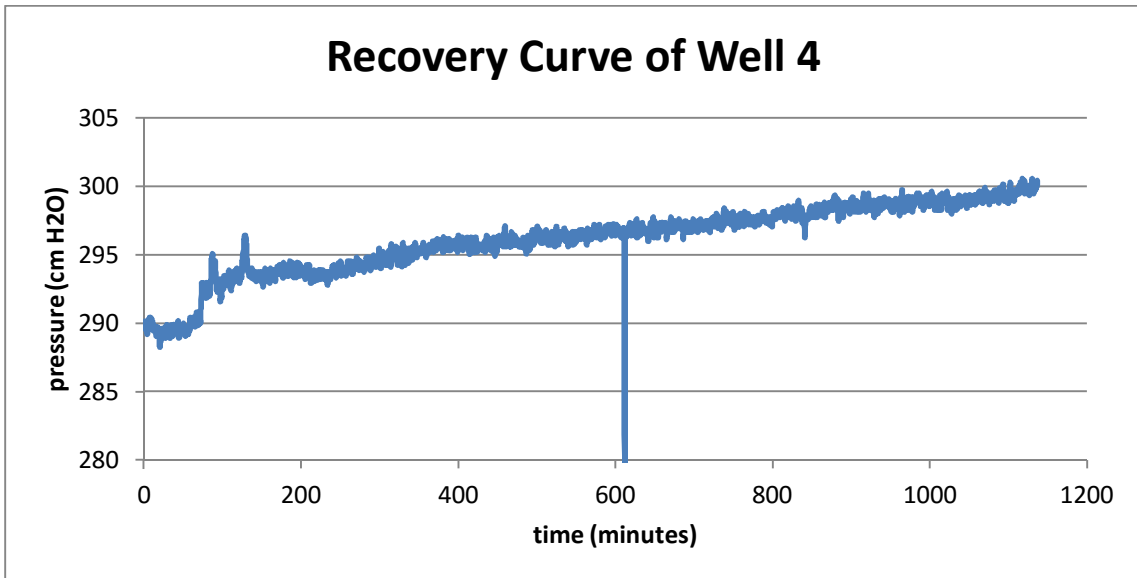
Well 2



Well 3

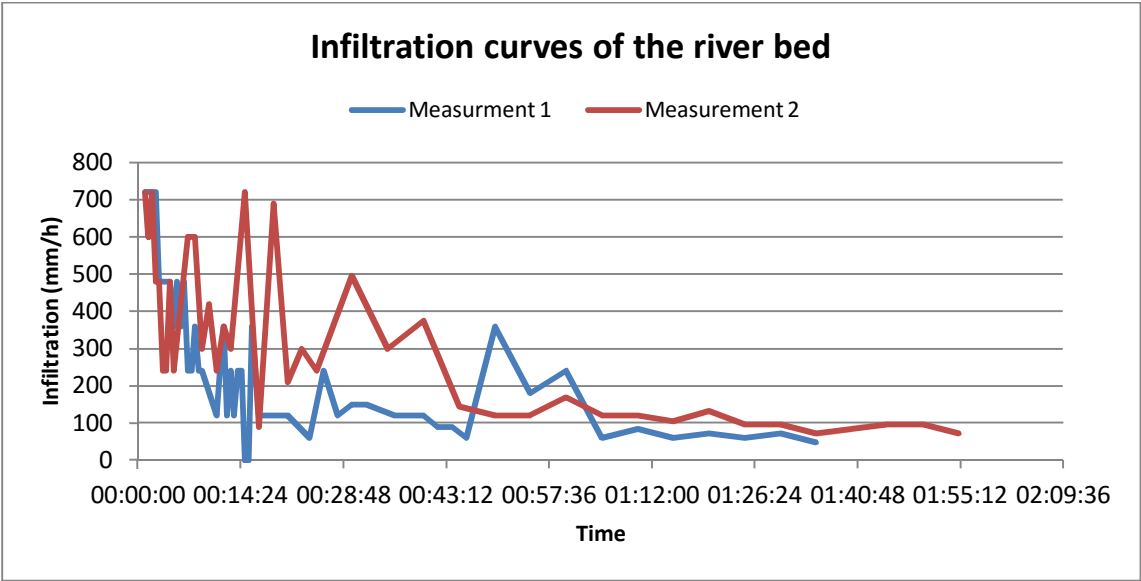


Well 4



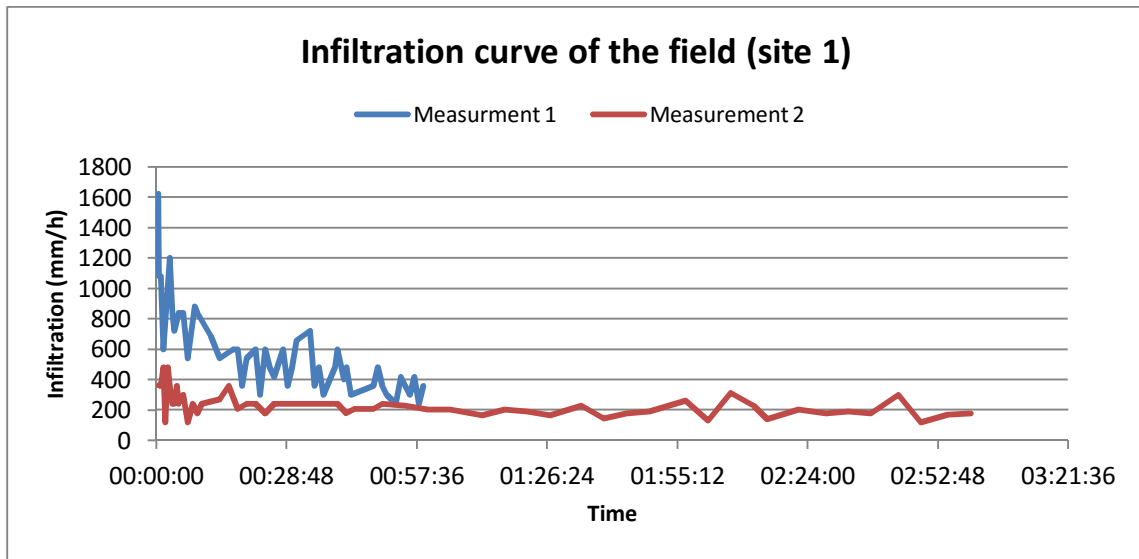
D.3 Infiltration curves

Riverbed

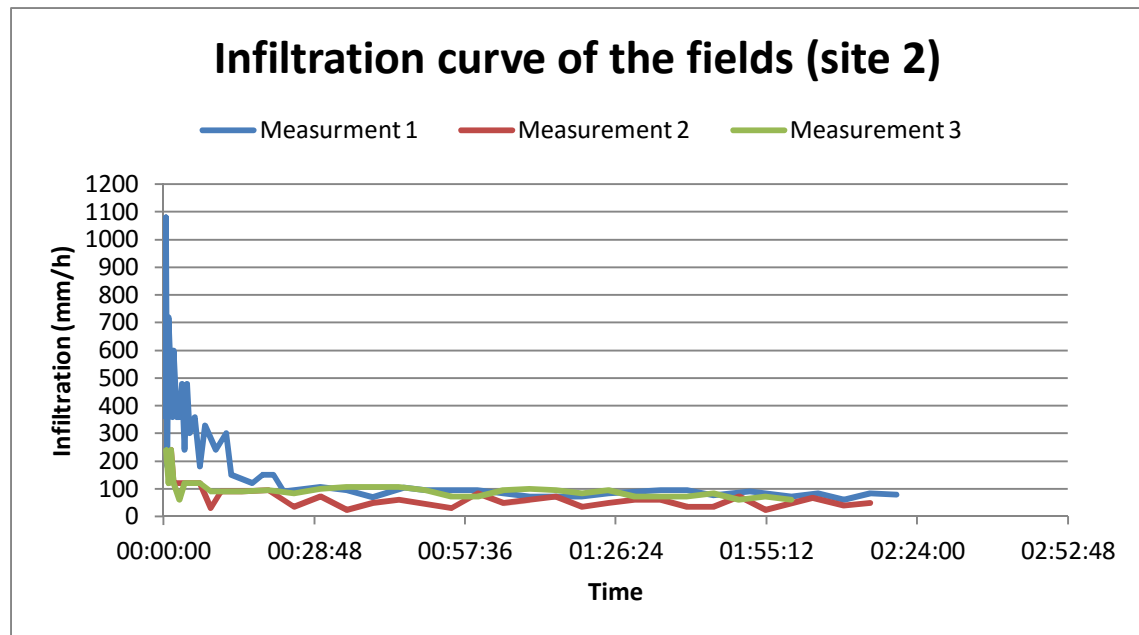


Fields

Site 1



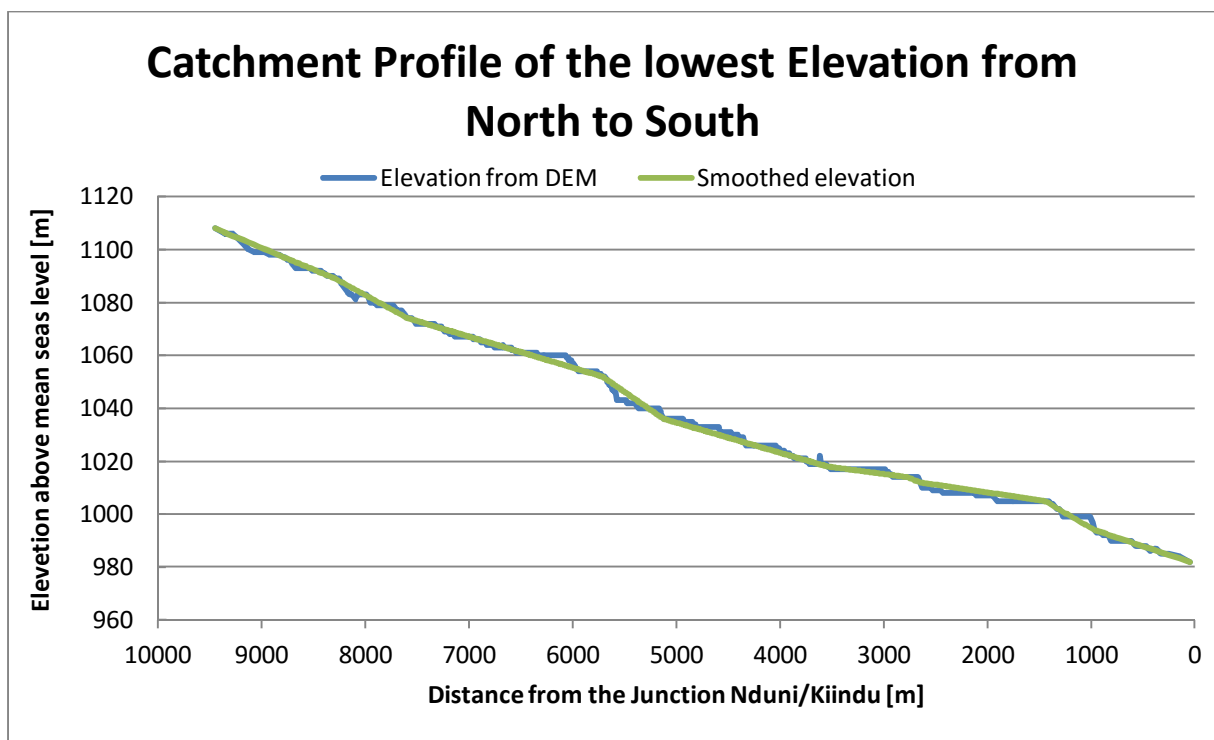
Site 2



E. Schematization

The distinction between these different sections was based on the following approach

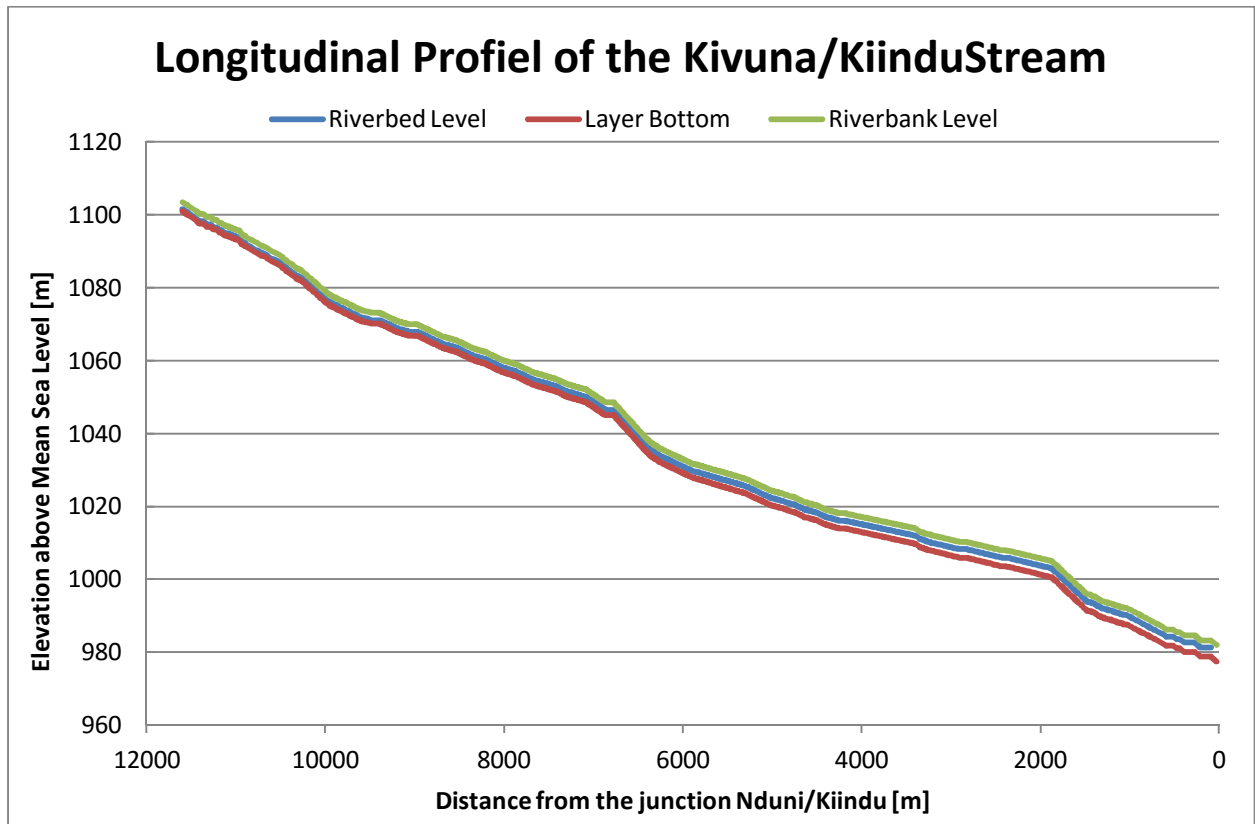
1. First the elevation of every grid cell was determined on the basis of contour lines created in Qgis.
2. In every row of cells with the same degree of latitude, the cells with the lowest elevation (which are located in the middle of the valley and represent the riverbed) were selected. These cells were used to generate a profile of the catchment from north to south (see figure below).
3. In order to get a smooth trend, this profile was categorized in different sections with similar gradient. The new generated levels of the cells (based on the smoothed profile) were assumed to be the surface level of the riverbanks (next to the riverbed) in the corresponding row of cells of same degree of latitude (see figure below).



4. Afterwards the cells were assigned to one of the following four different dominant soil types.
 - a. The cells with the lowest elevation of all cells with the same degree of latitude were the riverbed, consisting of coarse sand. The width of the riverbed was based on the observations during the field visit. The elevation of the riverbed is 2 meter lower than the elevation of the riverbank in the smoothed longitudinal profile (see **Fout! Verwijzingsbron niet gevonden..**
 - b. If the elevation (determined based on the Digital elevation map) of a cell was less than 3m higher than the riverbed cell with the same degree of latitude then the cell represented the clay layer, which covers the weathered rock on the riverbanks and hill slopes.
 - c. If the elevation (determined based on the Digital elevation map) of a cell was more than 3 m but less than 10 m higher than the cell of the riverbed at the same degree of latitude, the cell represented the weathered rock aquifer.
 - d. All cells with a more than 10 m higher elevation than the cell of the riverbed with the same degree of latitude represented hardrock and were therefore no flow cells.

- Finally the assumption, that the riverbank is 2.5 meter in the upstream and increases to 5 meter in the downstream, was applied to calculate the bottom of the aquifer (see figure below).

The longitudinal profile of the main stream is given in figure below.



This approach leads to model of a catchment with a variable gradient from north to south, but no gradient from west to east. Through this schematization, the drying up of wet cells and the wetting of dry cells is avoided and stabile simulations can be performed. In principle the approach needs to be followed for every sub-catchment separately. This model focuses on the Kivuna/Kiindu stream. Therefore the tributary is less adequate schematized and the results for the tributaries are less accurate.

This approach to determine different sections of a the aquifer is similar to the principle of the Height Above Nearest Drain (HAND) in hydrological modeling, where areas with different dominant hydrological processes are distinguished on the bases of their height, compared to the nearest drain.

F. Estimation of water use patterns

During the fieldtrip it became apparent that the population growth and economic development led to increased water use. However the exact water use is hard to evaluate quantitatively, because of the decentralized water use and the individual water use patterns. The first scenario is called water use of 1990 which represents estimated water use before the construction of the sand dams in the year 1990. The second scenario is called water use 2014 which represents estimated water use during the fieldtrip in 2014.

The determination of the water use patterns for the years 1990 and 2014 are basically based on rough estimates of the population and their water demand. The amount of water extracted in the vicinity of every sand dam is equal. Observed local variations in water use are not taken into account.

Water use pattern of the year 1990

For the water use pattern of 1990 the following situation is assumed. Before the construction of the sand dams 100 people with a domestic water demand of $0.02 \text{ m}^3/\text{d}$ lived in the vicinity of each future sand dam. Therefore all inhabitants together withdrew 2 m^3 from two scoop holes upstream of the future location of the sand dam. Furthermore there were two families per sand dam which have invested in a shallow well. From these shallow wells the families extracted $0.2 \text{ m}^3/\text{d}$ for domestic and agricultural use.

Water use pattern of the year 2014

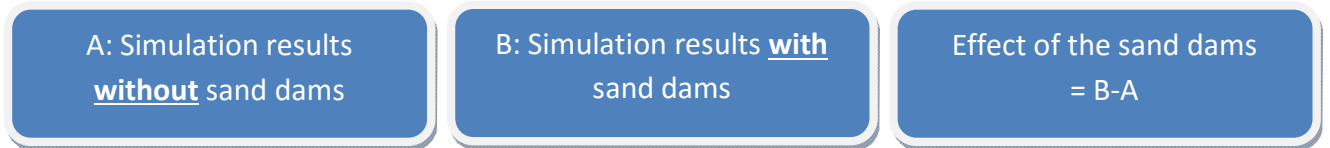
In the succeeding 24 years the population grew by 3% per year. Therefore the population in 2014 has doubled from 100 to 200 inhabitants. The domestic water use per person stayed constant 0.02 l/d so that the total domestic water demand rose to $4 \text{ m}^3/\text{d}$ in the vicinity of every sand dam. Furthermore the people also started to use $2 \text{ m}^3/\text{d}$ water for economic activities. (3 brick makers \times 200 bricks/day \times 3l/brick = $1.8 \text{ m}^3/\text{d}$; $0.2 \text{ m}^3/\text{d}$ for watering cattle, goats and donkeys). $2 \text{ m}^3/\text{d}$ water is extracted from each of the two existing scoop holes. Together with the sand dams also a public shallow well is constructed from where the remaining $2 \text{ m}^3/\text{d}$ are extracted. The number of wealthy families with private shallow well doubled from two to four. The amount of water extracted from the private shallow wells is $0.2 \text{ m}^3/\text{d}$ each.

G. Simulation Results

The appendix contains the results of the simulation discussed in the main report. The simulations are done for the whole catchment. The results for the Kivuna and Kiindu catchment are presented in separate figures. The hydraulic heads in the aquifer as well as further elaborated results are given in schemas described in the sub sections.

G.1 Groundwater levels and the effect of the sand dams

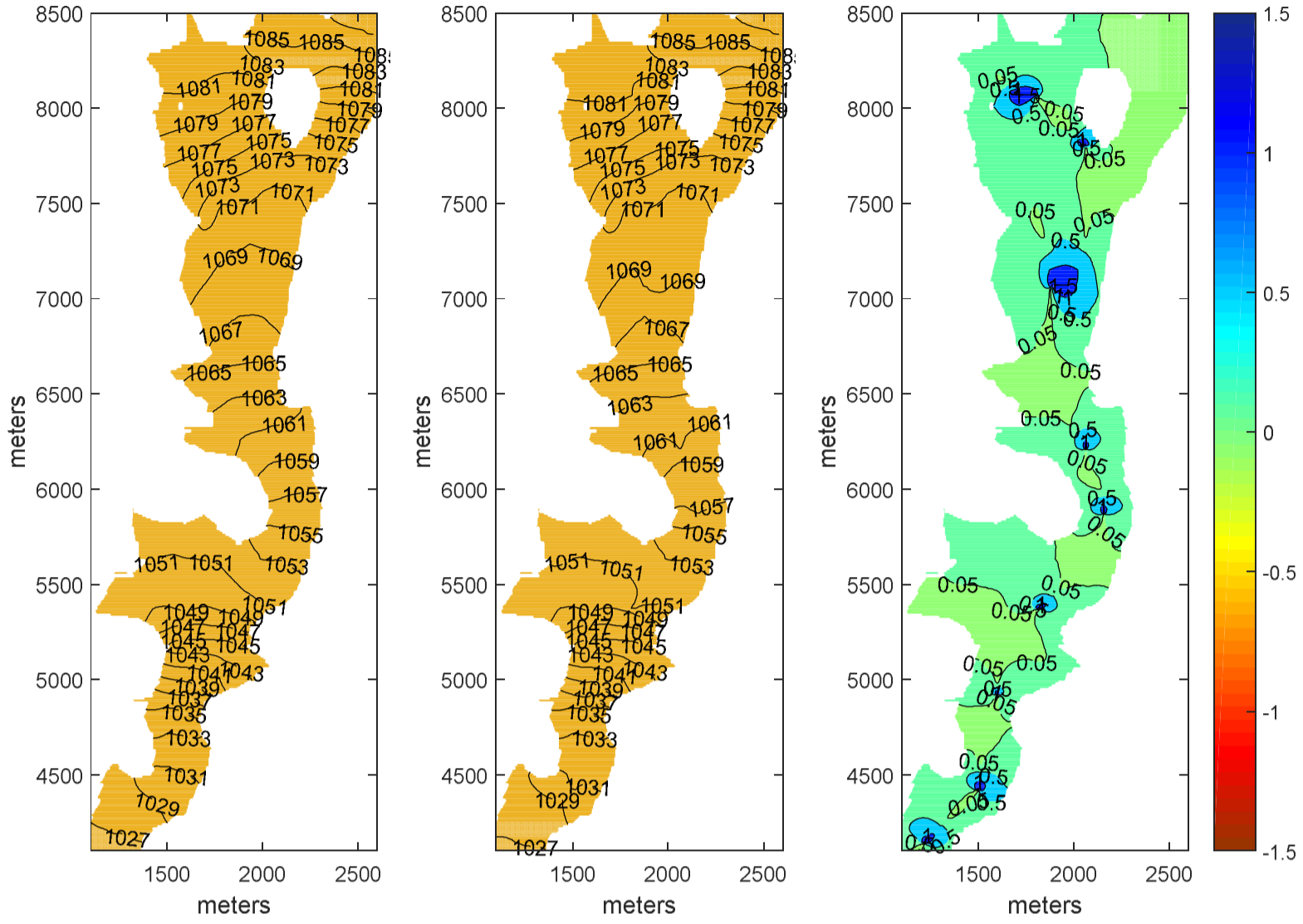
The model results are hydraulic heads in the catchment at different points in time. Because the master thesis focuses on the effect of the sand dams, next to the hydraulic heads in the catchments with and without sand dam, also the effect of the sand dams are illustrated as follows.



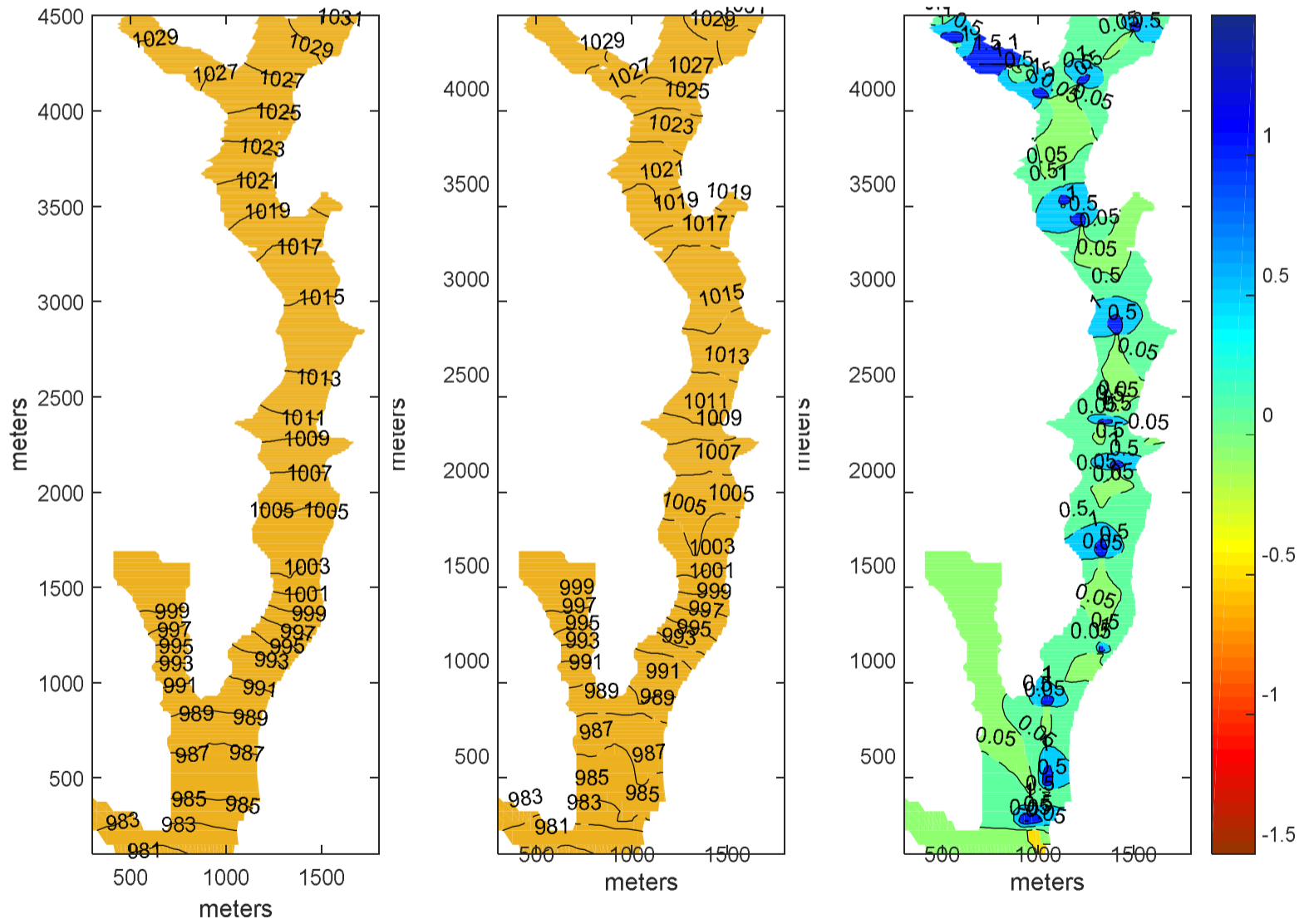
The analysis is done for the three points in time: after a wet season, after a regular dry season and a prolonged dry period.

G.1.1 After a wet season

Kivuna Catchment

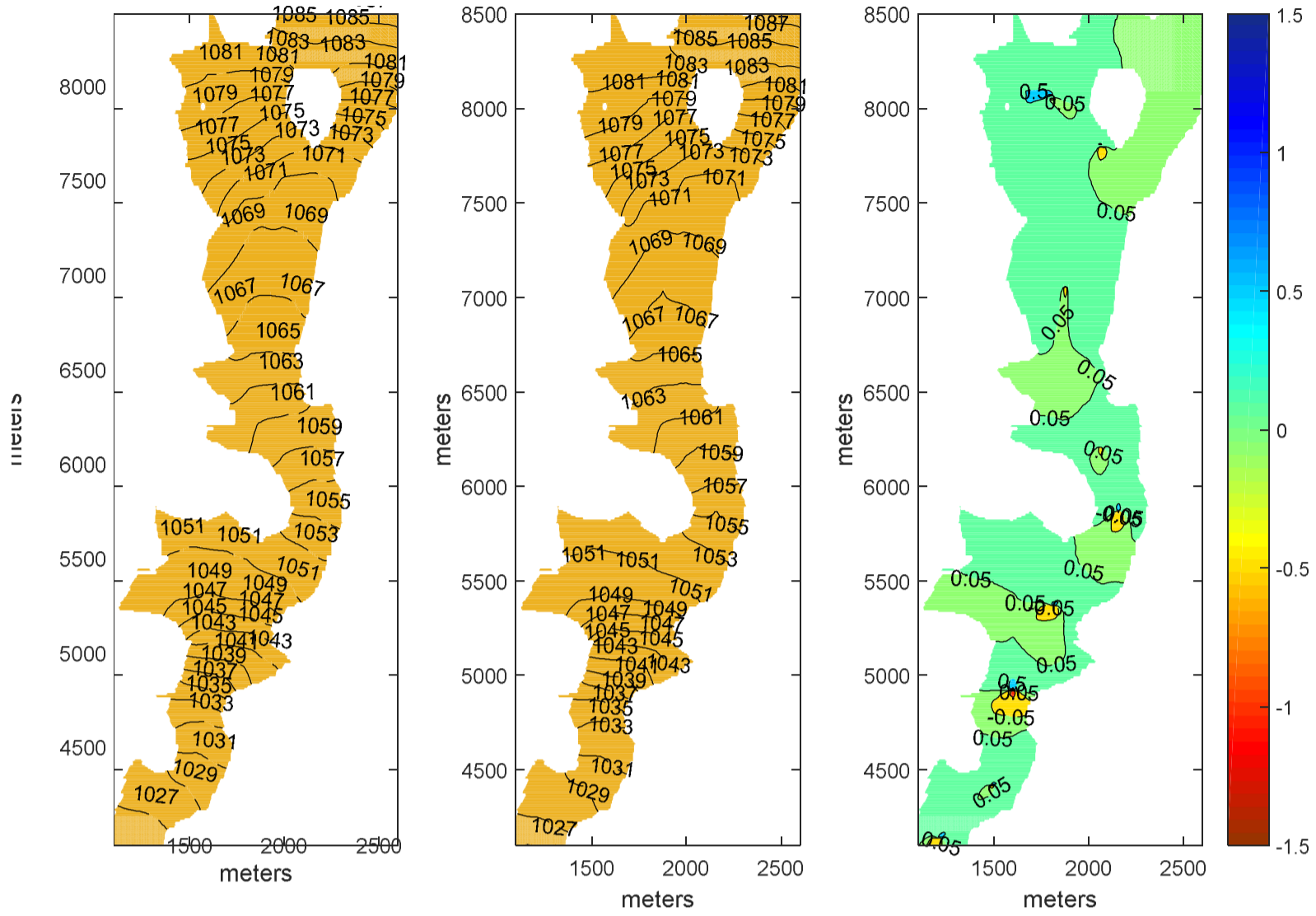


Kiindu catchment

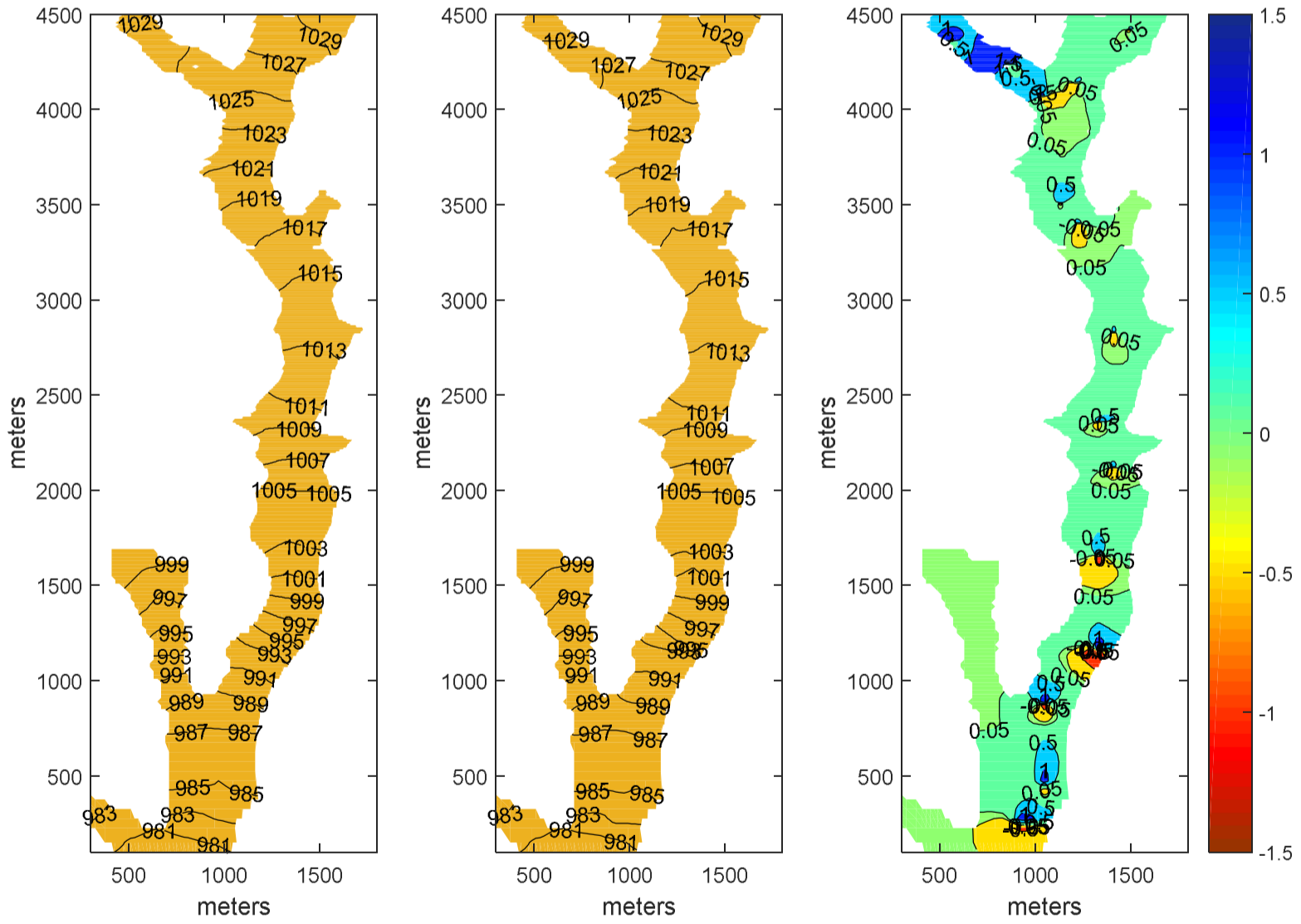


G.1.2 Water levels and effect of the sand dams after a regular dry season

Kivuna catchment

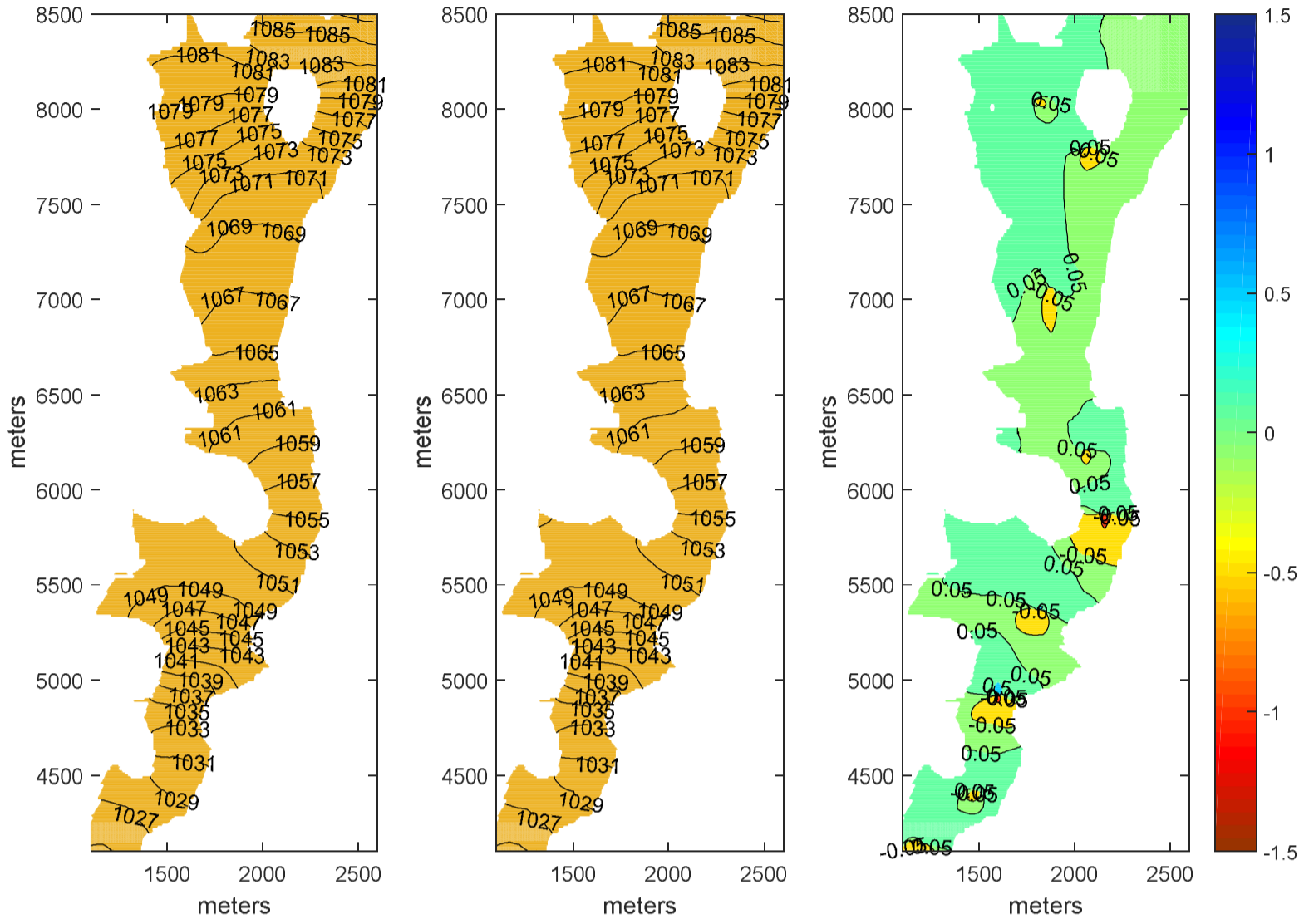


Kiindu catchment

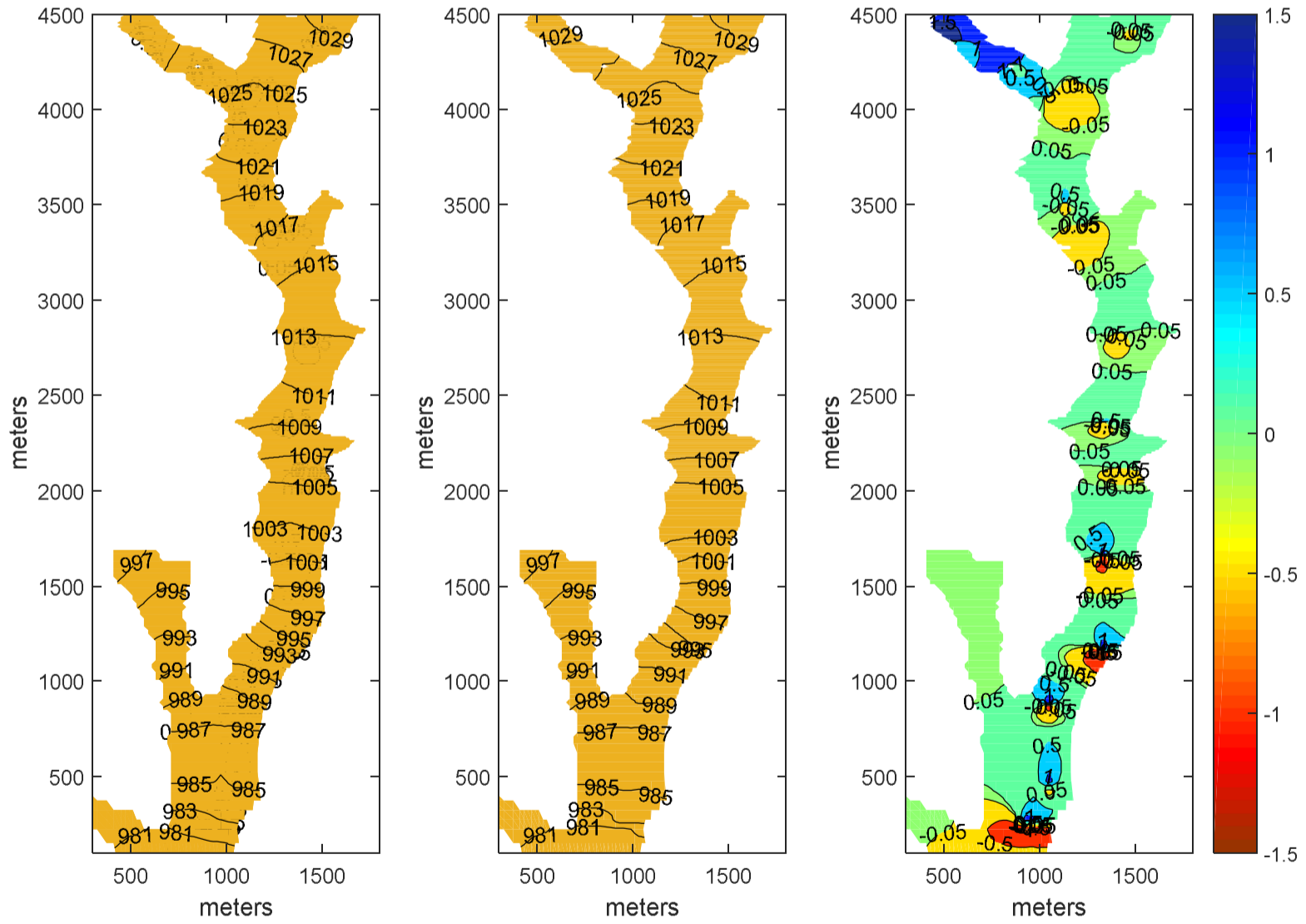


G.1.3 After a prolonged dry period

Kivuna catchment

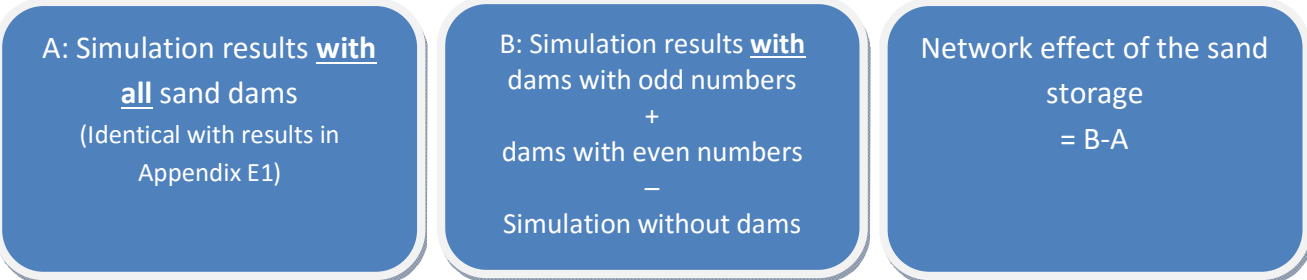


Kiindu catchment



G.2 Network effect of the sand dams

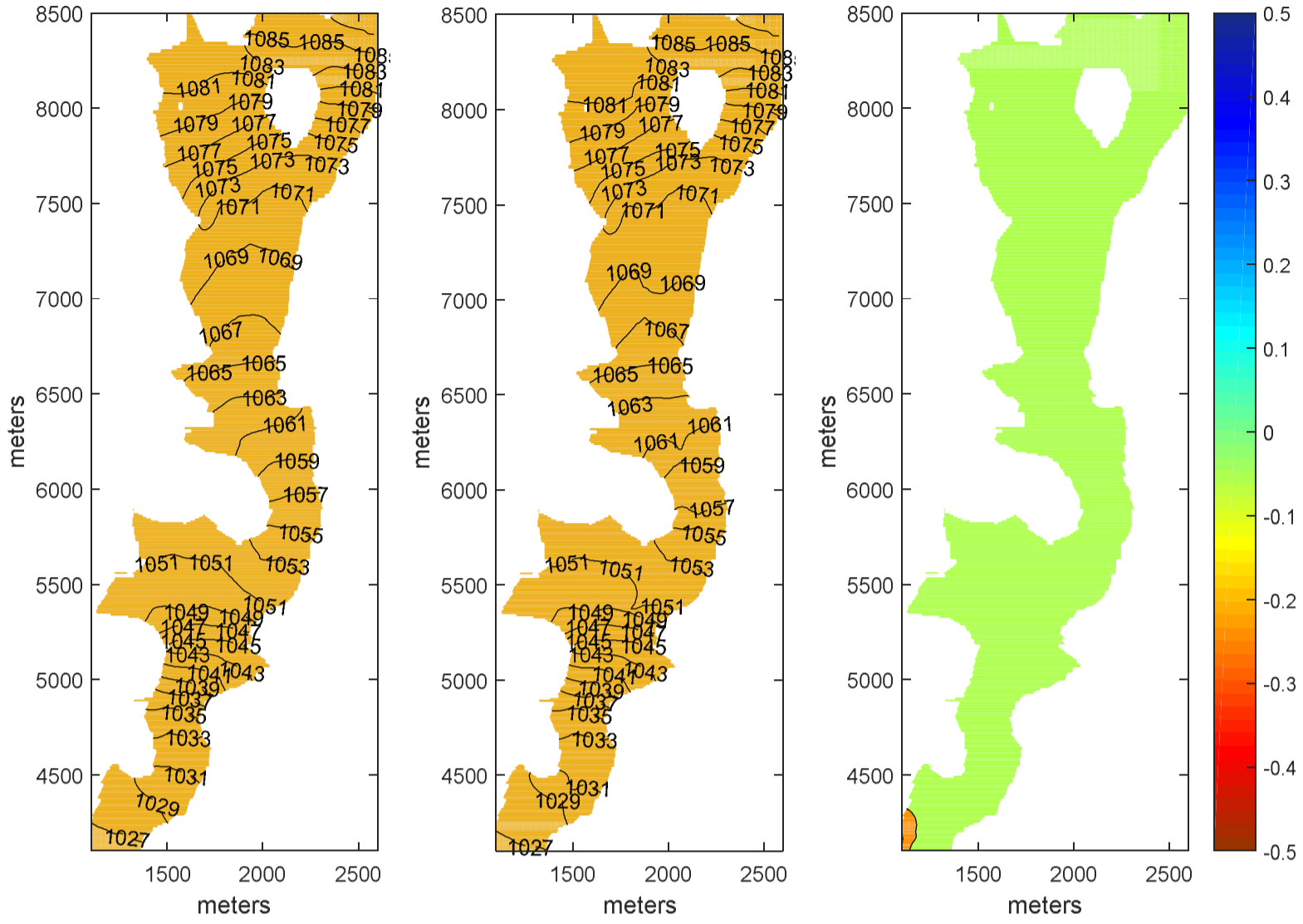
In the main report it is discussed whether or not sand dams have a network effect or not. The figures below illustrate whether the sand storage dams have a network effect or not as follows.



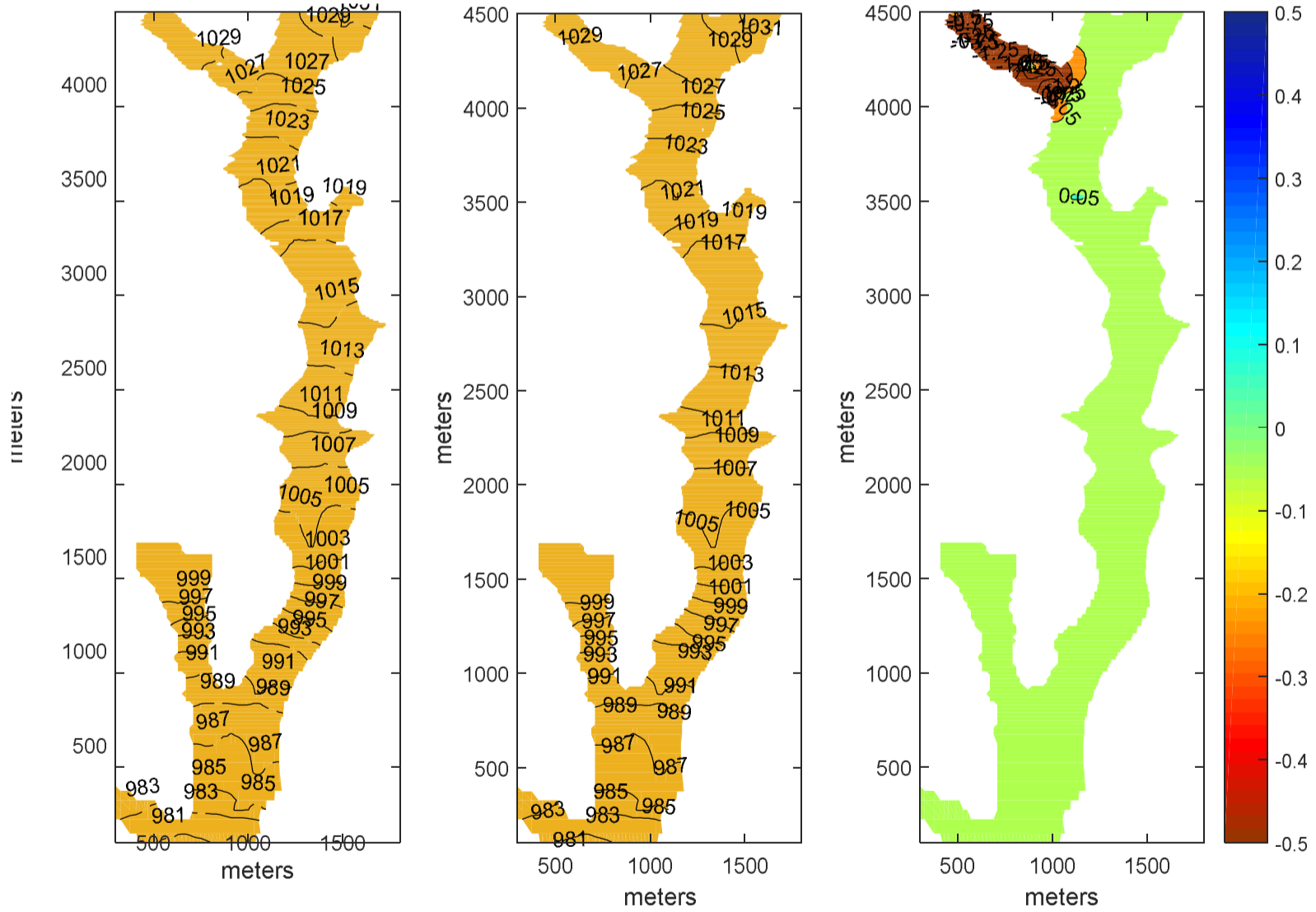
The analysis is done for the three points in time: after a wet season, after a regular dry season and a prolonged dry period.

G.2.1 After a wet season

Kivuna catchment

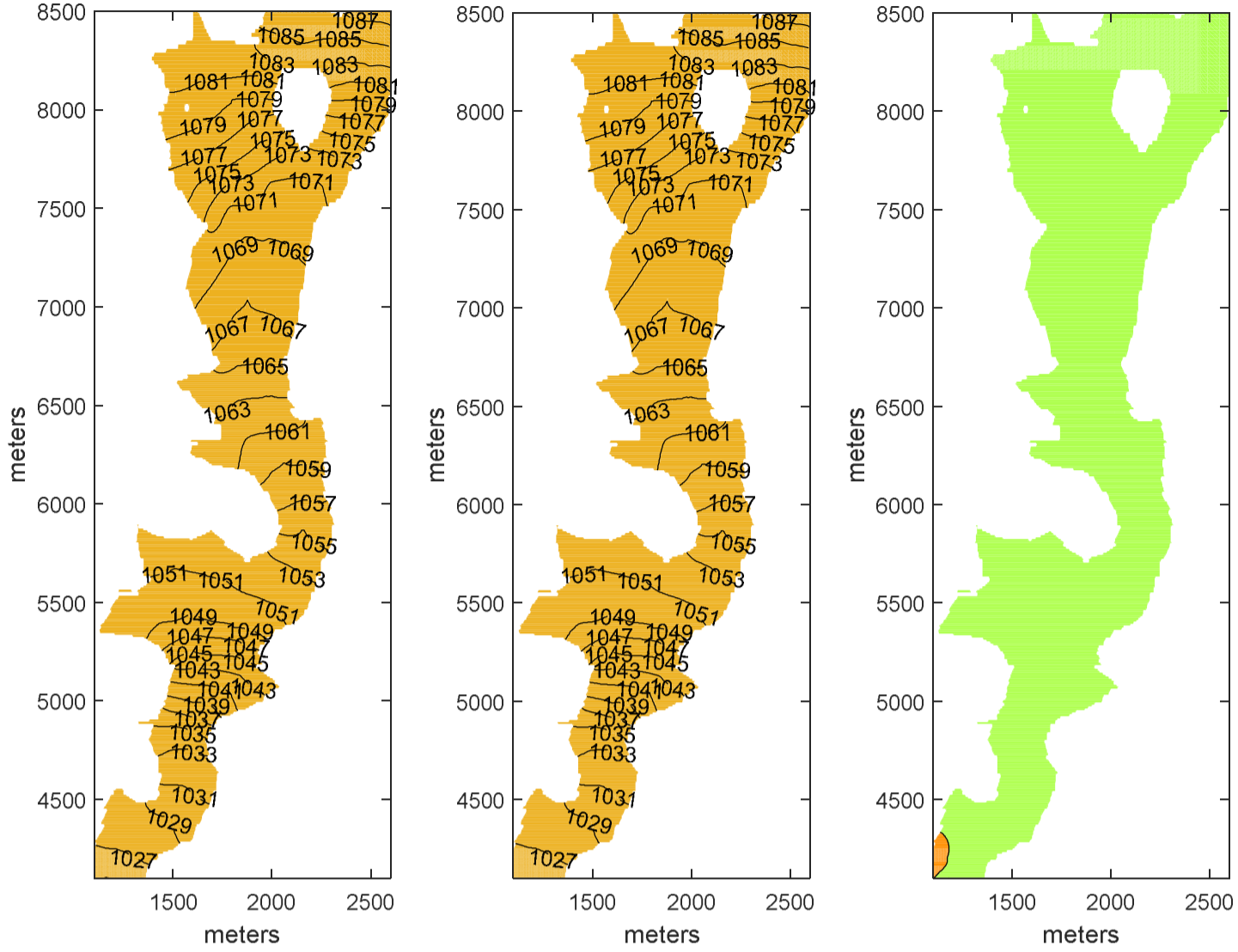


Kiindu catchment

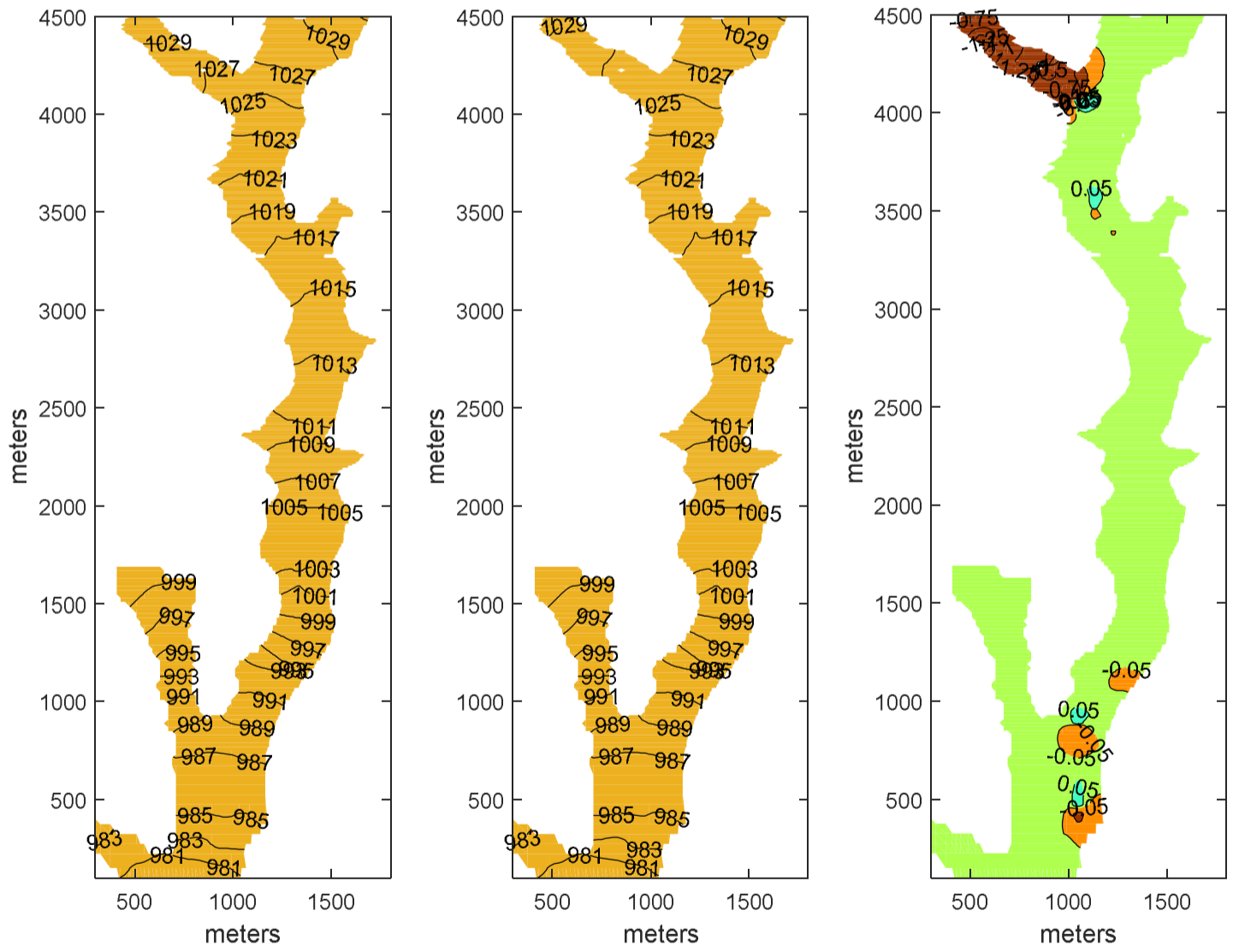


G.2.2 After a regular dry season

Kivuna catchment

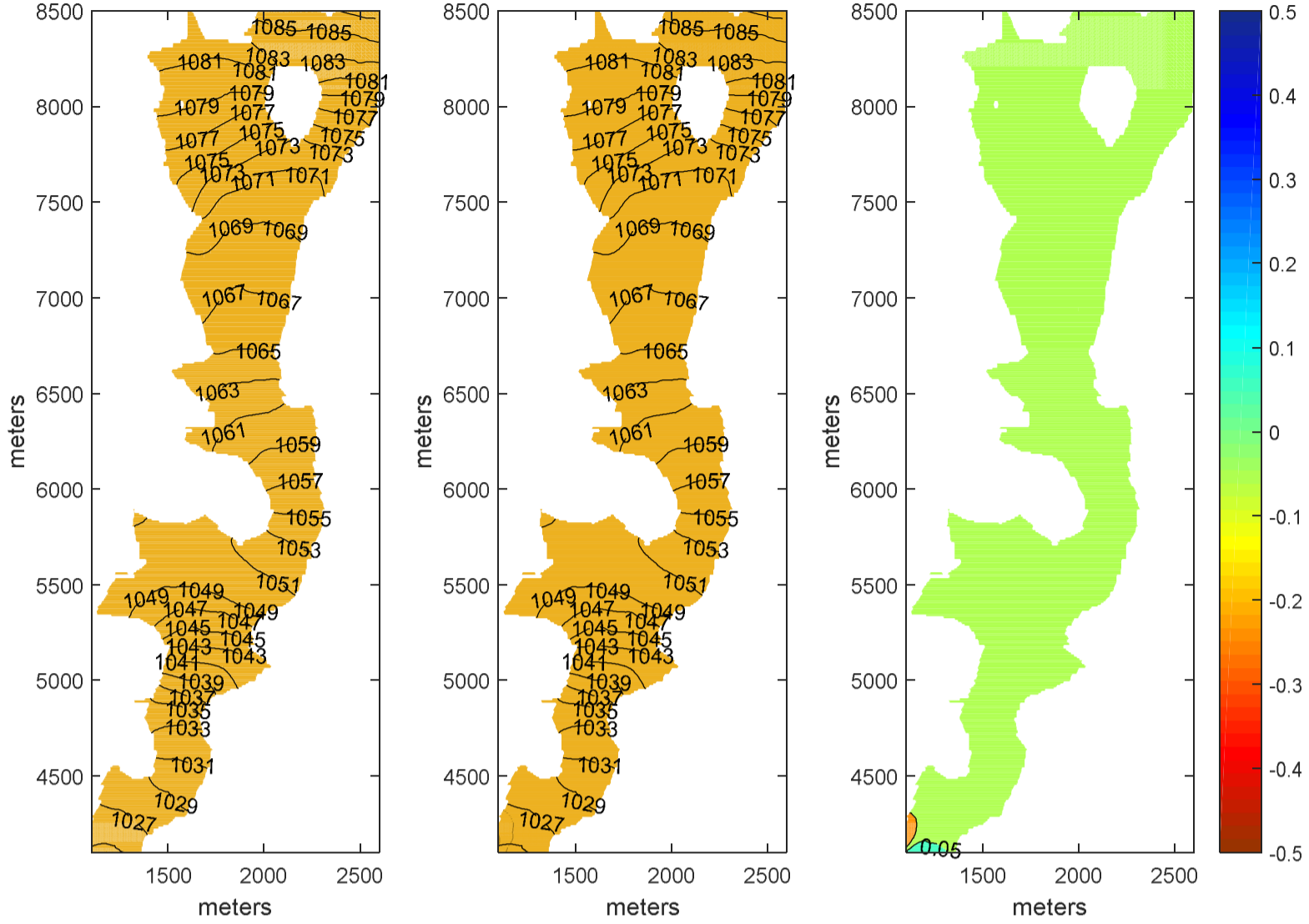


Kiindu catchment

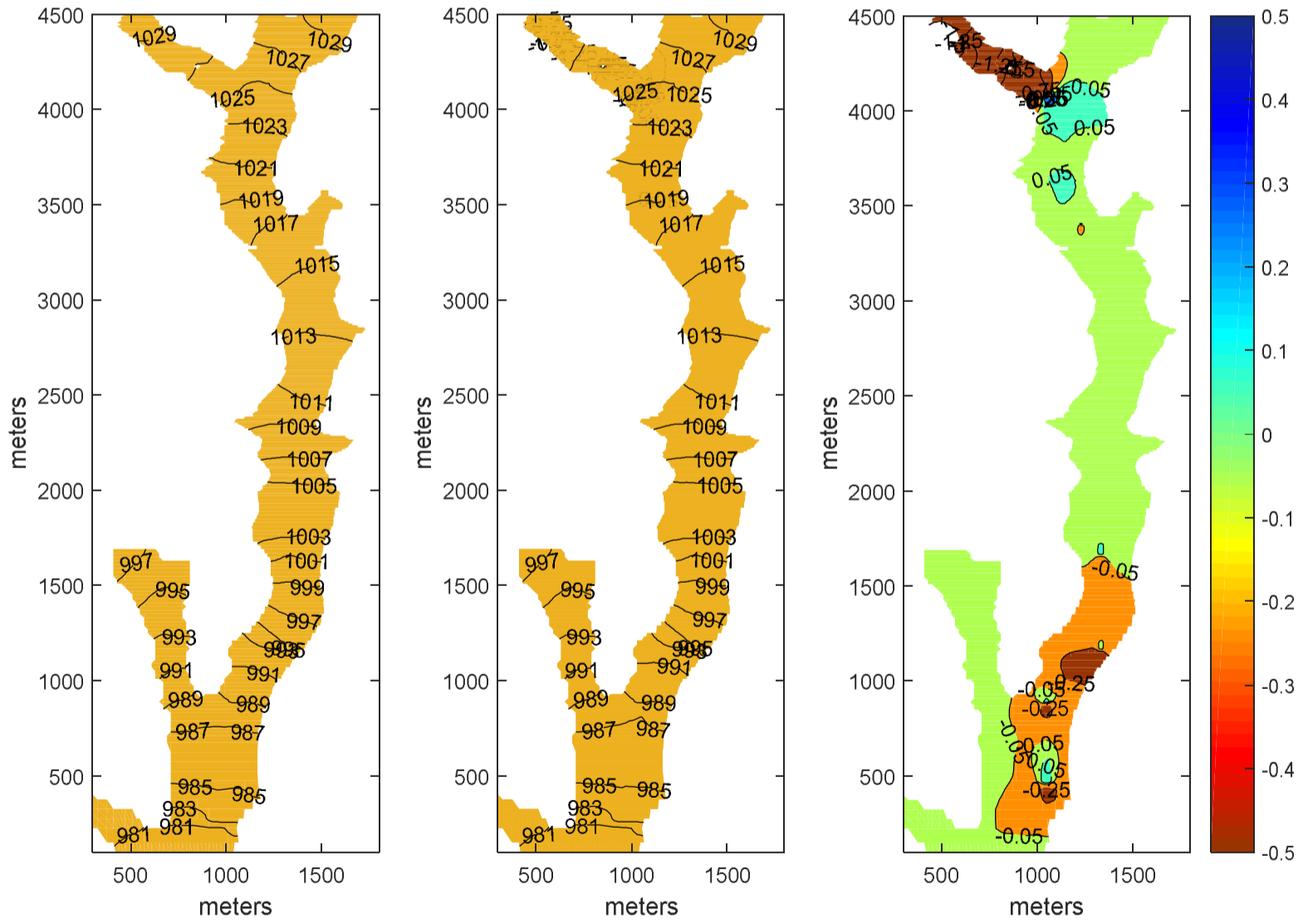


G.2.3 After a prolonged dry period

Kivuna catchment

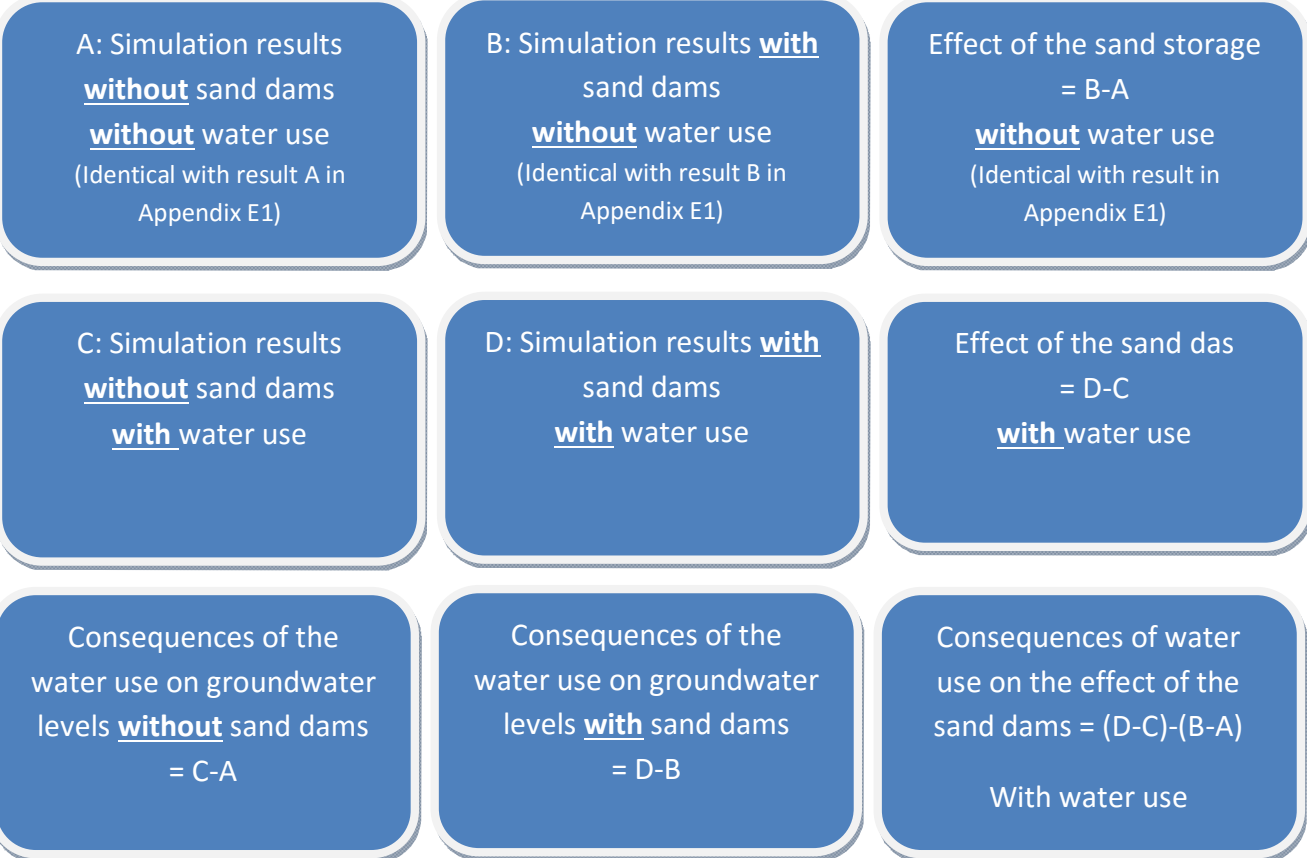


Kiindu catchment



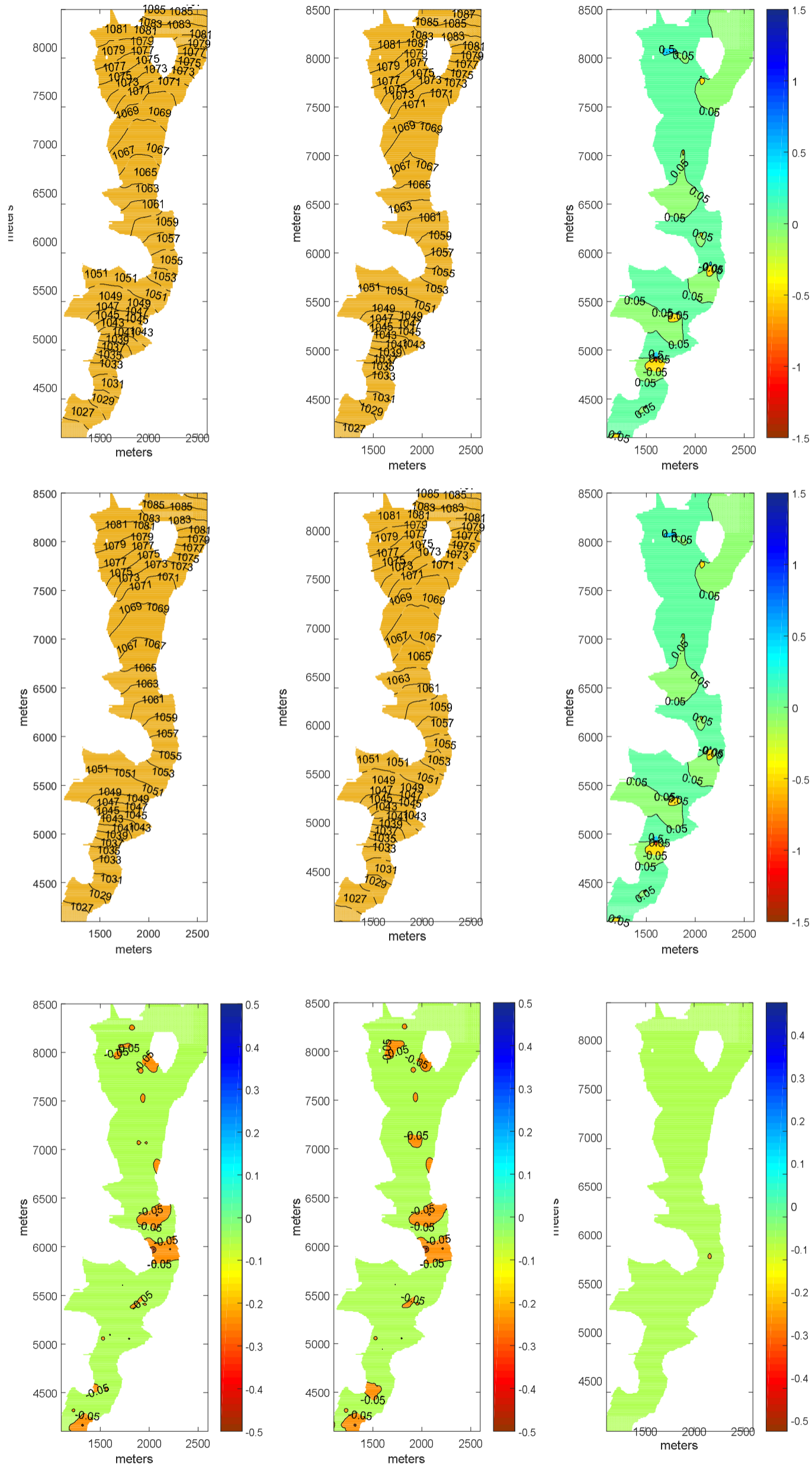
G.3 Appendix E3: Effect of different water use patterns

With the simulation results of the two different water use patterns also the consequences of these water use patterns are discussed. Therefore the results are illustrated as follows.

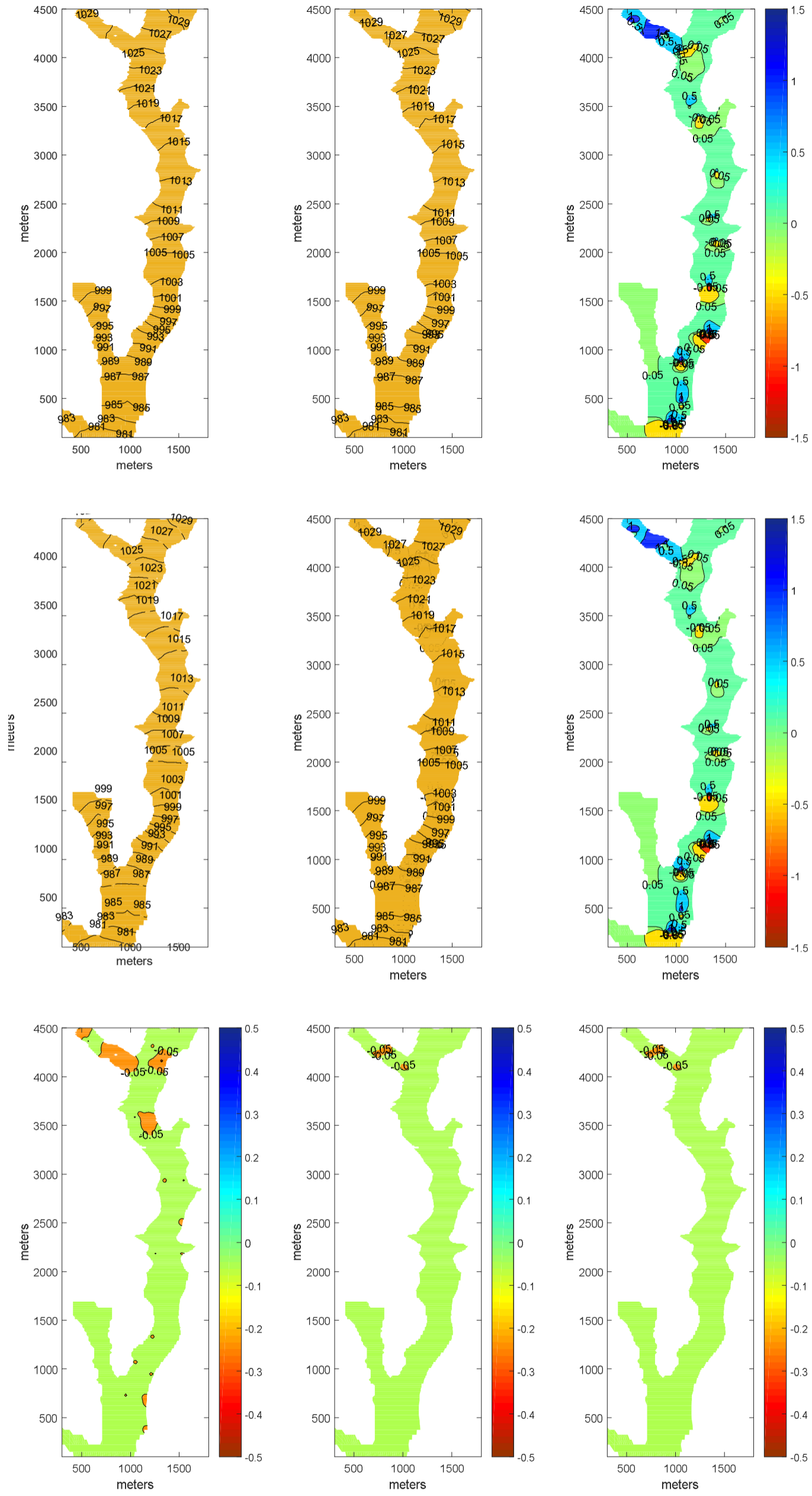


G.3.1 Estimated water use pattern of the year 1990

Kivuna catchment

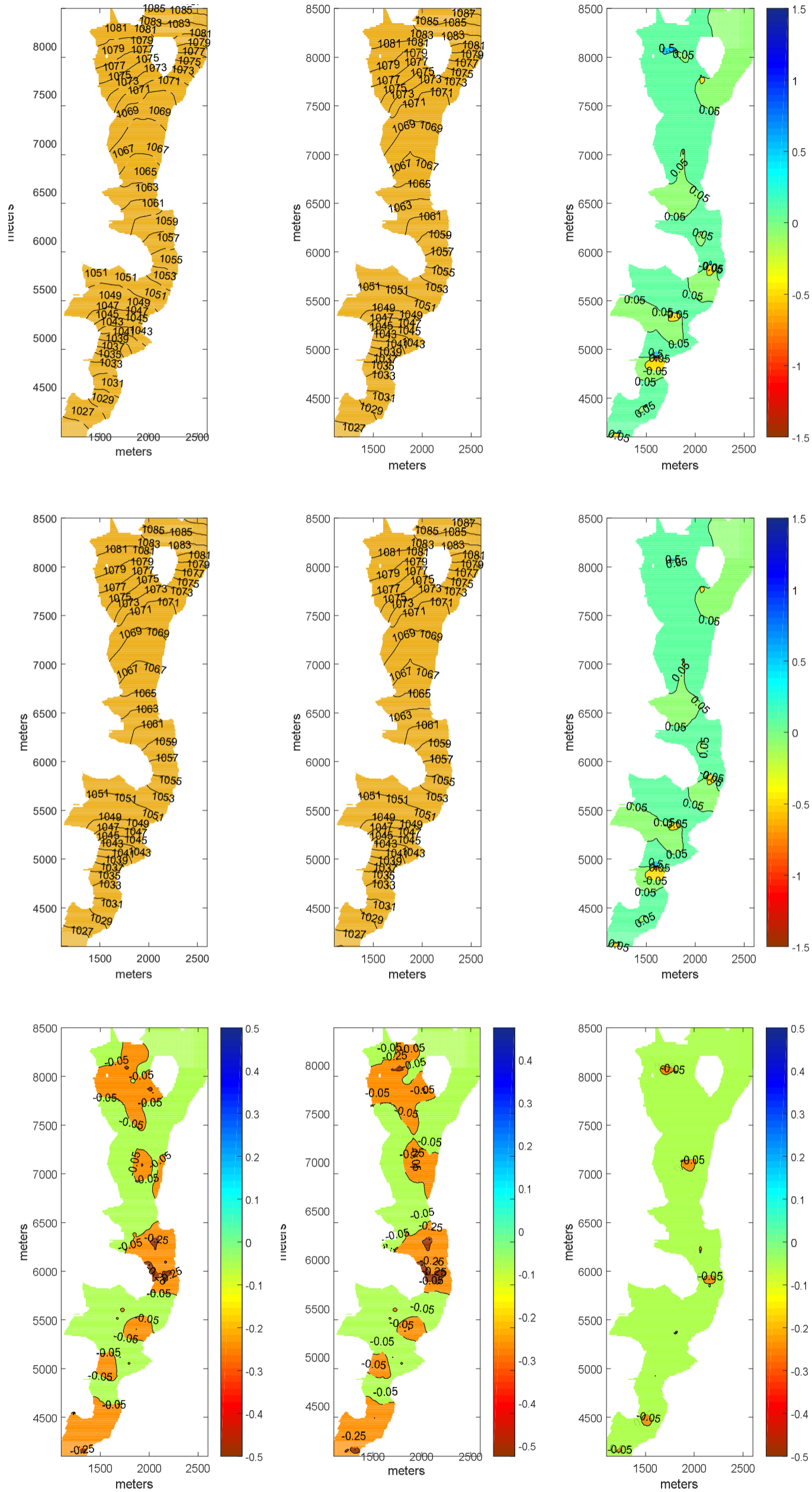


Kiindu catchment

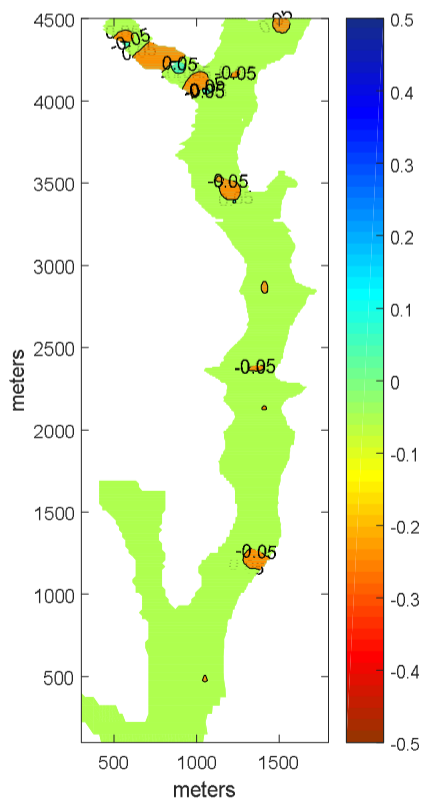
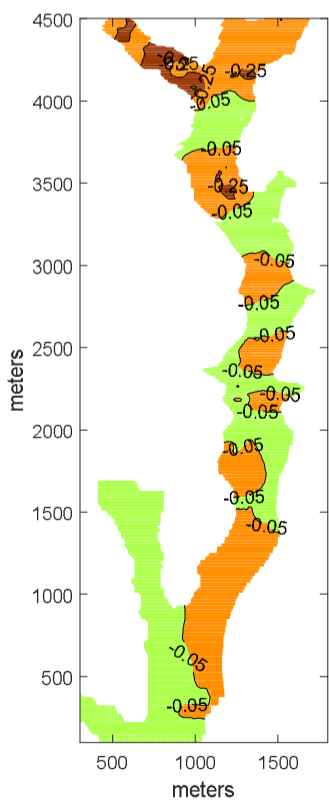
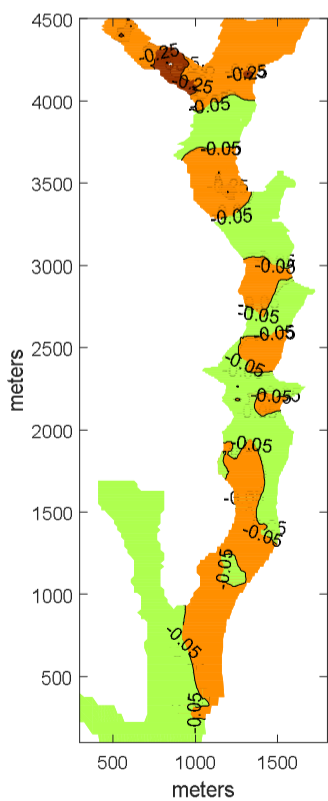
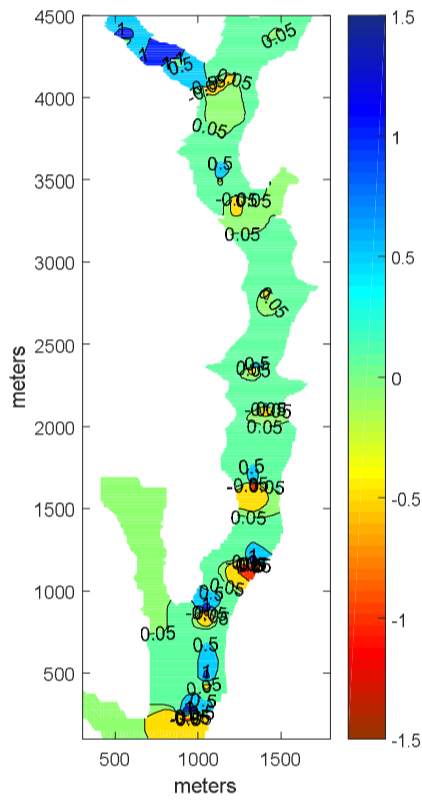
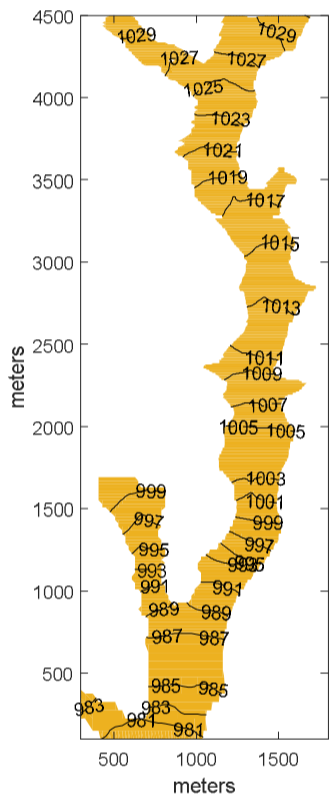
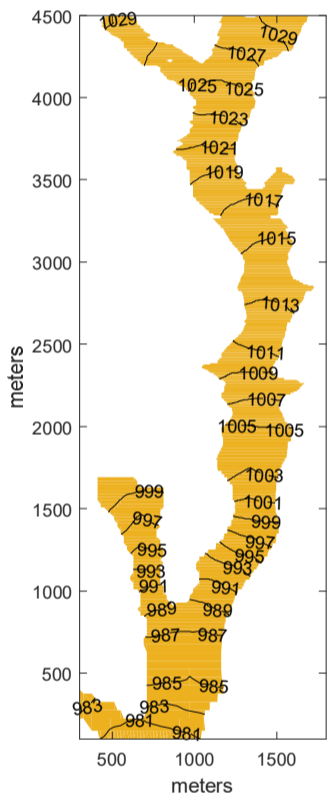
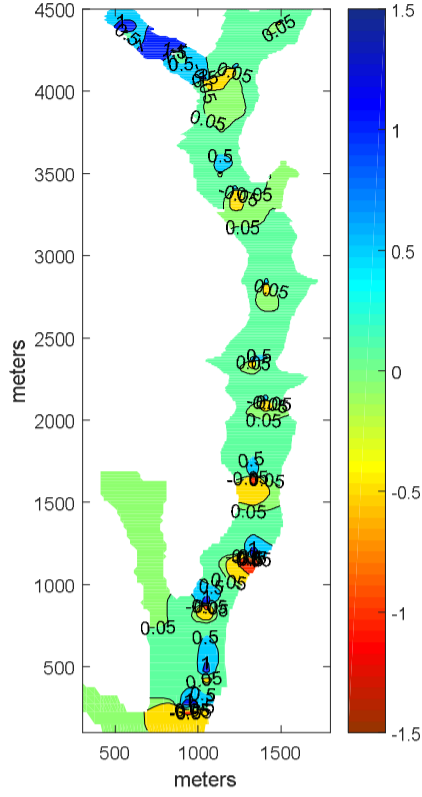
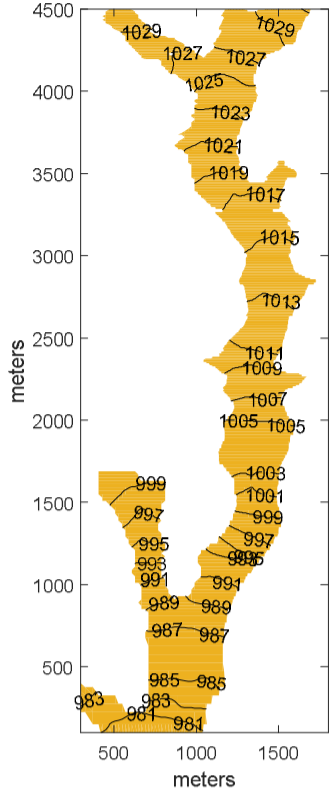
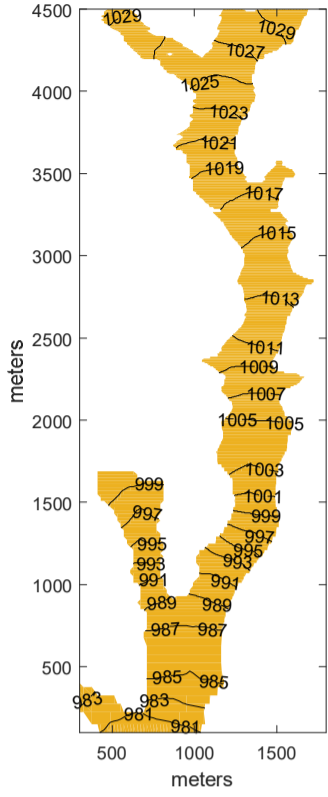


G.3.2 Estimated water use pattern of the year 2014

Kivuna catchment

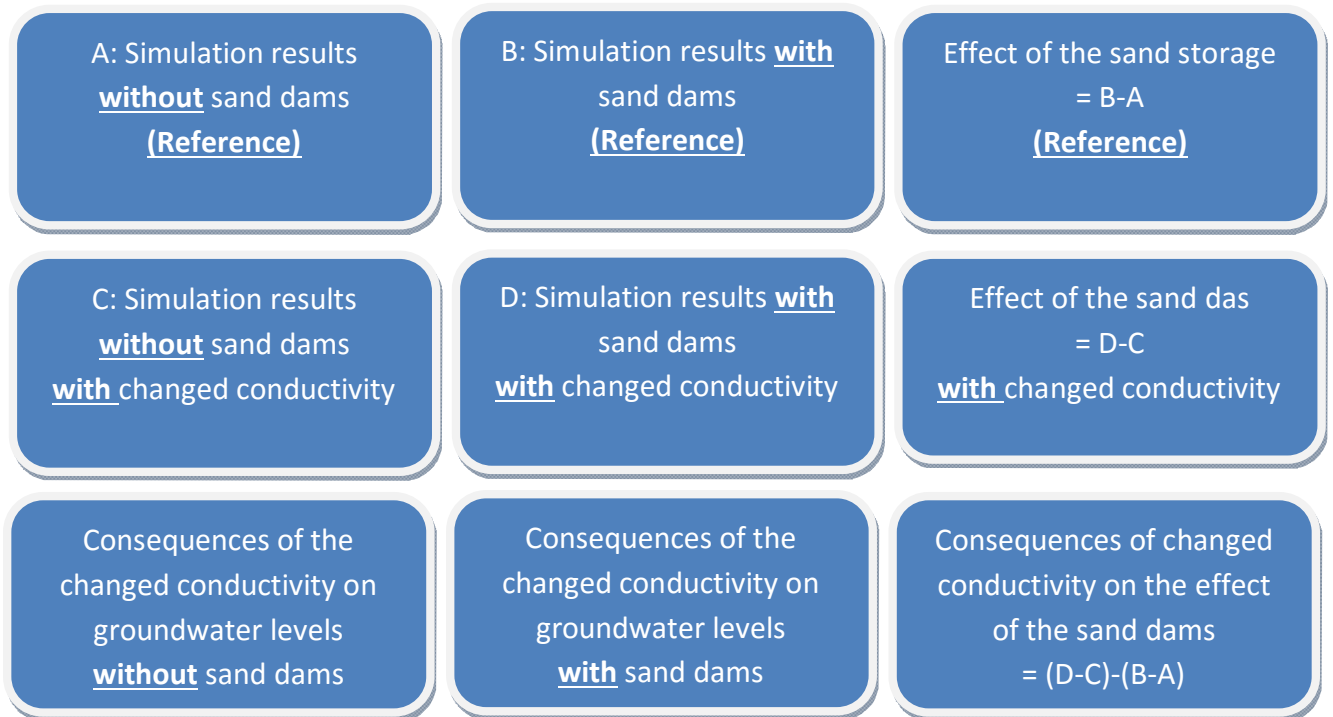


Kiindu catchment



G.4 Appendix E4: The effect of different sets of hydraulic conductivities

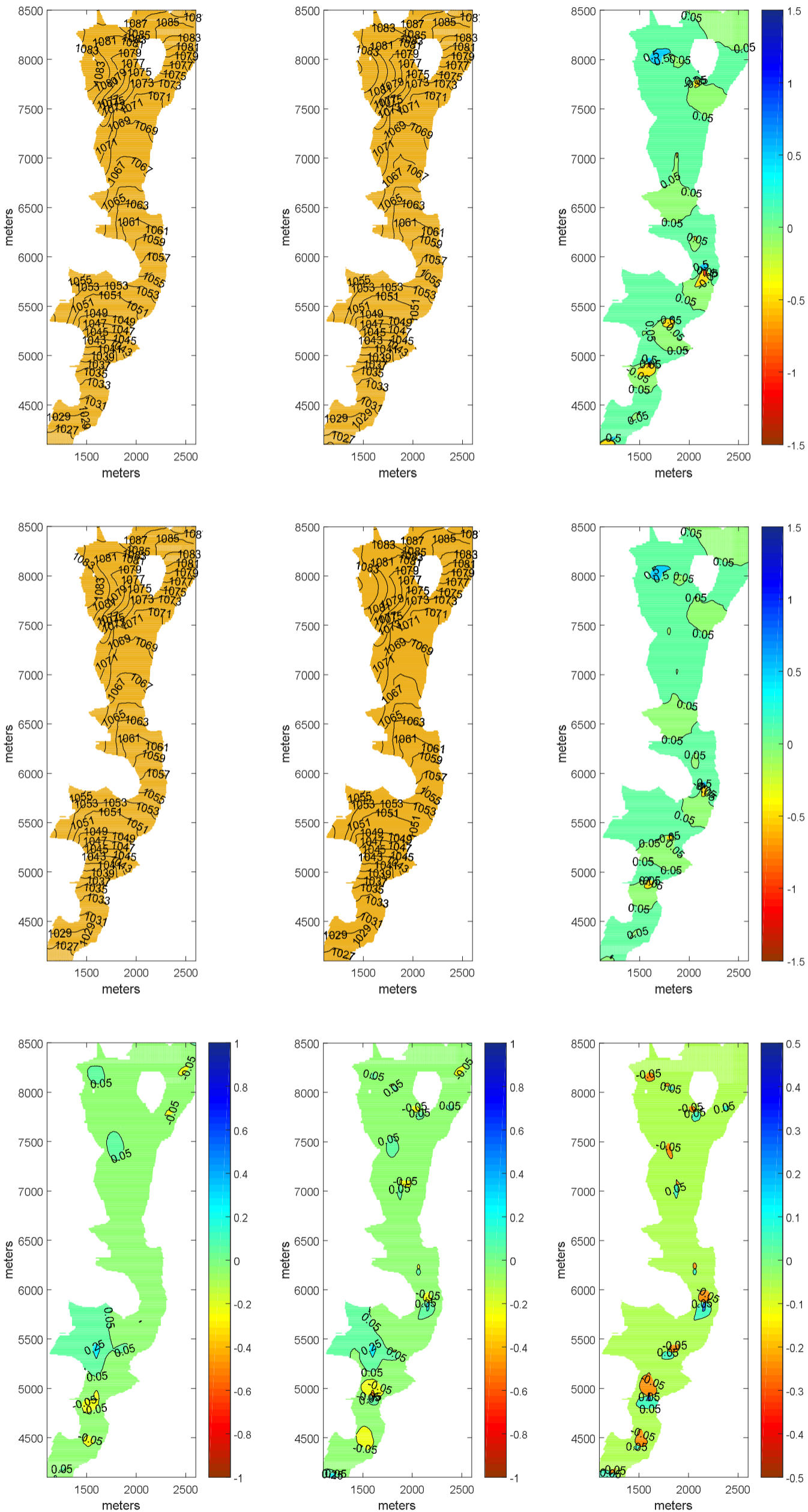
To analyze the influence of different sets of hydraulic conductivities on the effect of the sand dams, a reference set and three sets wherein the hydraulic conductivity of one of the three aquifer types is changed are simulated. The results are illustrated as follows.



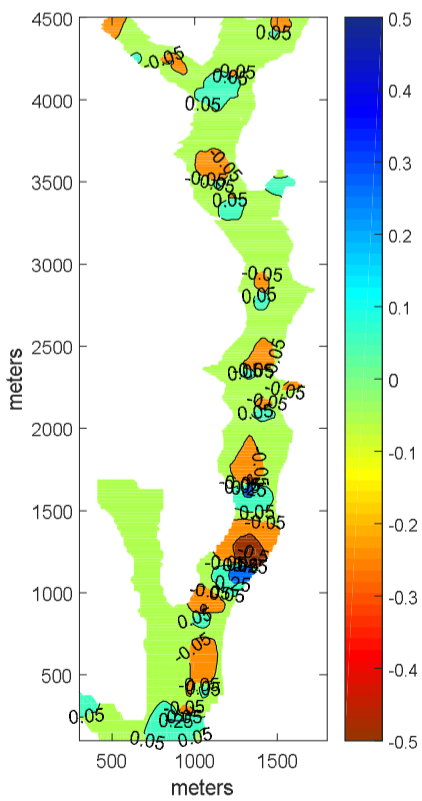
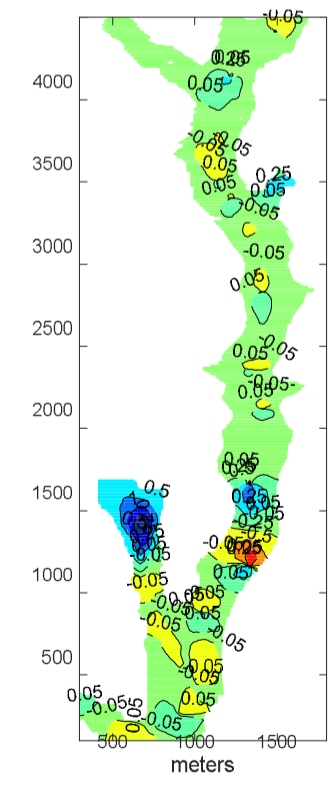
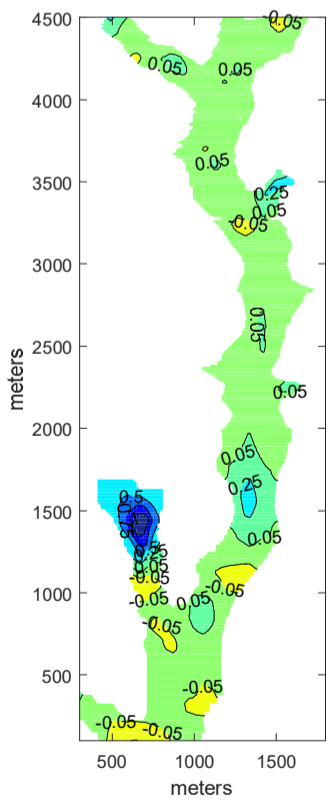
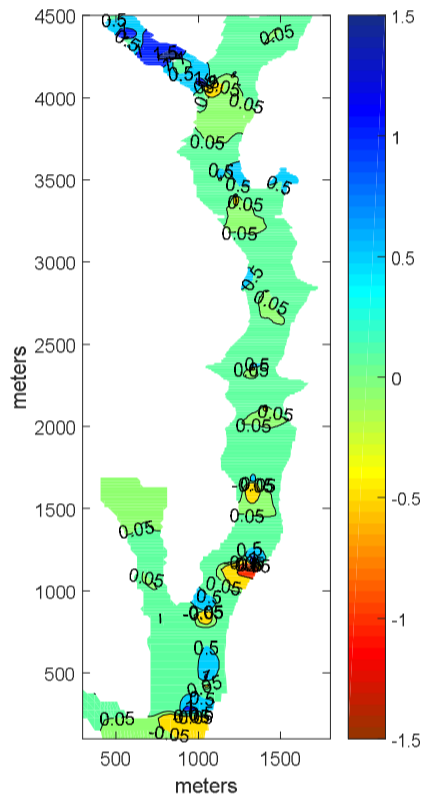
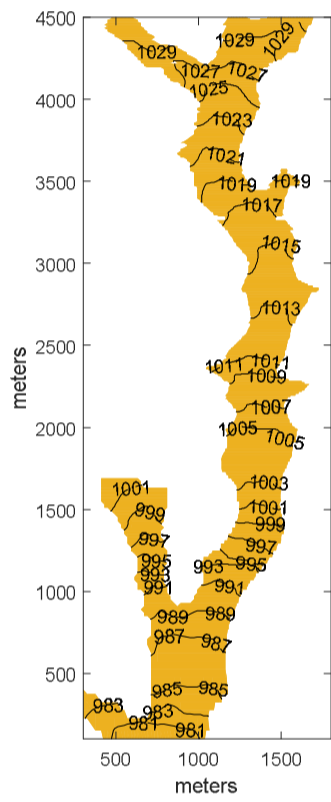
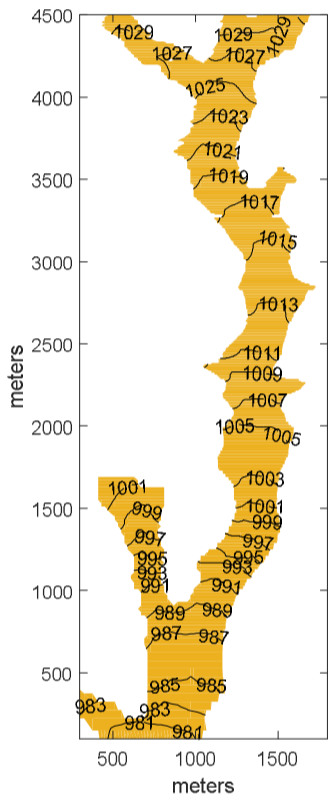
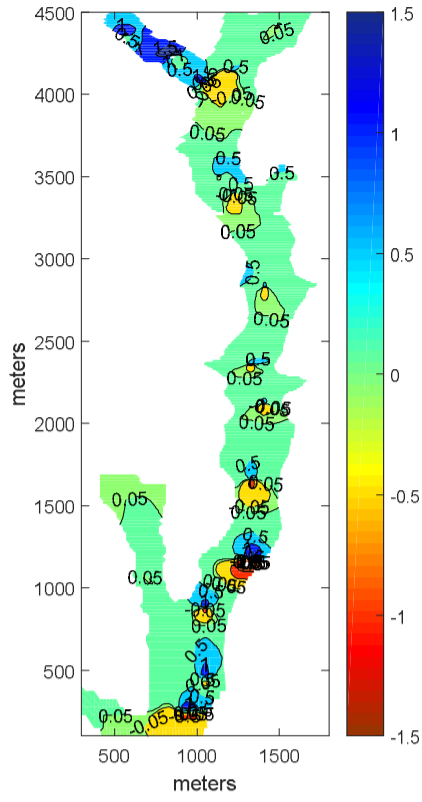
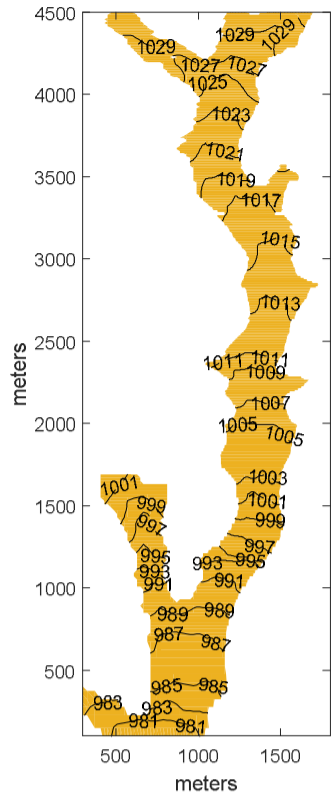
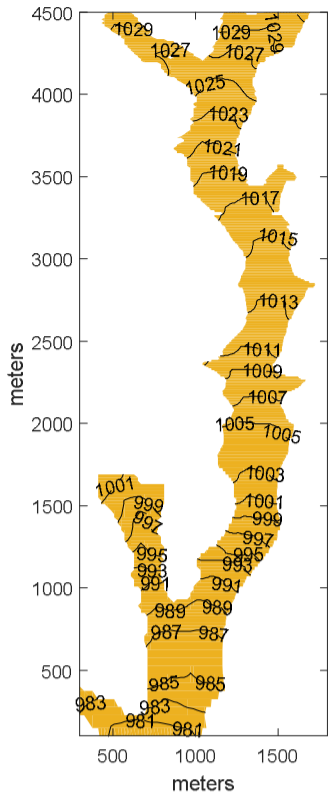
The reference case in the top row is the same for all three alternative sets of hydraulic conductivity. The simulations are made with older sets of hydraulic conductivities. Therefore the reference set is not identical with the simulations in appendix E.1-E.3. How the conductivities influence the effect of the sand dams is illustrated in the lower right figure on every page

G.4.1 The effect of a lower hydraulic conductivity of the riverbed

Kivuna Catchment

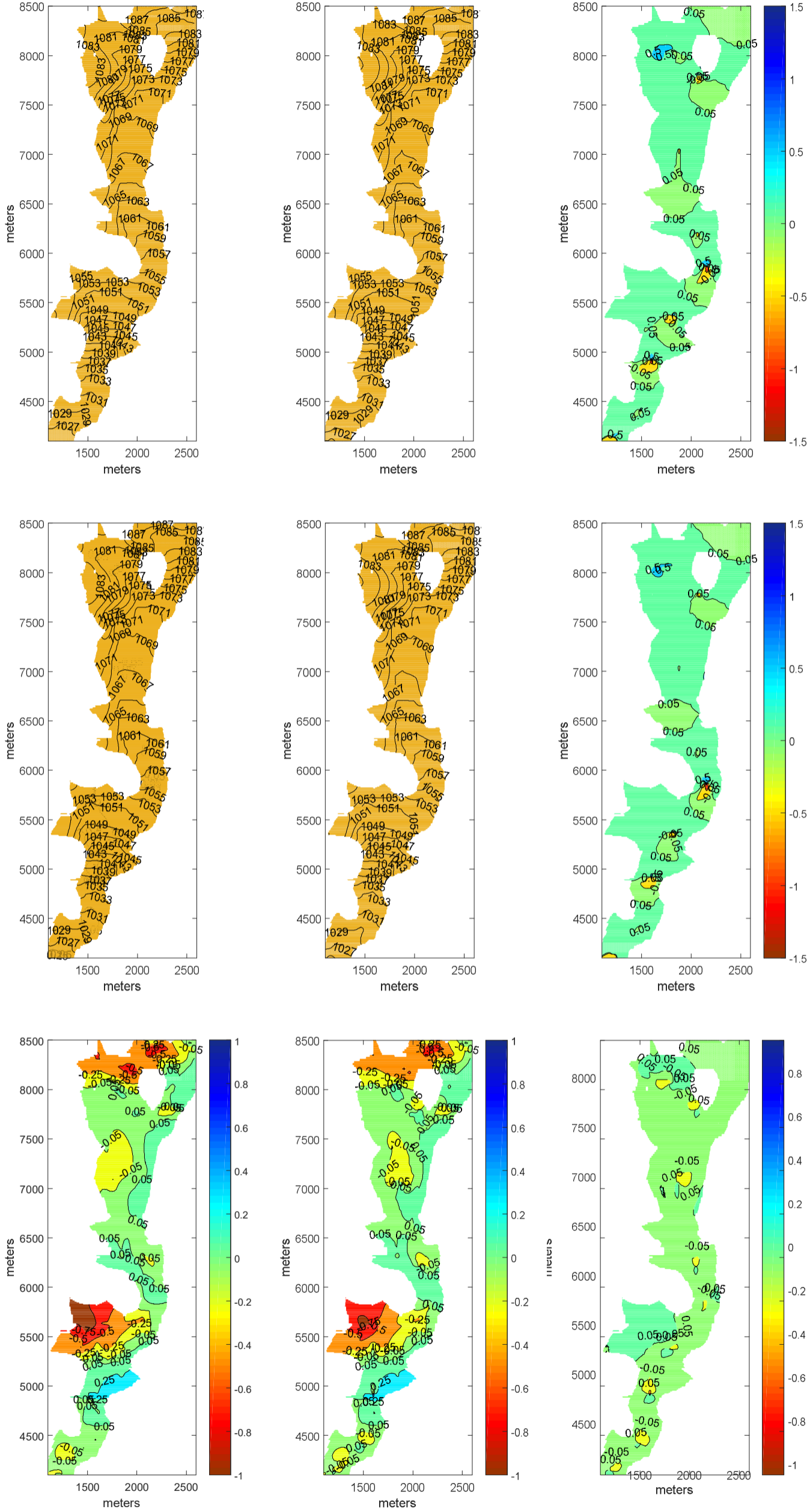


G.4.1.1 *Kiindu catchment*

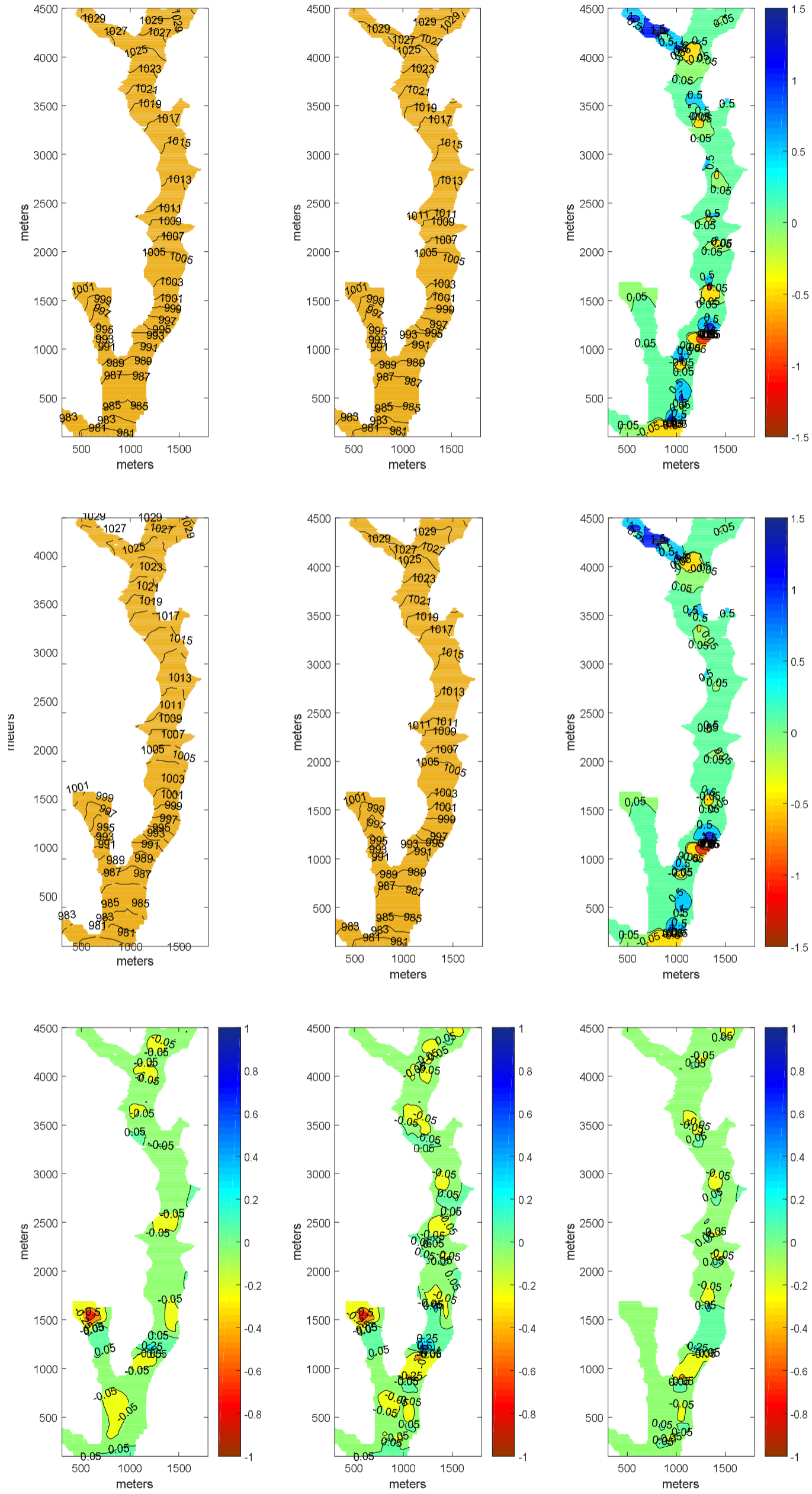


G.4.2 The effect of a higher hydraulic conductivity of the riverbank

Kivuna Catchment

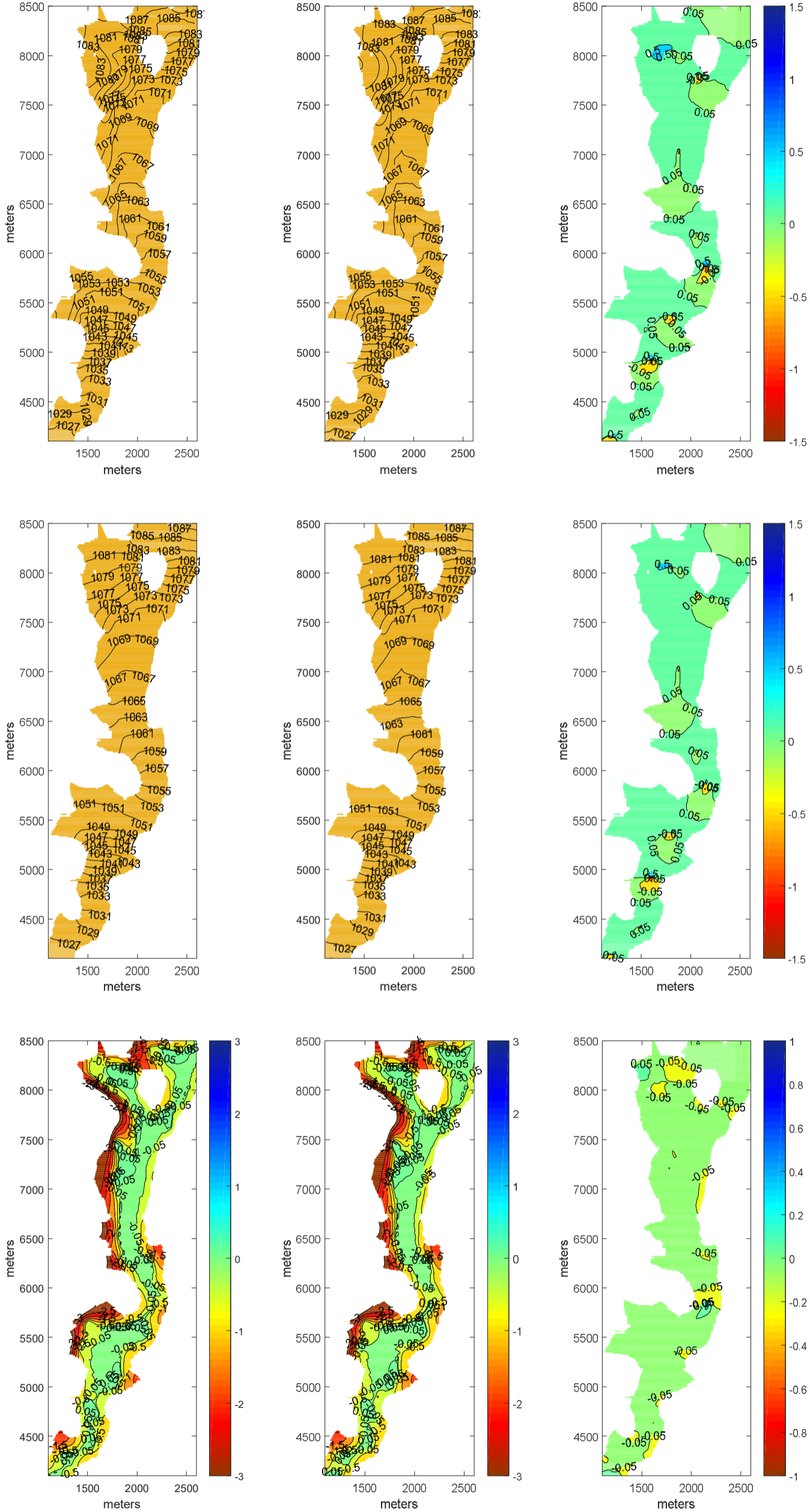


Kiindu catchment



G.4.3 The effect of a higher hydraulic conductivity of the weathered rock

Kivuna Catchment



Kiindu catchment

