Report on hydrology and possible relationships with patterns of water sources management and use

REAL Concept Deliverable D5b

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Title: Report on hydrology and possible relationships with patterns of water sources management and use

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Version: 1/1/1601 2:00 AM

Printed: 2020-09-07

File location:

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1 INTRODUCTION

1.1 Difficulties in arid and semi-arid land

Water is the key issue to development in semi-arid and arid lands, yet making it available and accessible is a major undertaking (SASOL and MAJI NA UFANZI, 1999), because it is the critical natural resource constraint on dry land crop production (Cleaver and Schreiber, 1994). New water resources have to be found, to sustain the growing needs. In recent years, there has been a shift towards increasing exploitation of rivers and groundwater, which are now the major sources of water supply across the world (Agarwal 2001).

1.2 Specific Situation of the Study Area: Kitui District, Kenya

Kitui District is located in Eastern Kenya. The district covers an area of 20556 km^2, including 6369 km^2 of the wildlife Tsavo National Park and is situated between 400 and 1800 m above sea level. In Kitui District, the climate is hot and dry for most of the year as in arid and semi-arid areas. As there are only a few water sources, the main problem in this area is an inadequate water supply for the large population. In this region, the major sources of water are perennial rivers (Beimers et al., 2001b; Frima et al., 2002). To access water, people and animals have to travel up to 25-30 km. Therefore, closeness to a source is an import criterion in choosing the correct technology for providing water (Mutiso and Mutiso, 2000).

Although central Kitui has an average rainfall of 760-1015 mm a year and Kitui South 225-510 mm a year (Mutua et al., 2002), rainfall is highly erratic, so wide fluctuations in the amount of precipitation are common. Rainfall is concentrated in two short rain seasons: November-December and March-April, the former being more reliable for growing maize than the latter. It is common that rains fail in one or both seasons and that for subsequent years. This implicates that drought can occur for long periods of time. This effects the cultivation of crops and can result in a food shortage (SASOL and MAJI NA UFANZI, 1999). Between 1897 and 1997 there have been 18 famines, eight of which lasted for more then one year (National Environmental Secretariat, 1981).

In Kitui District, surface water may flow for a few weeks or even months if there is sufficient precipitation. Usually, the flow is limited to a few days or hours during heavy rains, after which the water sinks below the level of the sand. People are accustomed to dig holes in the sand and scoop the water out. As the dry season progresses the water level continues to drop. Because of this, holes have to be deepened and the difficulty of getting water increases (SASOL and MAJI NA UFANZI, 1999).

Because of those reasons, a reliable source of water close to the population is necessary.

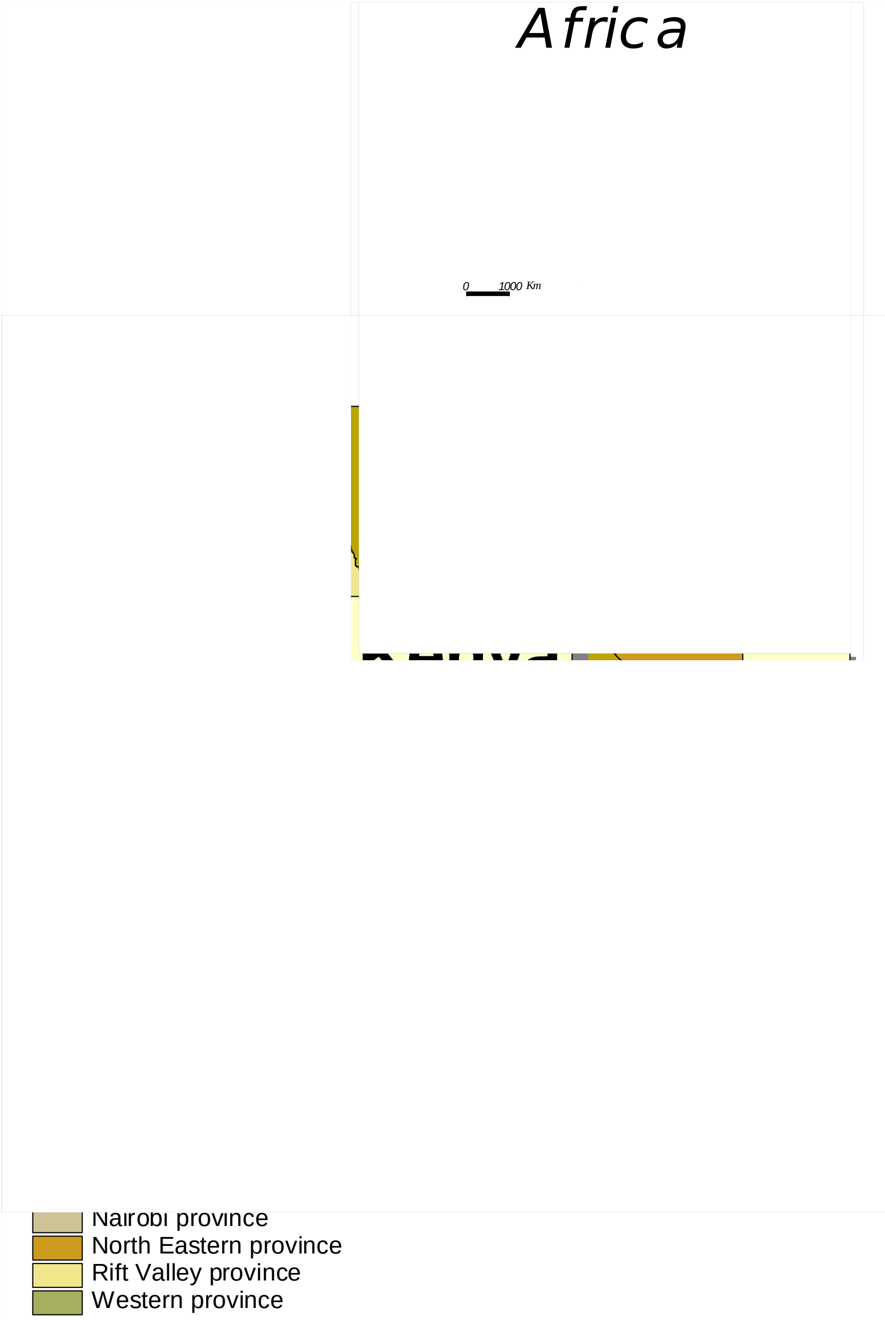

Figure 1: Administrative boundaries of Kenya (Source: FAO-Africover, 2003; Maidment D.R. and Reed S. M., 1996)

1.3 Solutions

1.3.1 General

Despite the wide spread problem of water shortage, it is generally believed that enough precipitation falls on the world's land surfaces to supply the global population (Price 1996 and Agarwal & Narain, 1999). In those areas a reliable water supply system can be based on harvesting dew water, drainage water or runoff water (Barrow, 1999; Nissen-Petersen, 1982), a technique is called 'water-harvesting'. Pacey & Cullis (1996) described this technique as 'The collection and storage of any farm waters, either runoff or creek flow, for irrigation use'. There is a need for a better understanding of such water-harvesting systems to conserve rainfall efficiently (Print C, 1997).

Some existing water harvesting systems are:

- Small earth dam can hold enough water to grow sugar cane, bananas and citrus fruit (Nissen-Petersen, 1982).
- Collection of runoff water from the compound around the house (Nissen-Petersen, 1982).
- Roof catchment system (Nissen-Petersen, 1982).
- Sand-storage dam (Barrow, 1999) is a type of dam, where impound water is accumulated in sediment upstream the dam site (Beimers et al., 2001a)

Most of these systems, seek to catch and hold runoff, which would otherwise miss agricultural land and become wastewater (Barrow, 1999). By recuperating this wastewater and using it for cultivation, the available water is used more efficiently. Implementation of water harvesting systems should create reliable water source and thus secure the harvest, increase yields, make diversification of crops possible and improve the sustainability (Nissen-Petersen, 1982).

Because water harvesting systems need little maintenance (Rapp and Hasteen-Dahlin, 1990; Pandy, 1991; Scrimgeour and Frasier, 1991) and are easy to adopt (National Academy of Sciences, 1974; Shanan and Tadmore, 1979; Hutchinson et al., 1981; UNEP, 1983; Pacey and Cullis, 1986; Giraldez et al., 1998; Laryea, 1992; Gould, 1994; Kronen, 1994; Tabor, 1995; Tsioutis, 1995) they are economically interesting (Nissen-Petersen, 1982) and can provide a long-term supply of high quality water without the need for modern technology (Vironi, 2000). These systems decrease breeding and spreading of diseases, often found in water sources in rural areas. This can improve local health conditions (Nissen-Petersen 1982 and Print, 1997). Water harvesting systems also help to protect against pollution, due to the filtering action of the aquifer (National Academy of Sciences, 1974; Asano, 1984 and Print, 1997).

Where droughts occur frequently, harvesting runoff water should be combined with water storage (Verma and Sarma, 1990; Barrow, 1999), to collect water to survive the dry periods. Example of the combination of water harvesting and storage is the sand-storage dam, a structure commonly used in Kitui District, Kenya.

1.3.2 Sand-Storage dams

For thousands of years, people have survived through dry seasons by scooping waterholes in sandy riverbeds in ecological zones ranging from semi-arid to desert. Even today many rural people use water-holes in sandy riverbeds as their only water source for domestic use, watering livestock and small-scale irrigation. Coarse sand and gravel in sand-rivers can trap and store water in 50 per cent of their volume. Up to 35 per cent of this water can be extracted. In other words, 350 litres of water can be extracted per cubic metre of sand (Nissen-Petersen, 1997). When the depth of the water in the sand deposits gets deeper as the dry season continues, the villagers find it often impossible to dig any further and travel long distances to fetch water. Damming the water during the rainy season and using it in the dry period is an obvious solution (Neesen et al., 2004; Puttemans et al., 2004).

These dams are sand-storage dams and are constructed above the ground. Sand and silt particles, which are transported during periods of flood, are allowed to deposit upstream the dam. Water is then stored in these deposits (anonymous).

In cases where flows can carry large amounts of sediment (Barrow, 1999), sand-storage dams can be used where (ephemeral) streams or springs cannot meet short-term demand but, provided evaporation losses are reduced, can accumulate sufficiently to be useful (Barrow, 1999).

The advantages of sand-storage dams are that they can withstand flash floods better than normal reservoirs, they supply clean water, mosquito breeding is less likely, aquatic weed or algal growth is impossible and evaporation is minimal once the water level drops to about 60 centimetres below the surface (National Academy of Sciences, 1974; Asano, 1984; Nilson, 1988 and Barrow, 1999). The main disadvantages are that the capacity of a sand-storage dam amounts only 25 to 35 per cent of an equal sized unsilted reservoir and that only sediment of a suitable size (coarse sand or fine gravel) may be collected (Barrow, 1999).

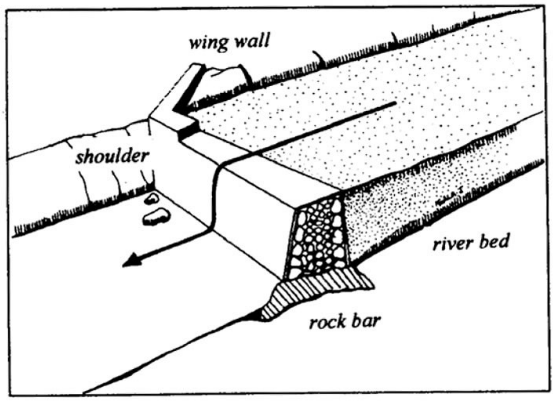

Figure 2: Cross section of a sand-storage dam (SASOL and Maji Na Ufansi, 1999)SASOL

SASOL is a non-governmental organisation (NGO), founded in 1990. To solve water scarcity in the dry season, SASOL (Sahelian Solution Foundation) has focused on improving the retention of groundwater through sand-storage dams (SASOL and MAJI NA UFANZI, 1999). Between 1990 and 2001 SASOL succeeded in building more than 300 sand-storage dams in Kitui District (Burger, et al., 2003). The aim is to create a network of sources so that no one would need to walk more then two kilometres to collect water (SASOL and MAJI NA UFANZI, 1999).

Table 1: Number of dams built by SASOL

Number of dams	Date	Source
100+	1999	SASOL and MAJI NA UFANZI, 1999
216	April, 2001	Beimers et al., 2001a
320+	2002	Muticon, 2002
300+	2003	Burger et al., 2003

The approach of SASOL is to develop a catchment in total. The catchment approach depends on the co-operation by the community in developing sequential sand-storage dams in their dry rivers coupled with terracing and tree planting (Beimers et al., 2001b), to obtain a catchment wide rise of the water level.

Based on accumulated experience, SASOL assessed the impact of sand-storage dams on the environment and agriculture (SASOL and MAJI NA UFANZI, 1999; Beimers et al. 2001a):

- Water levels upstream will rise.
- There is no reduced flow downstream the dam site.
- Sand-storage dams do not lead to flooding of the adjacent land.
- Planting in plots close to the riverbed and in the riverbed becomes possible during the dry season.
- A series of sand-storage dam has a cumulative effect, improving the environmental conditions.

Although a lot of experience and practical knowledge has been accumulated during the last 13 years, the need for a scientific assessment of sand-storage dams became obvious. Beimers et al. (2001a) published a proposal for hydrological research on sand-storage dams in Kitui District, Kenya, in June 2001. When the project 're-hydrating earth in arid lands' (REAL) started in September 2002, Work Package 3 continued the hydrological research. A first step was the publication of the research on sand-storage dams in Kitui district. (Burger et al., 2003). The main objective of the study of Burger et al. (2003) was to 'design a long term gauging system to enable a scientific study into the functioning and performance of sand-storage dams'.

2 STUDY OBJECTIVE

SASOL wants to optimise the effect of sand-storage dams (Frima, 2002). The primary goal of this deliverable is to assess the storage capacity of sand-storage dams and evaluate a selection of tools useful to predict the storage capacity of sand-storage dams. Different aspects of sand-storage dams will be examined:

- Determination of the water flux in/out the system of a sand-storage dam.
- Analysis of the water storage for subsequent years, during different seasons (rain and dry season) and during dry and wet years.
- Assessment of the change of the water level caused by the sand-storage dam.
- To examine the effect of land use on water availability.

3 RESEARCH PLAN

3.1 Relationship between hydrology and land use

This relationship will be explored with AVSWAT (ArcView Soil and Water Assessment Tool). This model simulates the discharge based on geographic information (e.g. soil and land use layers) and thus will determine the water flux in the system of the sand-storage dam The simulated discharge will be used to determine the relationship between hydrology and dam design.

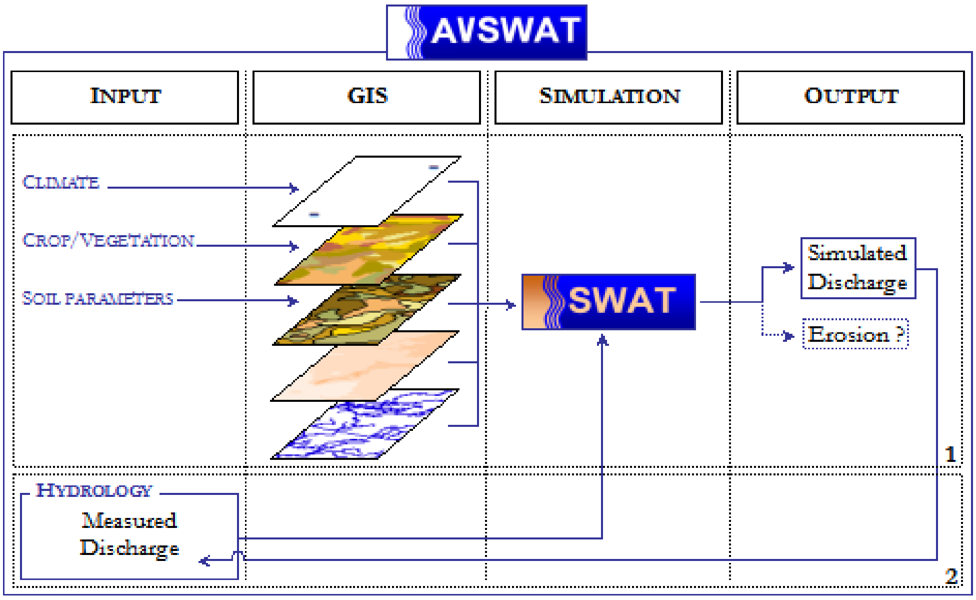

Figure 3: Research plan to examen the relationship between hydrology and land use

3.2 Relationship between hydrology and dam design

Subsurface storage should be created in quantity and quality to overcome drought periods guarantying continuous economic growth. To assess this statement, rainfall, evapotranspiration, seepage, discharge were measured, simulated or calculated. Based on these parameters, the water level will be simulated and compared with the measured level. The storage capacity of the dam can be calculated using the water level and the depth of the impermeable layer.

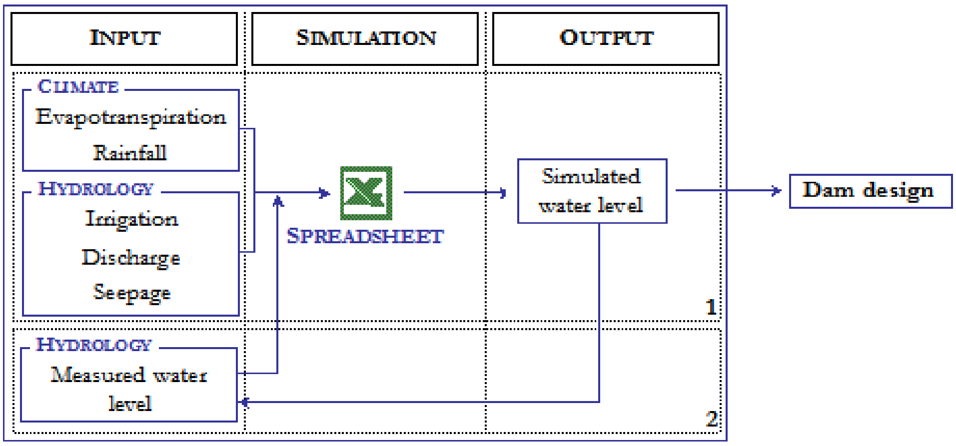

Figure 4: Research plan to assess the relationship between hydrology and dam design

4 MATERIAL AND METHODS

4.1 (AV)SWAT

The SWAT (Soil and Water Assessment Tool) (Arnold *et al.*, 1998) model is physically based. In stead of incorporating regression equations to describe the relationship between input and output variables, SWAT requires specific information of weather, soil properties, land use, topography, vegetation and land management practices as input. The physically based processes associated with water movement, sediment movement, crop growth and nutrient cycling are directly modelled by SWAT using the input data. The benefits of this approach are that watersheds with no monitoring data can be modelled. This means that no time series of the period of simulation are required. SWAT can also quantify the relative impact of alternative input data (land management, climate, vegetation…). Precipitation, minimum-maximum temperature, humidity, wind speed, solar radiation, relative humidity, land cover and soil maps are (in most cases) available from government agencies. SWAT allows the user to study long-term impacts. A disadvantage of SWAT is that it cannot simulate single events in time because it is a continuous model. So no “snap shots” in time can be produced (Neitsch *et al.*, 2001).

AVSWAT (SWAT ArcView extension) is a graphical user interface for the SWAT model. In addition to the input of SWAT, AVSWAT requires two types of information: *ArcView map themes* (Digital Elevation Model, Land Cover/Land Use and Soil) and information in the form of *tables* (dBase) or text files. These files contain information on weather characteristics, soil properties, land use properties and locations of weather stations (Di Luzio et al., 2001).

4.2 Input data for of AVSWAT

In this chapter the ArcView maps (digital terrain model, land use and soil) and database files, used as input for AVSWAT will be discussed. These files provide specific information about climate, daily precipitation soil parameters.

4.2.1 Digitized maps

A topographic map (Transverse Mercator projection, Meridian of Origin 39°00’ East of Greenwich, Clarke 1880 (Modified) Speroïd. 1:50000) was digitized to obtain the elevation contours, the rivers and the roads of the area.

4.2.1.1 Digital Elevation Model (DEM)

From the digitized contour map, a digital elevation model was interpolated. This interpolation has been performed with an ArcView extension that uses a linear interpolation between any 2 neighbouring contour lines (Stuckens, 2004). The interpolated grid has a resolution of 2*2 metres. Altitudes in the area range from 680 metres to 1000 metres above sea level.

4.2.1.2 Land use

Land use of the catchment had to be obtained in situ because the spatial resolution of the available LANDSAT images of the area was too low (30*30 meters).

On the field, a map of the land use, seen from rocks and hills surrounding the catchments was drawn on the base map (Transverse Mercator projection, Meridian of Origin 39°00’ East of Greenwich, Clarke 1880 (Modified) Speroïd. 1:50000). A compass was used to orientate the map as good as possible to minimize the errors. The local knowledge of farmers was useful to correct the map and to fill in gaps.

Afterwards the identified land use was verified by walking transects and by validating the recognized area from another viewing angle. This strategy gives a good idea of the field/bush ratio in the area.

The different land units that have been distinguished are bush (mainly Acacia type), grass with scattered trees, villages (low density), maize/cowpeas fields and rock.

The five observed land use types have been assigned to the land use classes that can be founded in the SWAT land use file. Not all the land use classes could be recognized so the best available types have been chosen. Bush has been assigned to range brush (RNGB), grass with scattered trees to range grass (RNGE), villages (low density) to residential-low density (URLD), rock to residential high density (URHD) and maize and cowpeas fields to corn (CORN). Because no rock was present in the database, residential high-density land use was chosen, because of the similar runoff. The percentage of rock however is very small in the catchment so it will not be taken into account

The result is displayed in Figure 5.

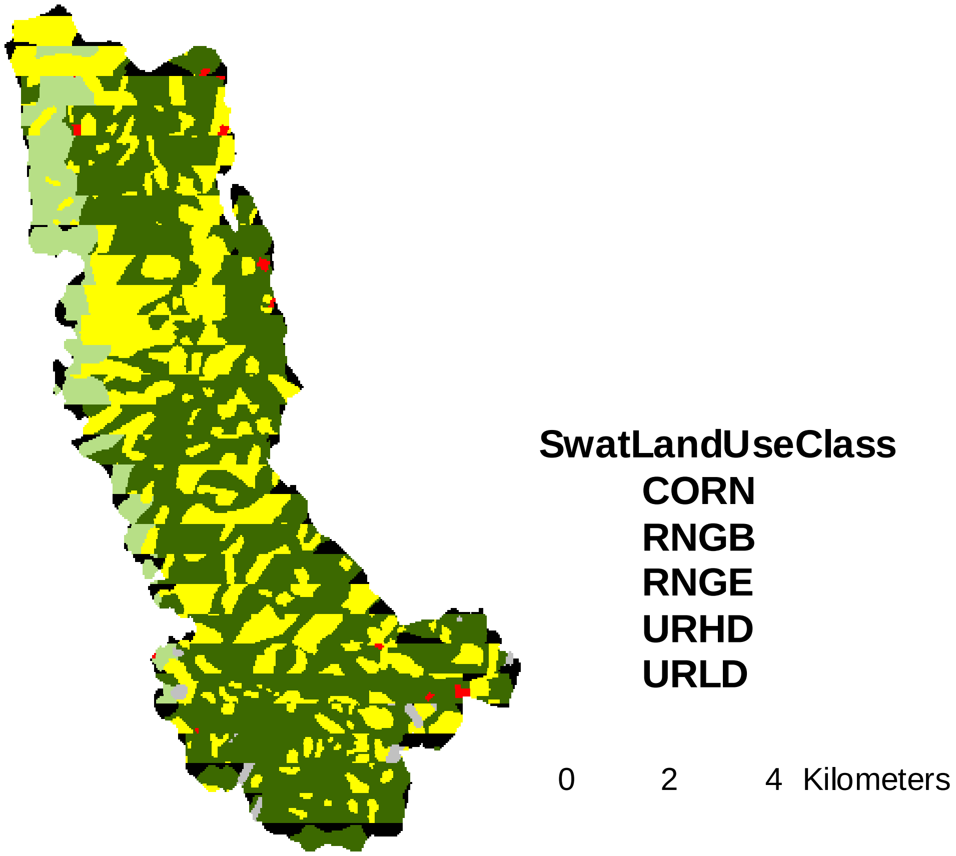

Figure 5: Land use of the Ngunga watershed

4.2.1.3 Soil

4.2.1.3.1 ARCVIEW MAP THEME

A digital soil map was produced with the different soil types of the area. The classification and delineation of the different soils is based on the experimental field and laboratory work. Delineation of the soils has been performed through interpolation of the analysed soils according to the contour lines. The soil map has been verified with existing soil reports of surrounding area's (Gachene, *et al.*, 1986; Mugai, 1978) and a soil map (scale 1: 250000; United States Department of Agriculture Soil Conservation Service, *et al.*, 1978). The produced soil map is displayed in Figure 6.

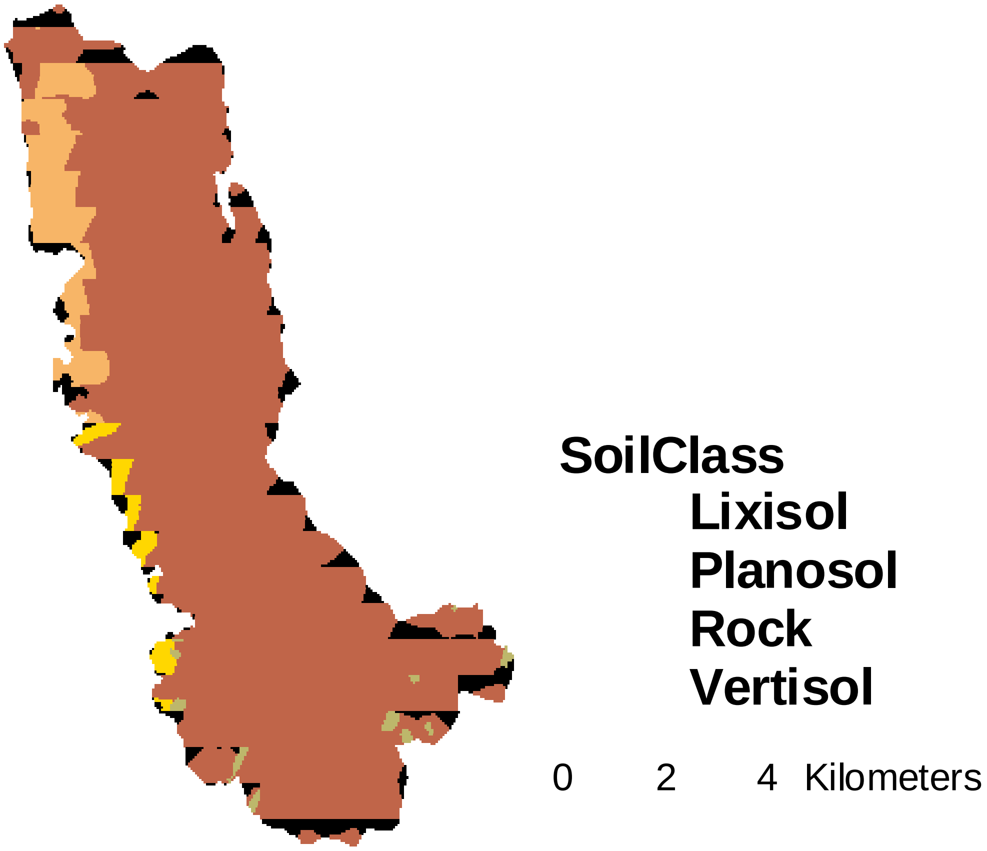

Figure 6: Soils of the Ngunga watershed

4.2.1.3.2 DATABASE FILE

To determine the soil types with their corresponding physical soil characteristics of the studied area, six profile pits were dug in the catchment. Because transportation throughout the region is difficult the profile pits were dug near roads. That is why the surroundings of the dam was examined most intensive. Local knowledge was used to determine and locate different soil types.

From the profile pits undisturbed samples were taken using kopecki-rings. From each layer, 3 samples were taken. Disturbed samples were taken for texture analysis.

Additional to the pits 20 drillings were carried out from which disturbed samples were taken. These drillings have been done in the whole catchment although, again for the same reasons, the south of the area was sampled more extensively.

From the different layers of the sampled soils the undisturbed samples were used to determine following parameters: saturated hydraulic conductivity (K_{sat}), bulk density, water content at field capacity (FC) and water content at wilting point (WP).

The *saturated hydraulic conductivity* is measured by means of the constant head method. A constant height of water is maintained over the upper end of the soil sample by an external manometer, and the bottom end is open to the atmosphere. The water volume flow is collected at the bottom and is used to calculate the water flux.

The *bulk density* is determined by drying the soil samples for 24 hours in an oven of 105°C. The dry weight can then be determined and divided by the volume of the sample in the kopecki-ring (100 cm^2) to obtain the bulk density.

The *water content at field capacity* is obtained by bringing the soil samples to a steady state condition in a low pressure press at a pressure corresponding with pF = 2.3

(negative pressure of 20 kPa). The sample can then be weighed and the water content can be determined through the known the dry weight of the sample.

The procedure for the moisture content at wilting point is similar. The procedure takes place with smaller samples in a high-pressure press at a negative pressure of 1550 kPa (pF = 4.2).

The obtained gravimetric water content can be recalculated to the volumetric volume content by means of the bulk density (Jury *et al.*, 1991).

The available water content (AWC) is calculated through following formula:

$$AWC=WP-FC \qquad (1)$$

Soil texture is determined of the disturbed samples, although at first the soil texture of the undisturbed samples would be measured. However due to a misunderstanding this was not possible anymore. The analysed disturbed samples were chosen to be representative to the analysed undisturbed samples. This way, a file with all necessary soil characteristics of the specific soils can be produced.

Soil texture is determined according to the ISO 11277: 1998(E) guidelines. The procedure consists of the determination of particle size distribution through sieving and sedimentation. First the particles larger then 2 mm (small pebbles) are removed by dry sieving. Organic matter is then destroyed by H_2O_2 . Soluble salts and gypsum are removed through dilution. If necessary, iron oxides and carbonates are removed as well (with sodium dithionite and HCl). The sand fraction is separated through wet sieving (> 53 µm). The clay and silt fractions are determined by Stokes' Law through sedimentation (International Standard, 1998).

A database file with following soil information is created:

- Soil hydrologic group
- Maximum rooting depth of soil profile
- Fraction of porosity (void space) from which anions are excluded
- Potential or maximum crack volume of the soil profile
- Depth from the soil surface to the bottom of the layer
- Moist bulk density per layer
- Available water capacity of the soil layer
- Saturated hydraulic conductivity per layer
- Organic carbon content per layer
- Clay content per layer
- Silt content per layer
- Sand content per layer
- Rock fragment content per layer
- Moist soil albedo
- USLE equation soil erodibility per layer

The values were obtained from the experimental analysis. However because not all parameters could be measured, values of soil reports of surrounding area's were used (Gachene, *et al.*, 1986; Mugai, 1978).

For more information see II Annex: Soil input data and III Annex: Major soil units in the Ngunga-catchment.

4.2.1.4 Climate

4.2.1.4.1 FIELD WORK

Because no weather stations were present in the studied catchment, two measurement stations were set up. One station is located in the Mbitini secondary school, in the north of the catchment and another station was set up in the Kisayani primary school at the southern border of the Ngunga-catchment. The measured data are daily minimum and maximum temperature and daily precipitation. In the weather station in Kisayani primary school also an evaporation pan and a humidity meter was installed. To guaranty the correct use of the instruments by the local people a manual was created (Bossenbroek & Timmermans, 2003) in cooperation with the Dutch colleagues of the DUT.

However the collection of the data is still in a preliminary stadium and the collected data are too few to be used as input for the AVSWAT-model. This is why other data of further located weather stations are used.

4.2.1.4.2 PRECIPITATION DATA

The weather data were partly purchased from SASOL and partly obtained from the Food and Agriculture Organization of the United Nations (FAO). Although several meteorological stations can be found in a range of 50 kilometres around Kisayani, the weather data of the stations are often irregular or imprecisely measured (missing precipitation data range from 12 % to 69 %). For the simulations, the “Mutomo agricultural station” (from June 1980 to May 1986), that has the most complete dataset and is located the closest to the study area, is chosen. In this area with erratic rainfall it is the most relevant to take the data of the weather station that is located the closest to the survey area.

4.2.1.4.3 OTHER METEOROLOGICAL INPUTS

For good modelling, the AVSWAT computer program requires several meteorological input data. These data are daily precipitation, daily minimum and maximum temperatures, average daily wind speed per month, average daily dew point temperature per month (estimated from relative humidity), average daily solar radiation per month. These date were acquired from the “Kitui agricultural office” weather station (FAO, 2000).

For more information see I Annex: Weather generation (Neitsch et al., 2001).

4.3 Data for calibration of the AVSWAT model

4.3.1 Discharge measurements

Discharge measurements of the river are needed for calibration and validation of the hydrological AVSWAT-model. However, the field study was performed in the dry season, so the Ngunga, an ephemeral river, did not flow. Therefore discharge measurements were impossible to perform.

4.3.2 Measurement of the groundwater table

For more information see IV Network of piezometers (Bossenbroek & Timmermans, 2003).

4.3.2.1 Placing piezometers

Measurements of the groundwater table are necessary to calibrate and validate the water balance of the reservoir model. This part of the study was carried out by students of the DUT. They have set up a groundwater measuring system by means of piezometers in and around the riverbed. The piezometer tubes are perforated PVC tubes placed inside a manually drilled hole. In some cases drilling was difficult due to the stone content of the soil (Bossenbroek & Timmermans, 2003).

In addition to this measuring system four extra piezometers were placed. Two piezometers were placed upstream of the existing Kamunyuni dam and two were placed downstream of the Kamunyuni dam. This was done to investigate the rise of the groundwater level caused by the dam.

4.3.2.2 Measuring the riverbed and piezometer locations

The location of the piezometer tubes, the height of the riverbed and the dept of the tubes, were measured with a theodolite. Also the river boundaries and the higher banks along the river were measured. Based on the measurements a map is produced in AUTOCAD through entering the points as polar coordinates. The AUTOCAD map is then exported to ArcView to produce a general overview of the riverbed and river valley with all the tubes.

4.3.2.3 Measuring the piezometers

The water level inside the piezometers was measured with a float, attached to a rope. The float was constructed of an empty bottle that was made heavier with a pebble. When the float hits the water, a sound is produced. Then the length of the rope was measured. The depths of the water levels are recalculated with the height of the piezometers as recorded with the theodolite. This way comparison between water levels could be made. It has to be noted that effective measurements of the piezometers were few, because the tubes were placed in the dry season. They were drilled until the rock layer was reached. Because of the extremely dry period, almost all of the piezometers were found dry. However, most of the tubes have not survived the beginning of the wet season for effective measurements. This is mainly due to collapsing of the tubes with dry sand after damage of the lit by cattle or curious people. To measure the groundwater level effectively in the future, a more sustainable solution must be found. The piezometers can be made of a stronger material, the lids should be more solid and should be able to be locked so that curious passengers cannot damage them. The extra costs of these adjustments will have to be considered. The auguring cannot be done in the dry season. However if an idea is to be obtained of the groundwater level in the sand bed of the river, piezometers will have to be installed in the riverbed. This will be impossible during the rainy season if the river is flooding. If the sand is saturated with water it will even be difficult to auger because auger holes in saturated sand are likely to collapse. Therefore it can be considered to install piezometers on the sides of the riverbed, were the texture of the soils is somewhat courser but where still an idea of the ground water level in the riverbed can be obtained.

4.4 Water balance for a sandy reservoir

To estimate the water supply of a sand-storage dam, a local water balance of the sandy reservoir will be set up. Although several parameters of this balance are uncertain, the water balance can gain an insight in the dynamics of the reservoir. The balance will be dynamic so that in a later stadium it can be easily adjusted when more detailed data are available.

4.4.1 Water balance

Theoretically, a water balance for the sandy reservoir of the sand-storage dam can be calculated by following formula:

$$\frac{dV}{dt} = Q + PA_r - EA_r - S - I \quad (2)$$

With: V: the water volume in the sand reservoir (m^3)

t: time (d)

Q: discharge (SWAT output) (m^3d^{-1})

P: precipitation ($m\ d^{-1}$)

A_s: sand-storage surface (m^3)

E: evaporation (md^{-1})

S: seepage (m^3d^{-1})

I: irrigation and domestic withdrawal (m^3d^{-1})

4.4.2 Estimation of the subsurface dam volume

The volume and water holding capacity of the reservoir is required to estimate the depth of the water table on every time step of the water balance. The depth of the water table is required to make an estimation of the actual evaporation.

An estimation of a subsurface reservoir is a difficult operation to perform. The underlying rock layer limits the subsurface sand reservoir. However, geological deposits are very irregular. To obtain the real reservoir volume, numerous measurements of the depth of the underlying rock have to be done. These measurements are not available. In the dry season it is very difficult to drill in the dry sandy river sediment. Auger holes are very likely to collapse so drilling until the rock layer is in most cases virtually impossible. From 10 points in the river, the depth of the underlying rock layer is known.

An overview of the situation is given in Figure 7.

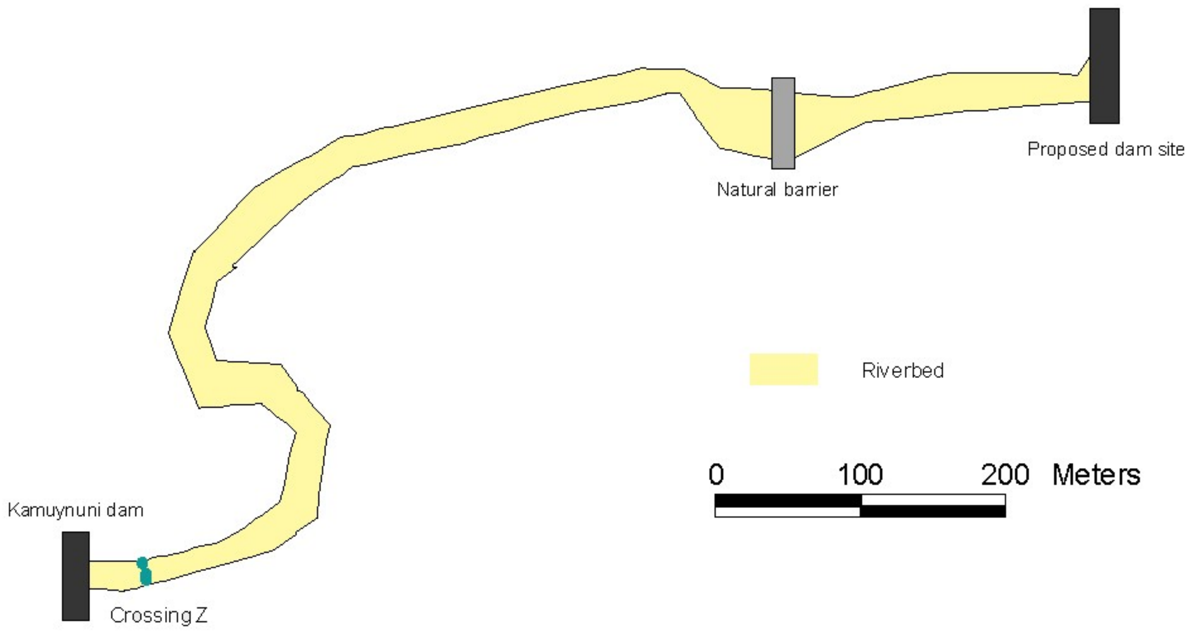

Figure 7: Riverbed between Kamunyuni dam and “Proposed dam site”

To perform an estimation of the subsurface volume of the sand reservoir, it is assumed that the sand reservoir of the “proposed dam” will be located between the “proposed dam site” and the natural barrier. This natural barrier is a natural rock outcrop in the river that stops the water (Figure 7).

From one cross-section, the depth of the impervious rock is known at three points in the river. To estimate the average depth (D) of the sand bed in the river, the deepest point will be taken. Although from local knowledge, it is known that these auger holes are not the deepest in the riverbed, this point will be taken as an average.

To estimate the shape of the sandy reservoir, it is assumed that the river has eroded the geological underground in a same way as the surrounding valley (Figure 8); this is a trapezoidal form. The surface of the river is measured with the theodolite. To obtain the length of the river, the following formula is used:

$$L = \frac{P - W_{nat.barrier} - W_{prop.dam}}{2} \quad (3)$$

with L: length of the river

P: perimeter (calculated in ArcView)

$W_{nat.barrier}$: width of the river at the natural barrier

$W_{prop.dam}$: width of the river at the "proposed dam site"

The surface of the river is simplified to a rectangle, so the average width can be calculated through following formula:

$$W_{riv} = \frac{A}{L} \quad (4)$$

with L: length of the river

A: surface area of the river (calculated in ArcView)

W_{riv}: average width of the river

D: maximum depth of the sand reservoir

The angel is estimated according to the surrounding riverbanks.

Following values have been calculated:

L	209 m
W_{riv}	24,8 m
D	2 m 78
γ	60°

Table 2: Reservoir parameters

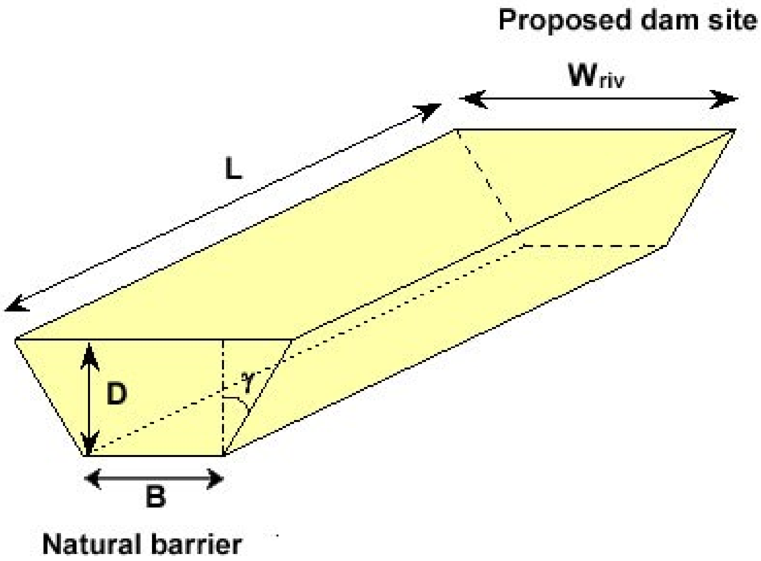

Figure 8: Reservoir dimensions

Through following formula the maximum volume of the sand reservoir is calculated:

$$V = L\left(B * D + D^2 * Tan(g)\right) \qquad (5)$$

This way, a volume of 11611,63 m^3 was obtained. This is however the volume of a reservoir filled with sand. To calculate the maximum volume of water this reservoir can contain, the porosity of the sand must be calculated with following formula:

$$n = 1 - \frac{r_b}{r_{part}} \qquad (6)$$

With n: porosity

$_b$: bulk density (bulk density of the river sand is 1,65 g/cm^3)

$_{part}$: particle density (particle density of sand is 2,65 g/cm^3)

With this calculation, the water volume that can be contained by the sand reservoir is estimated at 4381,75 m$^{3.}$

4.4.3 Irrigation and domestic water withdrawal

Irrigation will be ignored because the sand-storage dam has not yet been built. It is therefore difficult to estimate these requirements. In a later stadium however this parameter will have to be accounted for, as the dam will supply water for cattle, households and irrigation and withdrawals will be significant. For potential for small scale irrigation see Puttemans (2004).

4.4.4 Precipitation

Cumulative precipitation is a direct input in the reservoir. Absolute quantities have been obtained through multiplying the precipitation with the surface area of the sand reservoir.

4.4.5 Actual evaporation

The actual evaporation of the sandy surface was calculated as a function of the depth of the water table. To estimate the actual evaporation, the model HYDRUS-1D was used (Simunek *et al.*, 1998 a). HYDRUS-1D is a Microsoft Windows-based modelling environment for the analysis of water flow and solute transport in variably saturated porous media.

To estimate the actual evaporation, the water flux through a uniform sand profile was calculated for several water table depths.

The physical parameters of this sandy profile (texture, bulk density, water content at field capacity and wilting point) have been measured previously (see § 4.2.1.3). With these physical parameters the necessary Genuchten water retention parameters (residual soil water content, saturated soil water content, α: a parameter in the van Genuchten soil water retention curve, pore-size distribution) and the saturated hydraulic conductivity are calculated with the incorporated Rosetta DLL (Dynamically Linked Library) program. This way the water retention curve can be reconstructed with the van Genuchten model (Simunek *et al.*, 1998 b).

A constant potential evapotranspiration was maintained above the profile and the necessary boundary conditions were specified (pressure head of zero at the water table and wilting point is assumed at the top of the profile). Through iteration HYDRYS-1D finds the water flux at steady state through the profile.

The iteration was performed for 27 different water depths. As can be seen from Figure 9 the evaporation stays constant until a depth of 50 centimetres, and then the evaporation decreases exponentially. With the water table at a depth of 190 cm the evaporation is assumed to be zero.

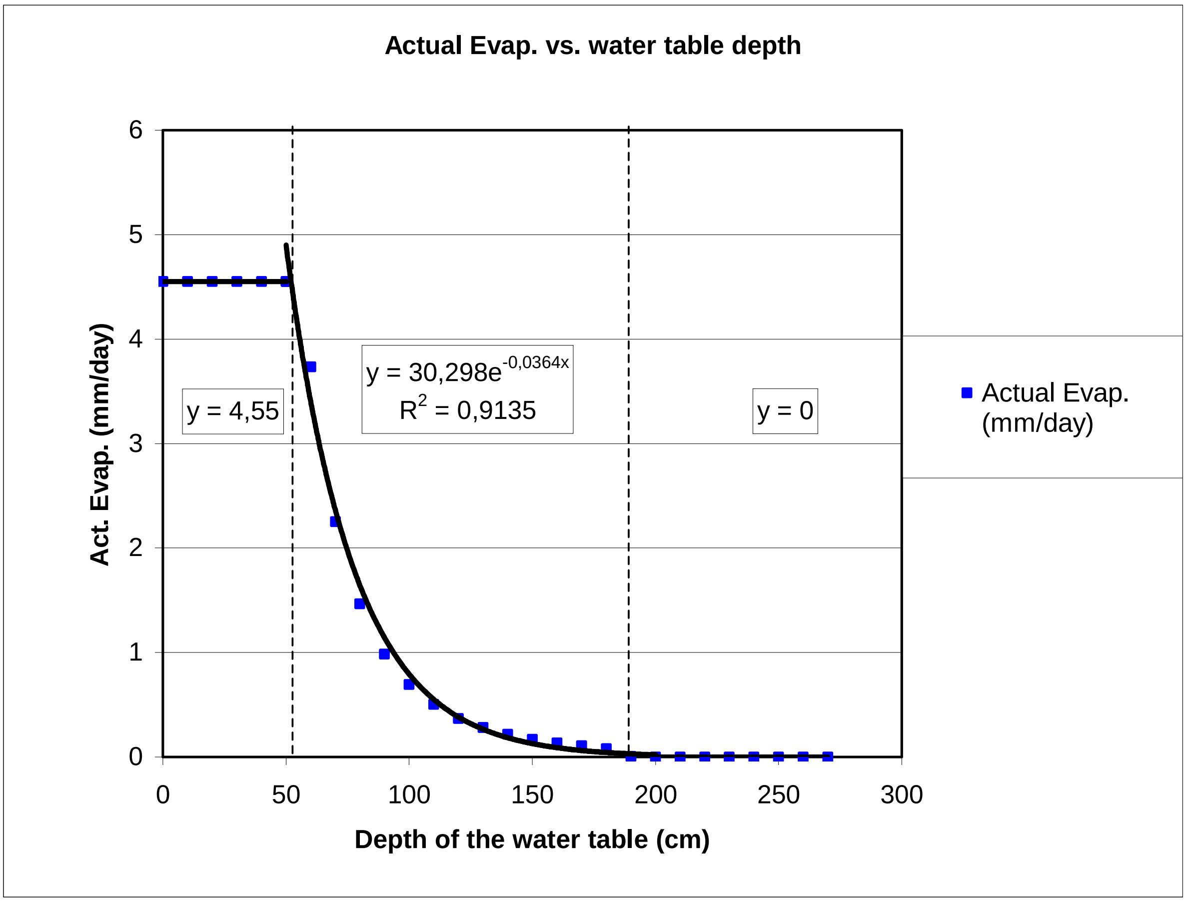

Figure 9: Actual evaporation vs. water table depth

Actual quantities of evaporation have been obtained through multiplication with the surface area.

4.4.6 Discharge

The values of discharge have been obtained from the output of SWAT.

4.4.7 Seepage

It is impossible to estimate the seepage of a sand-storage dam as this is dependent on the local conditions of the dam. Seepage is possible through the concrete dam, through the underlying rock layer and through the riverbanks. Although local knowledge states that seepage through the dam and through the “impervious” rock layer causes a raise of the water table downstream of the dam, no experimental research has been performed on this topic. For this research, it will be assumed that the sand-storage dams obstruct the water completely and do not have any seepage. If later research can provide a seepage coefficient, this can easily be integrated in the existing water balance.

4.4.8 Calculation procedure

The water balance of the reservoir is calculated at every daily time-step. The water volume is calculated as follows:

$$V_{t+1} = V_t + (P_{t+1} - E_{t+1})A_s - S_{t+1} + Q_{t+1} \quad (7)$$

The water volume is recalculated to the volume this water takes in the reservoir (dependent on the porosity of the sand). With the volume of the previous day, the depth of the water table can be calculated and the evaporation will be estimated according to Figure 9

5 RESULTS AND DISCUSSION

5.1 Simulation of discharge with AVSWAT

5.1.1 Simulation with one rain gauge

First, a simulation over six years (June 1980 - May 1986) of the discharge is performed based on the precipitation data of one weather station and one rain gauge, both placed in the “Mutomo agricultural station”. The discharge versus time graph is displayed in Figure 10.

As can be seen from the graph, an extremely high simulated discharge (5,620,320 m^3/day) is reached on November 12^{th}, 1984. This amount of water would put 8 centimetres of water on the whole catchment (of 66 km^2) if this would be flat. A discharge of this extent in a semi-arid watershed is impossible. The large discharge follows on a day with 200 mm of precipitation. Because the model is set up with only one rain gauge, this amount of precipitation is assumed to be evenly distributed over the whole catchment. In a semi-arid region with known spatial variability of rainfall, this is however unlikely, especially for an intensive storm of 200 mm.

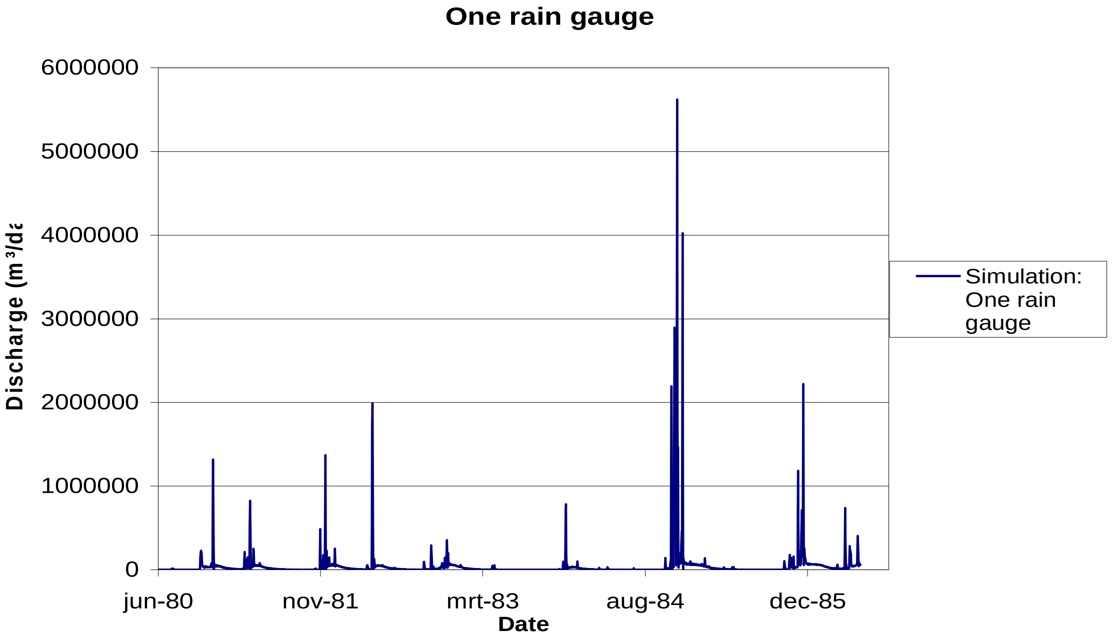

Figure 10: Discharge versus time: Simulation with one rain gauge

5.1.2 Simulation with six rain gauges

Because the results of the output of the simulation with one rain gauge were not satisfactory (see § 5.1.1) it was decided to create 6 fictive rain gauges. The “Mutomo agricultural station” is kept as weather station with other meteorological inputs as done in the former simulation. The rain gauges have been created because it is generally accepted that rainfall in semi-arid areas is highly erratic and normally falls as intensive storms, with high intensity and spatial and temporal variability (Rockström, 2000). It would be therefore unreasonable to assume that the rainfall will be uniform over an area of 66 km^2.

Because no precipitation data of weather stations within the catchment were available, the precipitation data of “Mutomo agricultural station” were used. For the simulation, the precipitation data were scrambled over the 6 years of the simulation period. The general idea behind this approach is that precipitation that falls in particular weather station in one year can fall in another place within the catchment in another year. The precipitation is distributed over the catchment by Thiessen polygons. Although this approach uses a few presumptions, it can provide an insight in the hydrology of a semi-arid catchment.

In the precipitation distribution is displayed of 12 December 1981 of the two simulation methods.

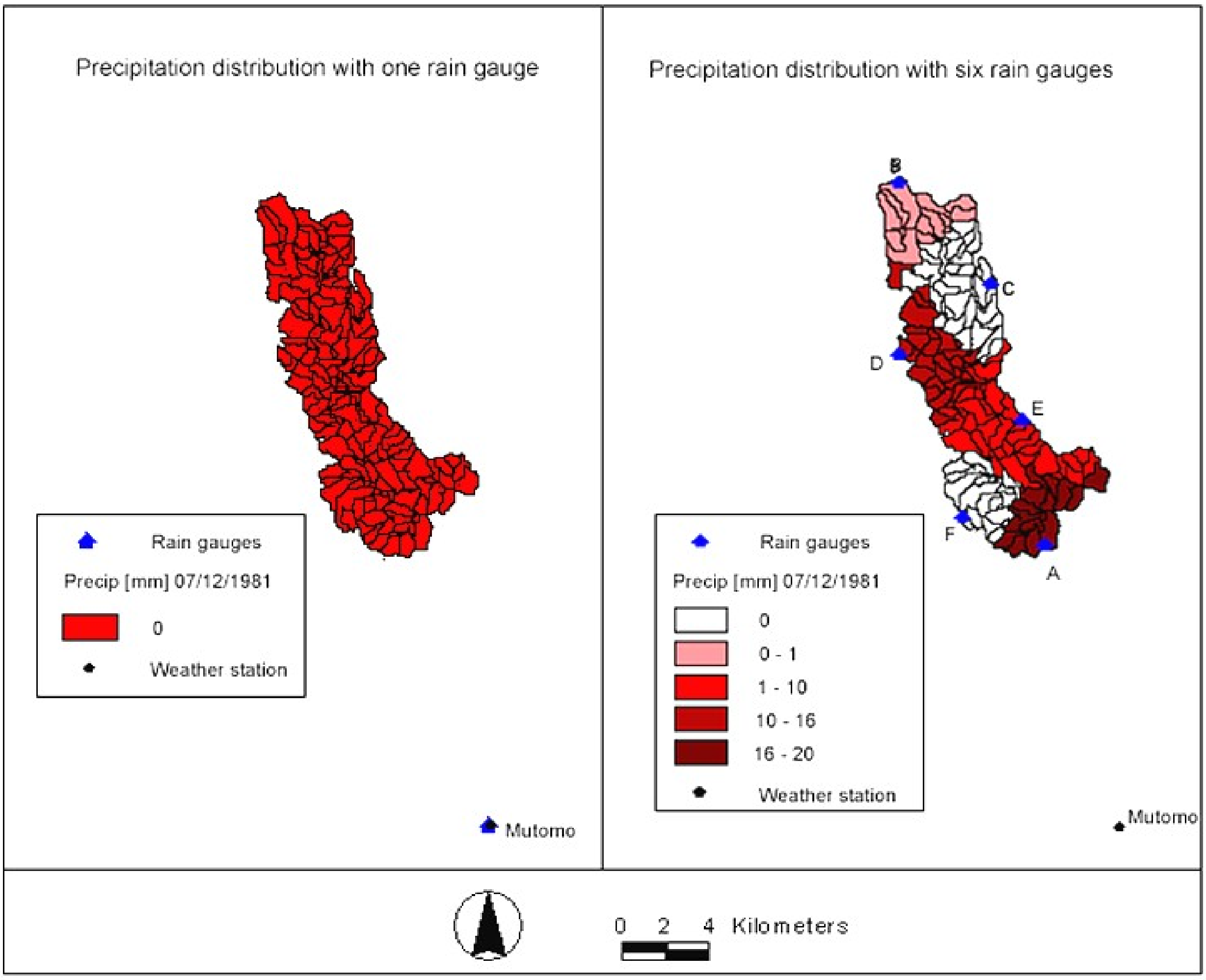

Figure 11: Precipitation distribution

If the 6 years of precipitation are scrambled, the high rainfall intensity (for instance the 200 mm) will not occur at the same time in all the weather stations. The high amount of rainfall will therefore not fall over a large area (see Figure 11), but will be spatially spread over the catchment. This scenario is more realistic because it represents the fact that rainfall in semi-arid regions has got a strong local nature. The scenario results in lower discharge peaks in comparison with the first simulation (Figure 12). The maximum discharge is 1322784 m^3/day.

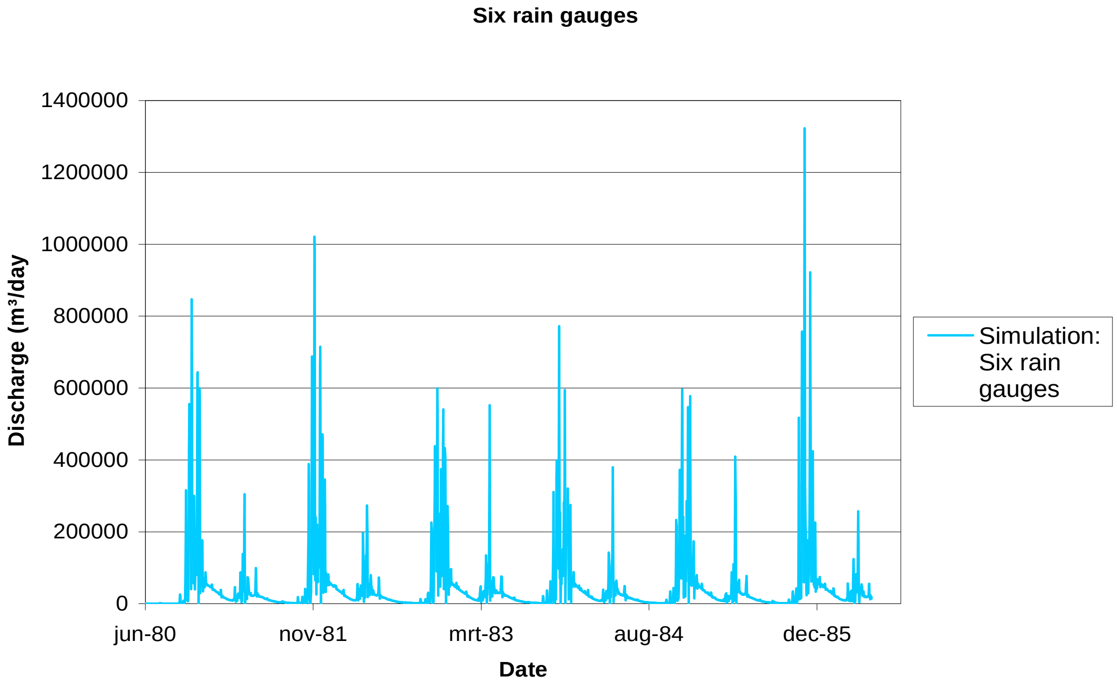

Figure 12 Discharge versus time: Simulation with six rain gauges

5.1.2.1 Qualitative calibration

Because no observed discharge data are available, a quantitative calibration cannot be performed. To conclude whether the model is realistic, a few parameters can be examined and compared with other case studies and measured records. Although this procedure does not provide more quantitative information, it does gain an insight into the main hydrological processes of the catchment.

5.1.2.1.1 VISUAL CALIBRATION OF THE DISCHARGE OUTPUT

Normally the discharge curve has an exponential slope because infiltration decreases exponentially with time. In the uncalibrated output this was however not the case. The model was calibrated on processes of channel routing, deep percolation and the effective hydraulic conductivity of the channel to obtain an exponential slope. Figure 13 represents the logarithm of the discharge, as function of the time, in this graph the slope should be linear. The calibrated output has got more or less a linear slope in the logarithmic discharge graph. However because no observed discharge data are available, the calibration will be done visually, based on the hydrograph.

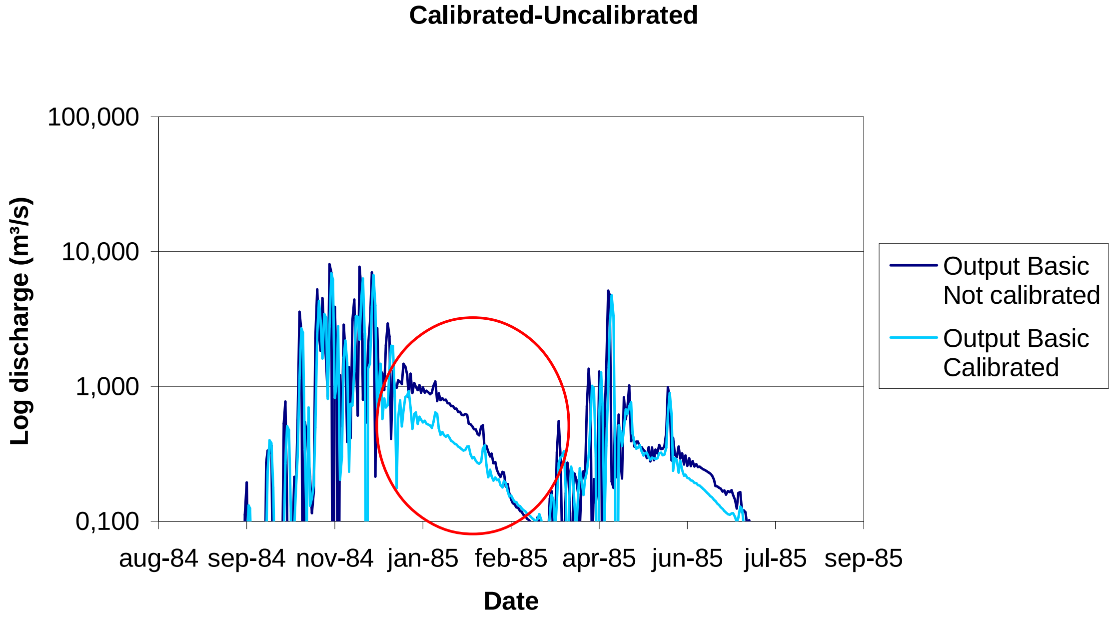

Figure 13: Date vs. log discharge of the calibrated and uncalibrated output

When the discharge as a function of time is compared with similar case-studies (Andersen *et al.,* 2001; Conan *et al*., 2003; Ye *et al.*, 1998) in semi-arid watersheds it can be concluded that the discharge curve is similar. High discharge peaks in times of precipitation are alternated with periods of no or almost no discharge in the dry season (Figure 12). This demonstrates the strong dependency of the discharge at the outlet of the catchment on the rainfall in the catchment.

5.1.2.1.2 DISCHARGE RESPONSE AND ACTUAL EVAPOTRANSPIRATION

Discharge response

Figure 12 shows that high discharge peaks occur. Periods of high discharge follow immediately days with high rainfall. This indicates the distinct rainfall-runoff response in the Ngunga-catchment. More rainfall results immediately in a higher discharge at the outlet of the basin. This clear response indicates the importance of the runoff to the discharge. In semi-arid areas, the contribution of base flow to the discharge is minor because the perennial rivers are located above the water table, which is usually located at a profound depth. Flow in the saturated zone therefore does not contribute to the discharge of the river.

Evapotranspiration

The actual evapotranspiration, generated by SWAT, per day is never higher then the generated daily potential evaporation. When the total actual evapotranspiration per month generated by SWAT is compared with the measured total potential evapotranspiration (PET) per month of the “Kitui agricultural office”, the actual evapotranspiration is on an average yearly basis 84% lower than the potential evapotranspiration. The average monthly actual and potential evapotranspiration as generated by SWAT is displayed in Figure 14.

Potential evapotranspiration is the amount of water transpired by a short green crop, completely shading the ground, of uniform height and never short of water. (Neitsch, *et al.,* 2001). In semi-arid areas however, vegetation will almost never be fully supplied by water. Plants will therefore have a limited transpiration and the soil evaporation will be drastically restricted.

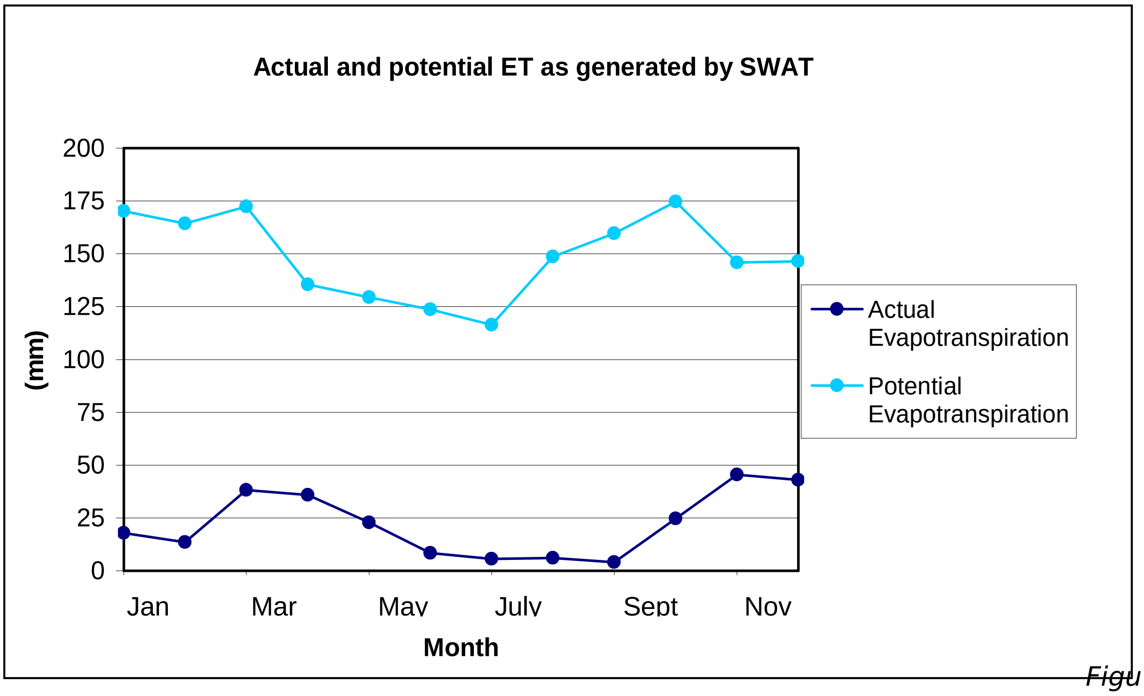

Figure 14: Actual and potential ET as generated by SWAT

5.1.2.2 Land use scenario analysis

To understand the importance of changing land use on the water balance of a watershed, different input scenarios will be provided and the output results will be examined.

The basic scenario will be with the experimentally determined soil classes, land use and climate parameters as described above.

For scenario 1, the output will be examined when the whole catchment will be cultivated with maize and cowpeas.

For scenario 2, influence on the output will be examined when the whole catchment will be under a sparse grass vegetation (range grass), as a result of the degraded soil.

The two scenarios are compared with the basic scenario; the result is displayed in Figure 15.

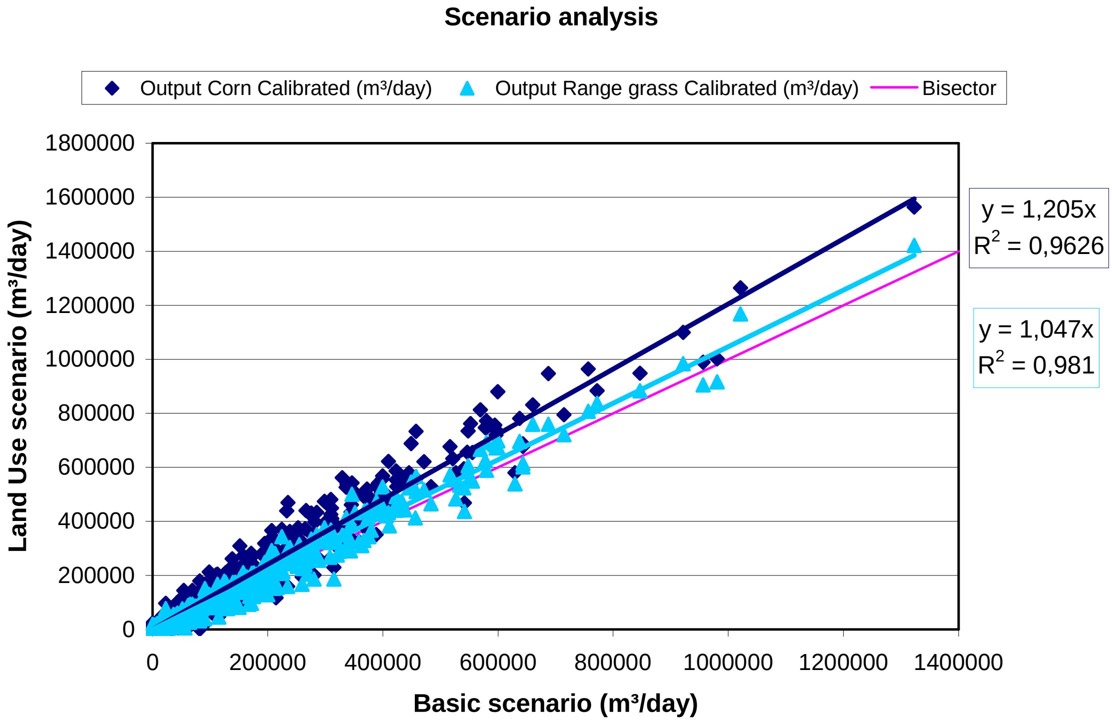

Figure 15: Scenario analysis

5.1.2.2.1 DISCUSSION

As can be seen in the previous paragraph, land use has only a minor response on the runoff characteristics of the catchment. Changes in land use have an influence on the surface runoff, infiltration and the actual evapotranspiration.

Soil Conservation Service (SCS) Curve Number (CN) procedure

The SCS curve number equation is used to calculate the runoff:

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \qquad (8)$$

with: Q_{surf}: the accumulated runoff or rainfall excess (mm H_2O)

R_{day}: the rainfall depth for the day (mm H_2O)

I_a: the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm H_2O), commonly approximated as 0.2S

S: the retention parameter (mm H_2O)

This equation is influenced by land use on the interception and infiltration of water in the soil. With different vegetation, these parameters will change.

The retention parameter S is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad (9)$$

with: CN the curve number for the day

Jan Mar May July Sept Nov

The curve number is a function of the soil's permeability, land use and antecedent soil water conditions (Neitsch *et al.* 2001). Different kind of land use will therefore have a different curve number and thus different runoff.

Actual evapotranspiration

SWAT first evaporates any free water intercepted by the plant canopy. The amount of free water that can be held in the canopy varies as a function of the leaf area index.

Next the transpiration is calculated. Because the Penman-Monteith equation is selected as the potential evaptranspiration method, transpiration is also calculated with this equation. The evaporation from the soil will then be calculated; this is dependent on the soil cover index (function of the aboveground biomass and residue) and the potential evapotranspiration.

As can be seen from Figure 15, both scenarios result in a slightly higher discharge. The runoff surplus can be explained through a higher curve number in the two scenarios. Corn and range grass can retain less water than bush, by consequence the infiltration will decrease.

5.2 Water balance for a sandy reservoir

5.2.1 Results

The output of SWAT and of the evaporation calculation is imported into the water balance model. The result is displayed in Figure 16.

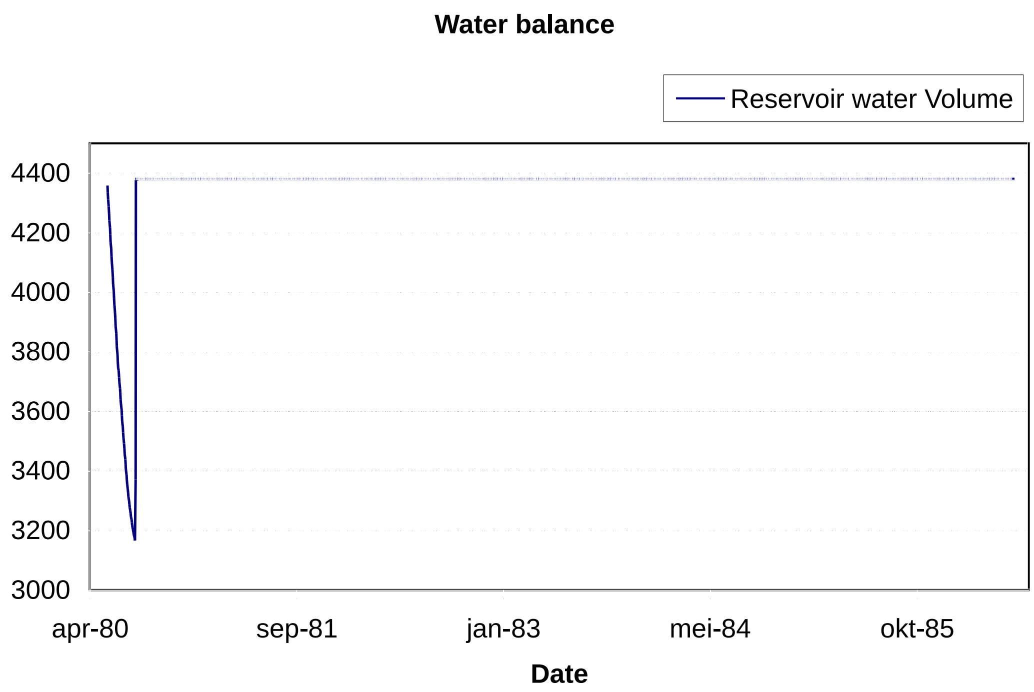

Figure 16: Volume water in the sandy reservoir versus time

5.2.2 Discussion

From Figure 16 can be seen that the sandy reservoir is almost always filled with water until the top. However, this is not what is known from other sand-storage dams. It is therefore reasonable to assume that the water balance gives an overestimation of the retained water in reality. There are several reasons for this overestimation. First, this water balance model is very dependent on the output generated by SWAT. This is because the sandy reservoir is provided by a very large runoff area. The output of SWAT will therefore be the most important contributor of the water balance model. Direct rainfall and evaporation occur over the relatively small surface of the sandy reservoir and will therefore have only a negligible contribution to the water balance.

However, the output of SWAT is uncertain because the model remains uncalibrated. Furthermore, because of the scrambling of the precipitation data, there are fewer days without precipitation anywhere in the catchment. In reality however, it regularly happens that a rainy season is delayed and a long dry period occur. By scrambling the rainfall data of one dataset, the locality of the rainfall can be modelled, but also a more regular course of the rainfall over the whole catchment will be shown. In reality, however, rainfall shows a highly erratic course. This means that the discharge modelled with the SWAT-model with six rain gauges will be less erratic and has got a more continuous display (compare Figure 10 and Figure 12). Because of this feature, the sand-storage dam will be supplied with water on a more continuous way. Sand-storage dams will fill up almost immediately when a high rainfall occurs (Ertsen and Biesbrouck, in press). The final result will be that with output of the SWAT model with six rain gauges, the sand-storage dam will be filled completely with water for a longer time, but that the extreme peaks in the discharge of the river will be lower.

Other uncertainties are the estimation of the sub-surface reservoir of the sand-storage dam. Because of the irregularities in the depth of the underlying rock, it is difficult to estimate the volume of the sub-surface reservoir. The irrigation and domestic requirements could not be included in the water balance because the dam is not yet built. Once the dam is built, also these parameters can be taken into account.

Seepage is another unknown parameter of the balance. Through measurements of the water levels before and behind the dam, an estimation of the loss of the water through seepage can be obtained. This parameter is also strongly dependent on the specific dam location and construction parameters.

An estimation of the emptying of the sand-storage dam is made. Hereby, it is assumed that there is no rainfall and the only source of water loss is through evaporation (no seepage). From this simulation it can be seen that the initially filled sand-storage dam will still be filled for 39% after two years. This simulation indicates that the water stored by sand-storage dams built with expertise is available for a long period and that a sand-storage dam can overcome the temporal shortage of water.

6 CONCLUSIONS

6.1 The AVSWAT software

AVSWAT is a complete, budget friendly program with extended possibilities. Especially the fact that AVSWAT does not need full time series to perform a simulation is a considerable advantage in developing countries where input data and budgets are restricted. Input data in AVSWAT are not lumped together, this has the advantage that the catchment area can be surveyed in a less intensive way and that decision-making is less subjective. In developing countries it is important that economical and sustainable solutions are found.

Although the AVSWAT-model can provide a good simulation with limited data, it does have some limitations and practical difficulties.

First, it is very time consuming to start a simulation from scratch. A lot of time is spent in creating the input of the model. A lot of errors can be made in creating this input. The fields of the required dbf-files all need a specific format (string, integer, character,..). These input files can therefore not be quickly adjusted with Excel. When input errors occur, the simulation cannot proceed. Often it is difficult to track the cause of these runtime errors. A lot of time is therefore spent in tracking and correcting input errors.

Another disadvantage of the AVSWAT-model is the amount of hard disk-space a project needs (up to 3 gigabytes in this specific case). This makes it very difficult to backup and to work on several projects without having a lack of hard disk-space. Some calculations in the pre-processing faze of AVSWAT take a long time (up to 6 hours for some calculations). Even with an up-to-date computer (Pentium IV processor: 2,26 GHz; 512 Mb RAM memory) AVSWAT will still regularly crash. It is therefore very important that a decent computer with enough hard disk space is available to simulate a complex watershed with AVSWAT. This makes it difficult to introduce AVSWAT as a sustainable and economical modelling tool in developing countries.

Also the ArcView interface of SWAT contributes to the practical inconveniences. It is not possible to simply move the AVSWAT-project to another directory or another computer. The project needs to be opened from the same directory as were it has been created. If not, the file paths have to be redefined. However an AVSWAT-project can contain more than 3000 separate files for all of which the paths have to be redefined. This makes it very difficult to pass on projects from one user to another.

It has to be mentioned that once the input of a project is finished, the simulation is performed relatively fast (± 1 hour to run SWAT and view the output). Mainly the calculations in the previous pre-processing steps are the most time consuming.

The previously mentioned features make the AVSWAT-model a complex model to use with quite a lot of practical inconveniences. These practical inconveniences and the need of expensive, up to date computers can complicate or even prevent the introduction of AVSWAT in developing countries. Even if a solution for the expensive hardware is found, these practical inconveniences can cause that AVSWAT will not be used although modelling results are satisfying. The model can be introduced but close monitoring has to be performed and education must be given to make sure that the introduction is sustainable.

6.2 Simulation of discharge with AVSWAT

Although the model is not quantitatively calibrated, a few conclusions can be made.

As been stated before, there is the clear rainfall-runoff response of the catchment and there are distinct periods without discharge. This points out the limited contribution of base flow to the discharge.

It can be said that if an accurate model from a semi-arid watershed is to be made, sufficient rainfall data collected within the catchment. Especially in a catchment of this size several rain gauges should be set up to get an idea of the temporal and spatial distribution of the rainfall. Collection of rainfall data for model studies is even more important in semi-arid climates than in temperate climates because of the erratic rainfall.

Modelling in dry climate is especially difficult because the dry periods cause changes in the density of the vegetation and in the structure of the soils (infiltration and runoff). It is generally known that semi-arid have a delicate hydrological balance.

As can be seen from the scenario analysis, there is a limited influence of land use changes on the discharge of the catchment. The two investigated scenarios are extreme situations. If land use changes within the catchment occur through taking into cultivation of more land or degradation of vegetation, these will have negligible effects on the water supply at the outlet of the catchment. Although local effects such as erosion and mudflows can occur.

6.3 Water balance of a sandy reservoir

The water balance is highly dependent of the AVSWAT results. The main reason of the overestimation of the water volume in the dam reservoir will be the simulated discharge that is too continuous. Also the negligence of seepage and water use for irrigation and domestic purposes will contribute to the overestimation.

6.4 General conclusions and recommendations

AVSWAT is a hydrological tool that can be used for modelling in semi-arid watersheds. However, the introduction in developing countries remains doubtful because of the expensive computers necessary and the practical inconveniences of the model.

The Ngunga watershed has a distinct rainfall-runoff response resulting in high discharge peaks in periods of high rainfall and no or negligible discharge during the dry season. To perform a valid simulation several rain gauges are required in the studied area. It is therefore essential that the weather stations that have been set up in the area are maintained and if possible a few rain gauges can be set up in the centre of the Ngunga catchment. The local nature of rainfall can be simulated through scrambling of the rainfall data, however this results in pattern of rainfall that is too regular because of the return of the same rainstorms every year. This simulation was however the best possible method to follow with the limited data available. Conclusions about the quantity of the retained water cannot be made because the model remains uncalibrated.

Land use changes have a limited contribution to discharge changes at the outlet. It is therefore more important to spend the available budget on the collection of rainfall data, in stead of monitoring the land use changes in the area.

To calibrate the model, discharge measurements and groundwater level measurements are indispensable. As been indicated before, installing piezometers is not straightforward in the area. Recommendations have been made in § .

In future research, more information should be obtained of seepage of sand-storage dams. Also a monitoring of the use of water for irrigation and domestic use should be performed. The estimation of the depth of the underlying rock can be done by using a terrameter. This way, more transacts of the river can be investigated so a more reliable interpolation of the rock surface can be performed. An estimation of the volume of the sandy reservoir can be performed more in detail this way.

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I. Annex: Weather generation (Neitsch *et al.*, 2001)[1].

RAIN_YRS

The number of years of maximum monthly 0.5 h rainfall data used to define values for the extreme half-hour rainfall for month *mon* (RAIN_HHMX (mon)).

If no value is input for RAIN_YRS, SWAT will set RAIN_YRS = 10.

TMPMX(mon)

Average or mean daily maximum air temperature for month *mon* (ºC). This value is calculated by summing the maximum air temperature for every day in the month for all years of record and dividing by the number of days summed:

$$\mu mx_{mon} = \frac{\sum_{d=1}^{N} T_{mx,mon}}{N}$$

where μmx_{mon} is the mean daily maximum temperature for the month (°C), $T_{mx,mon}$ is the daily maximum temperature on record d in month *mon* (°C), and *N* is the total number of daily maximum temperature records for month *mon*.

TMPMN(mon)

Average or mean daily minimum air temperature for month *mon* (ºC). This value is calculated by summing the minimum air temperature for every day in the month for all years of record and dividing by the number of days summed:

$$\mu mn_{mon} = \frac{\sum_{d=1}^{N} T_{mn,mon}}{N}$$

where μmn_{mon} is the mean daily minimum temperature for the month (°C), $T_{mn,mon}$ is the daily minimum temperature on record *d* in month *mon* (°C), and *N* is the total number of daily minimum temperature records for month *mon*.

TMPSTDMX(mon)

Standard deviation for daily maximum air temperature in month *mon* (ºC). This parameter quantifies the variability in maximum temperature for each month. The standard deviation is calculated:

$$\sigma\mu\nu_{\mu o\nu} = \sqrt{\frac{\sum_{\delta=1}^{N} (T_{\mu\nu,\mu o\nu} - \mu\mu\nu_{\mu o\nu})?}{N-1}}$$

where σmx_{mon} is the standard deviation for daily maximum temperature in month *mon* (ºC), $T_{mx,mon}$ is the daily maximum temperature on record *d* in month *mon* (°C), $\mu_{mx,mon}$ is the average daily maximum temperature for the month (°C), and *N* is the total number of daily maximum temperature records for month *mon*.

TMPSTDMN(mon)

Standard deviation for daily minimum air temperature in month *mon* (ºC). This parameter quantifies the variability in minimum temperature for each month. The standard deviation is calculated:

1 Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R. 2001. Soil and Water Assessment Tool, User Manual, Version 2000. Blackland Research Center. USDA-ARS, Texas Agr. Experiment Station, Texas. 448p.

$$\sigma\mu\nu_{\mu o\nu} = \sqrt{\frac{\sum_{\delta=1}^{N}(T_{\mu\nu,\mu o\nu} - \mu\mu\nu_{\mu o\nu})?}{N-1}}$$

where σmn_{mon} is the standard deviation for daily minimum temperature in month *mon* (ºC), $T_{mn,mon}$ is the daily minimum temperature on record *d* in month *mon* (°C), $T_{mn,mon}$ is the average daily minimum temperature for the month (°C), and *N* is the total number of daily minimum temperature records for month *mon*.

PCPMM(mon)

Average or mean total monthly precipitation (mm H_2O).

$$\overline{R}_{mon} = \frac{\sum_{d=1}^{N} R_{day,mon}}{yrs}$$

where $\overline{}$ is the mean monthly precipitation (mm H_2O), $R_{day,mon}$ is the daily precipiation for record *d* in month *mon* (mm H_2O), *N* is the total number of records in month *mon* used to calculate the average, and *yrs* is the number of years of daily precipitation records used in calculation.

PCPSTD(mon)

Standard deviation for daily precipitation in month *mon* (mm H_2O/day). This parameter quantifies the variability in precipitation for each month. The standard deviation is calculated:

$$\overline{R}_{mon} = \frac{\sum_{d=1}^{N} R_{day,mon}}{yrs}$$

where σ_{mon} is the standard deviation for daily precipitation in month *mon* (mm H_2O), $R_{day,mon}$ is the amount of precipitation for record *d* in month *mon* (mm H_2O), $\overline{}$ is the average precipitation for the month (mm H_2O), and *N* is the total number of daily precipitation records for month *mon*. (Note: daily precipitation values of 0 mm are included in the standard deviation calculation)

PCPSKW(mon)

Skew coefficient for daily precipitation in month *mon*. This parameter quantifies the symmetry of the precipitation distribution about the monthly mean. The coefficient of skewness is calculated:

$$g_{mon} = \frac{N.\sum_{d=1}^{N}\left(R_{day,mon} - \overline{R}_{mon}\right)?}{(N-1).(N-2).(\sigma_{mon})?}$$

where g_{mon} is the skew coefficient for precipitation in the month, *N* is the total number of daily precipitation records for month *mon*, $R_{day,mon}$ is the amount of precipitation for record *d* in month *mon* (mm H2O), $\overline{}$ is the average precipitation for the month (mm H_2O), and σ_{mon} is the standard deviation for daily precipitation in month *mon* (mm H_2O). (Note: daily precipitation values of 0 mm are included in the skew coefficient calculation)

PR_W(1,mon)

Probability of a wet day following a dry day in month *i*. This probability is calculated:

where *Pi(W/D)* is the probability of a wet day following a dry day in month *i*, $days_{W/D,i}$ is the number of times a wet day followed a dry day in month *i* for the entire period of record, and $days_{dry,i}$ is the number of dry days in month *i* during the entire period of record. A dry day is a day with 0 mm of precipitation. A wet day is a day with > 0 mm precipitation.

PR_W(2,mon)

Probability of a wet day following a wet day in the month *i*. This probability is calculated:

where *Pi(W/W)* is the probability of a wet day following a wet day in month *i*, $days_{W/W,i}$ is the number of times a wet day followed a wet day in month *i* for the entire period of record, and $days_{wet,i}$ is the number of wet days in month *i* during the entire period of record. A dry day is a day with 0 mm of precipitation. A wet day is a day with > 0 mm precipitation.

PCPD(mon)

Average number of days of precipitation in month *i*. This parameter is calculated:

where , is the average number of days of precipitation in month *i*, $days_{wet,i}$ is the number of wet days in month *i* during the entire period of record, and *yrs* is the number of years of record.

SOLARAV(mon)

Average daily solar radiation for month *mon* (MJ/m^2/day). This value is calculated by summing the total solar radiation for every day in the month for all years of record and dividing by the number of days summed:

$$\mu rad_{mon} = \frac{\sum_{d=1}^{N} H_{day,mon}}{N}$$

where μrad_{mon} is the mean daily solar radiation for the month (MJ/m^2/day), $H_{day,mon}$ is the total solar radiation reaching the earth's surface for day *d* in month *mon* (MJ/m^2/day), and *N* is the total number of daily solar radiation records for month *mon*.

DEWPT(mon)

Average daily dew point temperature in month *mon* (ºC). The dew point temperature is the temperature at which the actual vapour pressure present in the atmosphere is equal to the saturation vapour pressure. This value is calculated by summing the dew point temperature for every day in the month for all years of record and dividing by the number of days summed:

$$\mu dew_{mon} = \frac{\sum_{d=1}^{N} T_{dew,mon}}{N}$$

where μdew_{mon} is the mean daily dew point temperature for the month (ºC), $T_{dew,mon}$ is the dew point temperature for day *d* in month *mon* (ºC), and *N* is the total number of daily dew point records for month *mon*.

WNDAV(mon)

Average daily wind speed in month *mon* (m/s). This value is calculated by summing the average or mean wind speed values for every day in the month for all years of record and dividing by the number of days summed:

$$\mu wnd_{mon} = \frac{\sum_{d=1}^{N} \mu_{wnd,mon}}{N}$$

where μwnd_{mon} is the mean daily wind speed for the month (m/s), $\mu_{wnd,mon}$ is the average wind speed for day *d* in month *mon* (m/s), and *N* is the total number of daily wind speed records for month *mon*.

	Jan	Feb	Mrt	Apr	Mei	Jun	Jul	Aug	Sep	Okt	Nov	Dec
Complete Years (of 21)	19	18	20	18	18	17	14	14	17	17	19	19
PCPMM	82,04	17,09	74,43	141,66	29,16	3,39	2,89	8,36	17,79	48,33	294,62	160,85
PCPSTD (mon)	11,20	5,22	10,19	14,50	4,04	1,24	0,85	2,60	3,80	8,08	22,15	16,03
PCPSKW (mon)	6,32	11,22	5,89	4,64	6,35	13,78	10,81	15,95	7,62	8,59	3,51	2,93
PR_W(1,mon)	0,07	0,02	0,09	0,17	0,05	0,02	0,02	0,02	0,03	0,07	0,23	0,16
PR_W(2,mon)	0,50	0,18	0,30	0,39	0,45	0,11	0,11	0,17	0,36	0,32	0,58	0,51
PCPD(mon)	3,58	0,61	3,50	6,50	2,72	0,53	0,64	0,86	1,29	2,88	10,63	7,47
TMPMX (mon)	27,70	29,30	30,00	27,70	26,60	26,00	25,00	25,50	27,10	28,20	26,60	26,00
TMPMN (mon)	16,00	16,60	17,10	17,10	16,60	14,30	13,80	13,80	13,80	15,50	16,60	16,60
TMPSTDMX (mon)	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51
TMPSTDMN (mon)	1,35	1,35	1,35	1,35	1,35	1,35	1,35	1,35	1,35	1,35	1,35	1,35
WNDAV (mon)	2,30	2,50	2,50	2,20	2,60	2,60	2,80	3,10	2,80	3,20	2,60	2,80
DEWPT (mon)	16,80	17,20	17,80	18,30	17,10	15,20	14,00	13,60	13,70	14,60	17,10	17,40
SOLARAV (mon)	24,37	25,62	23,40	20,72	19,76	18,46	15,66	19,05	21,44	22,40	21,14	21,86
RAINYRS	10											

Table 3 Weather generation

	Source	Years
Daily precipitation	Mutomo (IMTR)	21 (not all complete)
TMPMX (mon)	Kitui Argic (FAO)	7
TMPMN (mon)	Kitui Argic (FAO)	7
WNDAV (mon)	Kitui Argic (FAO)	7

DEWPT (mon)	Kitui (FAO)	Argic	8
SOLARAV (mon)	Kitui (FAO)	Argic	?

Table 4 Source and years for calculation of weather generation

II. Annex: Soil input data

HYDGRP

Soil hydrologic group (A, B, C, or D). The definitions for the different classes are represented in Table 5.

A	Soils having high infiltration rates even when thoroughly wetted, consisting chiefly of sands or gravel that are deep and well to excessively drained. These soils have a high rate of water transmission (low runoff potential).
B	Soils having moderate infiltration rates when thoroughly wetted, chiefly moderately deep to deep, moderately well to well drained, with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.
C	Soils having slow infiltration rates when thoroughly wetted, chiefly with a layer that impedes the downward movement of water or of moderately fine to fine texture and a slow infiltration rate. These soils have a slow rate of water transmission (high runoff potential).
D	Soils having very slow infiltration rates when thoroughly wetted, chiefly clay soils with a high swelling potential; soils with a high permanent water table; soils with a clay pan or clay layer at or near the surface; and shallow soils over nearly impervious materials. These soils have a very slow rate of water transmission.

Table 5: Soil hydrologic group

SOL_ZMX

Maximum rooting depth of soil profile (mm)

If no depth is specified, the model assumes the roots can develop throughout the entire depth of the soil profile.

ANION_EXCL

Fraction of porosity (void space) from which anions are excluded.

If no value for ANION_EXCL is entered, the model will set ANION_EXCL = 0.50.

Because no values were found, this parameter was given the value 0.01.

SOL_CRK

Potential or maximum crack volume of the soil profile expressed as a fraction of the total soil volume. To accurately predict surface runoff and infiltration in areas dominated by Vertisols, the temporal change in soil volume must be quantified. (Optional)

SOL_Z(layer #)

Depth from soil surface to bottom of layer (mm).

SOL_BD(layer #)

Moist bulk density (Mg/m^3 or g/cm^3).

The soil bulk density expresses the ratio of the mass of solid particles to the total volume of the soil, $\rho_b = M_S / V_T$. In moist bulk density determinations, the mass of the soil is the oven dry weight and the total volume of the soil is determined when the soil is at or near field capacity. Bulk density values should fall between 1.1 and 1.9 Mg/m^3.

SOL_AWC(layer #)

Available water capacity of the soil layer (mm H_2O/mm soil).

The plant available water, also referred to as the available water capacity, is calculated by subtracting the fraction of water present at permanent wilting point from that present at field capacity: $WP = FC - AWC$

where *AWC* is the plant available water content, *FC* is the water content at field capacity, and *WP* is the water content at permanent wilting point.

SOL_K(layer #)

Saturated hydraulic conductivity (mm/hr).

The saturated hydraulic conductivity, Ksat, relates soil water flow rate (flux density) to the hydraulic gradient and is a measure of the ease of water movement through the soil. Ksat is the reciprocal of the resistance of the soil matrix to water flow.

SOL_CBN(layer #)

Organic carbon content (% soil weight). When defining by soil weight, the soil is the portion of the sample that passes through a 2 mm sieve. The organic carbon content is based on a soil report close to the catchement area.

CLAY(layer #)

Clay content (% soil weight).

The percent of soil particles which are < 0.002 mm in equivalent diameter.

SILT(layer #)

Silt content (% soil weight).

The percentage of soil particles which have an equivalent diameter between 0.05 and 0.002 mm.

SAND(layer #)

Sand content (% soil weight).

The percentage of soil particles which have a diameter between 2.0 and 0.05 mm.

ROCK(layer #)

Rock fragment content (% total weight).

The percent of the sample which has a particle diameter > 2 mm, i.e. the percent of the sample which does not pass through a 2 mm sieve.

SOL_ALB(layer #)

Moist soil albedo.

The ratio of the amount of solar radiation reflected by a body to the amount incident upon it, expressed as a fraction. The value for albedo should be reported when the soil is at or near field capacity. Only the moist albedo for the first layer has been specified because it is assumed that the soil layers will not move. The used values (see Table 6) are based on Taylor and Ashcroft (1972)[2].

Dry sand	0.35-0.45
Wet sand	0.20-0.30
Dark soil	0.05-0.15
Wet gray soil	0.10-0.20
Dry light clay	0.20-0.35

2 Taylor S.A. and Ashcroft. G.L. (1972). Physical edaphology: the physics of irrigated and non-irrigated soils, W.H. Freeman and Company, San Francisco, CA.

soil	
Dry light sand soil	0.25-0.45

Table 6: Moist soil albedo

USLE_K(layer #)

USLE equation soil erodibility (K) factor (units: 0.013 (metric ton m^2 hr)/ (m^3-metric ton cm)). These values are based on Van Rompaey[3] (2001) (see Table 7). The right textural class can be found with the textural diagram.

Textural class	USLE_K
A	0.041
L	0.037
P	0.026
S	0.019
Z	0.012
E	0.029
U	0.028

Table 7: Soil erodibility factor

3 Van Rompaey, A. (2001). Geomorphic and land use change modelling at regional scale. PhD-dissertation. Faculty of Sciences, K.U.Leuven, Belgium.

Lixisol													
HYDGRP	B	**Layer**	**SOL_Z**	**SOL_BD**	**SOL_AWC**	**SOL_K**	**SOL_CBN**	**CLAY**	**SILT**	**SAND**	**ROCK**	**SOL_ALB**	**USLE_K**
SOL_ZMX	1000	1	200	1,36	0,0993	273,39	0,7	12,26	13,37	74,36	0	0,25	0,019
ANION_EXCL	0,01	2	500	1,33	0,0598	270,39	0,5	22,67	1,45	66,90	0	0	0,029
SOL_CRK	0	3	700	1,39	0,0864	29,81	0,2	22,51	12,74	64,75	0	0	0,029

Table 8: Soil characteristics of Lixisol

Planosol													
HYDGRP	D	**Layer**	**SOL_Z**	**SOL_BD**	**SOL_AWC**	**SOL_K**	**SOL_CBN**	**CLAY**	**SILT**	**SAND**	**ROCK**	**SOL_ALB**	**USLE_K**
SOL_ZMX	800	1	40	1,40	0,0840	60,12	1,0	10,12	9,84	80,04	0	0,25	0,019
ANION_EXCL	0,01	2	1000	1,42	0,0810	40,00	0,5	20,14	7,65	72,21	0	0	0,029
SOL_CRK	0												

Table 9: Soil characteristics of Plansol

Vertisol													
HYDGRP	D	**Layer**	**SOL_Z**	**SOL_BD**	**SOL_AWC**	**SOL_K**	**SOL_CBN**	**CLAY**	**SILT**	**SAND**	**ROCK**	**SOL_ALB**	**USLE_K**
SOL_ZMX	40	1	550	1,49	0,1538	5,693	1,0	28,0	19,2	52,7	0	0,1	0,029

	0							5	4	1			
ANION_EXCL	0,01	2	850	1,44	0,1281	0,6693	0,5	31,20	19,47	49,33	0	0	0,029
SOL_CRK	0,15	3	1000	1,27	0,1670	2,8771	0,5	35,80	18,20	45,99	0	0	0,028

Table 10: Soil characteristics of Vertisol

III. Annex: Major soil units in the Ngunga-catchment

Lixisols

The dominant soils in the Ngunga-catchment are the strongly weathered Lixisols. In these soils the clay has been washed out of an eluvial horizon down to an argic subsurface horizon that has low activity clays and a moderate to high base saturation level. The argic horizon can be overlain by loamy sand or coarser textures.

Lixisols are typically found in regions with a tropical, subtropical or warm temperate climate with a pronounced dry season. Many Lixisols are assumed to be polygenetic soils with characteristics formed under a more humid climate in the past. Proofs of this more humid climate are the inclusions of fossil plintite found round eroded roads and hills in the catchment. Lixisols in the upper regions are associated with rock outcrops.

Most ‘unreclaimed’ Lixisols in the Ngunga-catchment are under bush or open woodland vegetation and are used for low volume grazing. The main crops on Lixisols in the area are maize and cowpeas. The fields are cleared by slash and burn. Soil labour is done by native hoes. Slash and burned releases necessary nutrients to the soils, which are by native poorly supplied with nutrients. However, to have an acceptable yield, these soils require recurrent inputs of fertilizers and/ or lime.

In the sloping study-area, the unstable surface soil structure makes Lixisols very prone to slaking and erosion through the direct impact of raindrops. It is therefore important to introduce conservation techniques to preserve the surface soils with its important organic matter. Tillage and erosion control measures such as terracing, contour ploughing, mulching and the use of cover crops help to conserve the soil (FAO, 2001). A Lixisol sample profile of the region is described in Figure III.1.

Horizon	Depth	Description
Ap	0-20 cm	Dark brown, loamy sand; many roots; gradual smooth boundary.
AB	20-50 cm	Reddish brown, clay, slightly hard, sticky many roots, many fine and few coarse pores, few calcareous concretions; smooth boundary.
B_t	50-100 cm	Light reddish brown, clay, sticky, plastic; roots until 100 cm; moderate medium subangular blocky; few calcareous concretions.

Figure III.1: Sample profile: Lixisol

Vertisols

In the East part of the Ngunga-catchment, a small area of Vertisol occurs. This area forms a part of a large, relatively flat Vertisol plain that reaches until the Semea River near Ikanga in the East.

Vertisols are heavy clays with a high proportion (>30%) of 2:1 lattice clays. These clays swell during the rainy season and shrink during the dry season with deep wide cracks from the surface downward as a consequence (see Figure III.2). Vertisols are soils with good water holding properties. However, a large proportion of all water in Vertisols, and notably the water held between the basic crystal units, is not available to plants.

Though these soils form a considerable agricultural potential, the major part of the Vertisols in the study-area are still unused. To cultivate Vertisols, appropriate management has to be applied. Although Vertisols have a high chemical fertility they are very difficult to cultivate because of the stickiness and plasticity in moist conditions and the hardness when dry. The susceptibility of Vertisols to water logging is an important factor that reduces the actual growing period. Surface drainage is therefore indispensable.

Natural vegetation on Vertisols consists of grass and scattered trees. Tree growth on Vertisols is limited because the roots have difficulties to establish themselves into the hard subsoil and because they are damaged as the soil shrinks and swells (FAO, 2001).

A Vertisol sample profile of the region is described in Figure III.3.

Figure III.2: Top view of the cracks in a Vertisol

Horizon	Depth	Description
Ap	0-10 cm	Black sandy clay, subangular blocky structure; surface cracks; sticky when wet; very plastic; smooth boundary.
AC1	10-55 cm	Black clay; few fine and medium whitish lime concretions; very hard; sticky when wet: very plastic; strong coarse prismatic structures; roots until 40 cm; smooth clear boundary.
AC2	55-85 cm	Black-dark grey clay; common whitish lime concretions; hard; sticky when wet; very plastic; slight coarse prismatic structures; gradual boundary.
C	85-100 cm	Grey clay with much lime concretions; very hard; sticky when wet; very plastic.

Figure III.3: Sample profile: Vertisol

Planosols

Associated with the Vertisols in the East, quite a large flat area of Planosols is found. Only a small part of this area is part of the Ngunga-catchment. The Planosols can be seen as the degraded form of Vertisols. Planosols are strongly degraded soils with bleached, greyish eluvial surface horizon with a sandy or loamy texture and a weak structure of low stability. The most prominent feature of Planosols is the marked increase in clay content on passing from the degraded eluvial horizon to the deeper soil. The latter may be a slowly permeable argic illuviation horizon, mottled and with coarse angular blocky or prismatic structural elements. Planosols show periodic water stagnation that is the result of the heavy texture in the subsurface.

The sandy surface material becomes hard when dry but not cemented. Especially on roads the top soil can become loose and single-grained and can cause clouds of dust.

In general, the poor Planosols are mostly left uncultivated. This is also the case in the study-area. The natural Planosol areas are covered with sparse grass vegetation with scattered shrubs and trees, similarly with the Vertisol vegetation. The trees have extensive, shallow root systems that are capable of withstanding both severe drought and seasonal or occasional water logging (FAO, 2001).

A Planosol sample profile of the region is described in Figure III.4.

Horizon	Depth	Description
A_h	0-20 cm	Grey coarse sand; hard but loose and dusty on the top; many pores; no cracks; diffuse boundary.
E	20-40 cm	Yellowish grey sand; hard; many pores; clear smooth boundary.
B_t	40-100 cm	Yellowish brown clay; hard; many pores; roots until 80 cm; moderate medium subangular blocky;

Figure III.4: Sample profile: Planosol

IV. Network of piezometers (Bossenbroek & Timmermans, 2003)[4]

The construction of the network in such way that after its completion, it should be possible to determine:

- Difference in water level in front and behind the dam
- Difference in water level before and after the construction of the sand-storage dam

Criteria and guidelines

Piezometers are installed in cross-sections. Because of the inability of the augur to drill through rocky soils and the unsuitability of some parts of the banks, five criteria and guidelines were formulated.

1. **Allocation:** The cross-sections must be close to the dam site.
2. **Soil characteristics:** auguring is or isn't possible depending on the type of soil:
   - *Fractured rock* in the banks is not suitable for research because auguring in this material is impossible. Furthermore, the amount of water present in the layer is hard to determine. There is actually bank infiltration but one can't determine the amount nor study the location because auguring here is impossible.
   - *Fresh rock* in the riverbed: Auguring is not possible. It can be assumed that there is no water table present. When it's possible to augur in the surrounding soils, then a cross-section can be installed.
   - *Weathered rock*: Sometimes weathered rock is so soft that auguring is possible. If not, cross-sections are not possible.
   - *Clay and silt*: In these soil types auguring is possible. Even below groundwater level auguring is possible. Placing piezometers with high groundwater table is no problem.
   - *Sand*: In this soil type auguring is possible, but only above groundwater level. Placing piezometers with high groundwater table is not very useful, because piezometers will become useless most part of the year, when the groundwater levels drops.
3. **Banks**
   - The banks must not be higher than approximately 2,5 meters above the riverbed. This is because the used augur cannot reach a larger depth than approximately 4 meters. Groundwater levels should be measurable to up to 1,5 meters below the riverbed. Beneath 1,5 meters groundwater levels are too low to measure.
   - Banks with lots of bush are not suitable. Roots and obstructing shrubs and trees make auguring impossible. Even when auguring succeeds, it might be hard to find the piezometer back in a later stadium.
4. **Riverbed:** The choice of a cross-section perpendicular on the riverbed is easier in case of a strait reach. This is however not a necessity.
5. **Practical indicators**
   - Permission of landowners is needed when piezometers are installed on their property.
   - Permission of landowners is needed when clearing the bush. They are often used as fences to prevent cows and goats from destroying crops.

4 Bossenbroek J.-K. and Timmermans T. 2003. Research at sand-storage dams: Setting up a measuring program at Kisayani, Kenya. Traineeship report. p. 71-89.

- Do not place piezometers on cattle or foot paths. Small shrubs might provide some protection against animals.

Installation

The piezometers used for this study are perforated PVC (polyvinyl chloride) tubes, which were installed using an augur. Piezometers were installed in different cross-sections. Those cross-sections and the surroundings were mapped.

Piezometers were made using PVC-tubes with inner diameters of 2 inches (50.8 mm) and 2.2 inches (55.9 mm) and a thickness of 1 mm. A hot arc saw blade of approximately 1 mm thick was used to perforate the tubes over each meter with cuts of 10 to 15 cm. The bottoms of the tubes were closed using a lid of 2-inch diameter. These were also perforated. They were attached to the bottom using PVC-glue. The cuts were needed to facilitate flow of water into and out of the tubes. The tops of the tubes were closed using lids made from pieces of the same pipes. They were closed on top with the same 2-inch lids used to close the bottom of the piezometers (see Figure 1).

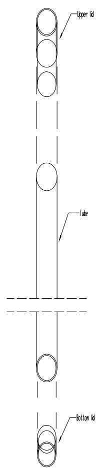

Figure 1: Tube with lid at both sides