“A study to up-scaling of the principle and sediment (transport) processes behind, sand storage dams, Kitui District, Kenya”

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Master thesis Hydrogeology
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aqua for all

Acacia Institute
Solutions in Groundwater

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Front: Modified sand storage dam Kwa Ndunda in the Kiindu Catchment

SUMMARY

The current study is the second component of the “Recharge Techniques and Water Conservation in East Africa – Up-scaling and Dissemination of the good practices with the Kitui sand storage dams” project. This project of the Acacia Institute and SASOL aims at using the experiences of the sand storage dams in Kitui to up-scale the construction of sand storage dams to other regions. Former research gave more insight in the hydrological processes around the sand storage dams. However, some questions remained unanswered. This second study (in combination with Hoogmoed and Jansen) is to provide an answer for the processes that remained unclear from the former research. This report describes a methodology for up-scaling of the sand storage dam principle combined with sedimentation processes in the surroundings of sand storage dams.

The Kitui District is one of the arid and semi-arid lands (ASAL) of Kenya. For drinking water local people rely on the water supplied from riverbeds from ephemeral rivers. Local NGO SASOL builds sand storage dams in the Kitui District. A sand storage dam is a dam in the riverbed, funded on an impermeable layer, behind which sand accumulates. When groundwater is recharged, water is stored below the newly accumulated sand, reducing evaporative losses and health risks. Because the sand behind the dam has accumulated a larger aquifer is created from which water can be obtained. This extra ground water buffer can be used to bridge the dry periods.

In October – December 2006 a fieldwork has been carried out in the Kitui District. Several catchment areas in the Kitui District, with both functioning and non-functioning sand storage dams, were visited. From each catchment site specific characteristics were observed and noted and from the surrounding area samples of the surface sediments were taken. These different conditions were compared to obtain criteria needed for good functioning of sand storage dams. In combination with available literature it appeared that sand availability in the riverbeds is one of the crucial components needed for the functioning of sand storage dams. Vegetation present in the riverbeds indicates that the sediments are less favourable in storing and subtracting water and therefore less favourable for the construction of sand storage dams.

In the Kiindu catcment a sand storage dam was selected for measurements. The dam was modified for more accurate discharge measurements. Near the dam supended load and bedload measurements were combined with discharge measurements. For both beldoad and suspended load a discharge-sediment load a relation was obtained. In the Kiindu catchment the distribution of surface sediments was measured using sediment samples throughout the catchment area. All sediment samples, including bedload and suspended load, have been analysed on particle size.

<u>Up-scaling</u>
A methodology for up-scaling of the project is developed in ArcGIS, based upon the information obtained from the field visits. In order to upscale the principle of sand dams different criteria have been refined. Therefore a study area is picked in which the field visits took place. Using satellite images sand rivers (ephemeral) can be distinguished from non-sand rivers. By identifying the sand rivers the overall characteristics of the supporting catchment area were studied. The identified sand rivers were compared to geology, lithology, slope, catchment area and precipitation.

For the study area a probability map is created based upon criteria obtained from the sand rivers in combination with site specific characteristics of the study area.

Most critical in the Kitui District appears to be the slope of the area. Catchment areas with an average slope smaller or equal to approximately 2° show large similarity with non-sandy riverbeds. Runoff generated in these catchment areas appears to be too low for transport of coarse grained material. No correlation could be obtained with precipitation.

Sediments

Bedload movement during the field period varied from 0 – ~34 tons/min during an extreme event. A good relation for low discharges could be obtained for the first stage of suspended load transport compared to discharge. Suspended load varied from 0 – ~3500 tons/min. At extreme discharges the linear regression relation for both suspended load and bedload gives an overestimation. Realistic values for extreme discharges will therefore somehow lower than calculated.

Suspended load is mainly transported during the rising limb. During the falling limb, when surface runoff is more controlled by baseflow, only a limited amount of suspended load is transported by the flowing river. This baseflow controlled runoff has an excess energy that is used for the uptake of sediments in the riverbed. In case of a filling sand storage dam, this water is responsible for transporting the fine grained material that has settled behind the dam. Catchment areas in which baseflow is limited have a higher risk of silt accumulation behind obstructions like sand storage dams. For upstream catchment areas it is therefore advisable to build the dams in different stages. For downstream areas with sufficient (base)flow and coarse sediment supply a single stage dam will be sufficient.

Grain size analysis throughout the study area pointed out the importance of the material on the riverbanks. There is large correspondence between the grainsize on riverbanks and riverbeds in different field visit areas. A smaller median grainsize on the riverbanks result in a relatively smaller median grainsize in the riverbed. One can conclude that coarse grained material is not mainly detached from deep into the weathered hardrock incised erosion gullies, but comes mainly from the riverbank surface.

Sedimentation speed is mainly dependent on slope and rainfall intensity. When increased this results in a higher flow velocity in the riverbed. With a higher flow velocity more and larger sediments will be transported, resulting in a higher sedimentation speed. This statement is based upon a sufficient availability of coarse sediments in the area.

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APPENDICES

1 INTRODUCTION

Episodical water shortage is a common problem in dry land areas in Kenya. This is especially the problem in (semi) arid regions where rivers are predominantly ephemeral and where groundwater is difficult to reach. In these dry lands water is the largest delimiting factor for development. Local people often use most of their productive time to collect water from water sources that are located far from their living areas. The socio-economic consequences manifest themselves in a low labour productivity, poor enrollment of children in schools, livestock mortality and diseases.
Management of the rainfall as rain during the rainy-season is therefore essential in order to live through the dry season. The growing population and change in climate variability have caused storage needs to increase.

Water conservation techniques are well known in arid and semi-arid environments. In many ways they are dependent on site specific and socio-economic conditions. Water security for urban use may include techniques like the construction of large dams or deep wells. For rural water supply, however, these techniques are often too expensive. Storage of rural water needs a more cost-effective approach, combined with easy maintenance. Community involvement is an important issue. Rural communities have developed, often with the help of local NGO's (Non Governmental Organisation) and local water authorities, several systems for storing and harvesting rainwater. These systems include improved groundwater recharge, ground water storage, surface water conservation and rainwater harvesting. When first information about different techniques was hardly available, but now several NGO's have written down their experience with rural water supply for specific areas. Examples of these are the handbooks written by ASAL and SASOL.

A successful example of rural water management is the construction of sand storage dams in the Kitui District in Kenya. These structures have been applied to different areas in the Kitui and Machakos region and have come to play a central role in the program of water development. They can store sufficient quantities of water for livestock and minor irrigation as well as for domestic use. Dams are built in the Kitui region from 1994 by cooperation between, local NGO, SASOL (Sahelian Solution Foundation) and the communities. Other NGO's like ASAL (Affordable water Supply in Arid and semi-arid Land) are constructing sand dams in the same area, combined with other water conservation techniques like subsurface dams and weirs. Both organisations have a large community involvement in both building and maintenance of the constructions using community training and guidance. To date, more than 500 sand storage dams have been constructed in the Kitui District, mostly by SASOL.

However not, all sand storage dams seem to work properly and apparently not all areas are suitable for the construction of these dams. The successful functioning of sand storage dams is dependent on a large amount of factors, including geology, geomorphology, precipitation and needs. These factors are in many cases unknown

The Acacia Institute and SASOL funded by Partners for Water have started the "Recharge Techniques and Water Conservation in East Africa - Up-scaling and Dissemination of the good practices with the Kitui sand storage dams" project to use the experiences in Kitui as a case study to upscale the construction of sand storage dams in other parts of Kenya (including in Kitui district) and in the surrounding countries. The challenge is to develop an effective strategy to accelerate the construction of the systems without affecting the community based approach. Such a strategy should be based on an exchange of existing experiences and the dissemination of good practices. The current research is part of the first component of the Recharge Techniques and Water Conservation in East Africa project and focuses on the hydrological evaluation of the Kitui sand storage dams. The research project was funded by Aqua for All (A4A) and the Vrije Universiteit Amsterdam (VUA) in cooperation with Sahelian Solutions Foundation (SASOL).

1.1 Former research

This study is a continuation of the research: Hydrology of Sand Storage Dams - A case study in the Kiindu catchment, Kitui District, Kenya written by L. Borst and S. de Haas (2006). In 2005 this project started with a case study which discussed the hydrological processes concerning sand storage dams. The main conclusions of this research are summarised below:

- Increased base level of groundwater behind a sand storage dam gives an increased storage in the river banks. 40% of storage in the banks is estimated;
- A cascade of dams might increases the storage effectivity of sand storage dams;
- Sand storage dams store 1% extra of the river discharge, concerning one single dam in a catchment;
- Sand storage dams increase the water availability from 2 m^3 a day to 11 m^3 a day.

Aspects of the study that needed further research can be summarised as:

- Insight in the sedimentation processes;
- Insight in amount and direction of flows in the river banks (transient groundwater modelling);
- The influence of better land management on the recharge;
- Groundwater quality;
- Optimisation of sand storage dams;
- Estimated parameters of the water balance, for example discharge needs to be refined;
- Up-scaling of the project to a larger area.

1.2 Objectives

As a continuation of the first study this research aims to acquire the information about the processes that remained unanswerd in the first research, as mentioned in Paragraph 1.1. The overall objective is to combine the results of the measurements in order to upscale and optimise the sand storage dam program to other parts of Kenya or East Africa.

To achieve these objectives the study has been divided in three individual parts.

- The first part will concentrate on groundwater direction and flow in riverbanks, combined with the influence of land management and ground water quality. As described in Hoogmoed (2007).
- The second part focuses on surface water flow. Combining a surface water model with sand storage dam characteristics so that an optimisation for dams can be obtained. As described in Jansen (2007).
- The third part concentrates on the up-scaling of the program to a larger area using ArcGIS combined with sedimentation processes for sand storage dams.

The last part will be described in this report. To achieve this, the following aspects have been dealt with:

- Inventory of available literature on sand storage dams, focussing on sand storage dam controlling criteria.

- Inventory of maps available in a GIS environment
- The amounts and characteristics of sediment transport of a river during discharge.
- Distribution of soils and sediments in the Kiindu Catchment area.
- Development of a methodology to define more specific criteria for successful application of sand storage dams and further up-scaling to a larger area.

Data collection started in July 2006. From 2 October – 17 December 2006 a fieldwork has been carried out to the Kitui District in Kenya. During this fieldwork a catchment area close to Kitui Town was selected to carry out hydrological measurements. Several field visits were made to other catchment areas with good working and failing sand storage dams to compare. The total area in which field visits have taken place is indicated as study area for the up-scaling project.

1.3 Outline

The report reflects the results of a research project to the up-scaling of sand storage dams to a larger area and the sediment(transport) properties in the Kitui District in Kenya. In the first Chapter the regional setting of the different study areas is described. The second Chapter describes the methodology used for further up-scaling of the sand dam principle and the measuring methodology. In Chapter 4 the results of the research are given. In Chapter 5 the results are discussed, including recommendations. In Chapter 6 the conclusions of the research are given.

2 REGIONAL SETTING

2.1 Kenya

2.1.1 Climate and Geography

Kenya is an East-African country and is located between Latitudes 4°21'N and 4°28'S and between Longitudes 33°50' and 41°45'E and has a sur face area of approximately 580.400 km^2. The country is bordered by Sudan and Ethiopia to the North, Uganda to the West, Somalia to the East and Tanzania to the South. Total population in 2006 was 34,3 million with an annual population growth of 2,3 % (The World Bank, 2005). In Figure 2-1 the land borders of Kenya are given, including fieldwork study areas.

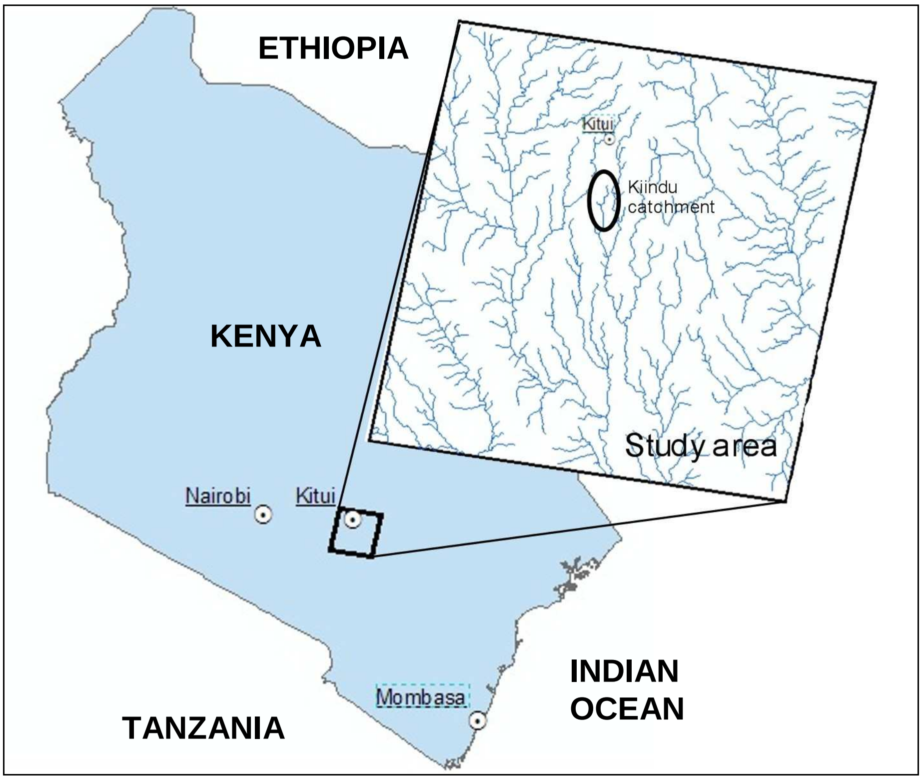


Figure 2-1: *Location of the study areas*

The dominant characteristic of rainfall in Eastern-African countries is its seasonality. This is a result of the North-South movement of the Inter Tropical Convergence Zone and its associated rains.
Kenya is divided into 7 agro-climatic zones based on a moisture index derived from annual rainfall expressed as a percentage of potential evapotranspiration. Areas with an index greater than 50% have high potential for cropping, and are designated zones I, II, and III. The semi-humid to arid regions (zones IV,V,VI, and VII) have indexes of less than 50% and a mean annual rainfall of less than 1100 mm. Semi-arid to very arid zones are generally referred to as the Kenyan rangelands (Neesen, 2004).

In Table 2-1 the characteristics of the different agro-climatic zones are given. Figure 2-2 showes the distribution of the different climatic zones over Kenya.

Table 2-1: *Agro-Climatic zones of Kenya with rainfall*

Agro-Climatic zone	Classification	Moisture Index (%)	Annual Rainfall (mm)
I	Humid	>80	1100 – 2700
II	Sub-Humid	65 - 80	1000 – 1600
III	Semi-Humid	50 - 65	800 – 1400
IV	Semi-Humid/Arid	40 - 50	600 – 1100
V	Semi-Arid	25 - 40	450 – 900
VI	Arid	15 - 25	300 – 550
VII	Very-Arid	<15	15 - 350

Rainfall in Kenya is highly variable and comes with intensive storms, with high intensity and temporal and spatial variability. Especially in the Arid and Semi-Arid regions rainfall is most unstable (Nissen-Petersen, 2006). Evapotranspiration during the growing season can vary from 600-900 mm. The result is a high risk of droughts in these zones. Because the rainfall intensity is very uneven distributed over the country water availability varies strongly within the country.

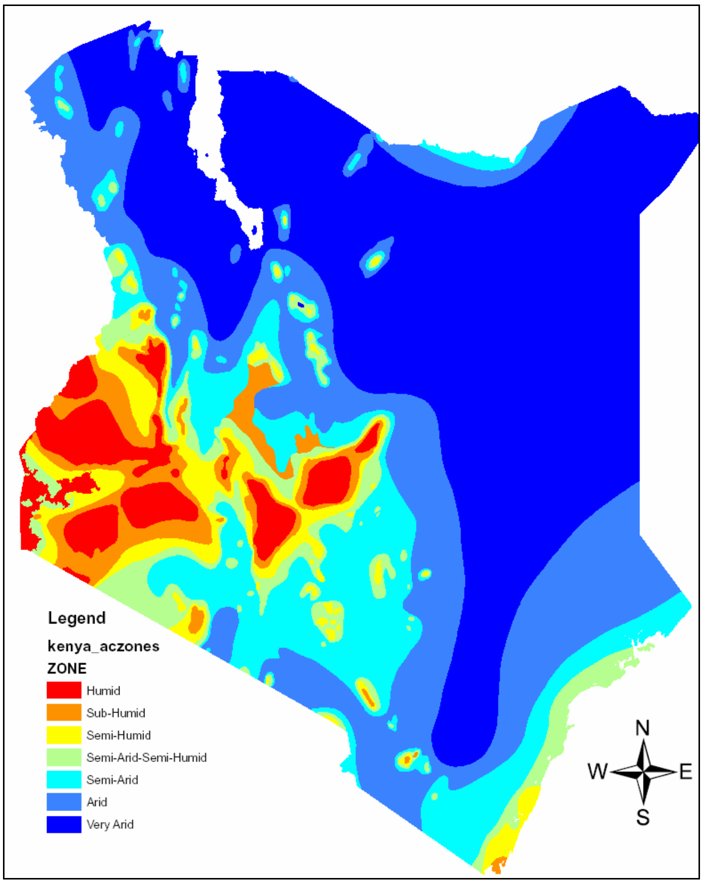


Figure 2-2 : *Distribution of Agro-Climatic zones over Kenya (source: Exploratory Soil Survey Report, 1982, FAO database)*

Kenya has a varied relief which controls its drainage system. The altitude in Kenya varies from sea level at the coast to over 5.000 meter at the top of the Mt Kenya. Four major relief zones are distinguishable within the country. These are the coastal and eastern plains (0-

500m), the central and western highlands (1500-5200m), the Rift Valley Basin (<500m) and the Lake Victoria Basin (500-100m). The longest rivers in Kenya are the Tana and the Athi river, both over 700 km long. Most of the other rivers in Kenya originate in the Kenya Highlands, which has a high amount of precipitation, and will eventually drain into the Athi or Tana river (Mathu and Davies, 1996). There are no perennial rivers in Kenya except for the Tana River. The water level in the rivers can vary greatly. Most rivers dry out during the dry season but swell in the rainy season, carrying large amounts of water and sediments. This is also visible in the pattern of the river Tana where the water level during the year can vary more than 4 meter (Borst and de Haas, 2006).

2.1.2 Geological setting

The major rock types constituting the geology of Kenya include: the Archaean-Palaeoproterozoic granite-greenstone terrane, found in the Western region of Kenya around Lake Victoria, the Neoproterozoic Kisii Group, the Mozambique Belt and the Upper Palaeozoic to Mesozoic Karoo sediments of coastal and norteastern sediments. Younger rocks are presented by Tertiary and Quartenary sediments in eastern Kenya and the coastal strip (Mathu and Davies, 1996). A generalised stratigraphy of these rock types is given in Table 2-2. An overview of the exact locations of different rock types is given in Appendix 1.

Table 2-2: *Stratigraphy of rock types in Kenya (Mathu and Davies, 1996, modified from Cole 1950, Haughton 1963, Saggerson 1972, Cannon et al. 1981)*

Era	Rock formations	Age	Major rock types
Cenozoic	Oloronga beds	Quaternary sediments	Clays, diatomites, shales, silts
	Magarini Beds		
	Fundi Isha Beds Faratumu Beds	Tertiary sediments	Sands, marls, clays Conglomerates, limestones
	East African Rift System, lavas and pyroclastic flows	Tertiary and Quaternay	Basalts, phonlites, trachytes, nephelinites, tuffs, agglomerates
Mesozoic	Maheran Series	Upper Cretaceous	Siltstones, sandstones, limestones, shales
	Mandera Beds Mazeras sandstones	Jurrasic	Coarse grits, feldspatic sandstone, sandy shales
	Mariakani sandstones Maji ya Chumvi Beds	Permo-Triassic	Sandstones, micaceous shales, mudstone, shales
Palaeozoic	Taru grits	Carbo Permian	Grits, shales
Precambrian	Mozambique Belt	Neoproterozoic (-0,75 – 0,45 Ga)	Schits, gneisses, marble, amphibolites, migmatites, granitoid gneisses
	Kisii Series	Neoproterozoic (-1,0 – 0,8 Ga)	Rhyolites, basalts, quartzites, conglomerates
	Mumias, Maragoli, Oyugis granites	Palaeoproterozoic (-1,8 – 2,4 Ga)	Granites, granodiorites, leucogranites
	Kavirondian Group	Archeaen (-2,5 – 2,8 Ga)	Shales, mudstones, greywackes, phyllites, conglomerates
	Nyanzian Group	Archeaen (-2,8 – 3,1 Ga)	Basalts, andesites, dacites, agglomerates, tuffs, rhyolites

Groundwater resources from the Mozambique belt are potentially available or exploited in the aquifers between the underlying Mozambique Belt and its overlying Cenozoic volcanics and sediments. Groundwater is also available in the pervious regions where shear zones, fault and joint systems are present (Mathu and Davies, 1996). The Mozambique Belt is a geological feature to be found in large parts of East Africa and stretches from Mozambique in the South through Kenya to Ethiopia and Sudan in the North.

2.2 Kitui District

Part of the information given in this paragraph is withdrawn from Borst and de Haas, 2005, unless reported differently.

Kenya is divided into eight provinces and each province is divided in districts. The case study area is located in the Kitui District in the Eastern Province of Kenya (for exact location of the study area see Figure 2-1). The district extends for roughly 200 km from north to south and 120 km from east to west. It covers an area of approximately 20.000 km² including more or less 6.400 km² occupied by the uninhabited Tsavo National Park. The Kitui district is populated by the agro-pastoral Akamba tribe. The district has a population of approximately 515.000 people (last census, 1999).

2.2.1 Case study areas

For this part of the research two different case study areas are used. The first case study area (Kiindu Catchment) is located close to Kitui Town. The Kiindu river is an ephemeral river with al length of approximately 16 km (for the location see also Figure 2-1). The entire catchment has a surface area of approximately 37 km^2 and is located between Wikelilye in the North (UTM 390230 m East, 9845760 m North), Mulango and Kyangunga in the East (UTM 390000 m East, 9837850 m North) and Yakalia and Kangalu in the West (UTM 386000 m East, 9838000 m North). The study area is chosen because of the large amount of data already available from 2005 research. In addition, the area appears to give a good representation of a catchment that meets the criteria for good functioning of sand storage dams. The main research area is in a stretch of approximately 5 km from the dam Kwa Langwa to the far North of the catchment area. Hydrological measurements have been carried out within a small range from the dam Kwa Ndunga. In this research this study area has been used as a pilot for hydrological characteristics and responses about the functioning of sand storage dams. Results of research in this area give more insight in processes from which optimised criteria can be obtained. More details about the study area are described in Borst and de Haas (2006).

The second study area covers a larger area and also includes the Kiindu catchment. The area covers a large part of the Kitui District from North to South and is located North (UTM 367500 m North, 9866876 m East) and South (UTM 416294 North, 9796062 East). The exact location of the study area is given in Figure 2-1. For this area a first probability map will be created, based on criteria defined from (earlier) research and literature.
Most of the dams built by SASOL are located within this area, apart from some recently built dams in Kitui South. The advantages of a second study area are that the area contains a large amount of functioning dams as well as non-functioning dams that can be compared with the results of the probability map and that the area has a large variety of climatological and geo(morpho)logical characteristics, that also can be compared. Another important issue is that ASTER satellite images of this area are available combined with available data throughout the area from field visits and researches.

2.2.2 Climate and geography

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

February and one from March to May. Most of the area receives less than 730 mm of rain per year. The higher areas around Kitui town however receive between 760 and 1270 mm. Amounts of precipitation decline South-Eastwards to approximately 500 mm. Average annual potential evaporation is approximately 1800 mm.

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

During rainfall events large amounts of sediments, eroded from the banks, flow into the river, creating a concentrated discharge flow with a high suspended load and bed load concentration. Most of this fine grained suspended load material is transported out of the catchment area, leaving the coarser grained bed load in the riverbed. The fine grained material can only be found in ponds or in very small layers in the riverbed.

Only a relatively small amount of rainwater over a catchment area actually recharges the groundwater. This is mainly due to soil properties and evaporation losses. Most of the water leaves the catchment area as surface runoff or evaporates, indicating that only a small amount is available for domestic use throughout the year.

2.2.3 Geological setting of the study areas

The Kitui District area is largely covered by Precambrian (540 Ma BP and older) crystalline rocks, which mainly consist of gneisses, granulites, schists, migmatites, with minor intrusives. These Precambrian rocks are generally referred to as the “basement system” and generally show a regional structural North-South trend of foliation. Originally this basement system consisted of sedimentary rocks. These rocks are metamorphosed. Hills in the area are mostly formed by the Granatoid gneisses, which are more resistant to erosion. This regional setting is in agreement with the geology of the Mozambique belt, as mentioned in Paragraph 2.1.2. More recently aged Quaternary and Tertiary deposits overlay this basement system, for example on hillslopes and in the riverbed. In the South-East of the Kitui District Palaeozoic sandstone hills can be found.

In the case study area in the Kiindu catchment rock types that are found are mainly gneisses, such as granitoid gneiss (feldspar, quartz and muscovite), biotite gneiss (biotite, feldspar and quartz), intersected with pegmatite veins. The gneisses appear in bands differing in width from half a meter to tens of meters. (Borst and de Haas, 2006). For a more detailed geological map of the study area is referred to Borst and de Haas (2006).

2.2.4 Hydrology

In the Kitui District four main groups of aquifers can be recognized (Louis Berger International Inc., 1983):

- Quaternary superficial deposits;
- Tertiary rocks;
- Paleozoic sedimentary rocks;
- Precambrium crystalline rocks.

The Quaternary superficial deposits consist of alluvium aquifers and Quaternary deposits. The Alluvium aquifers are sands and gravels along river channels. These sands and gravels have a high porosity and have therefore the possibility to store large amounts of water. When an (undulating) impermeable layer is available underneath these sediments, deposits can accumulate behind an outcrop and create an easy accessible aquifer. The other type of Quaternary aquifers are formed by deposits of talus or loose unconsolidated materials, e.g. at the base of steep slopes.

The Tertiary volcanic rocks that outcrop in the plains and along the Eastern boundary of the Kitui District have a low porosity and form poor aquifers.

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

The rocks of Precambrium age from relatively poor aquifers. Water can be stored in fractures or weathered zones but this is very locally. When fractured, these rocks can even cause a reduction of water in the overlain Quaternary deposits. Most of the Kitui District is underlain by this formation. Combined with overlaying sediments of Cenzoic age, the Precambrium rocks can form an impermeable layer upon which water can be stored in the overlaying (fluvial) sediments.

Recharge of groundwater only comes from rainfall, mainly at locations where runoff is concentrated in streams or ponds. Rainfall occurs mainly at the higher locations in Central and North Kitui.

2.3 *Sand storage dams*

2.3.1 Introduction

Many technologies have been tried to supply water to the communities in the dry periods. Boreholes are expensive to install. Shallow wells also offer an extractive technology. Water tanks are expensive and limited by size. Earth dams suffer from extensive losses due to evaporation; they also have a huge potential for contamination and risks to health. Sand storage dams offer a good alternative. A sand storage dam is a dam in the riverbed, funded on an impermeable layer, behind which sand accumulates. When groundwater is recharged, water is stored below the newly accumulated sand, reducing evaporative losses and health risks. Because the sand behind the dam has accumulated a larger aquifer is created from which water can be obtained. This extra ground water buffer can be used to bridge the dry periods. The water can be excavated using scoopholes or hand dug wells. The principle of a sand storage dam is given in Figure 2-3.

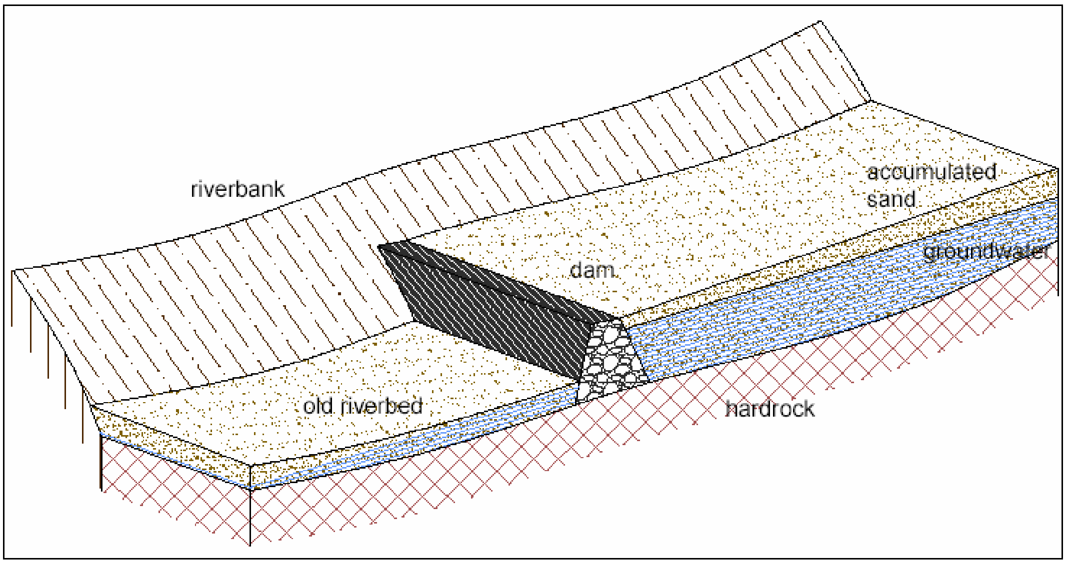


Figure 2-3: *Principles of a sand storage dam (illustration: Borst and de Haas, 2006)*

Sand storage dams are widely applied in the Kitui District. Most dams however do not reach an optimised stage. Seepage through the layer on which the dam is funded, or leakage underneath the dam wall decrease the efficiency of a sand storage dam. Sediment behind the dam is too fine grained which decreases infiltration rates and groundwater storage/extraction. A good location for sand storage dams meets a set of local and environmental criteria. Not all of these criteria are known and are nowadays partly underestimated during siting of locations, resulting in minor efficiency of constructed dams.

2.3.2 Literature

2.3.2.1 Local and environmental criteria

Sand storage dams are widely described in the literature. Combined with information obtained from the field this can give valuable information about the important factors controlling the efficiency of a sand storage dam.

Sand storage dams are a very old technology which is said to have been practiced by the Babylonians more than 4,000 years ago. The first sand storage dams in Kenya were built by the District Agricultural Officer, Eng. Classen, as part of a development project named *African Land Development Board.* 200-500 dams (based on estimations of different NGO's) have been constructed in Macahakos, Makueni, Kitui, Mwingi, Embu and Meru since the early 1970's (Nissen-Petersen, 2006). Nissen-Petersen also refers to an evaluation which indicated that only about 5 % of the sand storage dams, constructed in the last 40 years, is actually functioning. The main goal of a sand storage dam is to increase the volume of water and (coarse) sand in a riverbed in dry land areas where episodic shortages of water are common.
Several reports describe the basic local and environmental criteria concerning the successful construction of a sand storage dam (Nissen-Petersen, 1997 and 2006; Borst, de Haas, 2006; Munyao *et al*. (SASOL), 2004; Burger *et al*., 2003; Arnold *et al*., 2002; Frima *et al*., 2002).

2.3.2.2 Impermeable base

At first there is the necessity of an impermeable layer underneath the dam and sandy layer. This layer can be formed by bedrock or a thick clay layer. Without an impermeable layer, water will leach towards the deeper groundwater and will not be extractable from hand dug wells. Some writers prefer a thick clay layer above a bedrock layer, because a clay layer does not have fractures. Others prefer the bedrock layer, because a dam based on a clay soil will sink into the softer layer. Bedrock is often fractured and water will seep between the boulders, causing leakage of the dam and a decreasing storage. When a dam is built upon a clayey layer it has to be keyed deep enough into the clay so that no water will seep underneath the dam. Secondly an outcrop of this impermeable layer is preferred to build the dam upon. Water and sand behind the outcrop have already accumulated which increases the storage capacity of a sand storage dam.
The Black Cotton Soils (BCS) areas, that for example can be found in the South of the Kitui District, have also been researched as a possible location for the construction of sand storage dams. However, the exact characteristics of the soil are still unknown. The soil can be identified as impermeable and is often underlain by a more permeable white limestone layer (Kunkar Limestone). This layer is a product of the BCS's. Seepage through the BSC's is estimated on 20% (Frima *et al*., 2002). The water behind a sand storage dam will not be held but will eventually seep through the BSC layer. When it reaches the limestone layer the water will flow away in either downstream or sideway direction. Until further research has proved the opposite, this soil can be identified as non-suitable for the construction of sand storage dams.

2.3.2.3 River characteristics

Sand storage dams are mainly constructed in ephemeral stream beds, also called seasonal water courses. An ephemeral stream can be defined as 'a stream that flows only and for short periods in direct response to precipitation'. Most of the rainwater being transported downstream in the river beds appears as flash-floods. During high intensity rain events (during rain season) most water will be lost by evaporation and surface runoff and only a small amount of the water will infiltrate in the river beds and river banks. Flash-floods can be several meters high and contain large amounts of sediments. Erratic patterns of rainfall combined with different rain and dry periods, as found in arid and semi arid regions, increase the presence of ephemeral streams.
Most potential riverbeds for the construction of sand storage dams have hilly and stony catchments which produce coarse sand which can have an extraction rate of 35%. Riverbeds with fine textured sands or silts, originating mainly from flat areas, are unsuitable for sand

storage dams. Only a limited amount of water can be stored in the voids, so only a small amount of water will be available for extraction during dry periods. Also riverbeds with a width over approximately 25 meters are considered to be unsuitable for sand dams. Construction costs are too high due to the large amount of material and reinforcement for the dam wall. Table 2-3 shows the extractable volumes of water from various soil types as published in Nissen-Petersen, 1997.

Table 2-3: *Extractable volumes of water for various soil types (Nissen-Petersen, 1997)*

Soil type	Silt	Fine sand	Medium sand	Coarse sand	Small gravel	Large gravel
Grain (mm)	< 0.5	0.5 – 1	1 – 1.5	1.5 - 5	5 – 19	19 - 70
Sample (l)	4.0	4.0	4.0	4.0	4.0	4.0
Saturated (l)	1.52	1.58	1.63	1.80	1.87	2.05
Extracted (l)	0.18	0.75	1.00	1.40	1.65	2.00
Extraction (%)	5 %	19 %	25 %	35 %	41 %	50 %

The riverbeds need to have enough inflow and therefore catchment areas that are too small will not be suitable for sand storage dams. A shortage of inflow firstly creates a shortage in water infiltration and secondly the sediment uptake by the water will be very low. A low sediment uptake results in a slowly filling dam with finer grained material. Therefore writers prefer a riverbed with a lower gradient, more downstream in a catchment. A lower gradient has a larger reservoir behind the dam, compared to a higher gradient. A lower gradient will also enhance infiltration.
River banks are also important for the construction of sand storage dams. SASOL uses a height of at least 1.5 meters for the river banks, preventing the structure from being too large and expensive. Soil composition of the banks should be firm. For protection of the dams from surface erosion in many cases Napier grass is planted and wingwalls into the riverbanks are constructed.

2.3.2.4 Water quality

Another important issue concerning the location of sand storage dams is (ground) water quality. Due to soil characteristics the stored water behind a dam can be saline and therefore not suitable for extraction (drinking water). An example of a soil creating saline water is calcrete ($CaCO_3$). Calcrete is used by animals to gain necessary salt and other minerals. When calcrete is situated upstream of a sand storage dam the water will be saline and therefore not suitable for drinking. Also sodic feldspars and black iron (FeO), which also can be found in the Kitui District, can cause salinization of the storage water. Wanjogu *et al* (undated) write about the soil salinity in Kenya. A saline soil has an electrical conductivity of the saturation extract of > 4 dSm^{-1} and an Exchangeable Sodium Percentage > 15%. Saline soils are mainly found in the Agro-Climatic Zones V – VII, mainly at Vertisols, Fluvisols, Solonchacks, Solonetz, Geysoils, Regosols, Planosols and Luvisols. Saline soils have originated mainly due to marine and inland salinization processes. Therefore parent materials are mainly marine sediments and volcanics. They occur mainly in low altitude areas characterised by a high evaporation – rainfall ratio.

2.3.2.5 Climate

Sand storage dams are constructed in dry land areas (ASAL's) where episodic shortages of water are common. The main goal is to supply water to a community during a dry period, between two rain seasons. Seasonality therefore is an important issue. Areas without

seasonality may be suitable for sand storage dams but other sources of water storage might be more appropriate.
Borst and de Haas state that the effectivity of sand storage dams is less sensitive to the actual amount of rainfall. Only when the amount of rainfall drops below a certain threshold (20 mm for the Kiindu catchment) the amount of abstractable water will decrease. This however is dependent on the properties of the catchment area. Sand storage dams have also successfully been applied in parts of North Africa, indicating that sand storage dams are also applicable in areas with very low amounts of rainfall.

2.3.2.6 Socio-economics

For the construction and maintenance of sand storage dams an organised community is needed and materials like water, stones and sand should be available at the location. Households should be in the neighbourhood of potential constructing sites to construct and maintain the dam. SASOL keeps a value of at least 20 households close to the dam site. Also very important is the number of people that can benefit from the dam, in shorter terms: the necessity of extra groundwater storage per area. Areas with relatively large amounts of accessible (ground) water have a lower potential than areas with high water scarcity.

2.3.2.7 Design criteria

Many authors write about the design criteria of the sand storage dam. One of these criteria is to ensure that flood water will deposit coarse sand into the dam reservoir. Many reservoirs of sand storage dams contain silt and fine textured sand from where no or little water can be extracted. The flood water contains all sizes of silt, sand and gravel particles. Silt and clay particles move with the flood water as suspended load and can be found in the upper part of the flood water. More heavy sand and gravel particles are found in the lower part of the flood water as bedload. Nissen-Petersen therefore favours a dam built in stages of 30 cm, based on field experience. The first stage will trap the heavy coarse bedload (sand) and the lighter suspended load (fine grained silts) will pass over the barrier. A second stage upon the first 30 cm is built when the first stage is completely filled with coarse sand. This process will be repeated until the dam has reached its final height. Other writers and NGO's state that this is only needed when a dam is designed to be large. Hofkes and Visscher (1986) state that the maximum height of a dam is 2 meters above the riverbed for each season. This, however, is probably an estimation and not further researched.

2.3.2.8 Sediment transport processes

Erosion and deposition of eroded sediments form one of the key factors in success of sand storage dams. The processes of erosion can be described in three stages: Detachment, transport and deposition. A critical force needs to be exerted by either a raindrop or a flow before detachment can occur. Kinnell (2001) identifies four detachment and transport systems:

- Raindrop detachment and splash transport (RD-ST). Is common in interrill areas prior to the development of run-off and is highly dependent on slope gradient. It decreases rapidly with an increase of water depth;
- Raindrop detachment with transport by raindrop induced flow transport (RD-RIFT). Occurs when stream power is not enough to detach soil material from the surface or to entrain loose material on top of the soil. Sediment transport will occur when raindrop impact penetrates through the flow, lifting up the sediments. The transport efficiency varies with flow velocity;

- ❖ Raindrop detachment with transport by flow (RD-FT). Cohesion of the soil is large enough to prevent detachment by flow but not sufficient to prevent detachment by raindrops. The stream power is sufficient to transport detached material;
- ❖ Flow detachment with transport by flow (FD-FT). Is common with rill erosion and occurs when the stream power is high enough to detach soil material from the surface.

Soil erosion and –transport is highly dependent on the flow velocity and rain intensity. Rainfall intensity should be high enough to detach coarse grained material needed in the riverbed and flow velocity should be sufficient to transport the material. Flow velocity depends mainly on slope gradient and flow depth, in combination with rain intensity. Transport of coarse material in the study area-riverbeds and tributaries is mainly controlled by Flow Transportation (FT). In the Kiindu catchment detached coarse material is already available in the riverbeds.

The relation between particle movement and flow velocity can be derived using Shield's diagram. Zhou Liu (2001) gives a description of flow and sediment transport processes. The movement of sediments in a river is mainly dependent on:

- ❖ Critical friction velocity, the velocity where the grain is about to move;

$$u_{*,c} = \sqrt{\theta_c (s-1) g d}$$ Equation 2-1

In which:

θ_c = Critical Shields parameter;

s = ρ_s/ρ = 2650 kg/m^3 / 1000 kg/m^3 = 2,65;

g = 9,8 (m/s^2);

d = Grain diameter (m).

- ❖ Or, bottom shear stress, the average of shear stress along the wetted perimeter;

$$\tau = \rho \cdot u_{*,c}^{\;2}$$ Equation 2-2

In which:

ρ = Fluid density (kg/m^3);

$u_{*,c}$ = Critical Friction velocity.

- ❖ Or, critical Shields parameter $\theta_c = \frac{u_{*,c}^{\;2}}{(s-1)gd}$ Equation 2-3

Friction velocity, in case of sediment transport, is the velocity very close to the bottom of a channel and is therefore lower than flow velocity over the total river depth. The critical Shields parameter can be calculated using the converted Shields Diagram. An example of Shields Diagram is given in Appendix 2. Shields Diagram relates the critical Shields parameter (Θ_c) to a so-called sediment fluid parameter S_*.

$$S_* = \frac{d\sqrt{(s-1)gd}}{4\nu}$$ Equation 2-4

In which:

ν = Kinematic viscosity (10^{-6} m^2/s at 20 °C).

From above equations a critical velocity for displacement of coarse grained material can be calculated. A suitable grain size diameter for extraction of water behind a sand storage dam is ~0,5 mm (see Table 2-3). Using above equations in combination with the Shields Diagram results in a critical friction velocity, for d = 0.5 mm, of approximately 0.017 m/s.

In Figure 2-4 a direct relationship between flow velocity and particle size is given as derived by Kinell (University of Canberra, course presentation).

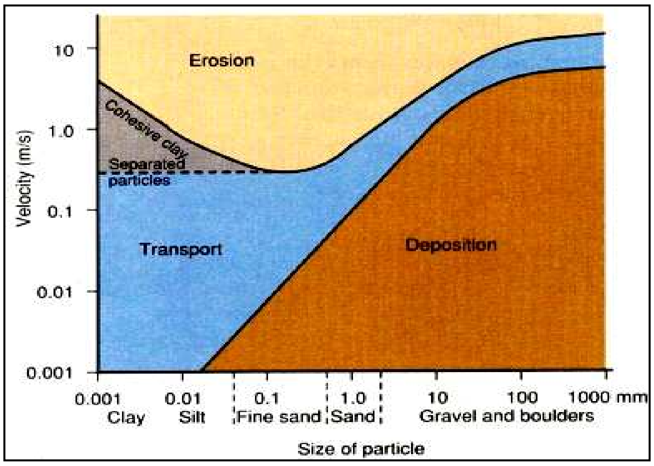


Figure 2-4: *Relation between particle size and flow velocity*

The figure indicates that for the transportation of coarse sand (>0.5 mm) a flow velocity of approximately 0.02 m/s is required, which is comparable with the calculated value from Equations 2-1 to 2-4. When flow velocity increases to 0.2 m/s also flow detachment from the soil material is possible.

2.3.3 Field visits

During the fieldwork several field visits to other dam sites have been performed. These visits were made accompanied by members of SASOL, mostly individually involved with the construction of the specific dam sites. Both recent and old dam sites are visited, including well-functioning and non-functioning sand storage dams. Because of the weather conditions not all preferred dam sites could be visited. The overall goal of the field visits is to compare catchment characteristics and properties of various dams sites in order to define controlling factors. This in combination with data known from literature. Visited locations are given in Figure 2-5. UTM coordinates of the different locations are defined using a handheld GPS receiver (Garmin).

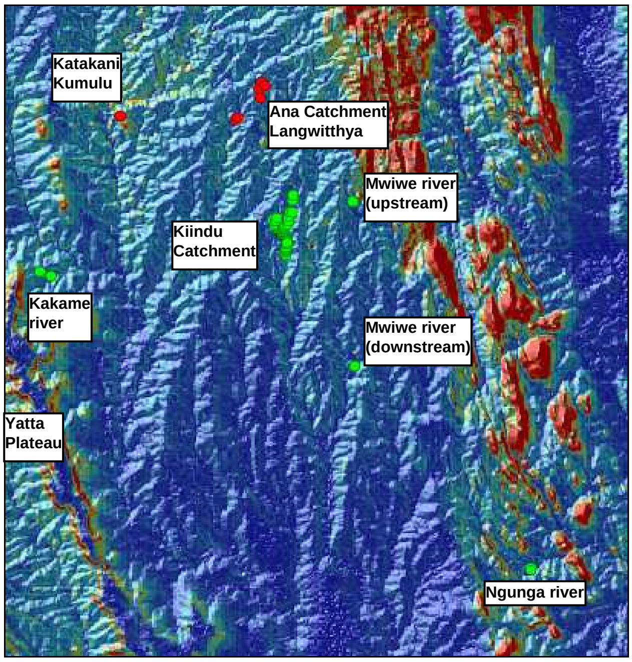


Figure 2-5: *Field visit areas over a slope area cover. A red dot indicates a low efficiency dam and a green dot indicates a high efficiency dam*

2.3.3.1 Ana Catchment

The Ana catchment is located West of Kitui Town UTM coordinates (WGS84, zone 37S) 1.35 Southing and 37.98 Easting. The catchment is divided in several sub-catchments. One of these areas is the Tungutu sublocation. This section is located close to Kitui town and sand dams are built in the catchment in 1997 - 2002 (source: SASOL). Dams in this catchment area appear to be less productive than dams in other areas and some dams take more than 9 years to fill completely. The catchment has a larger vegetation cover compared to the Kiindu catchment. The riverbanks are extensively used for cultivation and consist of sand/silt on the east side and more clay on the west side. Erosion measures are taken throughout the catchment to prevent further erosion from the cultivated areas during the rainy season.
Most dams (especially in the upstream part) in this catchment are totally filled, but several scoopholes behind of the dams show that the sediment is not only coarse sand. The first ~60 cm of the riverbed behind the dam consist of a coarse sand layer (see also Figure 2-6). The next layer up to the bedrock (1.5 – 2 meter –surface level.) consists of a low permeable silt/clay layer. This means that water will infiltrate in the upper ~60 cm, but infiltration will cease at the low permeable layer. The total storage of the sand dam is therefore assumed to be much lower than originally expected. The dam has a height of approximately 1 meter from base to top, with the base constructed on the basement layer. Subtracting the 60 cm of sand still leaves a layer of 40 cm of fine grained material that has accumulated after the dam was constructed. The soil in the riverbed, between two dams, consists mainly of rocks and silty material. Only close to the dams coarser material in the riverbed can be found. The outcropping basement rock appears to be fractured at the base. Stony riverbeds containing boulders and fractured rocks have the lowest potential for water extraction due to seepage caused by the fractured rocks and boulders (Nissen-Petersen, 2006).

Other dams visited in a nearby sub catchment (Langwitthya west location) showed different characteristics. Rivers used for the construction of sand storage dams often appeared to be very small (< 6 m wide) and small amounts of coarse grained material accumulated behind the dams. In the riverbeds no coarse material was available. Only close to the dams coarse material could be observed. Parts of the accumulated material were covered with vegetation, indicating that the material is more fertile compared to the coarse sand that can be found in other areas. Black soils could be found in the surrounding areas on the hill sides and the sediments behind the dams appeared to be smaller sized than observed at other inspected dams. Outcrops of bedrock are hardly found in the surroundings, indicating that the availability of coarse grained material might be limited.

Figure 2-6: *Silt layer under the sandy layer behind a sand storage dam*

2.3.3.2 Yatta Plateau, Kakame river

The Yatta Plateau is located West of Kitui, lying along the Athi river (see also Figure 2-5). The Yatta Plateau is a lava flow (300 km long and 10 km wide), and one of the largest and longest of the world. It was formed 11-13.6 millions years ago by a stream of lava flow of phonolite finding its way into an ancient river valley. Since, the surrounding land was lowered by erosion leaving the lava standing up as a small escarpment. Close to the Yatta Plateau is the Kakame river in which several dams are constructed. Also in the tributaries of the main river several dams are recently built (2006). The riverbed of the tributaries is covered with rocks and boulders. Sandy material can be found in between. Close to the dams the riverbed is completely filled with sand. The riverbed of the main river (Kakame River) is completely filled with sand. The riverbanks show a gently slope and have a clayey/silty composition. The weathered hardrock can be found close to surface level. Floodmarks on the river banks indicated that the water level of the river had been very high. Because the river itself is relatively small, a large sediment uptake can be expected during peak flow. According to local people al of the dams in this catchment filled up after one single event which confirms the assumption of a large sediment uptake.
The dams itself are subject to heavy erosion along the sides. From Figure 2-7 becomes clear that the dam is built into the weathered rock and not onto the hardrock. The river path is shifting and will eventually undermine the dam.

Figure 2-7: *Dam not fixed on impermeable layer (left) and rocks and boulders in the riverbed (right)*

A second dam close to Yatta has already been visited one year ago during the first hydrological research on sand dams (Borst and de Haas, 2006). During this visit the two year old Katakani Kumulu dam was completely filled with fine grained material. Water behind the dam could not infiltrate into the riverbed and therefore the dam had no increase of water storage. One year later the dam is still completely filled with silty/clayey material. Only a thin layer of sand (~10 cm) is covering the silt/clay in front of the dams spillway. The dam is located totally upstream in hilly surroundings with many rock outcrops. Only a small catchment area is available for water and sediment supply. This issue is comparable to that of the Ana catchment. Riverbeds close to the dam are very narrow and in the riverbeds no coarse sand was available (see also Figure 2-8).

Figure 2-8: *A small sandy layer is covering a silt/clay layer behind the dam (left). In the riverbed no sand was available (right)*

2.3.3.3 Mwiwe River

The Mwiwe River originates close to Nzambani rock. Three dams in this catchment were visited, varying from total upstream to downstream. The most upstream dam was located close to Nzambani Rock (for exact location see Figure 2-5) and showed a flowing river. This while the Kiindu river, located 10 km west, was dry. The riverbed was filled with coarse sand

and the dam seemed to be working perfectly. A well located in the riverbank showed a water level that was higher than that of the river. This indicates that ground water level in the river banks is higher and that river banks are already recharging the river. The banks are relatively flat which increases the infiltration of sheet flow.

More downstream, the river becomes wider and discharge increased as compared to that at the upstream dam. The width of the river increases up to >15 meters at the dam. The dam itself was not completely filled and the level of the sand was approximately 80 cm beneath the level of the dam. At this location the banks created an extra recharge to the riverbed. Farmers plowed their land extensively and many measures against erosion were taken (terraces). Along the riverbed several contact springs could be observed.

The location visited most downstream showed a dry riverbed filled with sand. When rivers start flowing the scoopholes are rapidly filled with sediment. Scoopholes in the sandy riverbed were still intact which indicated that no discharge had occurred so far. This can probably be explained by the randomly distributed rainfall in the area. The water from rainfall events in upstream areas has all infiltrated in the sandy riverbed and the amount of rainfall in the downstream area was not enough for surface water flow. The dam at the location was washed away during an early flood. The scoopholes in front of the dam indicated that the dam was built upon a clay layer. The top layer in the scoophole consist of a one meter thick sand layer which is underlain by a thick clay layer. Bedrock outcrops could not be observed in this area.
Constructing a dam in the Mwiwe river is also described by Nissen-Petersen (2006). The key and base of this dam were also excavated into a local dyke of solid and impermeable soil. The dam was built in stages, each 30 cm of height.

2.3.3.4 Ngunga River

The Ngunga river is located in the Kebwea sub-location in Kitui south. The area has few inhabitants compared to other parts of Kitui district. Compared to the Central Division where most of the NGO's activities are concentrated, rainfall is less and more erratic, topography is rougher and soils are different in this part of the district. Sandstone hills can be found in the direct surroundings of the Ngunga river.
The average rainfall over on yearly basis in this area can be estimated at 625 mm (Burger *et al.*, 2003). According to local people and SASOL sand storage dams in this area fill up in one single event. The bedrock close to the dam can be found at a depth of approximately 1 meter beneath surface level but shows an undulating character. The bedrock can reach a depth of more than 3 meter beneath surface level (Burger *et a*l., 2003).
Vegetation in this area is denser than in the Central Division. Also from the type of vegetation one could notice that soils are more fertile. Thorny bushes are hardly found in this part of the District. A more detailed soil description of this area is given in Puttemans (2004).
The visited dam in this area appeared to be working perfectly, although the necessity of a dam in such a low populated area is doubtful. More dams are located in the Ngunga river and are several kilometres apart.

2.3.3.5 Kiindu Catchment

Most of the research has been done in the Kiindu Catchment. A detailed description of the characteristics of this area is given in Borst and de Haas, 2006. The land can be defined as a peneplain in which rivers have incised, creating valleys. Riverbeds in the Kiindu catchment are completely filled with (coarse) sand. At few locations small layers of silty material can be found in between. Dams in this area fill up in a period of 5 – 7 years (Borst and de Haas, 2006). Soils in the Kiindu catchment are mostly clayey and silty. The soils have developed on undifferentiated gneisses. These gneisses can be highly weathered forming a sandy layer with high porosity. Intense soil degradation can be found on the river banks. Gullies at the river banks can be more than 3 meters of depth and still increasing. These gullies are responsible for a large part of the sediment deposition in the riverbed as they have incised into the weathered rock zone, taking up the coarse sands during rain events. Coarse sediments from the land surface are mainly transported by these gullies and guided into the riverbed or larger gullies. In Figure 2-9 an example of the sand deposition process is given as witnessed in a manmade drainage gully in the Kiindu catchment. In the gully a sandbag caused an obstruction of the stream flow. The coarse sediments gradually moved towards the sandbag, eventually filling the complete area behind the bag.

Figure 2-9: *Deposition of coarse sediments behind an obstruction in a small manmade drainage channel*

From this observation, coarse grained material is assumed to be merely relocated within the catchment and not transported out of the catchment, as it took several rain events to fill the complete area behind the sand bag.

Coarse sediment in the gully was originating from erosion gullies incised in the weathered bed rock. The (weathered) bed rock at this location can be found at a depth of approximately 50 cm below surface level and is therefore easy accessible for transportation. Bedrock throughout the area can be found at a depth of 0 – 3 meter below surface level. Near the gully the bedrock could be found close to the surface, at approximately 1 meter. Upstream bedrock outcrops are increasing and at various locations in the upstream area boulders can be found in the riverbed.

Vegetation increases upstream of the catchment, together with the amount of rainfall. Vegetation consists mainly of Acacia's and thorny bushes, indicating the scarcity of water. A large presence of *Acacia Seyal*, for example, indicates that the depth to the water level is 9 – 20 meter (Nissen-Petersen, 2006).

2.3.3.6 Combined findings

Most of the catchment areas visited during the field visits appear to be suitable for the construction of sand storage dams. However, areas exist in which sand storage dams did not reach an optimised condition. Locations of these areas are given in Figure 2-5 with red dots. Because these areas are mainly located in the most upper part of a catchment area only a small area will contribute to the supply of sediments in the riverbeds and only a relatively small amount of runoff will be available. This also often results in a slower sedimentation speed behind the dams. It appears that surface water flow velocity is restrained by the dam, causing the water velocity to be too small for the transport of coarser sediments near the dam. Finer sediments are more easily displaced by an equal amount of water (suspended load). When the area behind the dam fills up with sediments the restrainment by the storage dam will decrease, allowing coarser sediments to be transported. Riverbeds near the most upstream dams are relatively small and have a higher slope which decreases the storage capacity of a sand storage dam.

Conspicuous for these areas is also that a limited amount of sand is available in the river beds between the dams, resulting in a small sand layer. When coarse material is available in the riverbed, the bed itself gives an indication that the surrounding area is (geo)morphologically suitable of generation and deposition of coarse sediments. When the coarse sediments are not available in the riverbed the chance of deposition of unfavourable sediments behind a dam becomes larger.

Vegetation in the area appears to be of less importance. Areas with high density vegetation (for example Ngunga River) show equal sedimentation characteristics with low density areas (for example Kiindu catchment). Riverbeds that are covered by vegetation (for example grasses or bushes) indicate that the sediments are less favourable in storing and subtracting water. It is assumed that the infiltration speed of the water is much lower allowing the vegetation to settle on the sediment layer. Also for vegetation more fertile soils are needed.
When no bedrock outcrops can be found in an area the probability of the presence of coarse grained material appears to be smaller. Weathering of the bedrock appears to be the main supply for coarse material in the riverbed. Catchment areas that do not have rock outcrops (for example Langwitthya west location) have a larger supply of finer sediments that can also be found again in the riverbed.

3 METHODOLOGY

3.1 Up-scaling

3.1.1 Introduction

The field visits pointed out the importance of sand availability in a riverbed, as described in Chapter 2. From literature available on the sand storage dams successful application depends on topography and geology. When there is a thick layer of (coarse) sand in a riverbed the supporting catchment area provides a good environment for the detachment and transport of coarse sediments. In other words: The conditions for (top)geology, morphology and rainfall in the catchment area meet the environmental criteria for constructing sand storage dams. When there is no sand available in the riverbed the conditions in the catchment area do not meet the criteria for constructing sand dams. In this assumption the suitability of riverbed and riverbanks to maintain low costs and the structural integrity of the dam is not taken into account.

In order to upscale the principle of sand dams different criteria have to be refined. Therefore a study area is picked in which several field visits took place. In this study area there are known cases of operational and non-functioning dams which can be used for validation. A description of the study area is given in Paragraph 2.2.1.
By using satellite images sand rivers (ephemeral) can be distinguished from non-sand rivers. By identifying the sand rivers the overall characteristics of the supporting catchment area can be studied. These results will be compared in a GIS environment and criteria can be identified. These criteria include geology, geomorphology and precipitation data.

In Figure 3-1 the flow chart for the different processes is given. The final probability map will be first covering the extent of the study area and shows areas suitable for sand dams based on the defined criteria. Defined criteria can be used for further up-scaling. A note however is that not all critical factors will be available in the study area.

An important criterion for sand dams is the availability of an impermeable layer beneath the sand layer, as mentioned earlier in Paragraph 2.3.2.2. This layer can be non fractured bedrock or a thick (> 1m) clay layer (Nissen-Petersen, 2006). The impermeable layer has to be relatively easy accessible from surface level so that the dam can be constructed on top of the impermeable layer. The availability of this layer is strongly dependent on local geology and will show large variation within the same geological feature. As not enough data is available about the depths of impermeable layers in other parts of the study area, this criterion is left out of consideration.

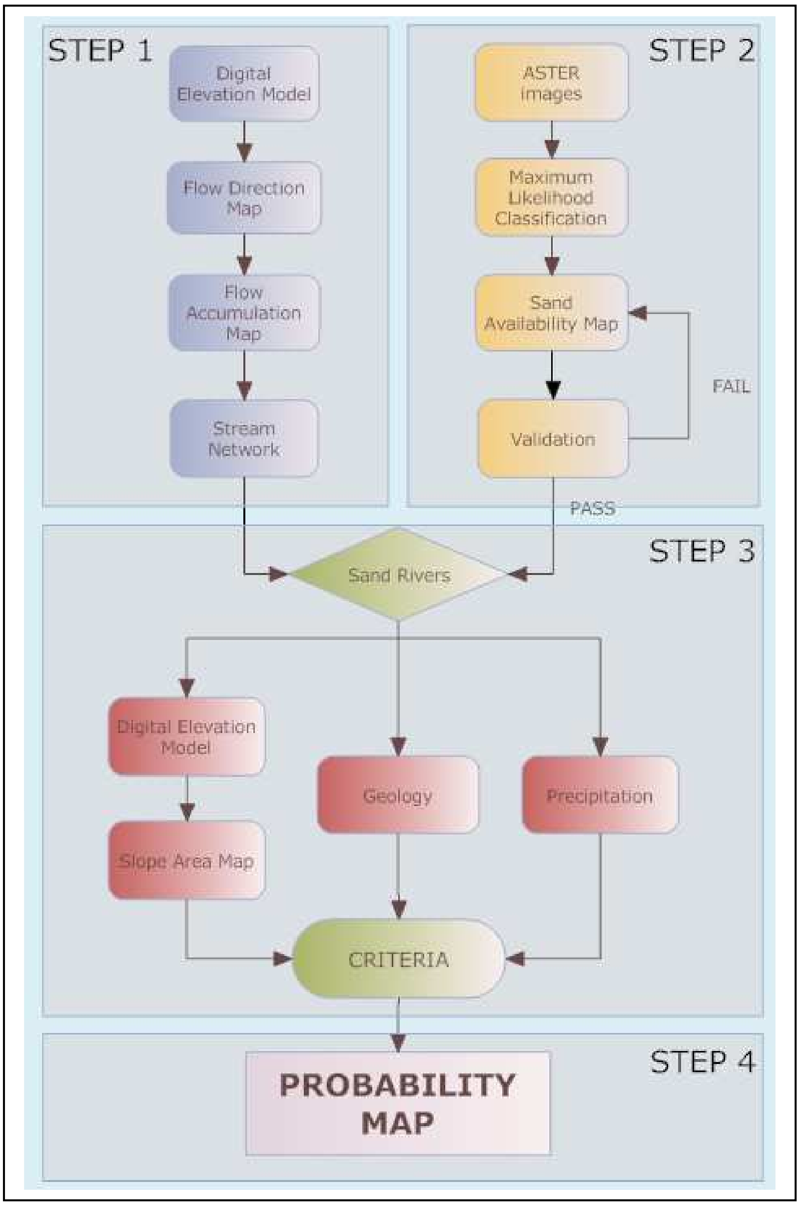


Figure 3-1: *Flow chart*

3.1.2 <u>Processing</u>

In the next paragraphs the different steps to the construction of a probability map are explained in more detail. Each step corresponds with the number given in. In the first step a map of streams is created that will be compared with the data from step 2. When a combination of these two steps successfully identifies sand rivers, the characteristics of successful catchments can be examined in step 3. The out coming criteria for geomorphology, geology and rainfall are based on sand rivers in combination with typical catchment characteristics. In the final step up-scaling of the data, based on defined criteria in step 2, will be performed. The data is processed in ESRI® ArcMap™ 9.1, ArcGIS.

3.1.3 STEP 1: Development of a stream network

The first step is to create a map in which different river paths or streams can be identified. This map has to be compared with the map of sand rivers (as will be discussed in the next paragraph) in order to identify sandy and non-sandy rivers. Digital elevation data is used to create a stream pattern for the given area.
The imported elevation data is from the Shuttle Radar Topography Mission (SRTM). An advantage of the SRTM data is that it can be freely downloaded from the internet (*ftp://e0mss21u.ecs.nasa.gov/srtm/*). A disadvantage however is that the offered spatial resolution of the model is rather low at 90 m, which makes it less reliable in creating streams, especially in steeper areas. Besides the low spatial resolution the SRTM data often indicates the top of vegetation as surface level. SRTM data will therefore often deviate several meters from ground true data. The raster based data is available at a spatial resolution of 1 arc second (~30 m) for the United States and at a 3 arc seconds resolution (~90 m) for the rest of the world. The digital elevation models are being developed from the SRTM C-band radar. Data are in binary format and are divided into one by one degree latitude and longitude tiles in geographic projection.
Before the elevation data can be used sinks and peaks in the data have to be removed. Sinks (and peaks) are often errors due to the resolution of the data or rounding of elevations to the nearest integer value. Sinks should be filled to ensure proper delineation of basins and streams. If the sinks are not filled, the derived drainage network may be discontinuous.
The direction of flow is determined by finding the direction of steepest descent from each cell. This is calculated as:

*change in z value / distance * 100* (ESRI ArcGIS)

The flow direction map is an input for the flow accumulation map (FAM) which creates the stream network. The flow accumulation function calculates accumulated as the accumulated weight of all cells flowing into each downslope cell in the output raster. If no weight raster is provided, a weight of one is applied to each cell, and the value of cells in the output raster will be the number of cells that flow into each cell. (ESRI ArcGIS)
The stream network can than be generated stating that all values of the FAM > 0 equals 1. This last parameter needs to be adjusted in order to get an optimised stream network. A larger value for the flow accumulation corresponds with a higher concentrated stream and a larger contributing catchment area. A value of 800 is chosen for this map. So FAM > 800 equals 1, which indicates that the river path is visualized when 800 cells are combined. This corresponds to an area of 11,3 km^2 before the river starts flowing. In this way minor tributaries are excluded from the map, increasing the surveyability of the map.

3.1.4 STEP 2: Development of a sand area map

In the second step satellite images are used to identify sand areas. The sand area map is created using image classification. The overall objective of image classification is to automatically categorize all pixels in an image into land cover classes or themes. Normally multispectral data from satellites are used to perform the classification. The spectral pattern present within the data for each pixel is used for the numerical basis for the categorization. Different feature types manifest different combinations of digital numbers based on their inherent spectral reflectance and emittance properties (Lillesand and Kiefer, 1994).
The satellite data used for the classification of the study areas are from the Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTER) sensor. The specifications of the sensor are given in Table 3-1. The first three spectral bands are used for

classification, considering the Visible and Near Infra Red (VNIR). The maps are georeferenced based on one degree latitude longitude tiles in WGS 84 projection. The ASTER image is from November 2005 at the starting of a rainy period. Riverbeds were still very dry, increasing the chance of a good riverbed identification as less vegetation is covering the target area.

Table 3-1: *Characteristics of sensor used for classification. (Source: NASA)*

Sensor	Spectral band	Spectral range	Resolution	Launched
ASTER	1	0,52 – 0,6 µm	15 x 15 m	18/12/1999
	2	0,63 – 0,69 µm	15 x 15 m	(still operational)
	3	0,76 – 0,86 µm	15 x 15 m	

3.1.4.1 Training stage

The overall objective of the training stage is to assemble a set of statistics that describe the spectral response pattern for each land use type to be classified in an image. The point that must be emphasized is that all spectral classes constituting each information class must be adequately represented in the training set statistics used to classify an image. When for example multiple water bodies with different spectral classes occur in an image, training statistics would be required for each of the spectral class that might represent a water body. (Lillesand and Kiefer, 1994)

The locations of the training areas for the study areas are established by polygons. These polygons have been carefully located to avoid pixels along the edges between the different land cover types. Within each training area site the digital numbers for the pixels are extracted. These pixels values then form the sample used to develop the statistical description of the training area.

Five different land use types are distinguished: 1) Potential sand areas, 2) Cultivated areas, 3) Vegetation, 4) Clouds and 5) cloud shadows. For each land use type at least 4 training areas are defined. The locations of some of the training areas are visualized in Figure 3-2. For identification of the sand rivers many ground truths have been used, as sand rivers are the main target for the classification. Urban areas in Kenya are often very sandy and roads are difficult to distinguish from sandy riverbeds. The training areas chosen for the Maximum Likelihood Classification are identified during the fieldwork and mainly concentrated close to field visit locations. Figure 3-2 shows the training areas chosen near the Kwa Ndunda dam in the Kiindu Catchment.

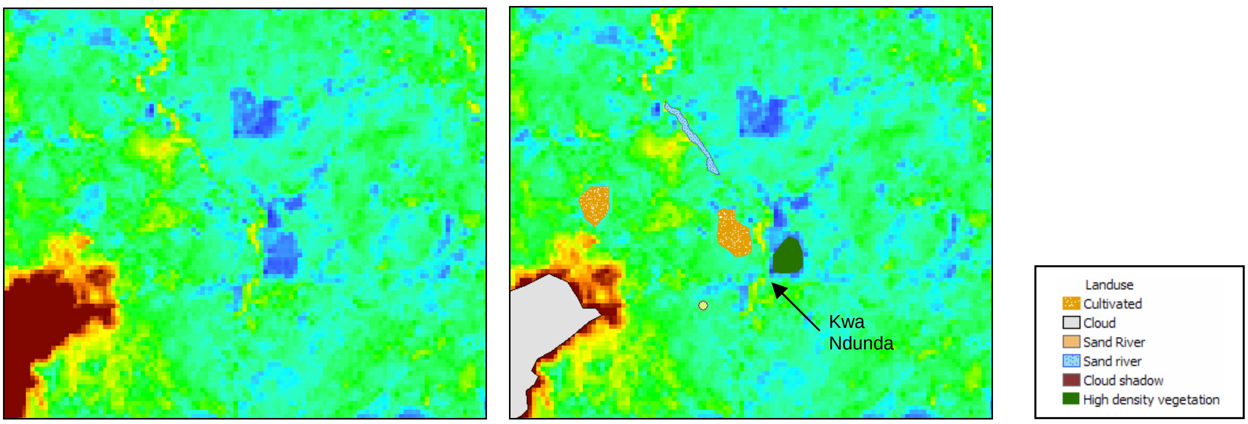


Figure 3-2: *Locations of some training areas in the Kiindu Catchment, close to the sand storage dam Kwa Ndunda*

In ArcMap the training areas are then used to create a signature file. The signature file contains 1) the general information for all classes, such as the number of layers, input raster names, number of classes, etc. and 2) statistics for each class which consists of the number of samples and the means and covariance matrices. The covariance matrices and means are required for the classification.The reliability of a signature file can be tested using a dendrogram. A dendrogram shows the attribute distances between each pair of sequentially merged classes. The larger the distance between the classes, the smaller the chance of overlapping of classes and therefore the lower the uncertainty.

3.1.4.2 Classification approach

For this study we applied a supervised classification with the Maximum Likelihood Classification (MLC further on in the report) methodology, which is available as a tool in ArcMap. MLC is a technique that quantitatively evaluates both the variance and covariance of the category spectral response when classifying an unknown pixel. Therefore the assumption is made that the distribution of the cloud of points forming the training area is normally distributed. Under this assumption, the distribution of a category response pattern can be completely described by the mean vector and the covariance matrix. With these parameters the statistical probability of a pixel value being a member of one of the classes can be computed. (Lillesand and Kiefer, 1994) The MLC in ArcMap is also based on Bayes's theorem of decision making. If the likelihood of occurrence of some classes is higher (or lower) than the average the classifier assists in the allocation of cells that lie in the statistical overlap between two classes. These cells are more accurately assigned to the appropriate class, thus resulting in a better classification.

When the Maximum Likelihood Classification is performed, a rejectgrid is produced. This grid shows the levels of classification confidence. The number of levels of confidence is 14, which is directly related to the number of valid reject fractions values. The reject fraction identifies the portion of cells that will remain unclassified due to the lowest possibility of correct assignment. Cells closest to mean vector will have the highest certainty. The reject fraction used for the classification was set on 0.005 which indicates that cells with the lowest level of confidence will be assigned as No Data (ESRI ArcGIS).

After completion of the MLC the data is compared to the data collected from the field visits during the validation. The catchment areas classified as ‘good’ during the field visits should equal the sand rivers. If not some additional adjustments to the training stage had to be made. The MLC is also compared to an NDVI (Normalised Difference Vegetation Index) image. NDVI is a numerical indicator that can be used to assess whether areas on images contain live green vegetation or not. Values of NDVI vary from 0.0 – 1.0, respectively the response to free standing water and tropical rainforests. NDVI indicates where vegetation is present and can therefore be compared with identified vegetation areas from the MLC. NDVI images can be obtained from the EOS Gateway (*nsidc.org/ims-bin/pub/nph-ims.cgi/u65655*) using the MODIS/Terra satellite. The data offers a spatial resolution of approximately 250 meters. For this study an image from March 2007 is chosen, at the end of a dry season. As both ASTER and NDVI images are from dry periods similarity between the two maps indicates a good classification result for areas with high vegetation properties.

3.1.5 STEP 3: Analyzing catchment characteristics

The catchment characteristics are analysed for different catchment areas in the study area. Therefore three variables are used for the study area. Slope, geology and precipitation

appear to be most critical for the creation of sand rivers in an area. Precipitation needed for the application of sand storage dams is limited. Only a small amount of precipitation is needed to fill up a dam. However, precipitation should be sufficient to generate a high energy surface flow, capable of transporting larger sediments.
Comparing these variables with the known locations of sand rivers will give an indication of the sensibility of the variables towards the availability of sand in riverbeds in the study area. Eventually, when a parameter appears to be critical in the study area the criteria for this parameter can be obtained. These criteria will then be used in STEP 4 to create a probability map for the study area. Further on the criteria will be applied to the total extend of Kenya.

3.1.5.1 Catchment areas

Catchments in the study area are identified for every intersection point between two streams using the stream link and watershed function in Arc Map. Stream link identifies the links between both the intersections and the water divides. With the stream link as input, the watershed function generates a catchment area for each stream link. The sizes of the calculated catchment areas, especially at the start of a river or tributary, are dependent on the input of the stream network. A larger amount of stream results in a larger amount of smaller catchment areas.

3.1.5.2 Slope

Slope is assumed to be one of the controlling factors concerning sediment deposition in the riverbeds as runoff is decreasing with decreasing slope. This is mainly due to lower flow velocities and subsequently a longer time of concentration (defined as the time needed for a drop of water to reach the outlet of a catchment from the most remote location in the catchment). This means that the water is exposed for a longer duration to infiltration and evaporation before it reaches the measuring point. The same applies when catchment areas of different sizes are compared. The longer and steeper a slope is, the higher the risk of erosion. This was also observed by Kinnell (2000).
A slope map is created using the modified SRTM data in ArcMap. The slope function identifies the maximum rate of change in value from each cell to its neighbours. Therefore horizontal and vertical units in the projection should be the same. For each catchment area a mean slope is calculated.

3.1.5.3 Precipitation

The effectivity of sand storage dams appears to be less sensitive to precipitation (Borst and de Haas, 2006). When locating suitable regions for sand storage dams the precipitation will be important in influencing the availability of coarse grained material in the riverbeds. As higher annual precipitation will lead to an increase of storm events, these areas might have a higher potential than regions with a lower annual precipitation. For this study two sets of data are used and compared.

The first set of data is obtained from the TRMM mission. The Tropical Rainfall Measuring Mission (TRMM) satellite carries a precipitation radar with a spatial resolution of 4.3 km and covers the region between 35°N and 35°S. Data are a vailable on the internet on monthly basis. When rain is produced, the energy originally used to evaporate the water from the Earth's surface is released into the atmosphere. Averaged over the entire Earth the heat released by precipitation is about five times greater than that produced by variations in surface heating. TRMM uses this difference in energy to quantify precipitation. Data for this study are downloaded from http://neo.sci.gsfc.nasa.gov/Search.html?group=39. Data is available from 1998 - onwards. For this study we selected a mean dataset covering 1998 - 2004. An advantage of TRMM is that monthly rainfall data is available in GEOTIFF format and, when properly georeferenced, directly applicable in ArcGIS.

The second set of monthly and annual precipitation data is obtained from New Locclim. New LocClim is developed to provide an estimate of climatic conditions at locations for which no observations are available. New LocClim also the offers effective rainfall. To achieve this, the programme uses 28800 stations of FAOCLIM 2.0, a global agroclimatic database maintained by the Agrometeorology Group of FAO (source: www.fao.org). For the total area of Kenya 706 stations are available and used for a nearest neighbourhood interpolation. The highest density of stations is located in the South-West of Kenya, including the Kitui District. The study area has a coverage of 18 rain stations.

A rainfall intensity map is generated using New LocClim. A raster of 36 points over the study area is created from which the longitude-latitude coordinates are put in New LocClim. For each point a table in New LocClim is created, showing the monthly effective precipitation and amount of rainy days during the month, based on data from the 18 rain stations in the study area. The effective precipitation is the part precipitation that will continue as surface runoff. Rainfall intensity is can than be calculated in mm/day. On annual basis the intensity is averaged over 8 months. Data during the dry months (June – September) is excluded in order to reduce too high variables in the intensities. Rainfall events during the dry period often results in extremely high intensities, but are very rare and local.
The annual averages for each point in the raster are interpolated over the study area using nearest neighbourhood interpolation in ArcMap.

3.1.5.4 Geology

The local geology is responsible for the deposition of fluvial sediments in the riverbeds. For the geology of Kenya a geological map available from USGS is used. This map is part of the open file report 97-470A, version 2.0 2002. with a scale of 1:5,000,000. The dataset is an interim product of the U.S. Geological Survey's World Energy Project (WEP) and can be freely downloaded from the internet. The map has an RMS error that does not exceed 3500 m, indicating that the map is less suitable at smaller scales.

3.1.6 STEP 4: Probability map

Criteria identified in STEP 3 are combined to the total study area. The probability map indicates in which areas it is possible to built sand storage dams, based on the criteria subscribed in STEP 3. On the other side the map shows locations where construction of sand storage dams is not advisable, based upon the information obtained from the study area. The criteria obtained from the study area can be used for further up-scaling to the size of Kenya.

3.2 Sediments

3.2.1 Introduction

The accumulating sediments behind the dam partly define the effectivity of a sand storage dam. Soils are responsible for the erosional product that eventually will be transported or deposited by a concentrated stream flow. Catchment areas with different soil and geological characteristics will lead to different types and sizes of (depositional) sediments, both favourable and non-favourable for the construction of sand storage dams. Using suspended load and bedload measurements an estimation can be given of the amount of sediments being transported out of the catchment or relocated within the catchment, during different stages of flow. An overview of all sediment samples is given in Appendix 3.

3.2.2 Soil samples

To get an overview of the distribution of soils and sediments, samples are taken throughout the Kiindu catchment of both riverbanks and riverbeds. From sand storage dam Kwa Langwa towards the upper North of the catchment samples from riverbanks were randomly collected as well as samples of the sediments deposited behind sand storage dams. For comparison of the Kiindu catchment with other catchment areas, samples of riverbed and riverbanks were also collected during field visits. The samples are collected in small bags of approximately 30 mg per sample, in order to reduce weight.

At four locations close to the Kwa Ndunda dam runoff plots were created with particular slope and land use. The plots are located on a loamy/clayey soil and silty/sandy soils with slopes varying from 4 to 9 degrees. A further description of these plots is given in Jansen, 2006. From each runoff plot the surface material is sampled to get an indication of the type of sediment coming from different soils also the accumulated sediments in the gutter of the runoff plots were sampled. The amount of sediments coming from the runoff plots during a storm event was unfortunately impossible to measure because heavier sediments will partly accumulate in the gutter and in the hose, resulting in an overestimation of suspended sediments in the collection barrel. Therefore, the sampled sediment from the runoff plot gutter is assumed to give an underestimation of smaller grain sized material.

During placement of the piezometers, as described in Hoogmoed, 2006, samples were taken from different soil layers to get an indication of grain size distribution in the vertical direction.

In Appendix 4 an overview of the sampling locations at the Kiindu catchment are given. In Appendix 5 an overview of sediment samples per field visit site is given.

3.2.3 Suspended load

Suspended load samples are collected at the Kwa Ndunda dam during various stages of discharge in the Kiindu River. Measurements are mostly combined with discharge measurements, which are described in Jansen, 2006. A relation between discharge and sediment transport was made. Samples were taken filling a 5 litre barrel with stream water at approximately ½ of the stream depth. The exact amount of the total suspension was measured using a measuring-glass. To each sample a small amount of nitric acid was added to increase the settling speed of the suspended sediments. After two days of settling the water was removed from the barrels by making holes in the barrel just above the sediment layer. The residue was then ovendried and weighed using a balance with an precision of 0.1 gram.

3.2.4 Bedload

Bedload samples are collected at the spillway of the Kwa Ndunda dam and in the riverbed close to the dam using a hand held sheetmetal Helly-Smith bed load sampler. An example of a Helley-Smith bedload sampler is given in Figure 3-3.The opening through which bedload passes is 3x3 inch. The flare causes pressure-differences within the samplers and encourages deposition in an attached bag. The bag attached to the sampler had 0.2 mm mesh, catching the coarse sand and letting through the finer grained material.

Figure 3-3: *Hand-held Helley-Smith bedload sampler (left) and irregular sediment movement in the Kiindu river (right)*

Rates of bedload transport, measured under comparable conditions of flow, can differ substantially, often up to an order of magnitude, because of the irregular nature of sediment movement in typical, coarse-grained streams (see also Figure 3-3). When possible, bedload samples are therefore taken in the middle of the spillway of the Kwa Ndunda dam. Water from the river is guided through the spillway which has a fixed width. Measuring in the spillway was not always possible due to a large scoophole in front of the spillway which trapped the sediment. Measuring at the spillway started when the scoophole was completely filled with sand. All measurements have been taken for a time period of 30 seconds and have been performed twice to compare the amounts of bedload visually. When comparable, one of the two samples is used for analysis. All samples were ovendried and weighed using a balance with 0.1 gram accuracy.

3.2.5 Grain size analysis

Samples of soils, suspended load and beload, obtained in the field, have been analysed particle-size. All measurements were performed on a Fritsch Analysette 22 Laser Particle Sizer (VU Amsterdam), which results in a grain-size distribution with 56 size classes in the range of 0.15 – 2000 µm. Before analysing organic matter and carbonates were removed from the samples as described in NEN-5753 (Dutch Norm). An exact description of pre-treatment of the samples is given in Appendix 6. The amount of material needed for analysis depends on the grain-size characteristics, typically 100 – 200 mg for clays and 5 – 10 g for sandy material.

4 RESULTS AND INTERPRETATION

4.1 Up-scaling

4.1.1 Development of a stream network: STEP I

The first step in creating a probability map for the study area is to construct a stream network of the study area. This network is created using the different maps as described in Paragraph 3.1.3. In Figure 4-1 the result of this calculation is given.

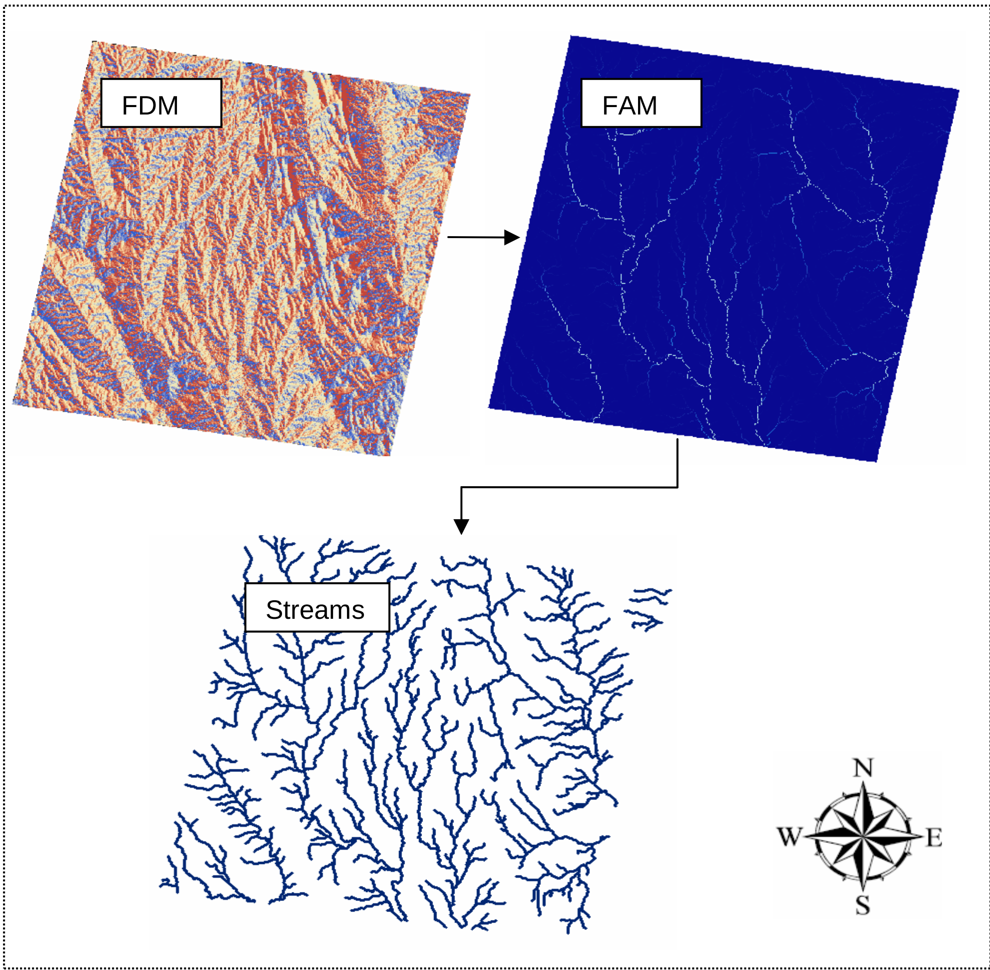


Figure 4-1: *Development of a stream network*

The flow accumulation map (FAM) is created for an area larger than the study area. This is done because some larger rivers cross the study area. When created only for the study area these rivers would be assumed to rise within the study area and therefore be underestimated as compared to other (smaller) rivers in the study area. When smaller tributaries are excluded from the map also parts of larger rivers would be removed.
The map gives a good representation of the streams in the area, however, the larger meandering rivers in the North-East of the area deviate from the real course of the river.

4.1.2 Development of a sand area map: STEP 2

The sand area map gives an indication of areas in the study area that have equal spectral responses with known sand locations from field observations. To identify these locations the study area is divided in 5 different classes that are used in the Maximum Likelihood Classification:

- Potential sand area (sand rivers, open sand areas, urban areas)
- High density vegetation (forests, bushes)
- Cultivated land (land used for crops, bare land, grass land)
- Clouds
- Cloud shadow

Urban areas appear as potential sand areas, mainly because this class shows large correspondence with known sand areas. Apart from Kitui Town most roads in the study area have a sandy or loamy composition and living areas are not concentrated into large villages. Local people live in small compounds that are mainly constructed of natural material, located far apart from each other. Urbanised areas are therefore hard to identify.

The result of the Maximum Likelihood Classification is given in Figure 4-2. A more detailed version of the map can be found in Appendix 7.

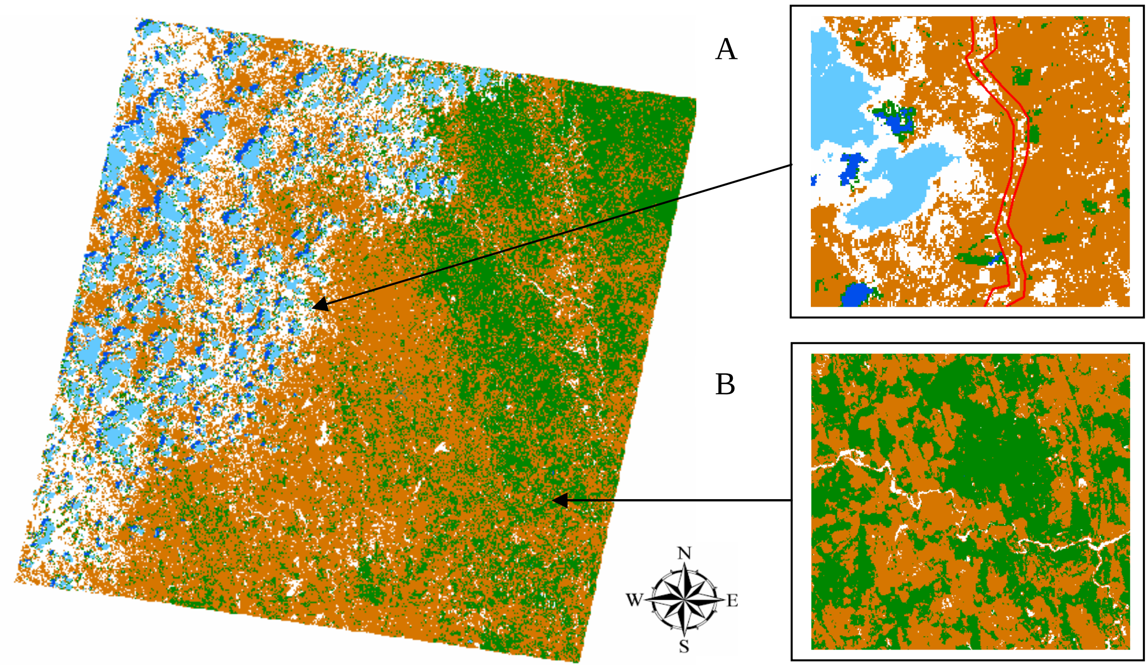
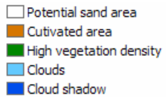


Figure 4-2: *Maximum Likelihood Classification with the Kiindu River in the upper right corner (A) indicated in red and the Ngunga River in the lower right corner (B)*



The reliability of the maps appears is tested using dendrograms for the created signature files. In Table 4-1 the remaining distances between pair combined classes are given.

Table 4-1: *Distances between pair combined classes*

Remaining Class	Merged Class	Between-Class Distance
Potential sand area	Cultivated area	3.23
Potential sand area	High vegetation density	7.78
Potential sand area	Cloud shadow	11.26
Potential sand area	Clouds	21.97

The smallest between-class distance between cultivated area and potential sand area indicates that attached pixels for these classes show the largest comparison and are therefore more difficult to distinguish.
As shown from the figure the vegetation coverage in the area increases towards the East. Similarity can also be identified with local topography. Vegetation coverage increases with increasing topographical heights. An increase in vegetation towards the East of the study area can also be observed from the NDVI image. Vegetation areas in the MLC show large similarity with the vegetation areas from the NDVI image. Both images are given in Appendix 8. Most of the area is covered by cultivated or bare land. From the classification sand rivers are, when substantially smaller than the spatial resolution of the ASTER images, difficult to identify. The pixel value will become a mixture of the riverbed and riverbanks, both with a different textural composition. Combined with the small between-class distance between sand areas and cultivated areas, as indicated in Table 4-1, errors for smaller sand rivers might be expected. These parts of rivers are mostly found in the upstream part of a catchment area. Larger sand rivers, as for example the Ngunga River, are relatively easy to identify.

4.1.2.1 Spatial adjustment

When comparing the MLC map with the stream network a slight difference between the maps can be noticed. The rivers visualized on the MLC map do not perfectly correspond with the rivers as visualized in the stream network. The maps cannot just simply be combined to one map that shows sand rivers. The main reason for this difference is the difference in spatial resolution for both the maps (90 m for the SRTM data against 15 m for the ASTER data). In addition, meandering rivers are difficult to identify with only elevation data because of the small local elevation difference. In Figure 4-3 the result of the combination of the STREAM map with the MLC map (filtered sand classification) is given. In green a high probability sand river is given and in red a low probability sand river is given.

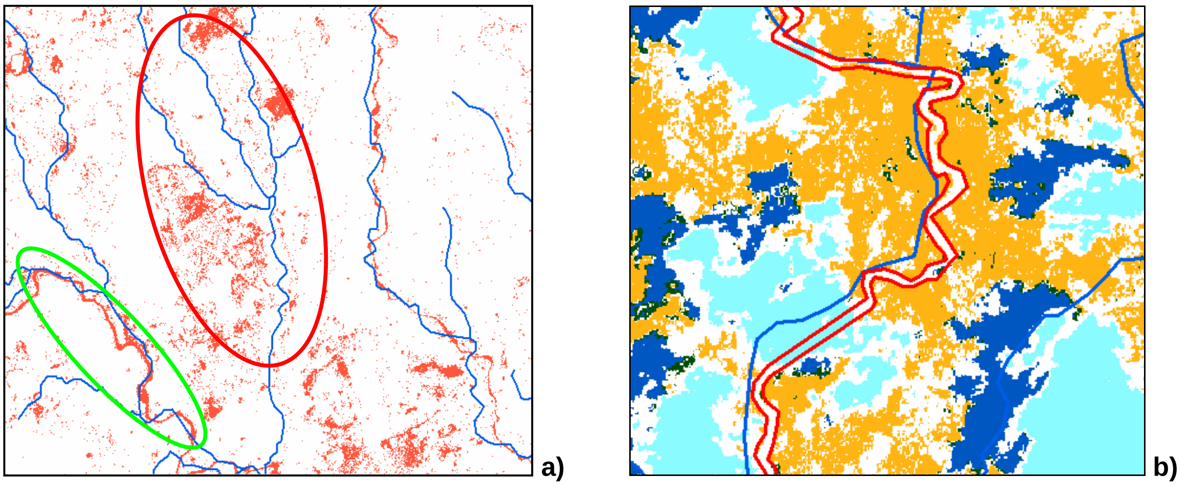


Figure 4-3: a) *Comparison of Stream network with MLC sand area map* ***b)*** *Identification of sand rivers in heavy cloud coverage*

The available ASTER data shows heavy cloud coverage in the North-West of the image. The regions below the clouds are not covered by the sensor. Also regions with cloud shadows have different spectral properties when compared with cloudless images. Within a Maximum Likelihood Classification clouds can easily be identified. However, the edges of the clouds have lower reflection and will be confused for other classification types. This causes overestimation for one classification type, as shown in Figure 4-3. The edges show large comparison with potential sand areas which are therefore overestimated in the North-West of the classification map. Also smaller sandrivers are more difficult to depict as mentioned in Paragraph 3.1.4.

To overcome the problems as mentioned above the MLC map and different ASTER bands are also manually compared to the stream network. Especially downstream sand rivers have distinct features which can be identified relatively easy using a Maximum Likelihood Classification. These rivers are wider downstream compared to upstream and therefore easier to identify. Furthermore from the smaller sand rivers visited during the field visits the spectral pattern can be obtained from the ASTER data. However, these small rivers are more difficult to define. In Figure 4-4 the 3 bands images for a part of the Kiindu river are given.

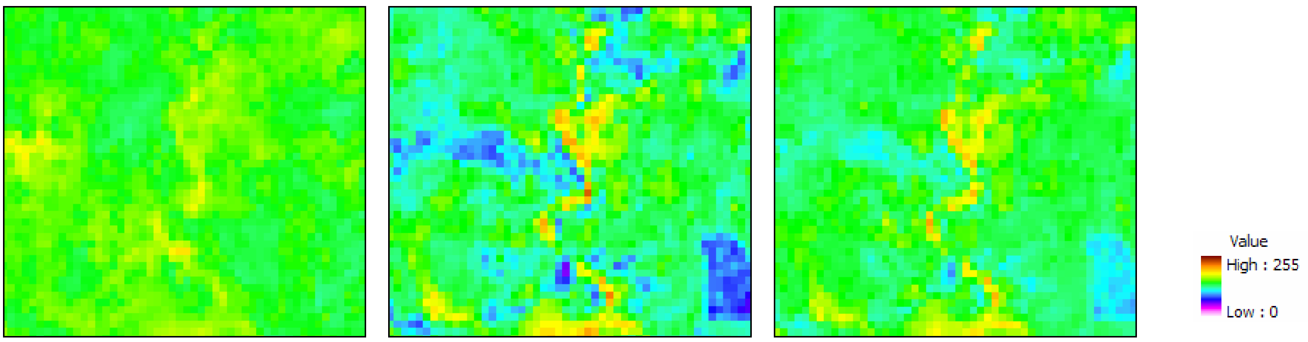


Figure 4-4: *Spectral response of a part of the Kiindu river in different spectral bands. Band 3 is on the left, band 2 in the middle and band 1 on the right*

Using the knowledge of the different spectral responses combined with the stream network and the Maximum Likelihood Classification the sand rivers can be classified. A difference in classification is made between sand rivers and rivers that show a clear difference from the spectral response of sand rivers. The last also includes streams or tributaries that are too small for the ASTER data set to identify. In Figure 4-5 the 3 bands images for a river, that deviates from the spectral response of sand rivers, are given.

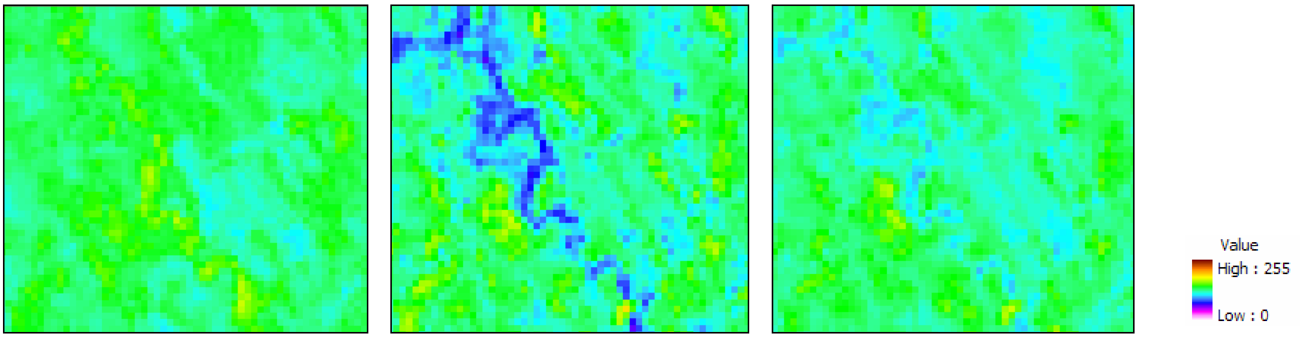


Figure 4-5: *Spectral response of a non-sand river in different spectral bands. Band 3 is on the left, band 2 in the middle and band 1 on the right*

The river in Figure 4-5 shows a substantially lower spectral response for all three bands than the Kiindu River as indicated in Figure 4-4. Especially in bands 1 and 2 Also from the MLC most of this river is identified as dense vegetation. This indicates that most of the riverbed appears to be covered by vegetation. River beds with a high vegetation cover are assumed to be less favourable, as mentioned in Paragraph 2.3.3.6. It should be noted, however, that the discussed river has not been visited. No information about the composition of the riverbed is therefore available. As such the river can only be identified as a *low probability sand river*. It also seems that vegetation is only covering the riverbed and not the river banks. Rivers in the area with heavy cloud coverage are identified as shown in Figure 4-3. Most of the streams between the clouds could be identified by the MLC and interconnected using the STRM generated stream network. The ones that could not be identified are estimated using the downstream characteristics of the river.

4.1.2.2 Validation

Different soil types have different grain sizes and spectral responses. The size and arrangement of the soil particles have an impact on the soil reflectance. Obtaining a relationship between the grain size and the spectral response of the sediment samples taken in the study area validates whether pixel values are correctly identified as sand. Samples used for the validation are from the Kiindu Catchment and the Ngunga Catchment. The width of the riverbeds at these locations approaches the spatial resolution of the ASTER images, allowing a more detailed study on the grain size for sands. The result of this study is given in Figure 4-6. In Appendix 9 the Digital Numbers and grainsizes per sample, used for the validation, are listed.

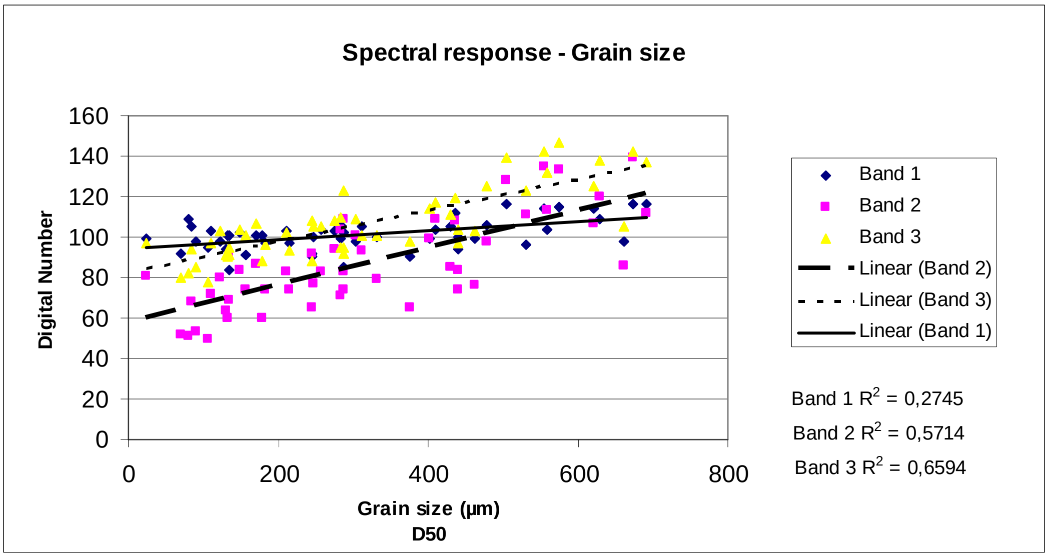


Figure 4-6: *Spectral response of sediment samples compared to median grain size (D50) for the first three spectral bands*

The spectral response to grain size shows the largest variation in the in Bands 2 and 3, varying from Digital Number (DN) 50 to DN 147 and from smaller median grain size (107 µm) to larger median grain size (673 µm). Band 1 shows the smallest variation. The best relationship between DN and D50 is obtained for band 3, with an R^2 of 0,66. As shown in Figure 4-6, spectral reflectance linearly increases with increasing median grain size.

To obtain a better view of the influence of three different bands combined on the median grain size also multiple regression to the data is applied. The result of this analysis is given in Figure 4-7. The regression equation is also given in Figure 4-7. B_1, B_2, B_3 are Band 1, 2 and 3 respectively.

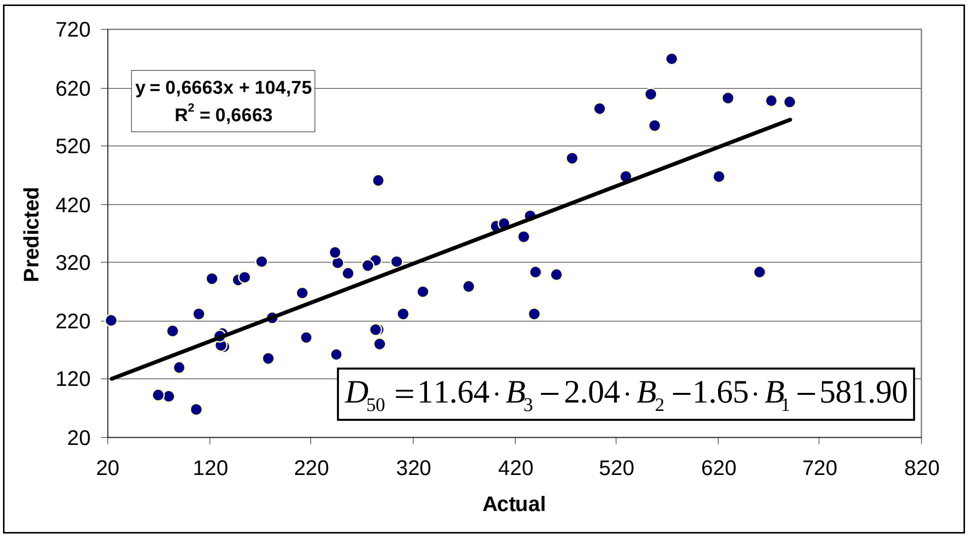


Figure 4-7: *Multiple regression analysis of field samples*

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The relationship obtained from the multiple regression also indicates a linear increasing reflectance with increasing median grain size. The reliability of the linear relationship is comparable to that of band 3 (R^2 = 0,66).

A linear relationship for sand and clay was also found by Gerbermann and Neher (1979), with increasing amounts of sand and increasing reflectance for wavelengths of 0.44 – 0.86 µm. The variance in reflectance for equal median grain sizes can be explained by the relatively low spatial resolution of the ASTER images compared to the small sampling areas. Grain size, for example, in a riverbed can vary extensively with the sample location as depositional size is dependent on the turbulence of the water. Vegetation coverage also influences the spectral response. Vegetation coverage at the image date is relatively low as the ASTER image is from the end of the dry season and only little vegetation is present.

From the signature file used to create the MLC the mean Digital Numbers per layer can be obtained. For the two soil classes used in the MLC these values are given in Table 4-2. The estimated median grain size is estimated from the obtained relationship between Digitals Numbers (DN) and Median Grain Size.

Table 4-2: *Mean digital numbers as used for Maximum Likelihood Classification for two classes and estimated median grain sizes for single and multiple linear regression*

Classification layer	DN	DN	DN	Median grain size	Median grain size	Median grain size	Median grain size
	Band 1	*Band 2*	*Band 3*	*Band 1*	*Band 2*	*Band 3*	*Multiple*
Potential sand areas	98.58	123.28	141.31	190 µm	710 µm	769 µm	649 µm
Cultivated area	94.91	91.70	104.57	21 µm	366 µm	288 µm	292 µm

Cultivated areas are located on the riverbanks which have a more silty/loamy composition, compared to sand in the riverbed. As averaged median grain size of the riverbanks in the study area varies from 100 µm – 370 µm the MLC appears to give a good representation of the cultivated areas. Potential sand areas are slightly overestimated. Averaged median grain size for sandy riverbeds in the study area varies from 400 µm – 590 µm.
The smallest correspondence of grain size and digital numbers can be found for band 1. The low spectral variation with different grain sizes combined with smallest level of confidence of the relationship make this spectral band less effective in detecting soil properties. Band 2 and 3 appear to be more appropriate in identifying different soils. Using multiple regression, and combining the three bands, gives the most reasonable result, including the highest level of confidence. Especially sand areas are more comparable to the multiple linear regression equation than the single linear regression equations. Sand rivers in the study area have an overall grain size > 400 µm. In Figure 4-8 a partition is made of samples larger and smaller than the overall grain size in sand rivers for band 3.

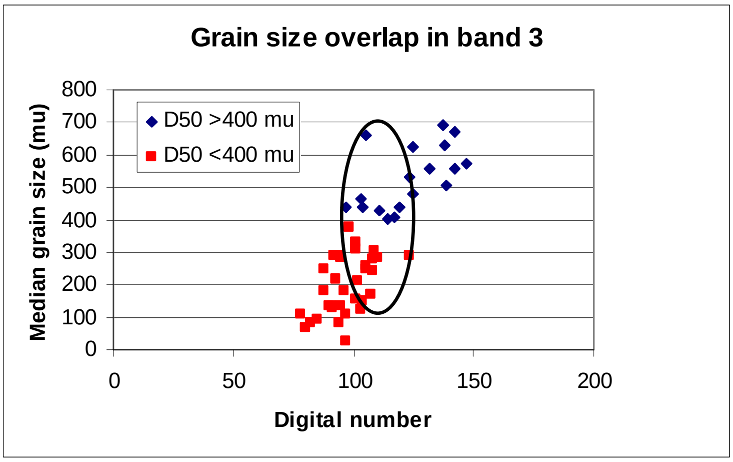


Figure 4-8: *Overlapping area of varying grain sizes combined with spectral response*

The circled area in Figure 4-8 indicates where the two groups of comparable grain sizes (< 400 mu and > 400 mu) show the largest different spectral responses and visa versa. In the region of DN 100-120 the largest overlap can be found. In this region also the largest variation in classification can be expected. In the Maximum Likelihood Classification a value is applied to the highest level of confidence. As substantially more values of finer sized material are available in the overlapping area, the pixel will be identified as so. Median grain sizes >500 µm, as indicated as fine sand that is still suitable for subtraction of water by Nissen-Petersen (2000), show nearly no overlap with grain sizes < 500 µm (see also Figure 4-8). Sand river beds that are wide enough to be covered by one pixel, as for example the Ngunga river and parts of the Kiindu river, mainly cover this region, indicating that a higher spatial resolution of satellite images will further increase the accuracy of identifying coarse sands in riverbeds. The relation between digital numbers and median grain size indicates that sandy areas using Maximum Likelihood Classification can be successfully classified.

4.1.3 Comparison: STEP III

Combining the data from step I and II results in a map that locates the potential sand riverbeds in the study area. The result of this combination is given in Figure 4-9.

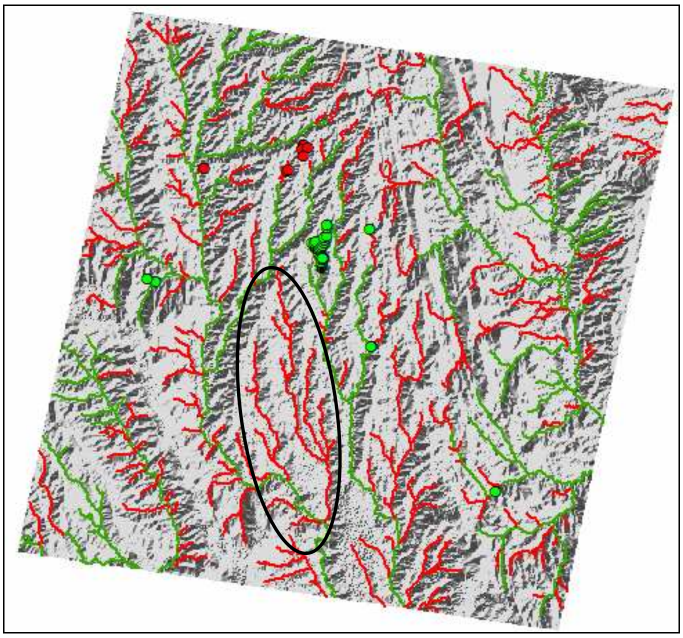


Figure 4-9: *Sand river map with a low probability catchment circled. Potential sand rivers are indicated in green, rivers where no sand is available are indicated in red*

The rivers indicated in red can be identified as rivers that do not have coarse sand available in the riverbed. Rivers indicated in green can be identified as rivers in which coarse sand is available in the riverbed. In most cases coarse sand is not available in the smaller tributaries that flow into larger streams. These tributaries often have a relatively small surface covered with sand and are therefore harder to identify. At several locations however sand in the riverbed is available moving more downstream in the tributary. This indicates that, although sand is not available in the riverbed, the area appears to be suitable in generating coarse grained material. For those areas only a limited amount of coarse sediments is available due to a smaller supplying area. For those areas, where larger streams combined with large supplying areas do not show the availability of coarse sand, the surrounding area appears to be unsuitable for the generation and supply of coarse depositional sediments. An example of such an area is also given in Figure 4-9. Rivers in these areas also show a different spectral response from sand rivers. A potential sand river is crossing the area however this river is originating far North and deposited coarse sediments in the riverbed are probably detached from the parent rock in this upstream region.

4.1.3.1 Slope

The low probability rivers are located mainly in low sloping areas. This can be visualised by combining the sand river map with a slope map. For each individual catchment area a mean catchment slope is calculated.

The result of this calculation is given in Figure 4-10 A. That larger catchment areas with low potential sand rivers show large comparison with the mean slope, is visualised in Figure 4-10 B. When dividing mean catchment slope areas with respectively slope areas > 2 degrees and slope areas < 2 degrees all low probability sand rivers fall within the region of the second classification. Also smaller areas located in the North and North-West of the study area show similar properties concerning spectral response and slope. Because of the higher vegetation density (also on the river banks) in these areas the rivers are harder to identify.

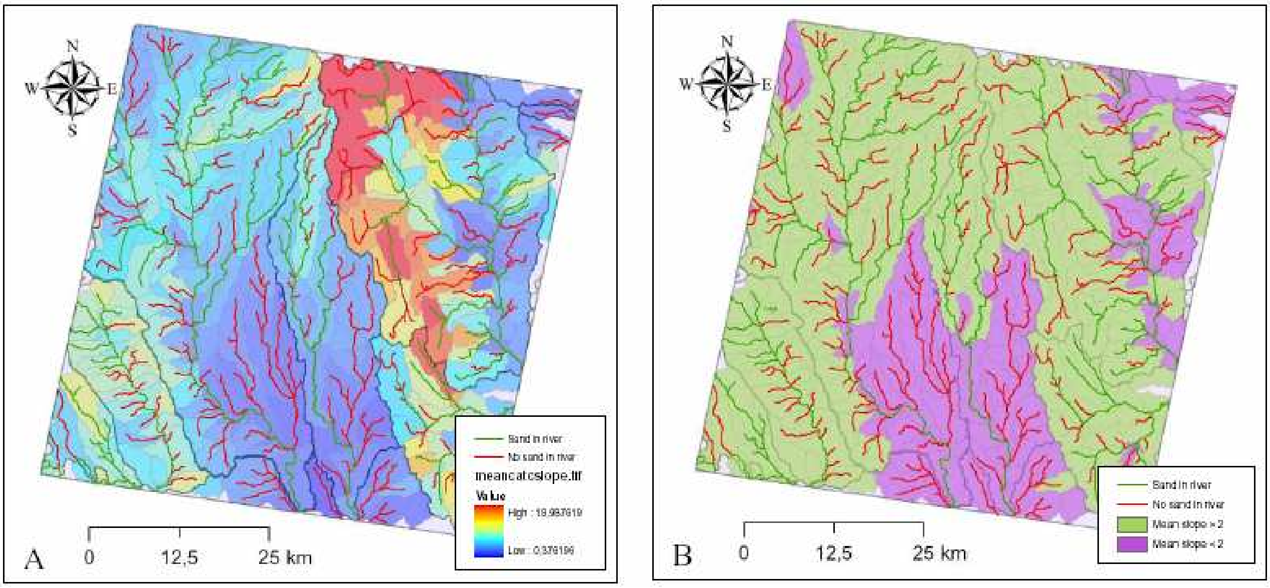


Figure 4-10 A and B: *Mean catchment slope compared to low potential sand rivers*

Catchment slope appears to be critical in defining a suitable area for the construction of sand storage dams. A critical slope value of an averaged 2 degrees per area can be maintained based on the data available from the study area.

4.1.3.2 Geology

In addition to the sensitivity of the sand river data to mean slope the data are also compared to geology and soils in the study area. The geology in the study area, as presented from the geological map, encloses three types: Holocene (Qe), Precambrian (pC) and Tertiary igneous rocks (Ti). Figure 4-11a shows the local geology compared to the sand river map.

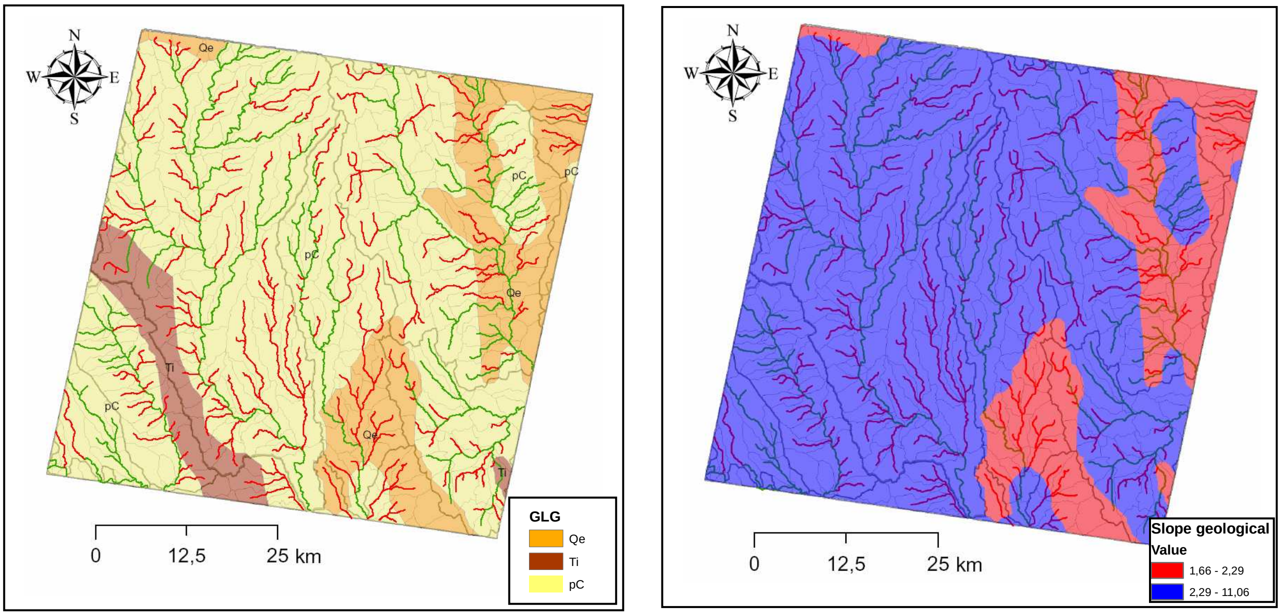


Figure 4-11: a) *Sand rivers compared to geology* **b)** *Geology compared to slope*

The geology shows less distinct characteristics to the high and low potential sand rivers than was observed by the mean catchment slopes. The rocks of Precambrian age have the highest potential and cover most of the study area. The Precambrian covers both high potential sand rivers as well as low potential sand rivers. Therefore the low potential rivers in this geological feature appear to be controlled by slope more than by geology. The Precambrian rocks can be identified as suitable areas in which coarse depositional material can be found in riverbeds.

The Holocene sediments appear to be less successful in generating coarse depositional material. Most of the streams originating within the Holocene feature are low potential sand rivers. That not all streams within the feature are identified as low potential sand rivers, can be probably assigned to the large scale of the geological map. As a maximum error of 3500 m can be expected this data has a lower accuracy than for example the slope map. In Figure 4-11b the mean slope for each geological feature in the study area is calculated. It appears that the mean slope for the Holocene feature is close to 2 degrees and that the other geological features have higher mean slopes that reach from 2.7 to 4 degrees. For the Holocene feature a low slope can be expected, based on the observations from Figure 4-11. Not all low-sloping areas however are underlain by the Holocene. Therefore this geological feature is apparently not suitable for the construction of sand storage dams. The feature will be classified as a low probability layer.

The Tertiary igneous rocks (the Yatta Plateau in the study area) appear to be suitable in generating and depositing coarse material in riverbeds. As the topographical high functions as a water divide no larger rivers or streams are available. Streams that originate from the Plateau however alter more downstream into a stream area in which coarser sediments can be observed.

4.1.3.3 Precipitation

Precipitation from TRMM varies from an annual average of 1264 mm in the North to 1192 mm in the South-East of the study area. Annual precipitation in the study area using New LocClim varies from 958 mm near Kitui Town to 679 mm in the South-East, based on nearest neighbourhood interpolation over 15 available rain stations. Several reports mention the averaged annual precipitation in the Kitui District, for example Borst and de Haas (2006), Burger *et al* (2003). In Table 4-3 rainfall data for the Ngunga River are compared to measured data from Kitui Town and the Ngunga River.

Table 4-3: *TRMM compared to interpolated New LocClim*

Location	Measured (mm)	TRMM (mm)	New LocClim (mm)
Kitui Town	1006	1264	958
Ngunga River	624	1192	714

TRMM precipitation data appears to give an overestimation in both locations. New LocClim data gives reasonable results in the North of the study area, but also shows a 90 mm variation with measured values in the South of the Kitui District. This can probably be assigned to the highly erratic pattern and the intensity of the precipitation events in this region. With increasing erratic patterns of rainfall the accuracy of the predicted amount of rainfall decreases substantial for both TRMM as New LocClim data. The difference for TRMM data however is much larger than for the New LocClim data, especially in areas with highly erratic rainfall like Kitui South. For this research New LocClim is therefore preferred over TRMM. Rainfall intensity increases towards the South-East, contradictional to precipitation quantities. Precipitation in the South of the study area is therefore more erratic than in the North. Effective rainfall intensity varies from an averaged 7 mm/day in close to Kitui Town to 8.8 mm/day in the South-East of the region. Due the highly erratic pattern, effective rainfall intensities per event are higher than the indicated values per day (see also Jansen (2007)). The pattern however gives a reasonable indication of the distribution.
In Figure 4-12 the distribution of annual precipitation and intensities in the study area compared with the sand rivers is given.

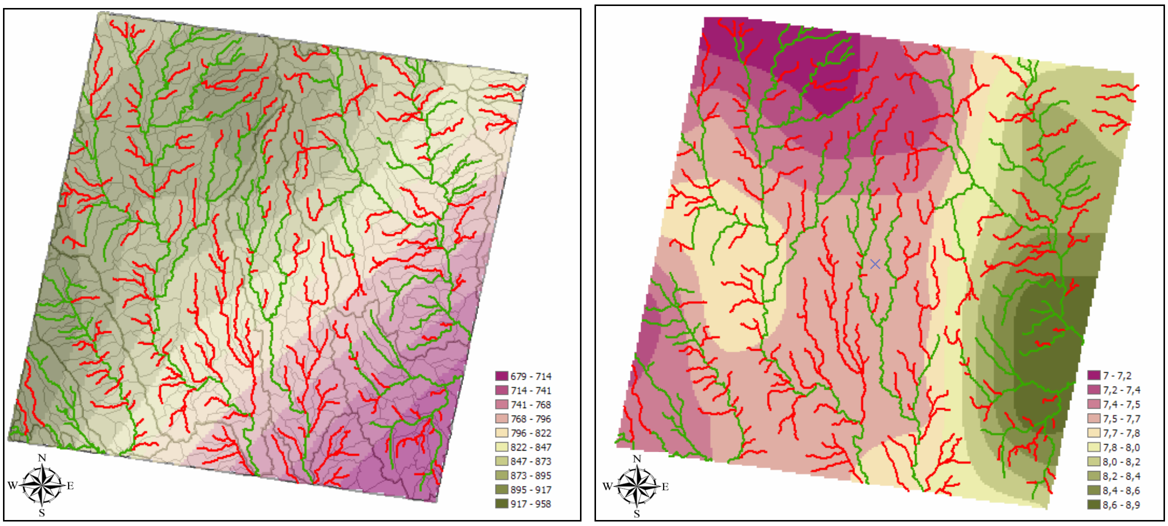


Figure 4-12: *Averaged annual precipitation in study area in mm (left) and averaged effective rainfall intensity in mm/day (right)*

Neither the precipitation amounts nor the precipitation intensities seem to have any influence on the availability of coarse grained material in riverbeds of the study area. Therefore it is assumed that precipitation, in this study area, satisfies the requirements for detachment and transport of coarse grained material needed for the successful construction of sand storage dams.

4.1.4 Probability map: STEP IV

Combined criteria from the above steps result in a probability map as given in Figure 4-13. The map indicates areas in which a successful application of sand storage dams has respectively a high and a low probability. Compared to these areas, all the field visit sites, indicated as red and green dots on the map, are located in high probability areas. This alleges that field visit sites with low efficiency are located in areas that are affected by other local conditions, since no difference in geology and slope could be found. More detailed geological maps from the area from Schoeman (1948) and Sanders (1954), as published in Borst and de Haas (2006), show no difference in geology as well. For these sites a different cause of inefficient performance should be found. This will be further in Chapter 5: Discussion and recommendations.

The map indicates that 36 % of the study area has a low probability of successful application of sand storage dams. Locations of sand storage dams built by SASOL are given in Figure 4-13. Not all dams built by SASOL however are measured in GPS coordinates. The dams shown in Figure 4-13 are therefore a selection of the total number of dams.
Figure 4-13 indicates that the dams with known coordinates are located within the areas with high-probability classification. Some dams are located in low probability sand rivers. These rivers are indicated as low probability because of their small size.

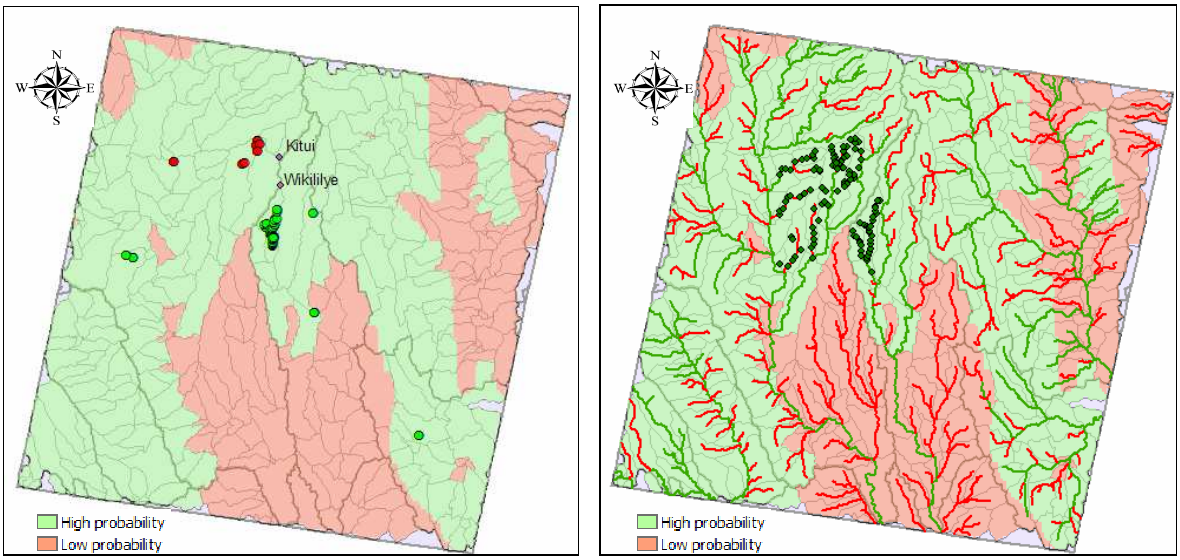


Figure 4-13: *Probability map for the study area, including the field visit sites. On the right dams with known coordinates built by SASOL are given.*

4.2 Sediments

4.2.1 Sediment transport equations

The estimation of river sediment load requires principally discharge and sediment concentration data. Bedload rates in the Kiindu riverbed are measured during different stages of flow. To calculate the yield of bedload, sample weight must first be expressed as a rate of transport. Mean rate of transport (Qb) is calculated using the sample weight (Gs) in kg (*Ryan and Porth, 1999)*:

$$Q_B = W_C \left[\frac{G_S}{W_S T} \right]$$ Equation 4-1

In which:

Q_B : Bedload transport rate (kg s^{-1})

W_C : Channel width (m)

G_S : Sample weight (kg)

W_S : Width of bedload sampler (m)

T : Total sampling time (s)

Using the above expression for each bedload sample a transport rate is calculated. Most of the samples are taken in the middle of the spillway of the Kwa Ndunda dam, with a fixed channel width. The first three measurements were taken approximately 150 meter upstream of the Kwa Ndunda dam. From these measurements no exact channel width could be measured and were estimated in the field.

Suspended load rates are measured during different stages of flow in the Kiindu river. Mean rate of suspended load transport (Qs) is calculated using the dry weight combined with the total volume of the sample.

$$Q_S = \left[\frac{G_{dry}}{V_S} \right] Q_{flow}$$ Equation 4-2

In which:

Q_S : Suspended load transport rate (kg s^{-1})

G_{dry} : Dry weight of the suspended material (kg)

V_S : Total volume of sample (dm^3)

Q_{flow} : Discharge of river (dm^3 s^{-1})

In Appendix 10 the results of the bedload and suspended load field measurements are given.

The relationship between sediment transport rate and measured river discharge is usually defined as a power function (Iadanza *et al.,* 2006):

$$Q_{sed} = aQ_{flow}{}^{b}$$ Equation 4-3

In which:

Q_{sed} : Sediment rate (kg s^{-1})
a,b : Regression coefficients (-)
Q_{flow} : Flow discharge (m^3 s^{-1})

Some interpretation to the regression coefficients is ascribed by Morgan (1995). According to Morgan the *a* coefficient represents an index of erosion severity; high *a* values indicate a high availability of weathered sediment in the basin, which can easily be eroded and transported by runoff. The *b* coefficient represents the power of the river to erode and transport the sediments; large values indicate rivers where a small increase in flow discharge results in a great increase in sediment transport capacity.

4.2.2 Sediment discharge in the Kiindu river

In Figure 4-14 the rating curve of sediment transport of suspended load against flow discharge is given.

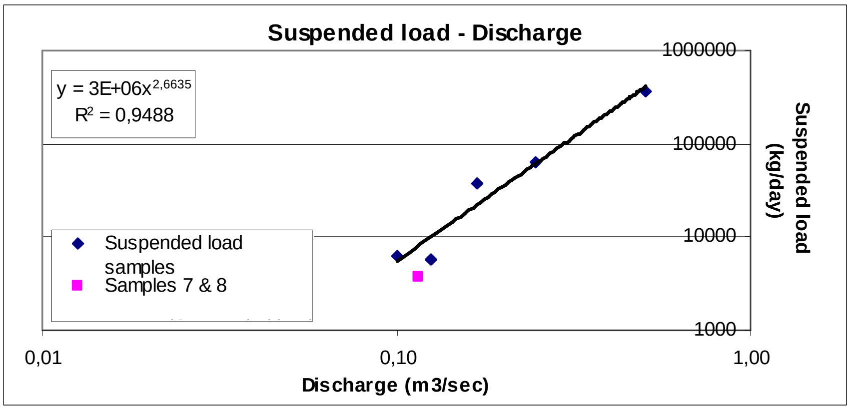


Figure 4-14: *Sediment rating curve for suspended load in the Kiindu river*

Discharge during measurement varied from 0,08 – 0,51 m^3/sec. The suspended sediment rates in the Kiindu Catchment show a very large response to discharge. Only a small increase of discharge results in a large increase of suspended sediments. The reliability of the regression curve appears to be good, considering an R^2 of 0.95. Hysteresis might influence the outcome of the suspended load rating curve caused by a difference in sediment supply during the falling and rising limb of the event hydrograph. This was also observed by Alexandov *et al.* (2002). During the rising limb discharge is mainly controlled by surface runoff, transporting large amounts of suspended material. Downgradient of the falling limb discharge will be dominated by baseflow, containing small amounts of suspended material. Sample numbers are given in Appendix 10. The amount of baseflow increases during the rainy season (see also Jansen (2007)), resulting in a constantly flowing river near the end of the rain season. For this reason the last two measurements (S7 and S8) are not taken into account when generating the regression line. Both samples were taken near the end of the rain season and are assumed to be controlled by baseflow. Suspended load samples are taken mainly during falling limb, except from sample 6. In Figure 4-15 the bedload rating curve is given.

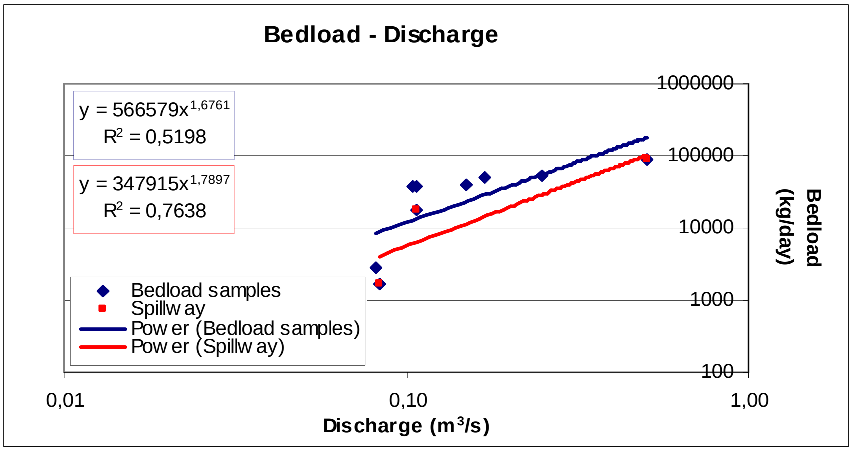


Figure 4-15: *Sediment rating curve for bedload in the Kiindu river*

The bedload sediment rates in the Kiindu catchment also show a large response to discharge. An R^2 of 0.52 indicates however that the reliability of the regression line is substantially less than that of the suspended load. This can mainly be ascribed to the irregular riverpath and riverbed of the Kiindu River. As suspended load is more or less equally divided over the stream flow, bedload differs at every cross-sectional position. As flow velocity changes over a cross-section the amount of transported bedload material increases with increasing flow velocity (see also Figure 2-4). At the spillway these problems are limited, although flow velocity, and therefore bedload transportation, is largest near the middle of the spillway. In Figure 4-15 regression lines for both the samples taken at the spillway as all samples combined are plotted. Samples from the riverbed seem to be overestimated compared to the samples taken from the spillway. R^2 increases to 0.76, indicating a higher reliability. However, not enough samples at the spillway could be taken, during different stages of flow discharge, to further verify this relation. The relation obtained from the spillway samples although will be used further on in the report as an overestimation of bedload transport is expected from the riverbed samples, based on Figure 4-15. In Figure 4-16 the responses bedload and suspended load are given, both in log-scale and normal scale.

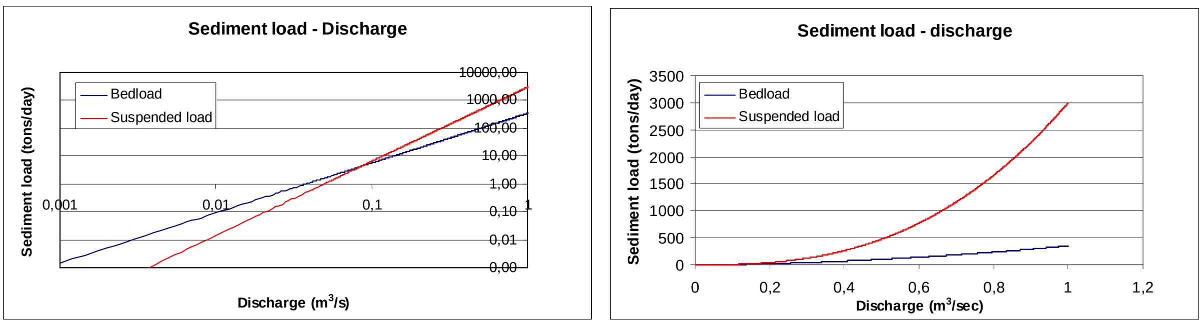


Figure 4-16: *Responses of suspended load and bedload to discharge of the Kiindu river*

Discharges lower than 0,09 m^3/sec are more or less dominated by bedload transport, although very minimal. Coarse grained particles are still being transported over the riverbed, while most of the finer particles have already been transported downstream. In Figure 4-17 the responses of bedload, supspended load and discharge during the field period are given. The responses for bedload and suspended load are based on the obtained relations. Discharge during the field period varied from 0 – 15,7 m^3/s. Especially for extreme events a large difference between suspended load and bedload can be noticed. Baseflow between different events varies between 0 – 2 m^3/s.

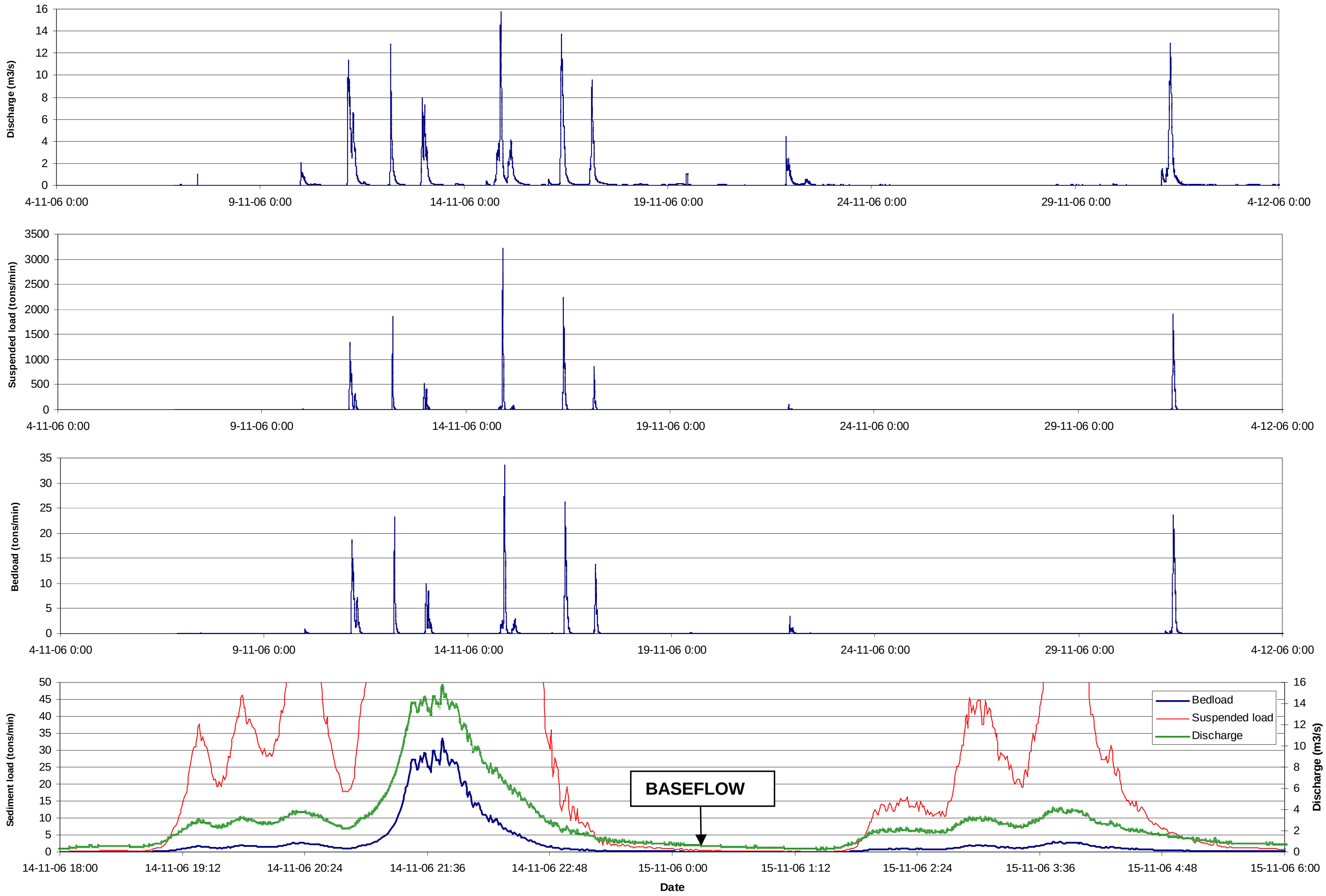


Figure 4-17: *Responses of bedload, suspended load and discharge during field period*

From the relation between sediment discharge and flow discharge in the Kiindu river an estimation of the total sediment discharge in the Kiindu catchment for the fieldwork period from 20 October 2006 – 15 December 2006 is made. This estimation is for bedload and suspended load separate, as bedload is assumed to be more or less relocated within the catchment and suspended load is transported out of the catchment area. Based on an Arc Map calculation the total catchment area behind the measuring point is fixed at 13.1 km^2. In Table 4-4 the results for this estimation are given. Besides the total sediment load also the mean median grain sizes for the sediments are given. For a total overview of the grain sizes per sample, including standard deviation and mean is referred to Appendix 11.

Table 4-4: *Sediment characteristics for suspended and bedload between 20 October – 15 December 2006*

	Total sediment load (kg)	Catchment area (km^2)	Grain size (μm) (D50)	Estimated erosion (kg/ha)
Bedload (**)	9.000.000	13,1	557	7.000
Suspended load	516.000.000	13,1	31	394.000

(**) Bedload grain sizes do not contain smaller particles (<0.2 mm) as they are passed through the sampling bag

4.3 Soil samples

4.3.1 Kiindu Catchment

In the Kiindu catchment soils and sediments from surface soils are sampled over the total area. The locations of the samples are given in Appendix 4. At first there is a clear difference in composition of the East riverbanks and the West riverbanks of the Kiindu river. A distinction is made between riverbanks upstream and downstream of the large stream divide. The results are given in Table 4-5.

Table 4-5: *Grain sizes of surface soils of riverbanks and riverbed in the Kiindu catchment. The standard deviation is given between brackets.*

	Number of samples	East riverbank (μm)		West riverbank (μm)		Riverbed (μm)	
Upstream East river	18	241	[132]	259	[212]	622	[133]
Upstream West river	17	187	[98]	244	[113]	592	[116]
Downstream	19	173	[110]	373	[79]	567	[92]
Total catchment	54	201	[112]	293	[161]	587	[110]

As median grain size increases downstream for the West riverbanks, the East riverbanks show opposite results and decreases downstream. As coarser grained material is located on the West riverbanks, most coarse sediments found in the Kiindu riverbed are expected to originate from the West banks. Besides this a higher infiltration rate can also be expected, increasing the baseflow component of the river. The riverbed shows a slight decrease in grain size moving downstream. From the runoff plots an estimation can be made of the different types of sediments coming from various soil and slopes. The locations of the plots are given in Appendix 4. One plot (RP 4) is located on the Western bank and three are located on the Eastern bank (RP 1-3). From runoff plot 2 two surface samples were taken because variability could be observed. A larger vegetation density was also observed on this plot so that interception of precipitation might negatively influence erosion. In Table 4-6 the soil characteristics are compared to those of sediments in the plot gutter.

Table 4-6: *Grain size analysis of runoff plot sediments and surface soils*

	Surface *D10 (µm)*	**Surface** *D50 (µm)*	**Surface** *D80 (µm)*	**Sediment** *D10 (µm)*	**Sediment** *D50 (µm)*	**Sediment** *D80 (µm)*	**Slope** *(º)*
RP 1	30	410	620	128	691	1034	4,1
RP 2	21	444	673	22	314	644	9,1
RP 2	93	267	441				
RP 3	11	171	380	*No sediment*	*No sediment*	*No sediment*	2,7
RP 4	13	244	430	4	133	535	4,6

Sediments in the gutter of runoff plot 1 are comparable with those found in the riverbed, making this soil layer suitable for the supply of coarse sediments towards the riverbed. Other runoff plots appear to be less suitable. Sediments form RP 2 show a wider range indicating that both fine grained and coarse grained sediments origin from the soil type. Especially plots 3 and 4 only generate finer sediments. Both runoff plots were located at agricultural lands and were ploughed for cultivation. At runoff plot 3 sediments could not be found in the gutter. As the barrel, connected to the gutter, contained turbid water it is assumed that sediments were too small to settle in the gutter. All soils on the runoff plots, apart from runoff plot 3, are able to supply coarse grained material. However, there is a large difference in the amounts of coarse sediments available. Runoff plot 1 generates large amounts of coarse material > 0,5 mm. The amounts of coarse grained material generated from plot 2 and 4 are considerably smaller. For example 80% of the sediment sample of RP 2 is smaller than 644 µm, compared to 1034 µm for RP 1. The amount of coarse grained sediments supplied by soils on the riverbanks is dependent on the (median) grain size of the soil surface. The higher the (median) grain sizes the higher the probability of coarse sediment generation. Slope might influence this, however this could not be observed from the results.

5 DISCUSSION AND RECOMMENDATIONS

5.1 Up-scaling

For up-scaling of the sand storage dam principle to a larger area, criteria are used that appeared to be important, as observed during field visits/measurements and reports for the Kitui District. The Kitui District has relatively distinct properties which are somehow equal distributed over the total district. Especially for the geology this is an important issue. Nearly the total study area, as indicated in Paragraph 2.2.3, is covered by rocks of Precambrian age, overlain by Quaternary and Tertiary deposits. A good distinction between suitable geology and not suitable geology could not be made based upon the availability of coarse grained material in the riverbeds for the study area. ASTER images and field observations were available for the study area and no other areas could be researched based upon the written methodology in this report. When applying the methodology to a larger area, for example the total size of Kenya, many ASTER images from equal time periods should be combined to one large image. As different ASTER images have different digital numbers for equal features, the digital numbers for all images combined should be converted into radiance. A conversion method is given at staff.aist.go.jp/s.tsuchida/aster/cal/info/equation/index.html. Given the size of one ASTER image of approximately 60x60 km at least 162 images are needed to cover Kenya. Also cloud coverage of different images will make that manual adjustment for each image is needed. Applying the methodology to a large scaled study area will therefore dramatically increase calculation time. The methodology as given in this report is therefore most suitable at smaller scale, i.e. within a single ASTER image.

Sandy riverbeds can be identified from other riverbeds, based on difference in reflectance. The spatial resolution (15 meter) of the ASTER images however appears to be too low for identification of smaller sand filled riverbeds, which are also extensively used for the construction of sand storage dams in the Kitui District. For smaller rivers a pixel represents a mixture of the spectral response of the riverbed and the riverbanks. In the Kiindu case this means a decrease in pixel value for the sandy riverbeds as coverage of the riverbanks (like vegetation and soils) show a lower reflectance, resulting in a lower pixel value. Satellite images with a higher spatial resolution (for example SPOT or IKONOS) will give a more detailed identification of sandy riverbeds and are therefore recommended for further usage of this methodology, based on an area similar to the Kitui District. A disadvantage however is that the costs of these images are considerably higher than that of ASTER images. One should also consider that this methodology is less efficient in areas where riverbanks and sandy riverbeds have comparable spectral properties. Field visits to potential dam sites will always be necessary to verify the conclusions drawn from satellite images.

In Qui *et al.* (2005) the mapping of geology, including sand areas, of an arid area in Africa is described, using ASTER images. The paper describes different analysis methods for an optimal characterization of different geological features, including a maximum likelihood classifier. Three other analysis procedures, spectral angle mapper, spectral feature fitting and linear spectral unmixing, result in better classification accuracies than maximum likelihood classification. Using a different classification method might also improve the classification of sandy riverbeds.

Low sloping areas appear to be less suitable for the construction of sand storage dams. This can be explained by the lower energy that is available for the transport of coarse sediments. These rivers are identified based on the difference in spectral reflectance compared to rivers with working sand storage dams. No field visits however have been taken on to verify the statement of a low probability area. Visiting the low probability areas and sampling the riverbeds might give more insight in the processes.

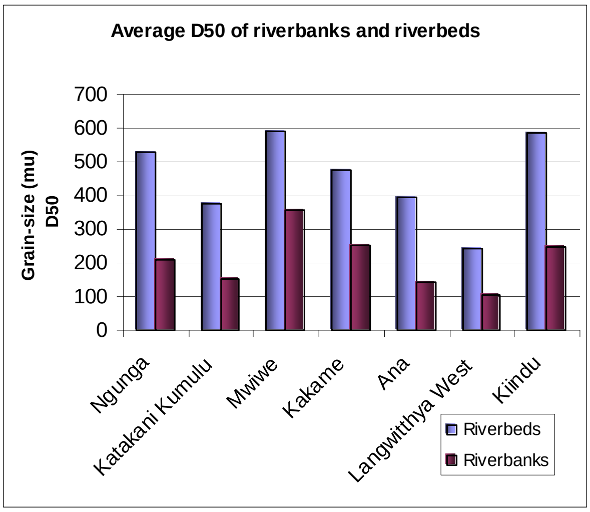
5.2 Sediments

Discharge in the Kiindu river during the field period varied from 0 m^3/s to 15.7 m^3/s. This last extreme event results in a suspended sediment discharge of 3.000.000 kg/min and a bedload discharge of 33.000 kg/min, indicating that extreme events are particularly important for the total sediment yield. For these high values of flow discharge no field measurements are available which make them less reliable. The total sediment yield is therefore an approximation.

For suspended load the total sediment yield indicates that approximately 394.000 kg/ha has eroded from the river banks during the field period, upstream of the measuring point. This is a very large amount. Assuming that the total catchment area would be covered by clayey/silty material with a density of say 1800 kg/m^3, the total catchment area would suffer from 2 cm land degradation, solely from detached sediments that moved into suspension. This number even increases when also coarse grained material is taken into account. Moore (1979) refers to erosion rates of 10 mm/year in the Machakos Hills, located close to the fieldwork area. This indicates that very high rates of erosion occur in the study area. However, it also indicates that the erosion rate in the Kiindu Catchment is probably overestimated, referring to the smaller time-scale in which the measurements took place. Another writer, Lal (1985) discusses observed erosion rates in Africa. Rates of over 1,800 ton/km^2 per year are observed in several location in Central Africa. These rates, however are considerably lower than the rates obtained from the linear regression equation. For this reason the results of the linear regression in the Kiindu river (or streams in semi-arid regions) might be less reliable for larger discharges and total sediment discharge is assumed to be overestimated. A power function relation is probably not the best fit for regions with highly erratic patterns of discharge and precipitation. The slope of the regression curve, as obtained in Figure 4-14, will not be a straight line but will eventually flatten when discharge reaches extreme values. Also an overestimation due to hysteresis might be expected (Alexandov *et al*., 2002). More samples during extreme events can result in better estimates. As the river discharge increased very fast (from 1 – 12,9 m^3/s in 82 minutes) and extreme events mainly take place during the night, an automated station is advisable. Very important however is the location of such an automated station. As the river contains large amounts of (wooden) debris and bushes there is a risk of clogging of, and possible damage to the device.

5.2.1 Catchment comparison

Grain size analysis is done for all sediment samples taken in the Kiindu catchment and catchments spread over the Kitui District visited during the fieldwork. For each sediment sample a median grain size (D50) is calculated that is used to distinguish the differences in grain size at catchment scale and regional scale. For each visited dam riverbanks and riverbed are sampled. To obtain an easier relation between the field visit sites, the median grain size for riverbanks and riverbeds is averaged for each catchment area. When only one dam could be visited in a catchment area the samples are assumed to represent the total catchment area. For each visited site also the percentage of the sample < 500 µm is calculated. A grain size of 500 µm is the minimum grain size needed for sufficient water extraction according to Nissen-Petersen (1997). In Figure 5-1 the result of the catchment comparison is given.



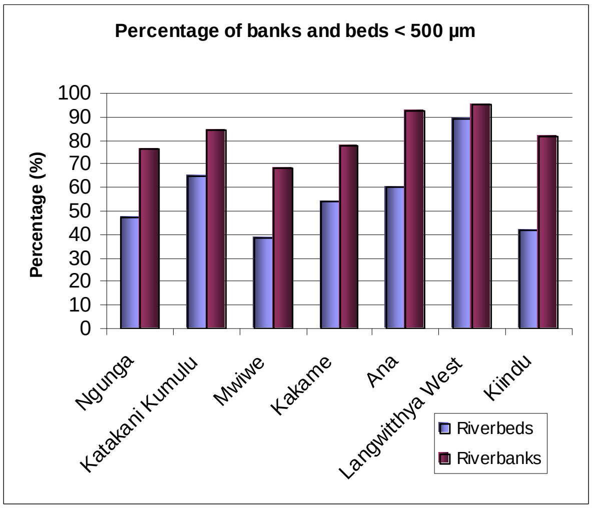


Figure 5-1: *Grain size comparison of riverbeds and riverbanks at field visit sites*

From the figure a difference in grain size from the riverbeds and riverbanks can be noticed. Riverbanks in all catchments have a considerable smaller grain size than the sediments that can be found in the riverbed. This is also an indication that fine grained material, eroded from the riverbanks, for all catchment areas are partially washed away during floods. However, there is a correlation between the sediments available on the riverbeds and on the riverbanks. The smaller the median grain size of the soils on the riverbanks the smaller the median grain size of the sediments in the riverbed. Catchment areas like Kiindu, Ngunga, Kakame and Mwiwe have averaged median grain sizes that are higher than that of the remaining catchment areas for both riverbanks and riverbeds. Riverbanks at the Langwitthya West location show the smallest median grain size, both for riverbanks as riverbeds. More than 90% of the samples of both riverbanks and riverbeds are smaller than 500 µm, indicating that nearly no suitable sediments for the application of a successful sand storage dam are available. The characteristics as found in the Langwitthya West location are however very local and can not be observed by soil- or geological maps. At the Kiindu and Ngunga catchment there is a large difference between the grain size of riverbanks and riverbeds. For both catchments a large amount of coarse sediments is available in the riverbed. Sand storage dams at the Ngunga river, however, fill up in one single event and the sand storage dams at the Kiindu river fill up in approximately 7 years (Borst and de Haas (2006)). As this cannot be explained by the difference in grain size various site characteristics, important for the functioning of sand storage dams, are listed in Table 5-1.

Table 5-1: *Site characteristics*

Sand storage dam site	Area (*km²*)	D50 Beds (*µm*)	D50 Banks (*µm*)	Slope (*º*)	P-intensity (*mm/day*)	Efficiency	Remarks
Kiindu Catchment	13,15	691	243	2,3	7,5	++	-
Kakame River upstream	1,32	449	250	3,9	7,8	++	-
Kakame River downstream	1,93	508	250	3,9	7,8	++	-
Katakani Kumulu	0,27	378	151	3,1	7,5	- -	Very limited amount of coarse sand
Langwiatthya West upstream	0,25	207	103	2,6	7,2	- -	No coarse sand observed
Langwiatthya West downstream	0,76	278	103	2,6	7,2	- -	No coarse sand observed
Ana Catchment downstream	6,37	442	142	2,3	7,2	+/-	Dam not completely filled, but coarse sand
Ana Catchment upstream	0,49	436	142	2,6	7,2	-	Silt layer under coarse sand
Ana Catchment upstream	0,96	437	142	2,6	7,2	-	Silt layer under coarse sand
Mwiwe upstream	3,51	622	355	3,1	7,5	++	-
Mwiwe downstream	63,81	559	355	2,2	7,7	++	-
Ngunga River	67,84	530	211	3,2	8,3	++	-

Field visit sites with a lower efficiency are indicated in red, those sites with a high efficiency are indicated in green. Catchment areas are calculated with ArcMap, based upon SRTM drainage areas. Efficiencies are based upon information obtained in the field as described in Chapter 2.3. The drainage area of the Kiindu catchment is substantially smaller than that of the Ngunga catchment. A difference in slope and rainfall intensity can also be noticed; respectively steeper and more intense for the Ngunga catchment. Slopes larger than 3° appear to result in a higher sedimentation speed. As rainfall intensity increases combined with a steeper slope, a higher flow velocity can be expected. A higher flow velocity results in a larger transport capacity (Kinell, course presentation, undated) so that sedimentation behind sand storage dams in the Ngunga catchment is expected to go faster than in the Kiindu catchment. The contributing area appears to be of less importance to the sedimentation speed when coarse material is widely available on the riverbanks. A smaller drainage area of the Kakame river, with relatively steep slopes and high rainfall intensities, also results in a single event fill of the sand storage dam.

Sand storage dams with a relatively small contributing drainage area appear to have less chance of success in the study area. Also an effect of grain size of the riverbanks can be noticed. Especially small contributing areas combined with finer grained riverbank material have a high probability of silt accumulation behind obstructions in the riverbeds. Slightly coarser material in the riverbanks, as for example at the Katakani Kumulu dam and the Ana catchment, make that some of this material detaches and is transported towards the dam, though in small amounts. When only limited amount of coarse material is available on the riverbanks no coarse sediments could be found in the river bed (Langwiatthya West). The Ana catchment and the Katakani Kumulu dam both show silt accumulation previous to sand accumulation and have a small contributing area. Runoff therefore is limited and next to it the flow velocity is restricted by the sand storage dam. Restriction of the flow velocity increases upstream with the height and size of the dam. While the velocity of the water is reduced, less energy is available for transport. Coarse sediments will take long to reach the dam as fine sediments are more easily transported towards the dam (see also Figure 2-4). Fine material will keep settling behind the sand storage dam until the flow velocity restriction is limited, as the height of the dam to the surface level of the riverbed decreases due to silt accumulation. When flow velocity restriction is limited, coarse sediment will be more easily transported towards the dam and will eventually fill the remaining volume. The amount of silt accumulation behind sand storage dams in the study area is in many ways dependent on the availability of coarse sediments and the size of the catchment.

Catchment size is in more ways important as runoff efficiency decreases with increasing catchment size (Critchley *et al.* 1991). A very small amount of flow is needed to transport fine particles, as can be seen from Figure 2-4. In alluvial channels the sediment flow is usual in or near capacity (saturation) condition, implying that the flow is saturated with the sediments available from the riverbanks and in the riverbed (Cellino and Graf (1999)). This mainly occurs when the flow is controlled by surface runoff. During a low rate of discharge (approximately 0 - 2 m^3/s for the Kiindu river) at the falling limb, flow is mainly controlled by base flow, containing considerably less suspended material than when controlled by surface runoff. This means that there is excess energy that can be used the uptake of sediments. As the flow contains a relatively small amount of suspended sediments a larger part of the capacity is available for transport. While small amounts of coarse grained material are still being relocated in the riverbed, finer particles that have settled in the riverbed in pools or behind obstructions are detached by settling of the coarser material and flow turbulences (caused by the dam and obstructions in the riverbed) and retaken into suspension. Most of the finer grained material will be transported downstream, leaving the coarser and heavier material in the riverbed. As baseflow at smaller catchment areas is limited (runoff efficiency decreases with increasing catchment size) the accumulated suspended sediments are not, or less, mixed and washed away with the flood, causing the dam to be filled with fine grained material.

5.2.2 Summarized sedimentation processes behind a sand storage dam

The processes of sediment transport and deposition behind a sand storage dam are schematized in Figure 5-2.

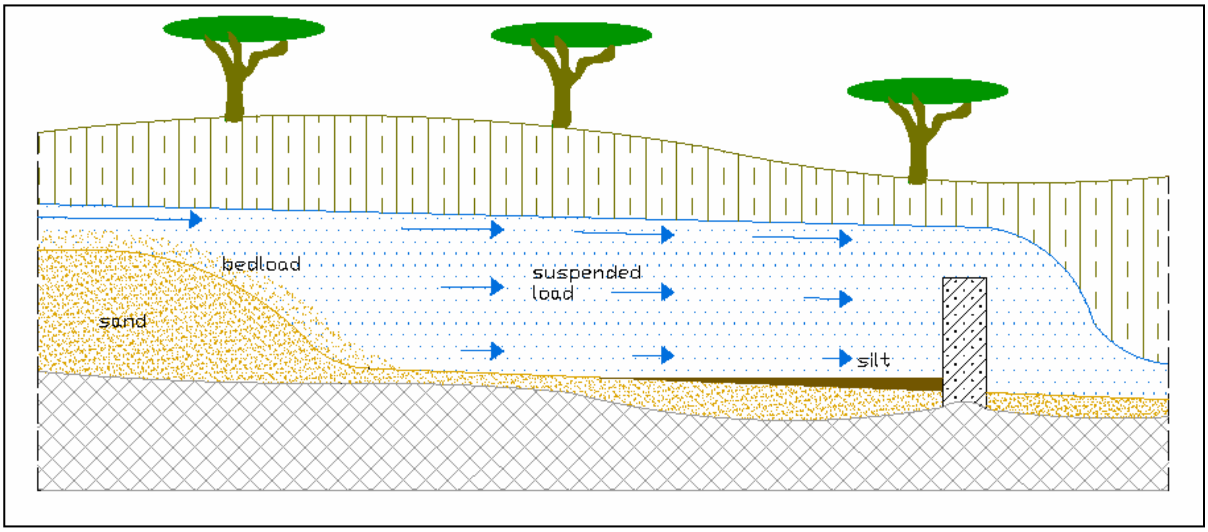


Figure 5-2: *Sedimentation processes behind a sand storage dam during discharge*

Coarse grained sediments (sand) in the riverbed are accumulating far from the dam where the flow velocity is already restricted by the dam, eventually forming a ridge. As flow velocity behind the ridge is higher, more energy is available for transportation of sediments. At the ridge a drop in flow velocity occurs causing the coarser sediments to settle. This process can be compared to a delta. The ridge of sand moves towards the dam as more and more coarse sediments settle during discharge events, eventually filling the total volume behind the dam. The duration of this process is highly dependent on the availability of coarse sediments, the size of the dam and runoff characteristics. The larger the dam, the higher the velocity restriction and the longer it will take for the ridge to reach the dam. Besides a higher velocity restriction a larger volume has to be filled. Especially at upstream locations where less water from runoff and less coarse sediments are available (due to a smaller contributing area) sedimentation behind the dam will take longer.

During discharge the streams in the Kitui District contain large amounts of suspended material. These finer sediments have a lower settling velocity than coarse material and are therefore transported directly towards a dam or obstruction. When the flow velocity near the dam is decreased dramatically also the fine sediments can accumulate, forming a silt layer behind the dam. The suspended sediments however take several hours to settle in stagnant water. When settled they form a very loose layer that can be easily disrupted and retaken into suspension. In Table 5-2 the grain size distribution of the suspended material is given. As the variation of grain sizes during different stages of flow appears to be minimal, the duration of the settling process behind the sand storage dam will be comparable for most stages.

Table 5-2: *Grainsize distribution of suspended load samples*

Sample nr.	Discharge	D10	D30	D50	D80	Mean (mu)	MSD (mu)
S1	0,25	1	3	8	26	8	237
S2	0,17	1	4	10	30	9	238
S4	0,10	1	5	18	136	18	132
S5	0,13	1	5	17	93	15	153
S6	0,51	1	5	13	41	12	219
S7	0,12	3	32	121	253	63	162
	Mean size	*1*	*9*	*31*	*96*		

Extreme events however might give different conceptions. Water behind the dam is never fully stagnant during discharge of the river due to turbulences caused by overflowing of the dam. Most fine grained sediments will therefore stay in suspension and will be transported over the dam. Only a relatively small part will accumulate behind the dam. When baseflow dominates river discharge at the end of a storm event, so called “hungry water” flows through the riverbed. As filtered by the soil this water has an excess energy that is typically expended on erosion of the channel (Matthias Kondolf (1997)). Fine sediments will be (re)taken into suspension and transported out of the catchment, leaving the coarser grained material in the riverbed. The coarser sediments will not be transported because of the lower flow velocity during baseflow controlled runoff.

In Figure 5-3 an example is given of the magnitudes of flow velocity and velocity vectors of an overflowing obstruction during laminar flow in a uniform riverbed (Rasipuran, course presentation). The velocity of the water at the inflow was fixed at 0,5 m/s. The 2D-model was created in Fluent 5.4. Roughness of the riverbed as well as air friction are not taken into account. The conditions are not an exact representation of the conditions found in the study area, but give an indication of what processes might occur when flow passes an obstruction, like a concrete sand storage dam, in the riverbed. The simulation is based on a small scaled obstruction in combination with a low-density fluid (lower than water).

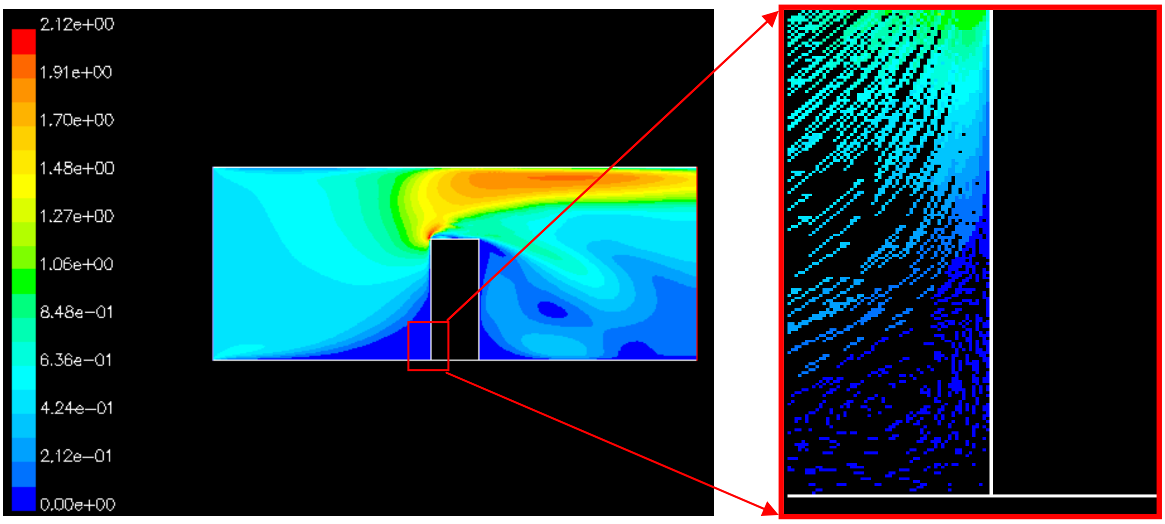


Figure 5-3: *Flow characteristics near a stream obstruction. The flow velocity (m/s) is given on the left and velocity vectors in front of the obstruction on the right.*

Figure 5-3 shows that flow velocity near the dam decreases substantial at the dam bottom. An increase in velocity can be noticed at the top of the dam. Turbulences can be found both upstream and downstream from the dam. The turbulences near the bottom of the dam indicate that the water kept by the dam is never fully stagnant, when the dam is overflowing. The velocity however is very small and not sufficient to transport coarse sediments. The turbulences prevent settling of (most of) the suspended load to the riverbed and keep the fine grained material in suspension. Because the velocity vectors near the dam are rather small some of the fine material will settle, creating a small silt layer behind the dam. When surface runoff is controlled by baseflow, most of this material will be retaken into suspension, as mentioned earlier.

In upstream catchment areas it is therefore recommended that sand dams are built in stages. As in most known cases of siltation the contributing areas are too small for sufficient baseflow generation and amounts of runoff are relatively small fine sediments will easily settle behind a large obstruction. Creating smaller stages gives a smaller velocity restriction leaving only a small silt layer behind the dam. When small enough, this layer will be washed away by the next flood. This process continues until the sand layer has reached the first stage of the dam. For the next stage the same process repeats until, after several stages, the complete dam is filled with sand. To define an optimal height of each stage more research is needed. The height is in many ways dependent on the amount of runoff.

When dams are built in one piece in more downstream areas it is important that baseflow is sufficient. Increasing infiltration on the riverbanks will be beneficial to both storage (Hoogmoed, 2007) when the dam is filled and the sedimentation process during filling. Increasing infiltration can be for example performed by creating terraces on the riverbanks and ploughing.

6 CONCLUSIONS

Field visits pointed out that the availability of coarse material in the riverbed is an important indication that a catchment area is suitable for the construction of sand storage dams. Satellite images can be used to identify sandy riverbeds, based upon its difference in spectral reflectance. Combining the locations of sandy riverbeds with local environmental data like slope, geology and precipitation(intensity), criteria can be obtained for suitable and non-suitable areas.

Most critical in the Kitui District appears to be the slope of the area. Catchment areas with an average slope smaller or equal to approximately 2° show large similarity with non-sandy riverbeds. Runoff generated in these catchment areas appears to be too low for transport of coarse grained material. Geological features in these areas are varying from Holocene (Qe) to Precambrian (pC) and Tertiary igneous rocks (Ti). Similarity can be found between the Holocene feature and low sloping areas. The Holocene areas therefore have a lower probability of successful application of sand storage dams. The Tertiary igneous rocks and the rocks of Precambrian age appear to be sufficient in generating coarse grained material that can be transported towards the riverbeds.

No relation could be obtained for precipitation(intensity) compared to sandy riverbeds and non-sandy riverbeds in the study area. As intensity increases towards the South-East of the study area a decrease in precipitation amounts towards the South-East can be noticed. Quantities and intensities in the Kitui District however appear to be sufficient for the application of sand storage dams as working sand storage dams are located both high- and low precipitation(intensity) areas.

For the study area above criteria result in a probability map with high- and low probability areas for successful application of sand storage dams. This map is given in Figure 6-1.

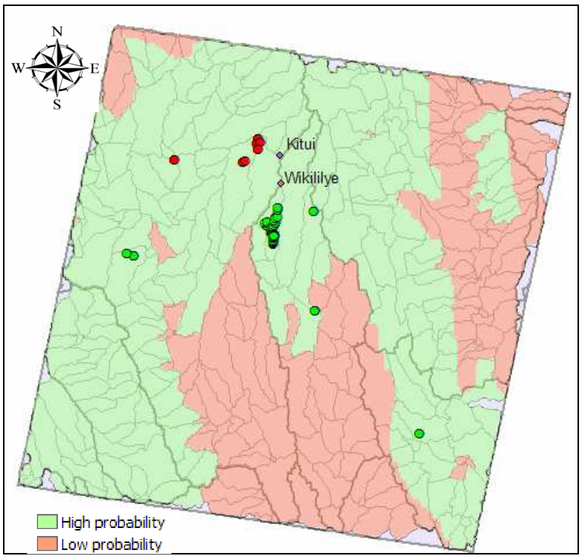


Figure 6-1: *Probability map for successful application of sand storage dams*

To obtain more detailed information about the sedimentation processes measurements of suspended load and bedload are carried out in the Kiindu catchment. Bedload movement during the field period varied from 0 – ~34 tons/min during an extreme event. A good relation for low discharges could be obtained for the first stage of suspended load transport compared to discharge. Suspended load varied from 0 – ~3500 tons/min. At extreme discharges the linear regression relation for both suspended load and bedload gives an overestimation. Realistic values for extreme discharges will therefore somehow lower than calculated.

Suspended load is mainly transported during the rising limb. During the falling limb, when surface runoff is more controlled by baseflow, only a limited amount of suspended load is transported by the flowing river. This baseflow controlled runoff has an excess energy that is used for the uptake of sediments in the riverbed. In case of a filling sand storage dam, this water is responsible for transporting the fine grained material that has settled behind the dam. Catchment areas in which baseflow is limited have a higher risk of silt accumulation behind obstructions like sand storage dams. For upstream catchment areas it is therefore advisable to build the dams in different stages. For downstream areas with sufficient (base)flow and coarse sediment supply a single stage dam will be sufficient.

Grain size analysis throughout the study area pointed out the importance of the material on the riverbanks. There is large correspondence between the grainsize on riverbanks and riverbeds in different field visit areas. A smaller median grainsize on the riverbanks result in a relatively smaller median grainsize in the riverbed. One can conclude that coarse grained material is not mainly detached from deep into the weathered hardrock incised erosion gullies, but comes mainly from the riverbank surface.

Sedimentation speed is mainly dependent on slope and rainfall intensity. When increased this results in a higher flow velocity in the riverbed. With a higher flow velocity more and larger sediments will be transported, resulting in a higher sedimentation speed. This statement is based upon a sufficient availability of coarse sediments in the area.

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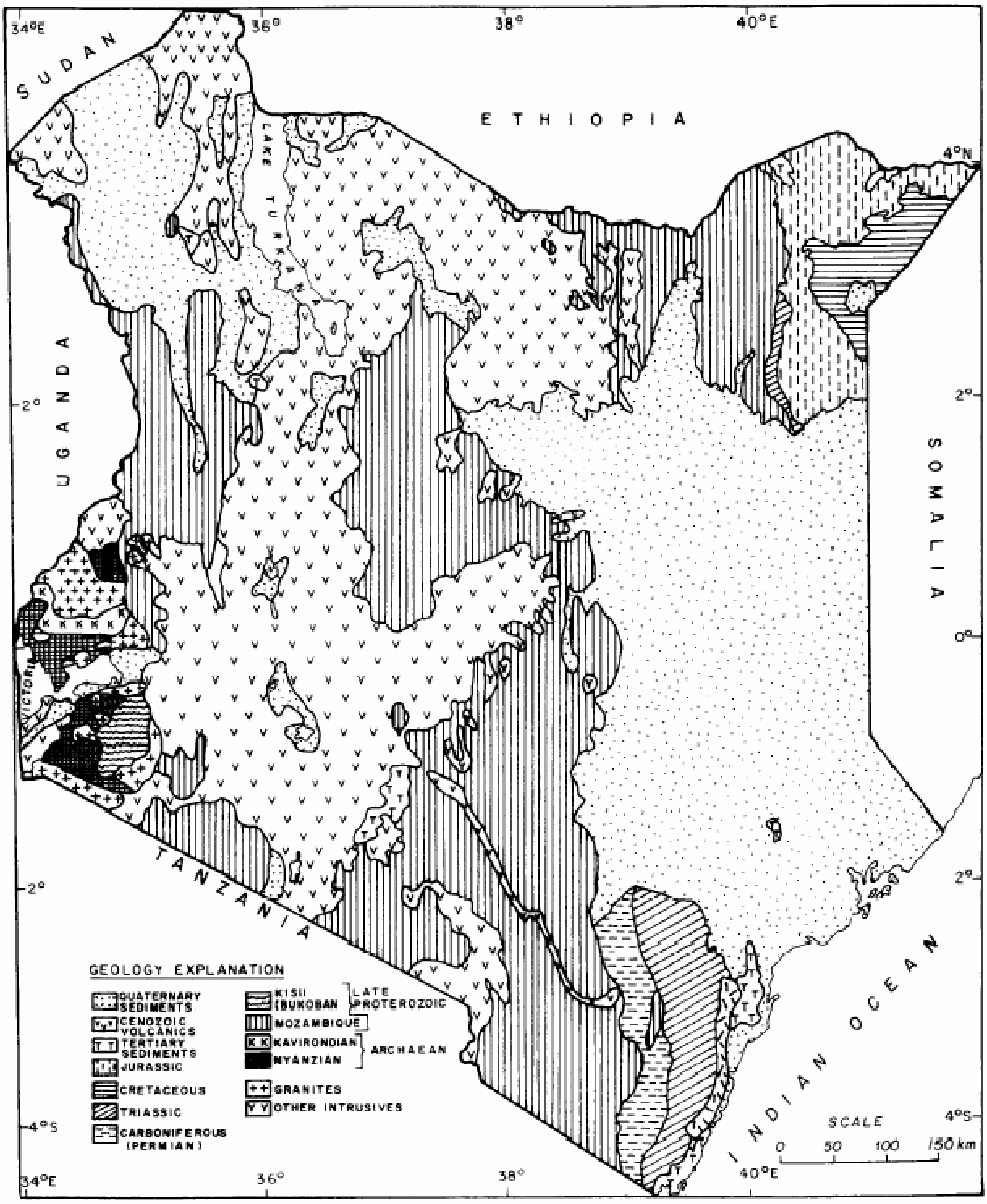
APPENDICES

APPENDIX I

Geological map of Kenya


34°E
36°
38°
40°E
SUDAN
ETHIOPIA
LAKE TURKANA
UGANDA
SOMALIA
4°N
2°
0°
2°
4°S
VICTORIA
TANZANIA
INDIAN OCEAN
GEOLOGY EXPLANATION
QUATERNARY SEDIMENTS
CENOZOIC VOLCANICS
TERTIARY SEDIMENTS
JURASSIC
CRETACEOUS
TRIASSIC
CARBONIFEROUS (PERMIAN)
KISII (BUKOBAN
LATE PROTEROZOIC
MOZAMBIQUE
KAVIRONDIAN
NYANZIAN
ARCHAEAN
GRANITES
OTHER INTRUSIVES
SCALE
0 50 100 150 km

APPENDIX II

Shields Diagram

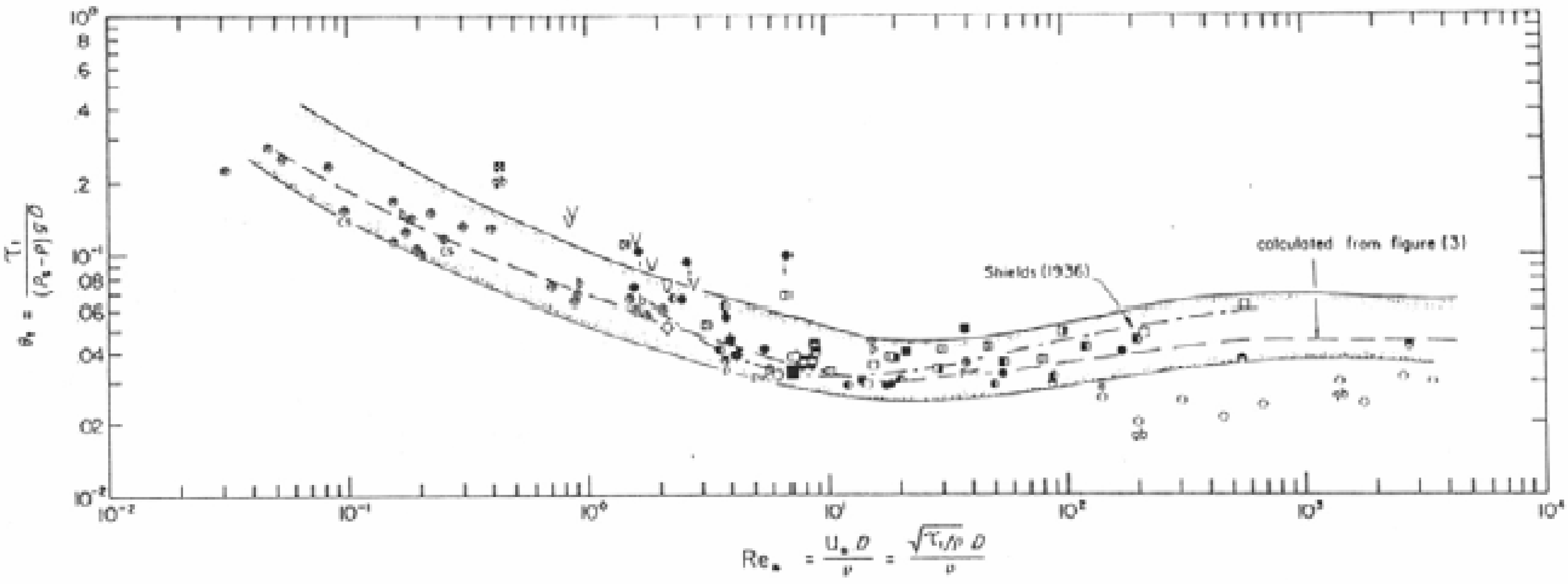


Figure 1: *Modified Shields Diagram (1977)*

APPENDIX III

Overview of sediment samples

NR	WayPoint	Location	S	E	Northing	Easting	Date	Foto NR	Depth	GRAIN SIZE D50	Remarks
040	D001	Broken dam, sample of river sediment	1,47092	38,00323	-1,47092	38,00323	24-okt	4965	surface	555	none
041	T001	Tributary near broken dam	1,47048	38,00329	-1,47048	38,00329	24-okt	4966	surface	498	none
042	T002	Tributary, sample of surface sediment	1,46864	38,00271	-1,46864	38,00271	24-okt	4967	surface	119	none
043	T003	Tributary, sample of surface sediment	1,46825	38,00241	-1,46825	38,00241	24-okt	4968/1364	surface	447	none
044	T003	Next to tributary West bank of river	1,46825	38,00241	-1,46825	38,00241	24-okt	4968/1364	bank	284	none
045	R010	Sample of East bank of river	1,46722	38,00283	-1,46722	38,00283	24-okt	1368/1367	bank	311	none
046	D002	Sample of East bank of river	1,46670	38,00318	-1,46670	38,00318	24-okt	1372	bank	24	none
047	D002	Sample of riverbed	1,46670	38,00318	-1,46670	38,00318	24-okt	1371	surface	436	none
048	D002	Small tributary on East bank near dam	1,46670	38,00318	-1,46670	38,00318	24-okt	1368/1367	surface	396	Red soil, few trees
049	T005	Tributary, sample of surface sediment	1,46508	38,00331	-1,46508	38,00331	24-okt	4971	surface	225	none
050	T006	Tributary, sample of surface sediment	1,46332	38,00361	-1,46332	38,00361	24-okt	4974	surface	546	none
051	R017	Sample of crust in riverbed	1,46326	38,00341	-1,46326	38,00341	24-okt	none	surface	168	none
052	R017	Sample of sand just deposited from T006	1,46326	38,00341	-1,46326	38,00341	24-okt	4974	surface	673	none
053	T007	Tributary, sample of surface sediment	1,46283	38,00341	-1,46283	38,00341	24-okt	none	surface	359	none
054		Sample of gutter sediment from RP 1	1,46274	38,00467	-1,46274	38,00467	25-okt		surface	440	Cement in sample
055	WP001	Sample of riverbed behind dam 3	1,46148	38,00389	-1,46148	38,00389	26-okt		surface	691	none
056	WP003	Tributary to Christina sediment in river	1,46055	38,00368	-1,46055	38,00368	26-okt		surface	159	none
057	WP007	Tributary East sediment	1,45998	38,00412	-1,45998	38,00412	26-okt	1391/1392	surface	435	none
058	WP011	Tributary East Sediment	1,45872	38,00235	-1,45872	38,00235	26-okt	1397/4981	surface	508	none
059	WP011	Riverbank on East side	1,45872	38,00235	-1,45872	38,00235	26-okt	1397/4981	surface	111	none
060	WP016	Riverbank on East side	1,45785	38,00160	-1,45785	38,00160	26-okt	1395	surface	123	none
061	WP019	Riverbank on East side	1,45725	38,00123	-1,45725	38,00123	26-okt	1399	surface	183	none
062	WP019	Riverbank on West side	1,45725	38,00123	-1,45725	38,00123	26-okt	1400	surface	375	none
063	WP021	Tributary West sediment	1,45705	38,00060	-1,45705	38,00060	26-okt	1398/4989	surface	758	none
064	WP023	Sediment behind dam 4 riverbed	1,45665	38,00079	-1,45665	38,00079	26-okt	1403/1401	surface	478	none
065	WP023	Riverbank on West side	1,45665	38,00079	-1,45665	38,00079	26-okt	1403/1401	surface	462	none
066	WP028	Tributary East upstream dam 4	1,45555	38,00029	-1,45555	38,00029	26-okt	4999	surface	588	none
067	WP031	Sediment behind dam 5	1,45557	38,00053	-1,45557	38,00053	26-okt	-	surface	505	none
068	WP034	Riverbank on West side	1,45477	38,00080	-1,45477	38,00080	26-okt	1407	surface	440	none
069	WP034	Riverbank on East side	1,45477	38,00080	-1,45477	38,00080	26-okt	1407	surface	287	none
070	WP036	Riverbank on West side	1,45341	38,00078	-1,45341	38,00078	26-okt	1411	surface	304	none
071	WP036	Riverbank on East side	1,45341	38,00078	-1,45341	38,00078	26-okt	1413	surface	257	none
072	WP039	Riverbed sample of West side of River Divide	1,45253	38,00080	-1,45253	38,00080	26-okt	1417	surface	575	Large divide of 2 main tributaries, sample taken in west river
073	WP040	Riverbed sample of East side of River Divide	1,45242	38,00129	-1,45242	38,00129	26-okt	1415	surface	630	Large divide of 2 main tributaries, sample taken in east river
074	WP041	Crust sample of East side of Rover Divide	1,45245	38,00107	-1,45245	38,00107	26-okt	1416	surface	360	Crust local
075	WP044	Sediment behind dam 6	1,45142	37,99972	-1,45142	37,99972	26-okt	-	surface	726	none
076	WP048	Riverbank on East side	1,45054	37,99894	-1,45054	37,99894	26-okt	-	surface	35	Part one of strain
077	WP049	Riverbank/bed on East side Flat part	1,45058	37,99884	-1,45058	37,99884	26-okt	-	surface	156	Flat part of more silty material directly next to riverbed (Part 2 of strain)
078	WP047	Riverbed sediment sample	1,45057	37,99878	-1,45057	37,99878	26-okt	-	surface	654	Part 3 of strain
079	WP050	Riverbank on West side	1,45075	37,99867	-1,45075	37,99867	26-okt	-	surface	403	Part 4 of strain
080	WP055	Slope next to gully	1,45065	37,99662	-1,45065	37,99662	26-okt	-	surface	68	Next to gully, loads of larger grainsized materials. Small material seems to be flushed away.
081	WP065	Tributary	1,44939	37,99707	-1,44939	37,99707	31-okt	5296	surface	620	none
082	WP064	Riverbed sample	1,44956	37,99703	-1,44956	37,99703	31-okt		surface	553	none
083	WP064	Riverbank west	1,44956	37,99703	-1,44956	37,99703	31-okt		surface	135	none
084	WP064	Riverbank east	1,44956	37,99703	-1,44956	37,99703	31-okt		surface	276	none
085	WP069	Riverbank east	1,44918	37,99607	-1,44918	37,99607	31-okt		surface	148	none
086	WP069	Riverbank west	1,44918	37,99607	-1,44918	37,99607	31-okt		surface	216	none
087	WP073	Riverbed behind dam	1,44831	37,99530	-1,44831	37,99530	31-okt		surface	463	none
088	WP074-080	Tributary	1,44839	37,99515	-1,44839	37,99515	31-okt		surface	685	none
089	WP086	Riverbed	1,44645	37,99552	-1,44645	37,99552	31-okt		surface	403	none
090	WP086	Riverbank west	1,44645	37,99552	-1,44645	37,99552	31-okt		surface	221	none
091	WP086	Riverbank east	1,44645	37,99552	-1,44645	37,99552	31-okt		surface	217	none
092	WP087	Riverbed on divide--> west river	1,44614	37,99535	-1,44614	37,99535	31-okt		surface	668	Divide of river in two tributaries
093	WP088	Riverbed on divide--> east river	1,44606	37,99553	-1,44606	37,99553	31-okt		surface	410	Divide of river in two tributaries
094	WP094	Sample of riverbed at last of river	1,44517	37,99354	-1,44517	37,99354	31-okt		surface	568	Sample taken AT divide. Two streams join, two types of sediment?
095	WP099	Riverbank west on east side of divide	1,44594	37,99550	-1,44594	37,99550	31-okt		surface	131	Strange looking green weathered rock

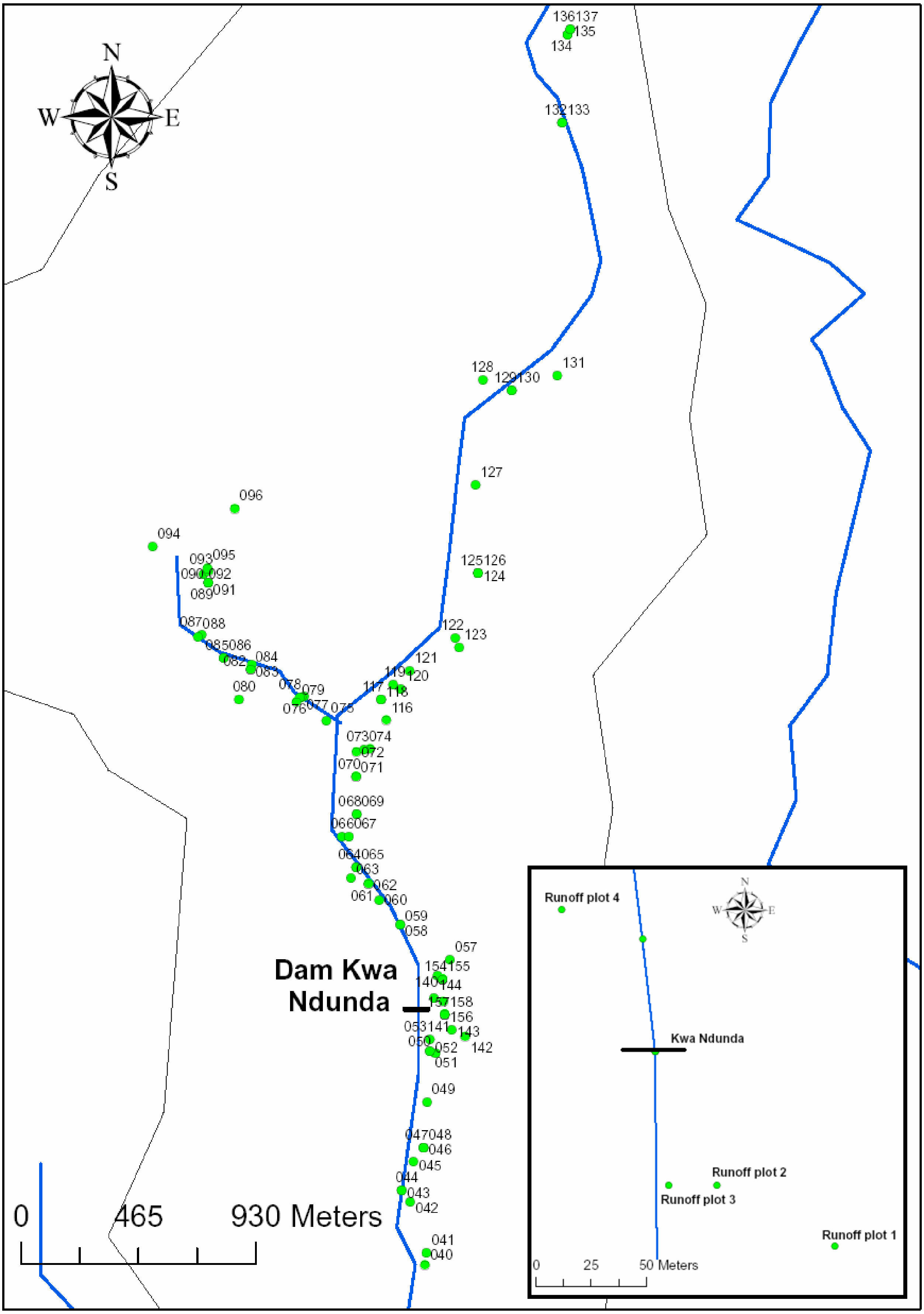
096	WP107	Riverbed	1,44381	37,99647	-1,44381	37,99647	31-okt		surface	699	none
097											
098			SAMPLES NOT TAKEN								
099											
100	WP116	Sand sediment behind dam most upstream (c	1,34344	37,98505	-1,34344	37,98505	1-nov	5538/5539	surface	437	Dam first filled with silt, only last 40 cm are sand
101	WP116	Silt sediment behind dam (40 cm till bedrock)	1,34344	37,98505	-1,34344	37,98505	1-nov	5538/5539	40	69	Dam first filled with silt, only last 40 cm are sand
102	WP116	Riverbank sample	1,34344	37,98505	-1,34344	37,98505	1-nov		surface	213	none
103	WP121	Sediment sample behind dam halfway catchm	1,37143	37,96666	-1,37143	37,96666	1-nov		surface	355	none
104	WP121	Sample over river bank	1,37143	37,96666	-1,37143	37,96666	1-nov		surface	132	none
105	WP126	Sediment sample behind dam halfway catchm	1,36987	37,96826	-1,36987	37,96826	1-nov		surface	442	none
106	WP126	Sample of riverbank	1,36987	37,96826	-1,36987	37,96826	1-nov		surface	81	none
107	WP128	Riverbed of river Mwiwe	1,43160	38,05211	-1,43160	38,05211	3-nov	IMG_0297	surface	622	River was flowing, upstream
108	WP128	Riverbank east (more sandy)	1,43160	38,05211	-1,43160	38,05211	3-nov	IMG_0295	surface	287	Riverbank east was more sandy than riverbank west
109	WP128	Riverbank west (more silty)	1,43160	38,05211	-1,43160	38,05211	3-nov	IMG_0296	surface	430	Silty (less infiltration)
110	WP131	Riverbed Ngunga river	1,70253	38,18161	-1,70253	38,18161	3-nov	IMG_318	surface	530	Flowing river
111	WP131	Riverbank Ngunga river West bank	1,70253	38,18161	-1,70253	38,18161	3-nov	IMG_318	surface	287	none
112-A	WP131	Riverbank Ngunga river east bank	1,70253	38,18161	-1,70253	38,18161	3-nov		surface	134	none
112-B	WP134	Riverbank East silt/sand	1,55249	38,05338	-1,55249	38,05338	3-nov	IMG_319	surface	107	Dam broken, downstream of WP128
113	WP134	Riverbank East more sandy layer in same bar	1,55249	38,05338	-1,55249	38,05338	3-nov	IMG_319	surface	595	Different layers in bank. More sandy layer
114	WP134	Riverbed depth 60 cm silty layer	1,55249	38,05338	-1,55249	38,05338	3-nov	IMG_320	60	139	Sample taken from scoophole in front of broken dam. First sand --> silty/clay
115	WP134	Riverbed depth 20 cm	1,55249	38,05338	-1,55249	38,05338	3-nov	IMG_320	20	559	Sand layer on top of silt layer
116	WP139	Riverbed	1,45139	38,00186	-1,45139	38,00186	6-nov		surface	443	East tributary of large divide
117	WP140	Riverbank east	1,45066	38,00168	-1,45066	38,00168	6-nov		surface	70	none
118	WP140	Riverbank west	1,45066	38,00168	-1,45066	38,00168	6-nov		surface	91	none
119	WP145/146	Tributary riverbed east	1,45013	38,00211	-1,45013	38,00211	6-nov		surface	274	none
120	WP147	Riverbank east in front of dam	1,45027	38,00238	-1,45027	38,00238	6-nov		surface	331	none
121	WP149	Riverbed behind dam	1,44963	38,00270	-1,44963	38,00270	6-nov		surface	501	none
122	WP154	Tributary east	1,44844	38,00433	-1,44844	38,00433	6-nov		surface	20	none
123	WP155	Riverbank tributary	1,44877	38,00445	-1,44877	38,00445	6-nov		surface	130	none
124	WP164	Riverbed	1,44613	38,00513	-1,44613	38,00513	6-nov		surface	581	none
125	WP164	Riverbank west	1,44613	38,00513	-1,44613	38,00513	6-nov		surface	284	none
126	WP164	Riverbank east	1,44613	38,00513	-1,44613	38,00513	6-nov		surface	246	none
127	WP169	Riverbed	1,44295	38,00504	-1,44295	38,00504	6-nov		surface	750	none
128	WP176	Riverbed	1,43919	38,00531	-1,43919	38,00531	6-nov		surface	709	none
129	WP178	Riverbank east	1,43958	38,00634	-1,43958	38,00634	6-nov		surface	212	none
130	WP178	Riverbank west	1,43958	38,00634	-1,43958	38,00634	6-nov		surface	179	none
131	WP184	Riverbank west	1,43903	38,00797	-1,43903	38,00797	6-nov		surface	247	none
132	WP204/205	Tributary	1,42999	38,00814	-1,42999	38,00814	6-nov		surface	749	none
133	WP204	Riverbed	1,42999	38,00814	-1,42999	38,00814	6-nov		surface	750	none
134	WP211	Riverbank east	1,42681	38,00834	-1,42681	38,00834	6-nov		surface	441	none
135	WP211	Riverbank west	1,42681	38,00834	-1,42681	38,00834	6-nov		surface	662	none
136	WP213	Riverbank west	1,42662	38,00843	-1,42662	38,00843	6-nov		surface	92	none
137	WP213	Riverbank east	1,42662	38,00843	-1,42662	38,00843	6-nov		surface	146	none
138	BL01	Riverbed	1,46068	38,00385	-1,46068	38,00385	7-nov		river	508	Sample of bedload of river during discharge measurement 1
139	BL01	Riverbed	1,46068	38,00385	-1,46068	38,00385	7-nov		river	548	Sample of bedload of river during discharge measurement 2
140	BL01	Riverbed	1,46068	38,00385	-1,46068	38,00385	7-nov		river	552	Sample of bedload of river during discharge measurement 3
141	D03	Chipoleti at dam	1,46194	38,00394	-1,46194	38,00394	7-nov		river	687	Sample of bedload of river at Chipoleti during discharge measurement 1
142	RP01	Runoff plot 1	1,46274	38,00467	-1,46274	38,00467	7-nov		surface	691	Sample of sediment in gutter of RP 1
143	RP02	Runoff plot 2	1,46249	38,00419	-1,46249	38,00419	7-nov		surface	314	Sample of sediment in gutter of RP 2. Gutter of plot 3 empty.
144	RP04	Runoff plot 4	1,46136	38,00356	-1,46136	38,00356	8-nov		surface	133	Sample of sediment in gutter of RP 4.
145	WP214	Riverbed	1,34888	37,98351	-1,34888	37,98351	9-nov		surface	436	Catchment bad working dams
146	WP214	Riverbank east	1,34888	37,98351	-1,34888	37,98351	9-nov		surface	177	Catchment bad working dams
147	WP214	Riverbank west	1,34888	37,98351	-1,34888	37,98351	9-nov		surface	43	Catchment bad working dams
148	WP215	Riverbed	1,34650	37,98808	-1,34650	37,98808	9-nov		surface	278	Catchment bad working dams
149	WP215	Riverbank east	1,34650	37,98808	-1,34650	37,98808	9-nov		surface	0	Catchment bad working dams
150	WP215	Riverbank west	1,34650	37,98808	-1,34650	37,98808	9-nov		surface	105	Catchment bad working dams
151	WP216	Riverbed	1,35511	37,98433	-1,35511	37,98433	9-nov		surface	207	Catchment bad working dams
152	WP216	Riverbank east	1,35511	37,98433	-1,35511	37,98433	9-nov		surface	85	Catchment bad working dams

153	WP216	Riverbank west	1,35511	37,98433	-1,35511	37,98433	9-nov		surface	156	Catchment bad working dams
154	BL01	Riverbed	1,46068	38,00385	-1,46068	38,00385	13-nov		river	498	Sample of bedload during flow of river
155	BL01	Riverbed	1,46068	38,00385	-1,46068	38,00385	13-nov		river	629	Sample of bedload during flow of river
156	D03	Chipoleti at dam	1,46194	38,00394	-1,46194	38,00394	13-nov		chipoleti	511	Sample of bedload during flow of river
157	D03	Chipoleti at dam	1,46194	38,00394	-1,46194	38,00394	15-nov		chipoleti	528	Sample of bedload during flow of river
158	D03	Chipoleti at dam	1,46194	38,00394	-1,46194	38,00394	20-nov		chipoleti	632	Sample of bedload during flow of river
159	S1	Suspended load sample								8	
160	S2	Suspended load sample								13	
161	S3	Suspended load sample								10	
162	WP143	Jatta Plateau dam 1 Riverbed	1,48599	37,83202	-1,48599	37,83202	24-nov		surface	508	none
163	WP143	Jatta Plateau dam 1 east bank	1,48599	37,83202	-1,48599	37,83202	24-nov		surface	54	none
164	WP143	Jatta Plateau dam 1 west bank	1,48599	37,83202	-1,48599	37,83202	24-nov		surface	513	none
165	WP144	Jatta Plateau dam 2 Riverbed	1,48328	37,82411	-1,48328	37,82411	24-nov		surface	449	none
166	WP144	Jatta Plateau dam 2 east bank	1,48328	37,82411	-1,48328	37,82411	24-nov		surface	39	none
167	WP144	Jatta Plateau dam 2 west bank	1,48328	37,82411	-1,48328	37,82411	24-nov		surface	394	none
168	WP145	Dam with silt Riverbed clay	1,36881	37,88238	-1,36881	37,88238	24-nov		surface	84	10 cm of sand rest is clay/silt
169	WP145	Dam with silt east bank	1,36881	37,88238	-1,36881	37,88238	24-nov		surface	31	none
170	WP145	Dam with silt west bank	1,36881	37,88238	-1,36881	37,88238	24-nov		surface	271	none
171	WP145	Dam with silt Riverbed sand	1,36881	37,88238	-1,36881	37,88238	24-nov		surface	378	none
172	D03	Chipoleti at dam	1,46194	38,00394	-1,46194	38,00394	22-nov		surface	608	Sample of bedload during flow of river
173	S4	Suspended load sample								18	
174	S7	Suspended load sample								121	
175	S5	Suspended load sample								17	

sample of runoff sediment
sediment samples of other catchments
samples of Kiindu Catchment

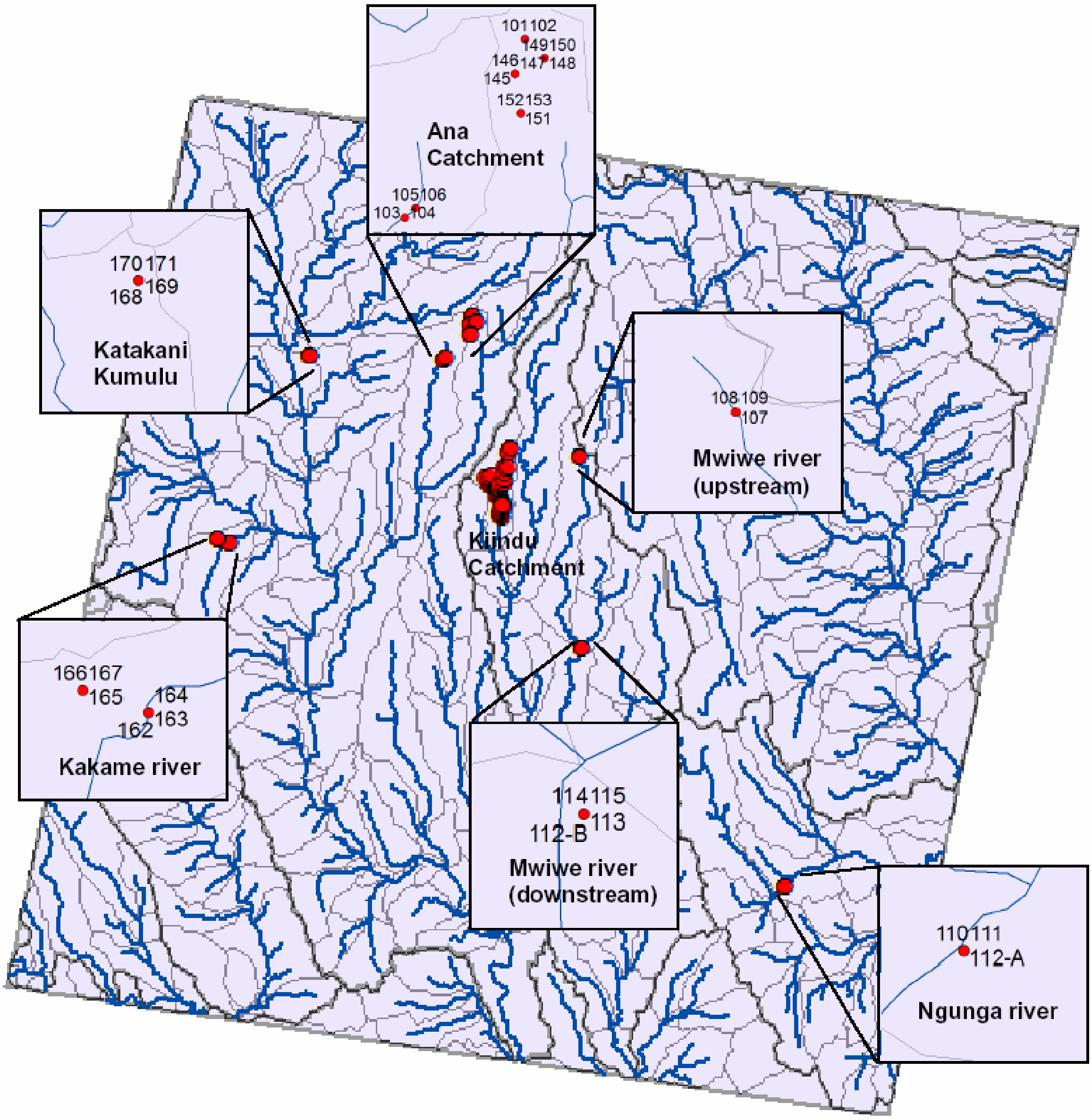
APPENDIX IV

Sampling locations in the Kiindu Catchment


N
S
W
E
136137
135
134
132133
128
129130
131
127
096
094
093095
090 092
089091
125126
124
087088
085086
082
084
083
122
123
121
119120
117
118
116
080
078079
076077 075
073074
072
070071
068069
066067
064065
063
062
061
060
059
058
057
Dam Kwa Ndunda
154155
140144
157158
156
053141
143
050
052
142
051
049
047048
046
045
044
043
042
041
040
0
465
930 Meters
Runoff plot 4
Kwa Ndunda
Runoff plot 2
Runoff plot 3
Runoff plot 1
0
25
50 Meters

APPENDIX V

Sampling locations at surrounding field visit sites



101 102
149 150
146 147 148
145
152 153
151
Ana
Catchment
105 106
103 104
170 171
168 169
Katakani
Kumulu
108 109
107
Mwiwe river
(upstream)
Kiindu
Catchment
166 167
165
164
162 163
Kakame river
114 115
112-B 113
Mwiwe river
(downstream)
110 111
112-A
Ngunga river

APPENDIX VI

Pretreatment method of sediment samples

A description of the pre-treatment for pipette and sieve analysis:

- Weigh 200 – 300 mg into weighed beakers of 800 ml. For coarse samples the weight is 5 - 10 gram.

- Oxidize with aliquots of 15 ml H_2O_2 30% until organic matter is removed. Destroy the excess peroxide by boiling.

- Add as much 1·0N HCl as necessary to dissolve $CaCO_3$ (4 ml per percentage $CaCO_3$) with an excess of 25 ml 1·0N HCl. Fill to 400 ml and heat until boiling-point. (NEN 5735 advises 15 min of boiling). If the carbonate content is not known, one has to analyse this precisely. In this study it was done following the Scheibler method.

- Rinse the walls of the beakers carefully to avoid loss of material during the next operations.

- Remove dissolved elements by filling with deionized water after removal of supernatant water; stand overnight and decant the clear liquid. Repeat one more time.

- Dry 48 h at 50–60 ^{o}C. Weigh the beakers.

- Disperse the samples by adding 50 ml, 0·120 M $Na_4P_2O_7 \cdot 10H_2O$, fill to 400 ml with deionized water and boil for 5 min.

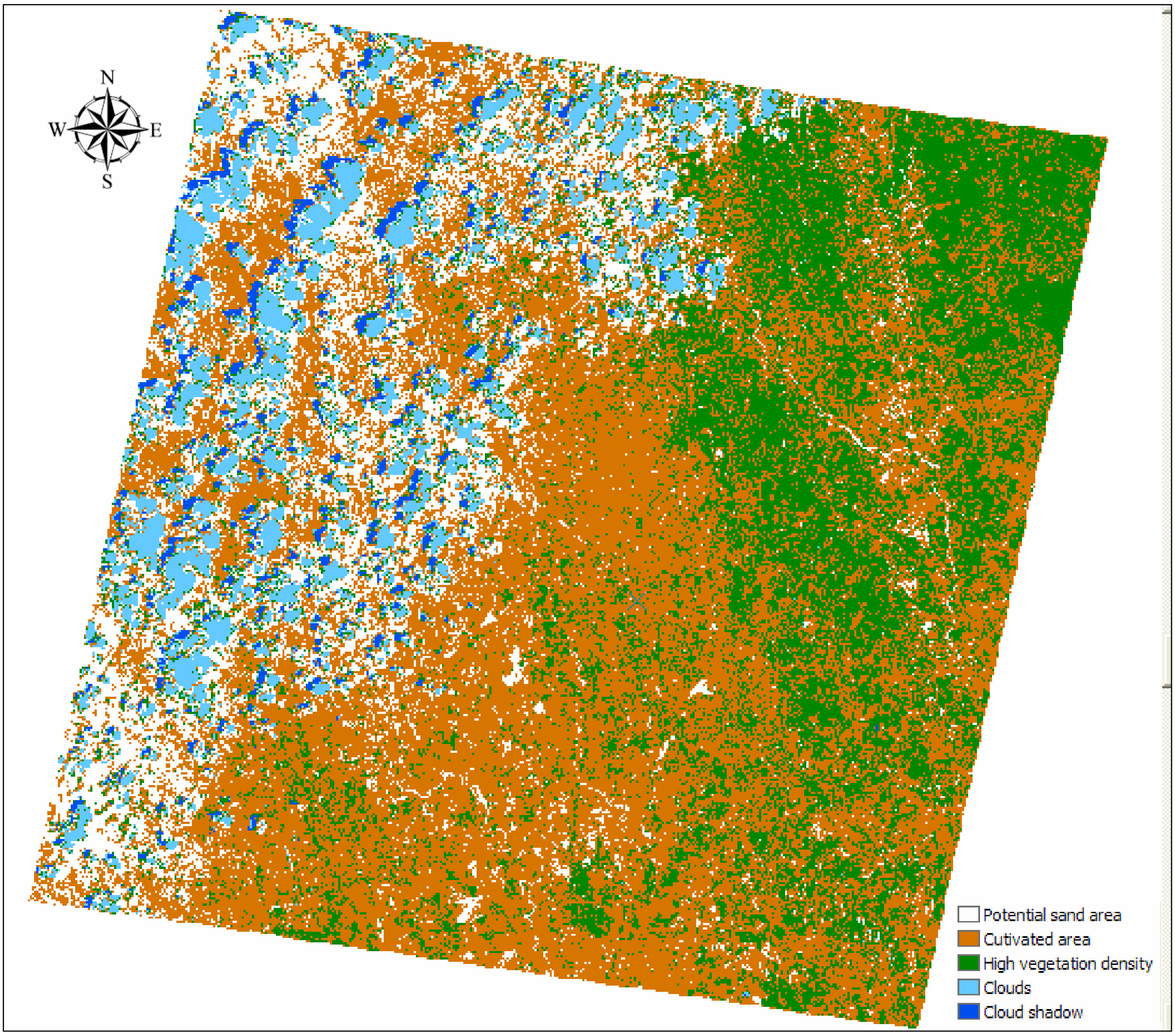
- Decant the samples quantitatively into cylinders of one litre with a diameter of 6 cm.

- Cool to 20 ^{o}C.

Source: *Konert and Vandenberghe (1997)*

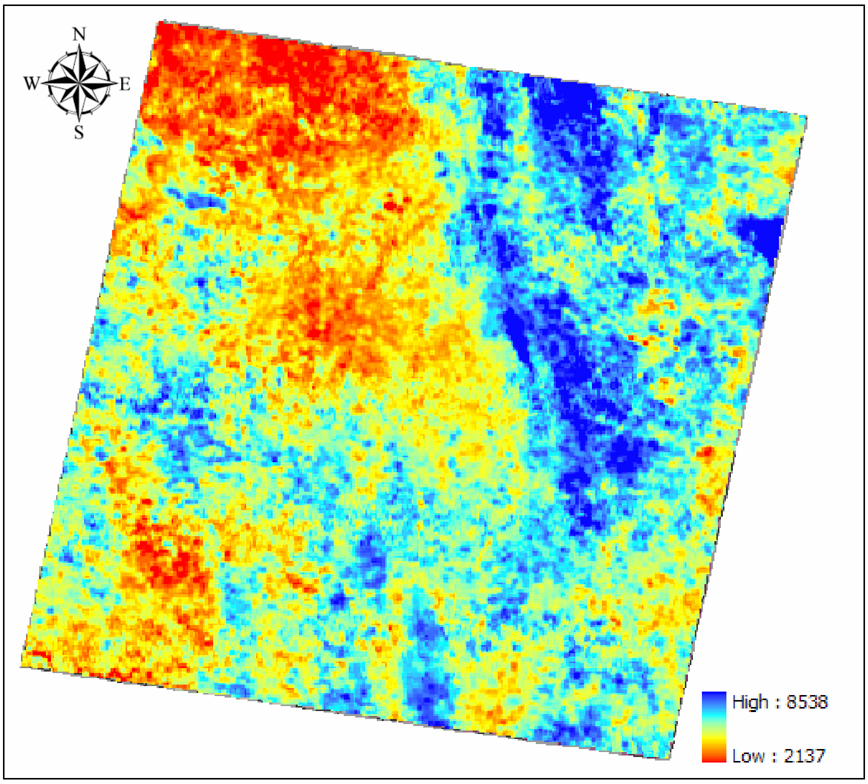
APPENDIX VII

Maximum Likelihood Classification study area

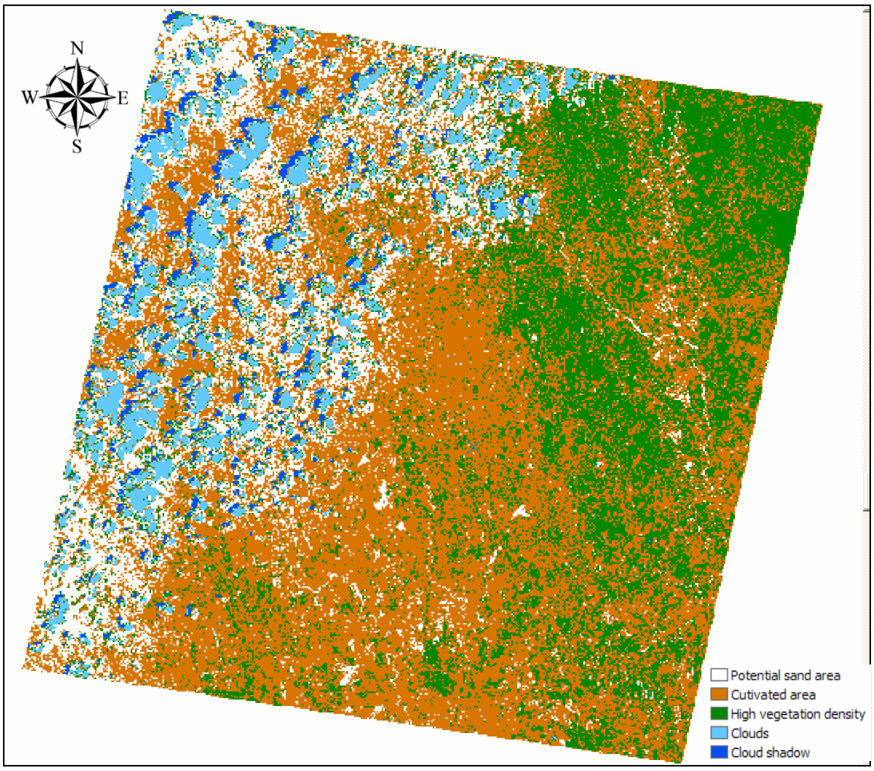

N
W
E
S
Potential sand area
Cutivated area
High vegetation density
Clouds
Cloud shadow

APPENDIX VIII

Maximum Likelihood Classification study area compared to NDVI



NDVI with high vegetation coverage in the North-East and low in the West



Maximum Likelihood Classification

APPENDIX IX

Digital Numbers and grain sizes per sample

samplenr	S	E	Northing	Easting	d10	d30	d50	BAND 1 DN	BAND 2 DN	BAND 3 DN
40	1,47092	38,00323	-1,47092	38,00323	123	343	555	114	135	142
47	1,46670	38,00318	-1,46670	38,00318	134	284	436	112	108	119
52	1,46326	38,00341	-1,46326	38,00341	161	431	673	116	139	142
55	1,46148	38,00389	-1,46148	38,00389	153	410	691	116	112	137
64	1,45665	38,00079	-1,45665	38,00079	153	312	478	106	98	125
67	1,45557	38,00053	-1,45557	38,00053	140	309	505	116	128	139
72	1,45253	38,00080	-1,45253	38,00080	179	382	575	115	133	147
73	1,45242	38,00129	-1,45242	38,00129	150	433	630	109	120	138
107	1,43160	38,05211	-1,43160	38,05211	199	457	622	114	107	125
110	1,70253	38,18161	-1,70253	38,18161	165	355	530	96	111	123
115	1,55249	38,05338	-1,55249	38,05338	118	366	559	104	113	132
044	1,46825	38,00241	-1,46825	38,00241	12	118	284	99	104	110
045	1,46722	38,00283	-1,46722	38,00283	17	170	311	105	93	101
046	1,46670	38,00318	-1,46670	38,00318	4	9	24	99	81	97
059	1,45872	38,00235	-1,45872	38,00235	9	49	111	103	72	97
060	1,45785	38,00160	-1,45785	38,00160	14	73	123	98	80	103
061	1,45725	38,00123	-1,45725	38,00123	20	100	183	97	74	96
062	1,45725	38,00123	-1,45725	38,00123	30	216	375	90	65	98
065	1,45665	38,00079	-1,45665	38,00079	23	270	462	99	76	103
068	1,45477	38,00080	-1,45477	38,00080	47	272	440	100	74	97
069	1,45477	38,00080	-1,45477	38,00080	13	124	287	102	109	123
070	1,45341	38,00078	-1,45341	38,00078	31	157	304	98	101	109
071	1,45341	38,00078	-1,45341	38,00078	31	153	257	104	83	105
079	1,45075	37,99867	-1,45075	37,99867	35	230	403	99	99	114
083	1,44956	37,99703	-1,44956	37,99703	24	75	135	101	90	95
084	1,44956	37,99703	-1,44956	37,99703	17	135	276	103	94	108
085	1,44918	37,99607	-1,44918	37,99607	12	80	148	102	84	104
086	1,44918	37,99607	-1,44918	37,99607	17	112	216	97	74	93
104	1,37143	37,96666	-1,37143	37,96666	7	67	132	101	60	90
106	1,36987	37,96826	-1,36987	37,96826	3	25	81	109	51	82
108	1,43160	38,05211	-1,43160	38,05211	31	171	287	102	74	95
109	1,43160	38,05211	-1,43160	38,05211	20	228	430	105	85	111
111	1,70253	38,18161	-1,70253	38,18161	11	140	287	85	83	92
112-A	1,70253	38,18161	-1,70253	38,18161	4	59	134	84	69	91
112-B	1,55249	38,05338	-1,55249	38,05338	7	50	107	95	50	78
117	1,45066	38,00168	-1,45066	38,00168	3	19	70	92	52	80
118	1,45066	38,00168	-1,45066	38,00168	7	43	91	98	53	85
120	1,45027	38,00238	-1,45027	38,00238	64	209	331	100	79	101
123	1,44877	38,00445	-1,44877	38,00445	3	25	130	94	64	91
125	1,44613	38,00513	-1,44613	38,00513	23	151	284	106	71	95
126	1,44613	38,00513	-1,44613	38,00513	8	89	246	90	65	88
129	1,43958	38,00634	-1,43958	38,00634	9	73	212	103	83	102
130	1,43958	38,00634	-1,43958	38,00634	19	92	179	101	60	88
131	1,43903	38,00797	-1,43903	38,00797	12	114	247	100	77	105
134	1,42681	38,00834	-1,42681	38,00834	128	307	441	94	84	104
135	1,42681	38,00834	-1,42681	38,00834	177	460	662	98	86	105
152	1,35511	37,98433	-1,35511	37,98433	4	28	85	105	68	94
153	1,35511	37,98433	-1,35511	37,98433	3	31	156	91	74	101
008 RP 1	1,46280	38,00466	-1,46280	38,00466	30	249	410	104	109	117
012 RP 3	1,46245	38,00388	-1,46245	38,00388	11	97	171	101	87	107
015 RP 4	1,46180	38,00372	-1,46180	38,00372	13	112	244	92	92	108

APPENDIX X

Results of suspended load and bedload measurements

Table 1: *Suspended load measurements*

NR	WayPoint	Location	S	E	Northing	Easting	Water height (cm)	Date-time	Suspension (liters)	Discharge (m3/s)	Dry weight (gr.)	Suspension (gr/l)	Sediment kg/day	Grainsize (D50)
S1	BL01	River middle	1,46068	38,00385	-1,46068	38,00385	23	7-11-06 11:05	4,70	0,25	13,7	2,9	62458,0	8,0
S2	BL01	River middle	1,46068	38,00385	-1,46068	38,00385	-	7-11-06 11:24	4,53	0,17	11,7	2,6	37712,7	10,0
S4	BL01	River middle	1,46068	38,00385	-1,46068	38,00385	18	13-11-06 11:15	4,20	0,10	3,0	0,7	6171,4	18,0
S5	D03	Chipoleti	1,46194	38,00394	-1,46194	38,00394	10	13-11-06 12:05	3,60	0,13	1,9	0,5	5725,5	17,0
S6	D03	Chipoleti	1,46194	38,00394	-1,46194	38,00394	27	15-11-06 18:09	4,65	0,51	39,6	8,5	372399,5	13,0
S7	D03	Chipoleti	1,46194	38,00394	-1,46194	38,00394	9	20-11-06 10:20	4,55	0,12	1,7	0,4	3734,1	121,0
S8	D03	Chipoleti	1,46194	38,00394	-1,46194	38,00394	5	22-11-06 14:20	4,54	0,08	0,5	0,1	792,9	-

Table 2: *Bedload measurements*

NR	WayPoint	Location	S	E	Northing	Easting	Water height (cm)	Estimated Width (cm)	Date/Time	Discharge (m3/s)	Weight (g/30 sec)	kg/sec *(eq. 4-1)*	Grainsize (D50)
138	BL01	Riverbed	1,46068	38,00385	-1,46068	38,00385	24	500	7-11-06 11:05	0,25	280,71	0,61	508
139	BL01	Riverbed	1,46068	38,00385	-1,46068	38,00385	12	400	7-11-06 11:24	0,17	333,79	0,58	548
140	BL01	Riverbed	1,46068	38,00385	-1,46068	38,00385	7	300	7-11-06 13:30	0,08	25,13	0,03	552
154	BL01	Riverbed	1,46068	38,00385	-1,46068	38,00385	11	350	13-11-06 11:12	0,11	282,56	0,43	498
155	BL01	Riverbed	1,46068	38,00385	-1,46068	38,00385	14	350	13-11-06 11:25	0,10	280,34	0,43	629
156	D03	Chiploleti at dam	1,46194	38,00394	-1,46194	38,00394	12	300	13-11-06 11:45	0,15	357,56	0,47	511
157	D03	Chiploleti at dam	1,46194	38,00394	-1,46194	38,00394	27	300	15-11-06 17:55	0,51	787,49	1,03	528
158	D03	Chiploleti at dam	1,46194	38,00394	-1,46194	38,00394	8	300	20-11-06 10:20	0,11	157,34	0,21	632
172	D03	Chiploleti at dam	1,46194	38,00394	-1,46194	38,00394	5	300	22-11-06 14:10	0,08	14,68	0,02	608

APPENDIX XI

Results of grain size analysis

Sample nr. (#) Code	Percentage < 500 mu	D10 (mu)	D30 (mu)	D50 (mu)	Mean (mu)	MSD (mu)	SK (mu)
Kiindu Catchment							
122742 #40	44,73	123	343	555	457	344	188
122743 #41	50,17	79	283	498	361	261	202
122744 #42	99,98	7	57	119	74	225	354
122745 #43	55,04	62	230	447	308	250	218
122746 #44	74,72	12	118	284	165	183	346
122747 #45	79,92	17	170	311	187	199	257
122748 #46	99,85	4	9	24	27	219	908
122749 #47	57,98	134	284	436	384	371	152
122750 #48	62,31	8	134	396	177	149	356
122751 #49	76,03	8	91	225	141	172	390
122752 #50	45,08	121	344	546	448	312	195
122753 #51	92,6	14	84	168	121	227	351
122754 #52	35,53	161	431	673	555	316	167
122755 #53	72,35	147	259	359	339	390	113
122756 #54	58,36	93	291	440	339	295	160
122757 #55	35,71	153	410	691	555	342	186
122758 #56	83,97	5	39	159	95	148	490
122759 #57	57,94	72	270	435	323	268	188
122760 #58	48,65	246	399	508	480	444	59
122761 #59	100	9	49	111	74	245	366
122762 #60	93,47	14	73	123	105	285	483
122763 #61	92,96	20	100	183	137	245	304
122764 #62	66,51	30	216	375	252	230	240
122765 #63	23,91	159	574	758	586	304	128
122766 #64	52,52	153	312	478	432	349	168
122767 #65	54,66	23	270	462	275	204	250
122768 #66	39,13	137	415	588	454	293	144
122769 #67	49,61	140	309	505	457	319	213
122770 #68	57,44	47	272	440	306	241	207
122771 #69	74,28	13	124	287	171	186	334
122772 #70	74,14	31	157	304	215	243	275
122773 #71	83,48	31	153	257	193	257	250
122774 #72	42,06	179	382	575	511	366	145
122775 #73	36,21	150	433	630	518	314	153
122776 #74	62,14	11	69	360	164	164	448
122777 #75	29,85	194	502	726	620	344	137
122778 #76	95,38	2	9	35	29	146	807
122779 #77	99,57	19	92	156	114	274	264
122780 #78	34,15	183	455	654	551	330	134
122781 #79	62,28	35	230	403	266	227	228
122782 #80	96,17	2	13	68	43	144	646
122783 #81	35,83	100	437	620	451	262	164
122784 #82	44,6	107	345	553	441	295	207
122785 #83	83,69	24	75	135	137	270	547
122786 #84	81,56	17	135	276	172	215	321
122787 #85	99,99	12	80	148	98	248	285
122788 #86	88,78	17	112	216	149	224	310
122789 #87	55,94	161	335	463	406	382	112
122790 #88	35,21	125	423	685	511	295	203
122791 #89	61,34	70	239	403	314	287	233
122792 #90	84,94	18	110	221	157	232	351
122793 #91	77,65	8	60	217	127	170	476
122794 92	33,03	186	465	668	566	356	129

Sample nr. (#) Code	Percentage < 500 mu	D10 (mu)	D30 (mu)	D50 (mu)	Mean (mu)	MSD (mu)	SK (mu)
Kiindu Catchment							
122795 #93	59,07	121	258	410	356	319	188
122796 #94	40,31	186	417	568	493	382	104
122797 #95	99,31	31	85	131	116	358	308
122798 #96	32,99	154	459	699	555	314	183
122818 #116	59,2	172	322	443	395	382	100
122819 #117	99,88	3	19	70	45	182	566
122820 #118	99,95	7	43	91	65	240	420
122821 #119	77,19	22	153	274	196	227	277
122822 #120	74	64	209	331	266	301	206
122823 #121	49,88	139	333	501	409	325	145
122824 #122	99,97	2	9	20	20	218	717
122825 #123	92,1	3	25	130	69	144	566
122826 #124	40,42	189	406	581	507	354	127
122827 #125	77,41	23	151	284	196	235	304
122828 #126	83,95	8	89	246	134	177	384
122829 #127	23,44	307	566	750	693	412	77
122830 #128	27,42	232	526	709	616	395	96
122831 #129	89,73	9	73	212	121	183	390
122832 #130	92,54	19	92	179	133	247	339
122833 #131	87,82	12	114	247	145	195	321
122834 #132	27,42	161	533	749	595	339	148
122835 #133	25,86	198	548	750	629	351	128
122836 134	59,27	128	307	441	382	387	149
122837 #135	33,66	177	460	662	570	356	158
122838 #136	95,7	7	43	92	72	207	566
122839 #137	99,15	10	84	146	103	240	312
122840 #138	48,91	99	328	508	376	310	159
122841 #139	44,08	120	368	548	438	314	167
122842 #140	42,81	92	362	552	401	314	180
122916 #141	30,42	108	493	687	497	293	163
122917 #142	31,42	128	480	691	525	281	153
122918 #143	66,74	22	146	314	216	219	325
122919 #144	77,43	4	36	133	92	129	586
122929 #154	50,35	169	354	498	432	392	104
122930 #155	31,67	182	483	629	525	374	100
122931 #156	48,1	139	359	511	415	379	118
122932 #157	45,83	113	354	528	403	342	152
122933 #158	32,13	145	475	632	511	369	130
122934 #159	99,99	1	3	8	8	237	801
122935 #160	99,98	1	5	13	12	219	732
122936 #161	100,01	1	4	10	9	238	732
122947 #172	39,68	132	367	608	493	363	228
122948 #173	99,85	1	5	18	18	132	853
122949 #174	99,82	3	32	121	63	162	451
122950 #175	99,96	1	5	17	15	153	790

Sample nr. (#) Code	Percentage < 500 mu	D10 (mu)	D30 (mu)	D50 (mu)	Mean (mu)	MSD (mu)	SK (mu)
Tana catchment							
122802 #100	58,8	82	278	437	319	270	158
122803 #101	98,69	4	25	69	49	192	525
122804 #102	77,07	2	44	213	96	111	476
122805 #103	61,63	55	194	355	289	245	293
122806 #104	100,01	7	67	132	77	225	310
122807 #105	56,15	80	259	442	342	264	222
122808 #106	100,01	3	25	81	48	191	476
122920 #145	60,05	59	270	436	289	253	183
122921 #146	91,58	9	97	177	125	196	310
122922 #147	99,83	3	10	43	34	176	742
122923 #148	81,17	12	139	278	172	210	312
122924 #149	99,19	2	9	50	32	149	707
122925 #150	99,12	6	49	105	74	215	470
122926 #151	97,59	50	144	207	171	332	177
122927 #152	97,24	4	28	85	60	180	563
122928 #153	85,39	3	31	156	81	131	532
Kakame river							
122937 #162	48,61	113	353	508	382	321	129
122938 #163	100,01	2	19	54	31	210	463
122939 #164	48,51	35	313	513	316	198	204
122940 #165	59,14	188	333	449	401	403	66
122941 #166	99,95	2	9	39	27	176	693
122942 #167	63,29	37	220	394	259	224	219
Mwiwe river							
122809 #107	34,83	199	457	622	532	330	106
122810 #108	79,63	31	171	287		224	264
122811 #109	58,29	20	228	430	247	191	259
122951 #112-B	92,81	7	50	107	85	199	476
122815 #113	41,06	164	387	595	503	323	148
122816 #114	98,28	6	66	139	85	192	418
122817 #115	42,69	118	366	559	435	321	174
Katakani Kumulu							
122943 #168	100	3	34	84	50	193	420
122944 #169	99,63	2	9	31	24	191	702
122945 #170	68,92	4	61	271	128	132	470
122946 #171	64,56	89	234	378	304	264	198
Ngunga river							
122812 #110	46,59	165	355	530	480	382	149
122813 #111	78,77	11	140	287	165	182	310
122814 #112-A	73,49	4	59	134	109	137	566