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# Measuring and modeling hydrological processes of sand-storage dams on different spatial scales

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ABSTRACT

Sand-storage dams are a successful water harvesting technology in Kenya and a promising solution to ensure water and food security in other semi-arid regions. Assessing the suitability of sand-storage dams for other semi-arid regions requires both a good understanding of the hydrological factors for success of a single dam and the regional effects of a network of dams. Results from a measurement campaign on hydrological processes in the surroundings of a single dam in the Kitui District in Kenya indicated that groundwater levels increase quickly after precipitation. Recession of groundwater levels during the dry season following the rains was more gradual. Based on these results, a groundwater model for a single sand-storage storage dam was developed. As the river banks are important recharge areas for the groundwater stored upstream of the dam, the model showed high sensitivity for parameters like thickness and hydraulic conductivity of the shallow aquifer on the riverbanks and thickness of the sand layer in the riverbed. Parallel to the single dam model, a model for a series of dams was developed. This second model indicated that the inter-dam distance is an important parameter. The distance between dams determined whether influence areas did overlap or that dams behaved as individual structures. When the influence areas did overlap, stored water volume per dam decreased. The results from measurements and modeling confirm that sand-storage dams can effectively increase water availability throughout the dry season. Since measurements and models explain how sand-storage dams successfully modify hydrological systems in semi-arid Kenya, the results can assist in planning introduction of the technology in other regions.

## 1. Introduction

Climate change is expected to increase the severity, duration and frequency of droughts (Lasage et al., 2008). Overcoming periods of low rainfall and drought will thus become increasingly difficult. Increasing droughts are a direct threat to water and food availability for millions of people, particularly in semi-arid regions. Increased water security can be realized when water from periods of relative excess can be stored to improve water availability in dry periods (UN, 2000, 2002). Local water storage can be an important strategy in semi-arid and arid regions outside the reach of perennial rivers and/or with no (or little) groundwater available (Barrow, 1999; Lasage et al., 2008; Mwenge Kahinda et al., 2007). In general, such local storage is sought in small surface reservoirs. These can be successful (Liebe et al., 2007), but surface reservoirs are vulnerable to sedimentation and loss of water through evaporation. An alternative could be to store water in the sub-surface. Although sub-surface reservoirs store smaller volumes of water compared to surface reservoirs, evaporation losses are lower and risks of contamination of stored water are reduced as direct contact is minimized and parasites cannot breed underground.

In Kitui District, Kenya, the local Non-Governmental Organization Sahelian Solutions has built some 500 sub-surface dams. Their success has attracted the attention of the international community. The Kitui experiences indicate that sub-surface water storage is a possible solution to overcome problems of drought and associated food insecurity in other regions. Within the research project "Rehydrating the Earth in Arid Lands", first efforts to study dam hydrology were developed (Ertsen et al., 2005; Ertsen and Hut, 2009; Hut et al., 2008). More recently, Acacia Water (formerly known as Acacia Institute) initiated a research program entitled "Recharge Techniques and Water Conservation in East Africa; Up-scaling and Dissemination of the good practices with the Kitui sand dams" (Aerts et al., 2007; Lasage et al., 2008). The program aims at promoting up-scaling of

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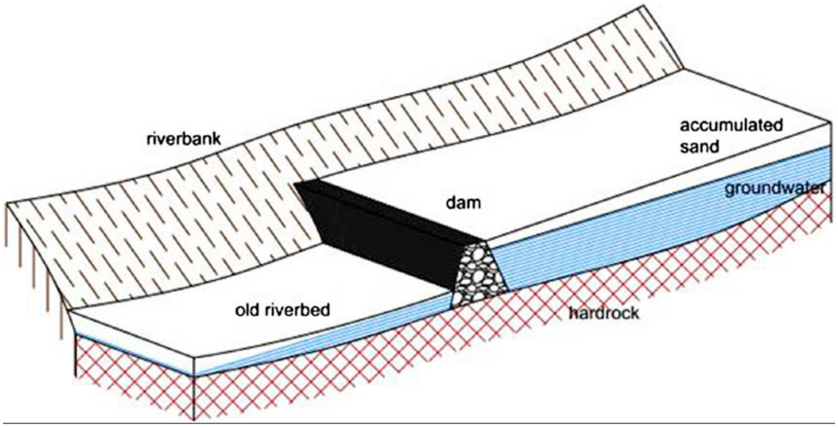

**Fig. 1.** Schematic representation of a sand-storage dam.

community based sub-surface dams and related water conservation techniques. Acacia Water, in cooperation with the Dutch RAIN Foundation, is currently identifying suitable catchments in southern Ethiopia to construct a cascade of several dams.

Determining dams' success requires understanding of potential water availability from sand-storage dams in relation to changes in hydrological patterns and in relation to potential changes in water consumption. This paper presents results of measurements on dam hydrology and discusses how modeling based on these results can be applied to support analysis and planning of interventions promoting sub-surface dams. The success of a dam program will be determined by issues on different spatial scales, including the viability of a series of dams in a larger network. In building a network of dams as in Kitui, however, success needs to be earned every single time a dam is constructed as it were, as one negative experience would immediately influence the possibilities for the next dam to be constructed. After reviewing available literature on sand-storage dams, data for the Kitui region are discussed. Then, the focus will be on two modeling efforts. First, a groundwater model of a single dam is described. Then, a cascade model of three dams is discussed. These two models differ in level of detail and model period. The single dam model studies a period of eighteen months using field measurements for calibration. The three dam model studies a forty year period using simplified seasonal input based on the measurements. It serves as a conceptual model focusing on understanding the links between individual dams.

## 2. Literature review

Water harvesting technologies, which concentrate precipitation through runoff and storage, including sub-surface storage, for beneficial use, have probably been in use since 9000 BC (Oweis et al., 2001). In the Alpujarra, Spain, irrigation channels were used to recharge groundwater (Pulido-Bosch and Ben Sbih, 1995). Dams obstructing groundwater flow were constructed on the island of Sardinia in Roman times (Nilsson, 1988). Water can be stored in sandy riverbeds of seasonal rivers upstream of so-called sand-storage dams, which are often referred to as sand dams: walls across the riverbed with a crest rising up to several meters above bed level (Fig. 1; Plate 1) (Aerts et al., 2007; Ertsen and Hut, 2009; Hut et al., 2008; Nilsson, 1988; Van Haveren, 2004). The Kitui dams are sand-storage dams. Such dams were already known several thousands of years ago in the Middle East, but have also been used for water supply in the southwestern United States and northern Mexico since the mid 1800s (Van Haveren, 2004). Other examples come from Namibia (Stengel, 1968). The sediments carried by the river during the rainy season will settle upstream of the dam. Gradually the reservoir will fill up with sand, which is used to store water from the rainy season. A single flash flood may fully recharge a sand reservoir. Upon full saturation of the reservoir, the remaining flash floods will pass over the dam. From the sand volume with its higher groundwater level, water will infiltrate into the riverbanks. Therefore, the effective storage of a sand-storage dam is

**Plate 1.** Example of a sand-storage dam.

higher than the sand volume directly caused by the dam. Water becomes available by wells or pumps on the river bank close to the dam or by using scoop holes in the sand reservoir.

Research on water consumption of communities from sand-storage dams is rare and not often officially published. Several project reports are available, such as for example Rempel et al. (2005) and Rhebergen and De Bruijn (2006). On the hydro-geological processes around sand-storage dams and how dams influence these not much is published either, although again several reports are available (including Borst and Haas De, 2006; Hoogmoed, 2007). Hofkes and Visscher (1986), Ishida et al. (2003) and Van Haveren (2004) describe general hydrological characteristics of sand-storage dams. Others have discussed relevant specific elements within the general hydrology of sand-storage techniques and not necessarily restricted to sand-storage dams. Whiting and Pomeranets (1997) discuss water storage in river banks and ways it influences base flows. Lange (2005) discusses infiltration processes and thus groundwater recharge in arid Namibia and concludes that single high magnitude flows are more important in recharging the groundwater than frequent smaller flows. Work of Mansell and Hussey (2005) presents results from surface and subsurface flow analysis for ephemeral rivers in Zimbabwe, concluding that the sand properties of the aquifer were largely controlling flows and storage in these rivers. Finally, dynamics of evaporation from sand volumes has been studied by Yamanaka et al. (1998) and Yamanaka and Yonetani (1999). Other studies directly applied in our work will be included when discussing the appropriate element of sand-storage dam technology.

Apart from the lack of knowledge of sand-storage dam hydrology, another issue to be dealt with is the lack of certainty when studying and/or planning for sub-surface water storage within the context of climate change. Most research studying strategies to adapt to climate change tends to focus on reducing future vulnerability based on predefined climate change scenarios (Lasage et al., 2008). This is an important aspect, as is shown by Aerts et al. (2007) who studied Kitui District in Kenya. Their model study showed that currently the sand-storage dams in Kitui capture maximally 3.8% from the total runoff generated in the wet seasons. Considering climate change and an increase in the number of dams, this percentage can become as high as 60%! With decreasing rainfall, this would be 60% of a lower total flow, but extensive downstream water shortages should be expected under climate change. However, the model applied in this study, the STREAM model (Aerts et al., 1999), did not take into account recharging processes during the wet seasons nor detailed hydrological processes around dams, including lateral base flow from the banks and longitudinal base flow in the riverbed. These detailed hydrological patterns are needed to understand the influence of sand-storage dams on local and regional hydrological patterns. Below we will discuss how measurements and modeling can build such understanding and can be applied in decision making on implementing sand-storage dam technology in other regions.

## 3. Methods

### 3.1. Single dam model

A physically based numerical groundwater model was set up in the Triwaco environment to improve understanding of hydrological processes regarding the functioning of a sand-storage

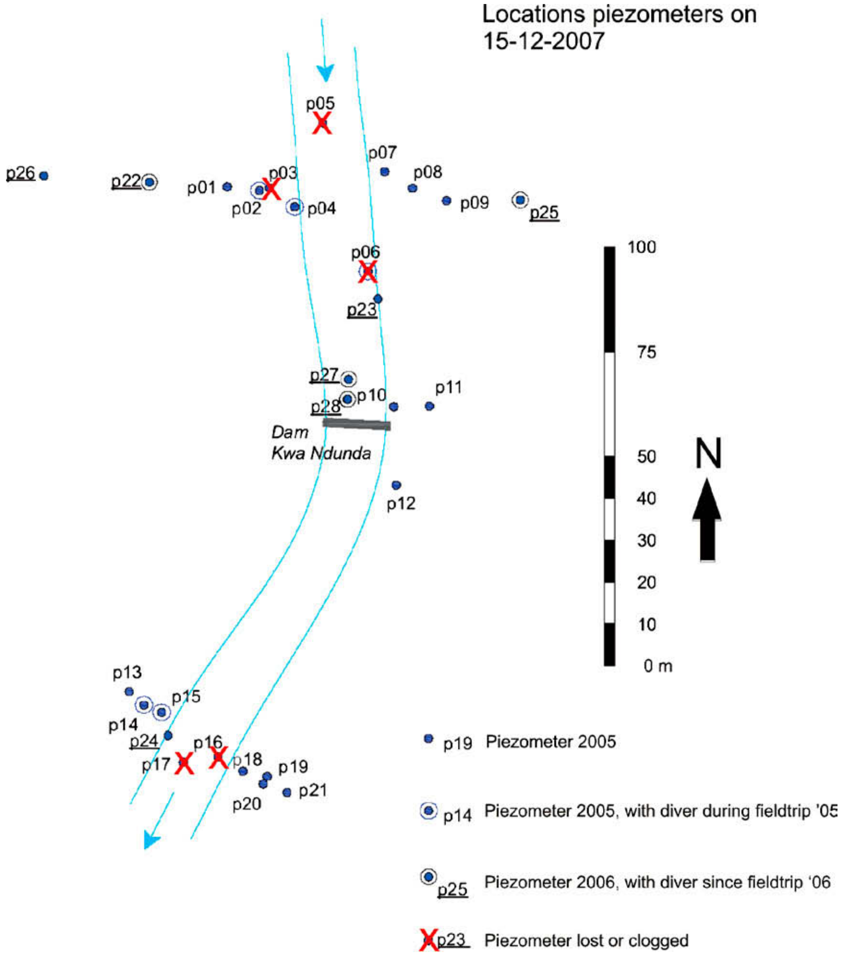

**Fig. 2.** Piezometers around the Kwa Ndunda sand-storage dam in December 2006.

dam (Hoogmoed, 2007; Royal Haskoning, 2002). The model was used to study which physical properties were determining the successful functioning of a dam. Calibration data were gathered during two field campaigns (October 2005 and October 2006) around a typical sand-storage dam in the Kiindu river (Kitui District, Kenya, UTM 389,200 m East, 9,838,380 m North). The Kiindu river is a small seasonal river with a length of 16 km and a catchment area of 37 km$^2$. Using the same numerical model, the influence of increased river bank infiltration on groundwater recharge and availability in relation to sand-storage dams is assessed.

In the Kiindu catchment, hard rock mainly consists of granitoid and biotite gneisses intersected by pegmatite veins. The gneisses form the basement of the area, underlying weathered rock formed by erosion during the Quaternary. Thickness of the layer and degree of weathering differ throughout the area. On top of the weathered rock a layer consisting primarily of clay and silt on the riverbanks and sand or silt in the riverbeds is present. At the location of the Kwa Ndunda sand-storage dam, the riverbed is filled with coarse sand, which is an erosion product of different lithological units, especially gneisses. The river banks consist of clay (west) and silt (east). Thickness of the sediment layer on the banks and in the riverbed varied because of the irregular shape of the basement.

The hydraulic properties of the sediments (river banks, river bed and weathered rock) were determined. Porosity was determined using a volumetric method based on weight. Hydraulic conductivity was determined using the inverse augerhole method and a double ring infiltrometer. Hydrological parameters were determined to provide the input to the model. Precipitation was measured using an automated tipping bucket rain gauge system and manual measurements using a totalizer (locally produced). Automated measurements were conducted during the field visits. The manual measurements are performed continuously on a daily interval from October 2005 onward. Evaporation has been measured during the 2005 field visit and through water chemistry using chloride as a tracer (Hoogmoed, 2007). In 2006, a total of 28 piezometers were installed, in which groundwater levels were measured manually on a daily interval during the dry season and twice a day during the wet season (Fig. 2). Additionally, data has been collected on discharge through establishing a discharge – surface-water level relationship (Jansen, 2007) and on the sediment – discharge relationship (Gijsbertsen, 2007).

A finite element model was used to construct a groundwater model of Kwa Ndunda dam. The model area was located between the dams upstream and downstream of Kwa Ndunda dam and between the water divides on both sides of the river to prevent

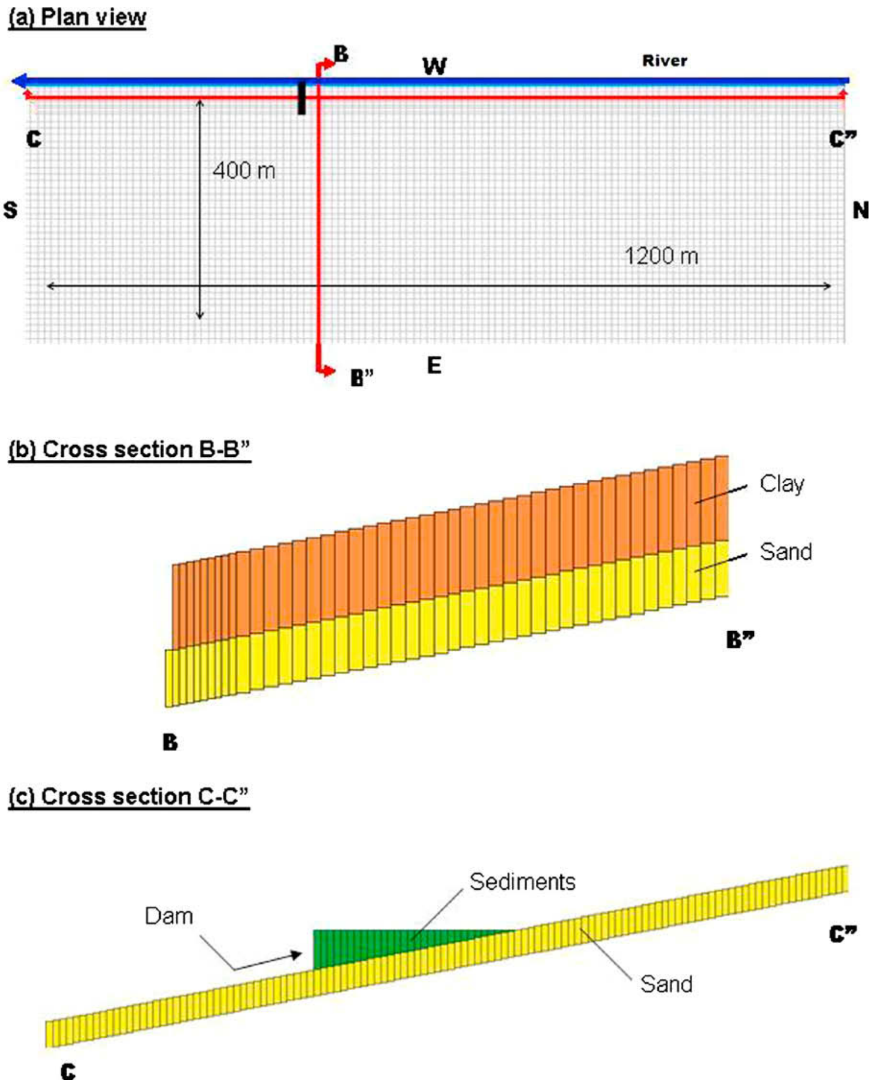

**Fig. 3.** Detail of one dam in the three dams model set-up.

the boundary conditions influencing groundwater flow in the study area. The model area was 1.9 $km^2$, with a length of 1900 m, and a width of 1950 m. Total number of nodes was 36,274. The sand-storage dam is modeled as a narrow zone of nodes with a very low conductivity. The resistivity between river bed and banks is incorporated likewise. The resistance to flow between river bed and banks is expected because suspended load might clog the transition between the permeable river bed and the less permeable river banks. The width of the river was set at 15 m as observed in the field. River stages were modeled using a controlled water level. To account for instabilities in the initial period, an initial year of simulation was added to the model. One year in advance of the actual model run proved to be sufficient to obtain a stable model; elevated groundwater levels due to recharge in the first time step of five days decreased to a constant groundwater level within fifty days (10 time steps), after which the drop of groundwater level was almost negligible. To determine the relative importance of parameters, a sensitivity analysis was performed. Parameter values from measurements were varied using various multiplication factors between 0.5 and 1.5.

### 3.2. Cascade model

To study the spatial relations between a series of dams, a cascade model was developed in Modflow, in which a series of three dams was included (Orient Quilis, 2007). The model results indicate how hydrological processes around three dams can be understood and which factors are influencing the hydrology on the longer term. The three dam modeling approach is similar as the approach discussed in Hut et al. (2008) for a single dam model, as the three dam model was not calibrated on actual measurements. Data from measurements over longer periods are not yet available. The field measurements that were available were used to ensure that the basic process of a sand-storage dam was captured by the model. The model consists of three similar dams linked to each other within a larger grid of 2600 by 400 m. Fig. 3 shows part of the modeling grid. The model consists of two aquifers. The sandy riverbed is represented as a layer of two meter with high conductivity. The riverbanks with their lower permeability are represented as a combination of a silty-clayey layer of three meter on top of a sandy layer similar to the layer in the river bed. The total system has a 1% slope along the river bed. Riverbanks have a 1% slope towards the riverbed.

The sand-storage dam itself was modeled as a wall located in the riverbed blocking the entire riverbed and with 5 m wing walls on both sides. The wall was modeled as an impermeable horizontal flow barrier without thickness extending 3 m above the riverbed. Upstream of the dam a wedge of sediments deposited by the river was assumed. The soils were considered to be homogenous and isotropic. The hydraulic conductivity values used are given in Table 1. The boundary conditions were set at a horizontal constant head of 1 m above the rock layer at the riverbed for the Northern and Southern boundaries an as no flow boundaries for the Eastern and Western boundaries. The dimensions of the grid and the distance between the dams and the boundaries were taken large enough to assure there was no influence of the boundary conditions on the observations next to the dam locations.

Two rainy seasons were defined: from February 1 to 28 and from November 1 to December 31. Rainy seasons were modeled as saturation of the riverbed and the reservoir upstream of a

**Table 1**
Hydraulic conductivities, specific yield, and specific storage of the modeled layers

| | Sand | Clay |
|---|---|---|
| $k$ (m/day) | 0.864 | 0.00864 |
| $S_y$ (−) | 0.3 | 0.08 |
| $S_z$ (−) | 0.0001 | – |

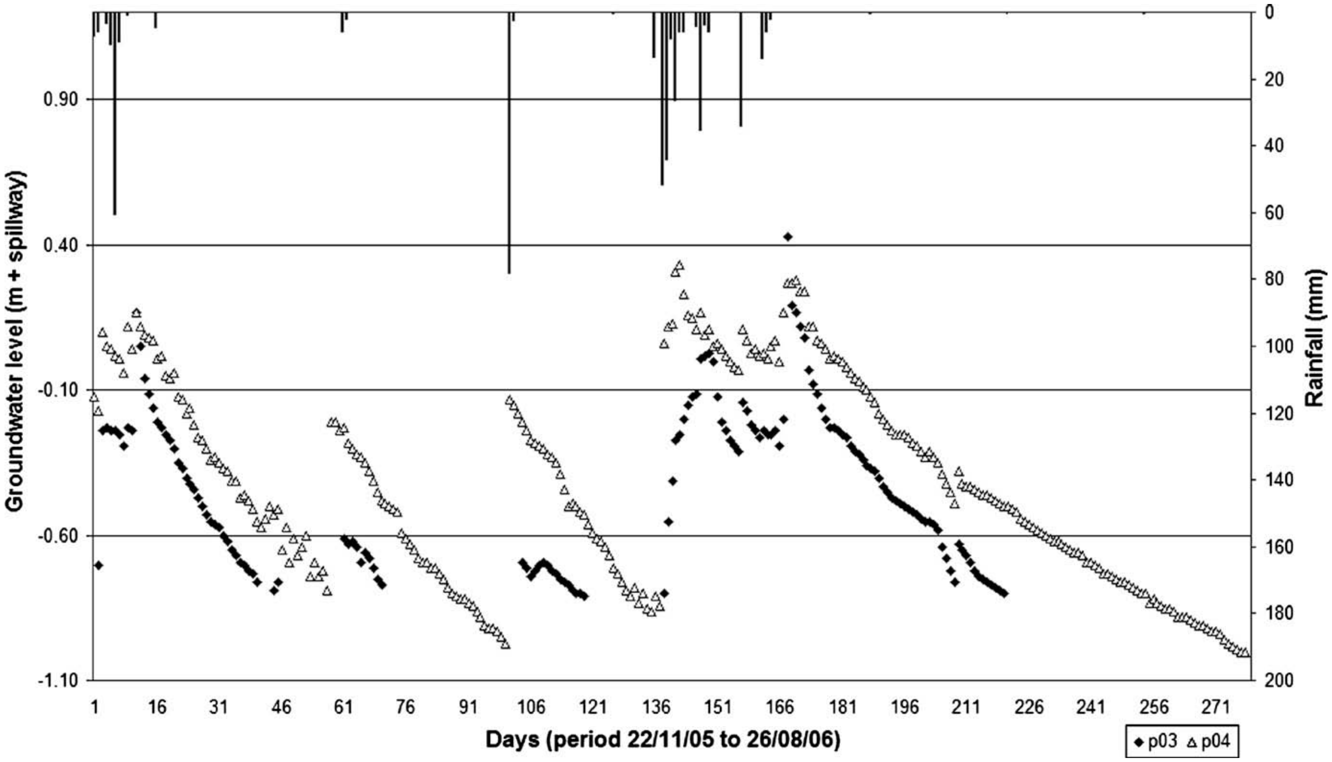

**Fig. 4.** Rainfall in the Kiindu catchment and groundwater levels in river bed and western bank.

dam. This was implemented by modeling a large recharge value to instantaneously saturate the riverbed with a drain located at the riverbed surface level with a very large conductance to prevent the heads from rising above the top of the riverbed. In all the simulations, time steps were 5 days. To account for instabilities in the initial period, additional years were run prior to the actual model simulations in order to arrive at a stable initial model.

## 4. Results

### 4.1. Single dam measurements

The coarse riverbed sand had a porosity of 0.42. Silty soils had a porosity between 0.30 and 0.34. Saturated hydraulic conductivity of silty soil varied between 10.1 and 14.6 m/d. Hydraulic conductivity of the clay was measured twice and showed a variation between

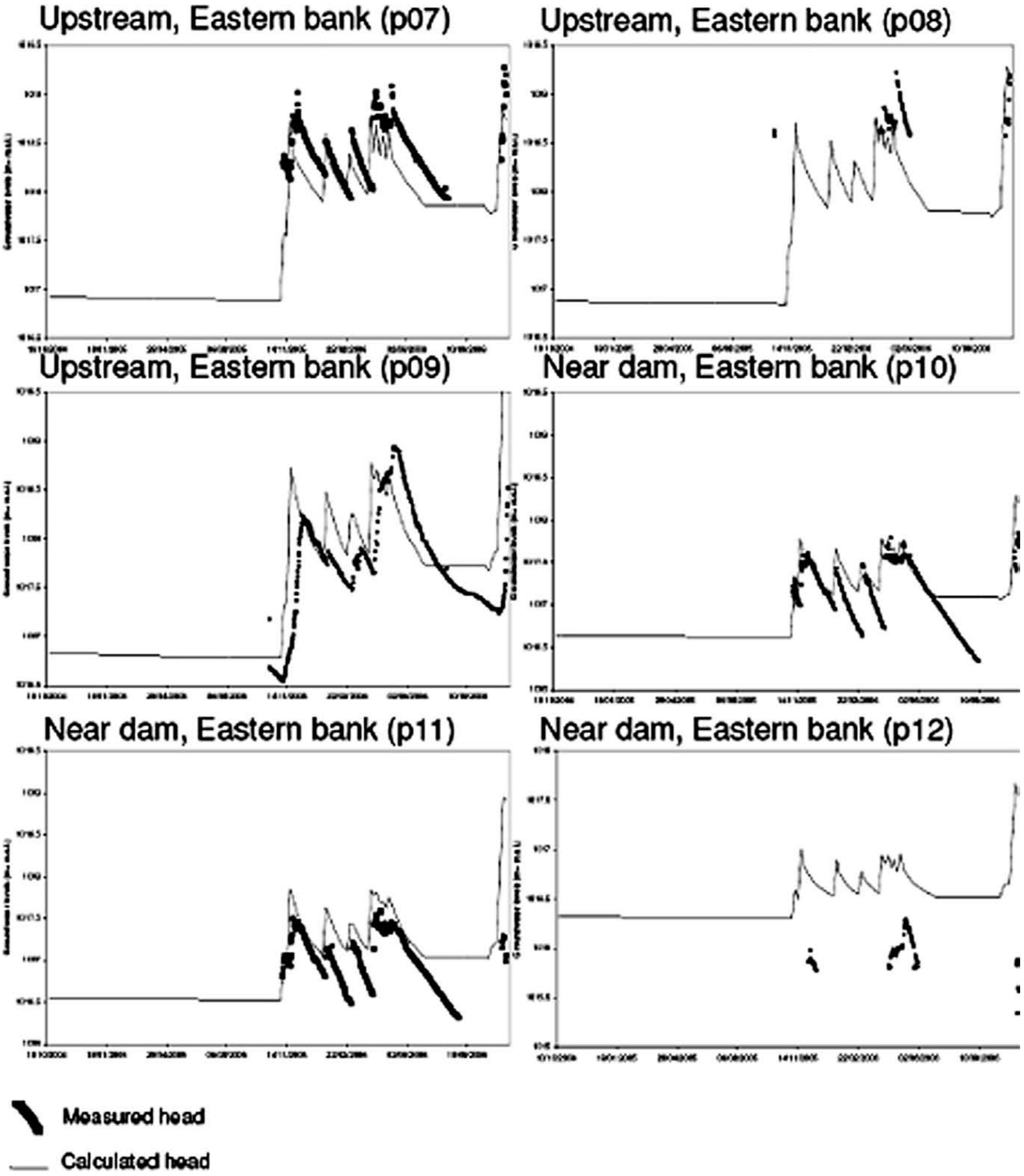

**Fig. 5.** Example model results.

**Table 2**
Hydraulic values used in the calibrated model

| Soil type | $K_{sat}$ (m/d) | Storage coefficient (Andersen and Woessner, 2002) |
|---|---|---|
| Slit | 10 | $1 * 10^{-3}$ |
| Clay | 2 | $1 * 10^{-3}$ |
| Weathered rock | 4 | $1 * 10^{-3}$ |
| Sand | 60 | $5 * 10^{-4}$ |

1.2 and 3.2 m/d. The hydraulic conductivity in the riverbed showed large variations: 35.7–56.7 m/d. The hydraulic conductivity of the weathered rock varied between 7.2 and 12.0 m/d.

Daily precipitation data and changes in groundwater levels seemed to be correlated: immediately during and after a precipitation event, groundwater levels started to rise in response to recharge, while during the dry season groundwater table lowered (Fig. 4). In general, in the measured groundwater levels three components could be distinguished: (1) the fast rise of the groundwater table as a response to runoff from precipitation, (2) the constant shape of the recession curves during short dry periods (e.g. day 58–100 in Fig. 4 (18-01-2006 to 01-03-2006)) which seemed to be dependent on soil types, since observed recessions in the sandy riverbeds were more gradual than those in clayey soils on the riverbanks, (3) during a prolonged dry season (e.g. day 184–278 in Fig. 4 (24-05-2006 to 26-08-2006)). The gradient of the recession curve evidently decreased when groundwater levels fell below the bottom of the sandy toplayer (−2.52 m + spillway).

As was stated above, groundwater levels responded rapidly to precipitation. The groundwater level in the riverbed showed the first and largest amplitude followed by the piezometer closest to the river bed. Amplitude decreased and response time increased with increasing distance from the river bed. The aquifer upstream of the sand-storage dam filled up in immediate response to precipitation. Although little has been published on groundwater dynamics in small semi-arid catchments, it is clear that groundwater levels can respond rapidly to runoff or precipitation (Butterworth et al., 1999). Studies of Andersen et al. (1998) and Wheater and Al Weshah (2002) on sand rivers of Botswana showed a single major rainfall event after a long dry period being sufficient to recharge the alluvial riverbed aquifer completely.

### 4.2. Single dam model

Model results fitted observed groundwater levels best when the thickness of the sediment layer was set at 1.6 m at the riverbed ranging to 4 meter on the eastern riverbank and from 1.5 m to 5 m on the western riverbank (Fig. 5; Table 2). At the location of the

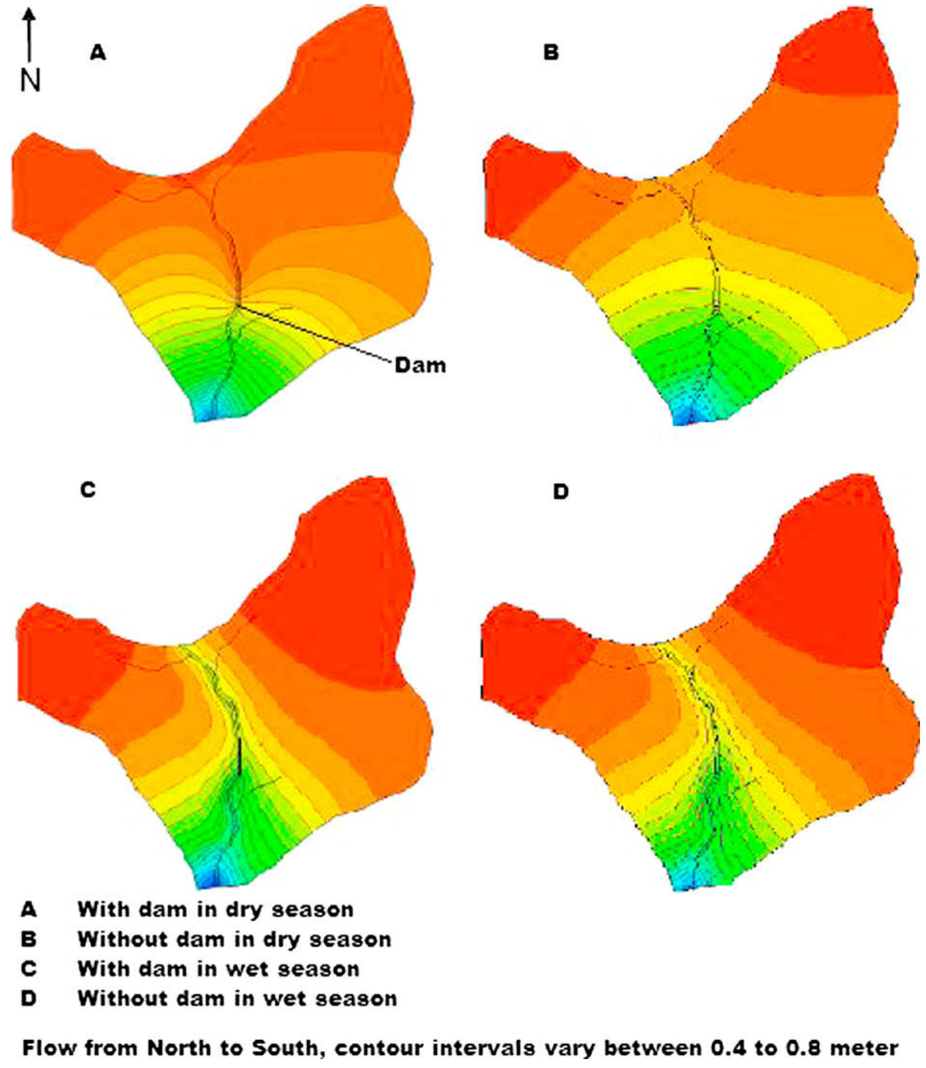

**Fig. 6.** Representative groundwater contours for dry and wet season.

riverbed, the sediment layer consisted of coarse sand. Thickness of the sand layer was largest directly upstream of the sand-storage dam (1.6 m), decreasing to 10 cm at the location of the upstream sand-storage dam. The same schematization was used for the sand

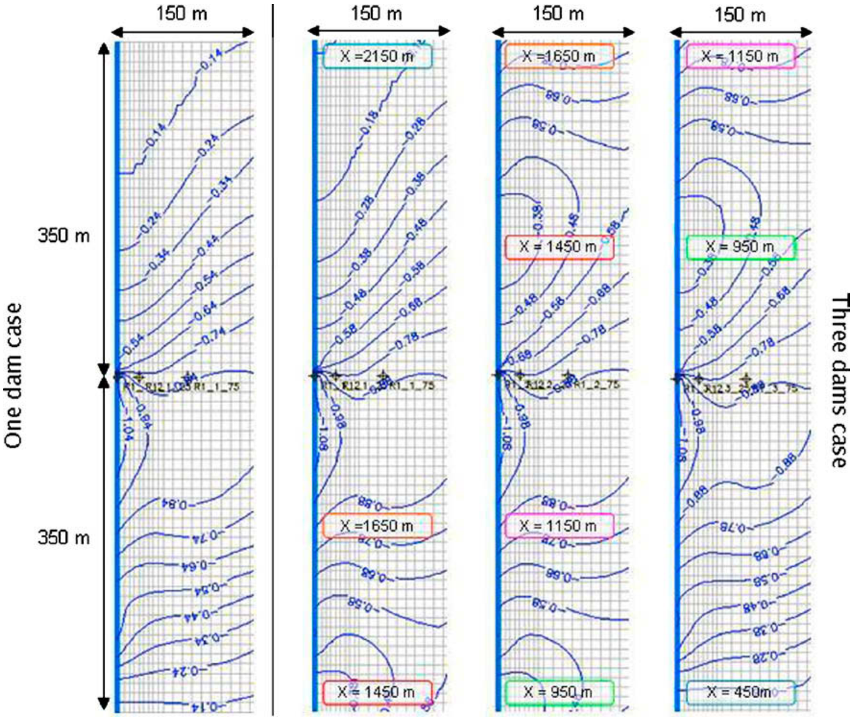

**Fig. 7.** Water table differences due to the construction of one dam (left) and three dams (right part).

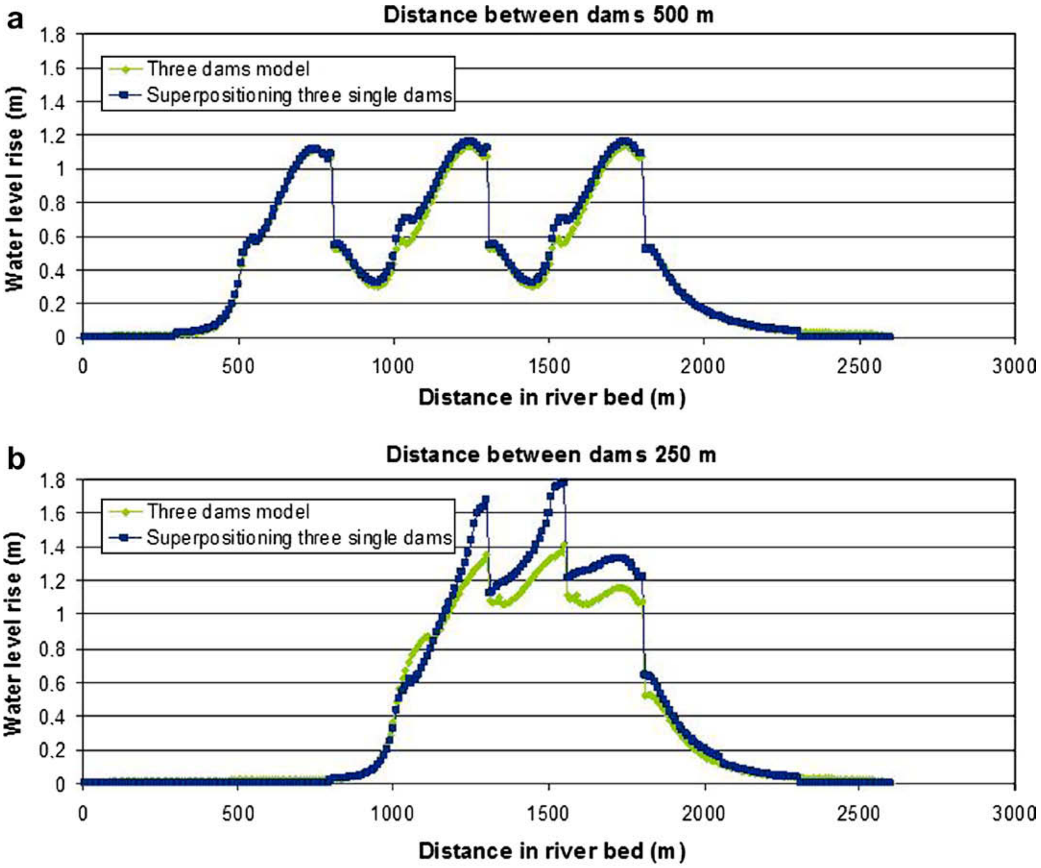

**Fig. 8.** Comparison of water levels in the riverbed between the three dam model and superposition of three single dams.

layer at the location of the river downstream of the Kwa Ndunda sand-storage dam. Borehole data indicated that weathered rock was not present in the riverbed. However, to guarantee continuity of the layer while ensuring an accurate physical representation of the sub-surface, the weathered rock layer was schematized, decreasing to 0.1 m at the location of the riverbed. The weathered rock layer reached a maximum thickness of 15 m at the eastern and western catchment boundaries. An optimal fit between simulated and measured groundwater levels was achieved when 2% of the precipitation was taken as groundwater recharge.

An analysis of the standard error of the measured and simulated heads showed that differences between measured and modeled heads were in the range of 0.10 m for all piezometers. Exceptions were generally due to a less accurate approximation of peak events or overestimation of groundwater levels during the dry period from 03-05-2006 to 15-10-2006. The model demonstrated that during the dry season, groundwater flow was generally oriented southward, in the same direction as the general topography and the riverbed (Fig. 6a and b). Due to the presence of the Kwa Ndunda sand-storage dam, groundwater flow through the permeable riverbed was obstructed, creating a sub-surface water basin (Fig. 6a). In the zone upstream of the sand-storage dam, groundwater heads were raised, resulting in groundwater flow from the riverbed into the riverbanks. At the start of the wet season, the flow of groundwater changes direction and was directed predominantly towards the river throughout the model area. The presence of a dam does not have significant influence upon this flow pattern (Fig. 6c and d). After the wet season, groundwater flows in the area upstream of the sand-storage dam changed orientation again, with groundwater flow again oriented from the riverbed towards the riverbanks upstream of the dam.

Model results appeared to be most sensitive to thickness and hydraulic conductivity of the sediment layer on the riverbanks. These parameters influenced the reaction of groundwater levels on precipitation as well as the gradient of simulated drawdown curves. In addition, the thickness of the sand layer in the riverbed had a large influence on calculated groundwater levels in the riverbed. Hydraulic conductivity and thickness of the weathered rock layer influenced model results to a lesser extent as compared to varying these properties in the sediment layer. Decreasing these parameters mainly results in a smaller gradient of simulated drawdown curves. Model results were relatively insensitive to changes in groundwater recharge of less than 20%.

### 4.3. Cascade model

For a single dam the influence area, that is the area showing changes in groundwater level due to the dam, extended about 350 m in both downstream and upstream direction from the dam. Fig. 7 shows how groundwater levels are affected by the dam. At about 350 m in upstream and downstream directions, changes in groundwater level become negligible. Maximum groundwater level increase immediately upstream of the dam was around 100 cm, while maximum groundwater level increase downstream was 80 cm. The increased groundwater level downstream of the dams is caused by the increased head upstream of the dam. Although the dam itself is impermeable, groundwater flows around the edges. With distances between the three dams initially set at 500 m, we expected that the three dams would show overlap of influence areas. The results indicated that the water levels in the vicinity of each of the three dams were as good as the same as in the one dam case (Fig. 8a). When the distance between the three dams was reduced to 250 m, the effects of the three dams together were less pronounced compared to super positioning the effect of three single dams (Fig. 8b). Between dam 2 and dam 3, where the rises were maximal as a result of the overlap of three (!) influence areas, the water level rise was less than the sum of individual rises for each single dam.

The additional water storage capacity for a single dam was determined as 21,000 m$^3$. When the distance between dams was 500 m, the gain of water was three times the value obtained for the single dam case. When the distance between the dams was set at 250 m, the total storage of the three dams was 41,000 cubic meter. The modeling results suggested that when several dams were built in a row in the same riverbed at ‘overlapping’ distances, water levels rise extra. However, stored water volumes were less compared to volumes stored by the same number of single dams at larger, ‘non-overlapping’ distances. The inter-dam distance is therefore an important parameter in the optimal design of a series of sand-storage dams in a certain region. If the distance between dams is such that influence areas do not overlap, dams behave as individual structures and effects on groundwater storage of single dams within a network can be added up. However, if the influence areas do overlap, stored water volume per dam decreases, thereby reducing the availability of water for dam-dependent communities.

## 5. Discussion

The hydrological success of sand-storage dams is relatively straightforward, as experience, measurements and models discussed above show. The dams have clear influence on groundwater levels, both on short and long terms. Models and measurements confirm what socio-economic research already showed: water has become available in such quantities within relative short distances from communities that agriculture prospers (Lasage et al., 2008; Muticon, 2002). It is based on this success of single dams that the next community was prepared or even asked to construct the next dam. As a result, in some twenty years Kitui District is covered by a network of some 500 dams. Next to the result of hard, prolonged labor of communities and local non-governmental organizations, the success of the Kitui dams is based on the favorable hydro-geological conditions at the dam sites, particularly the sediment size (Ertsen and Hut, 2009). The coarse sediments increase storage volumes because of the higher porosities. Furthermore, abstracting water from the reservoir is easier for coarse material. This favorable sediment size may not be available on other sites, however. This may bring in a need for constructing dams in stages, as suggested by the literature (Nilsson, 1988; Stengel, 1968). In each construction stage, usually each wet season, the crest level is raised allowing the reservoir to gradually fill up with coarse sediment, as higher flow velocities will flush fine particles across the dam.

The issue of sediment in relation to community involvement shows the importance of both short and long term planning and designing interventions for sub-surface storage on different spatial scales. The type of sediment in a dam reservoir strongly determines the hydrological effectiveness of a sand-storage dam. The type of sediment needs to be favorable, which may ask for constructing dams in several phases and thus years. Community involvement, however, will only be guaranteed when its members experience success in relation to the efforts asked from them. Furthermore, community involvement in construction, maintenance and use of dams will be related to the location of other dams. When other communities construct dams too close to existing dams, those people using the existing dam may feel that their water source is threatened.

Ertsen and Hut, 2009 distinguish three dimensions to be considered in planning of sand-storage dam program: (1) Planning, or the different planning demands for construction versus sedimentation; (2) Scale, or hydrological effects of single dams versus multiple dams; and (3) Use, or impact analysis on networks or single dams. Both models discussed in this paper can assist in clarifying these dimensions. The single dam model has proven to capture short-term and local hydrological processes around a single dam satisfactory. With the model and local data on rainfall, river sediment and soils, including porosity and conductivity, scenarios for new locations can be developed to establish potential success rates of a dam in terms of volumes of guaranteed water storage. When these storage volumes are related to water use scenarios (as in Hut et al., 2008), estimations on number of water users per dam and thus number of dams per community can be made, although for longer term analysis of use patterns the single dam model described may be too detailed to be practical. The cascade model could be used for such longer term analysis. Furthermore, it can be employed to estimate effects of different spacing scenarios of single dams.

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