SOUTH EASTERN KENYA UNIVERSITY

SCHOOL OF WATER RESOURCES SCIENCE AND TECHNOLOGY

ASSESSMENT OF THE INFLUENCE OF SAND GRADATION ON SITE SUITABILITY FOR CONSTRUCTION OF SAND DAM; A CASE STUDY OF KITUI SOUTH SUB COUNTY, KENYA

By

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DECLARATION

I declare that is my own original work and has not been submitted for examination in any other university

...

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This thesis has been submitted for examination with our approval as university supervisors

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DEDICATION

I dedicate this work to my beloved wife Ms Esther Kennedy, my daughter Abigael Kavutha and son Mumo who gave me the time and encouragement to focus on my studies in addition to other work related obligations. Also my mum Joyce for showing concern on my progress and brother Dennis Mutinda who was very instrumental in the course of my data collection. Lastly my friends who participated in various ways to make my work enjoyable.

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ABSTRACT

This study was undertaken in Kitui South in Kitui County in the south eastern parts of Kenya. The main objective of the study was to develop a spatial model that can be used for selection of suitable sites for sand dam in Kitui South. Data analysis was done using three approaches. The first approach involved the use of the Remote Sensing (RS) technique where data was preprocessed and analyzed using Erdas Imagine software and Geographical Information Systems (GIS) for spatial modelling. Sand samples were collected from seasonal rivers which included Mwila, Kakya, Wiitu, Nguni, Ngunyumu, Muvuko, Kanzilu, Masaa, Katiliku, Ngulungu, Nzeeu, Koma and Katitika. The results from the spatial model which integrated all factors shows that 16% of the studied sites were fairly suitable for construction of sand dams while 79% were classified as suitable and 5% are categorized as very suitable. Several sites in the central and the entire eastern parts of Mutha Ward were found not suitable for sand dam construction due to poor conditions such as the lack of suitable sand particles, lack of bedrock exposure on the riverbeds, flat terrain, very shallow stream banks, and weak soils on the riverbanks. Suitable sites for sand dams were found on the western and central areas of Kitui South where production and high accumulation of coarse sands while few excellent sites were observed in Ikanga ward and near Mutomo hills. Optimum accumulation of sands along the seasonal streams was identified at a slope ranging between 1.5 and 6%. Accumulation of different grades of sand especially the medium sands (r= 0.76) and coarse sands (r=0.75) were found to be strongly influenced by the changes in elevation along the stream. Out of 80 investigated sites, 59% of them were dominated with uniform sands (C_u<3), 30% were intermediate sands and only 11% were well-graded sands (C_u>5). The study also found that86% of the sites along the seasonal streams were dominated with medium sands while 10% were dominated with fine sands and the rest (4%) dominated by coarse and gravelly sands. From the results this study concludes that 59% of the 80 sites that were investigated in this study have a high potential for providing suitable sites for sand dams in Kitui South Sub-County.

Key words: Sand Dams; Particle Size Distribution; Hydrology; Water Management; Kitui South, Kenya.

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LIST OF ABBREVIATIONS AND ACRONYMS

AHP	Analytical Hierarchy process
ASALs	Arid and Semi-Arid Lands
ASDF	African Sand Dam Foundation
ASTM	American Standard Test Method
DEM	Digital Elevation Model
DRSRS	Department of Resource Surveys and Remote Sensing
ERDAS	Earth Resources Data Analysis System
ESRI	Environmental System Research Institute
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic Information System
GLOVIS	Global Visualization System
GPS	Global Positioning System
ILRI	International Livestock Research Institute
ISO	International Organization for Standardization
KNBS	Kenya National Bureau of Statistics
LAI	Leaf Area Index
LULC	Land Use and Land Cover
MCDM	Multi-Criteria Decision Making
MCE	Multi-Criteria Evaluation
NGO	Non-Governmental Organization
NIR	Near Infrared NIR
RS	Remote Sensing
RUSLE	Revised Universal Soil Loss Empirical
SAHP	Spatial Analytical Hierarchy Process
SASOL	Sahelian Solutions Foundation
SEKU	South Eastern Kenya University
SMCA	Spatial Multi Criteria Analysis
SRTM	Shuttle Radar Topography Mission
SSA	Sub-Saharan Africa
SSD	Sub-surface and Sand dams Development

SWIR	Short Wave Infra-red
TM	Thematic Mapper
UNDP	United Nations Development Programme
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
UTM	Universal Transverse Mercator Coordinate System
WEPP	Water Erosion Prediction Project
WWD	Westlands Water District
Cu	Uniformity Coefficient
Ck	Coefficient of gradation
dh/dL	Hydraulic gradient
O_m	Original mass
M_R	Retained mass

CHAPTER 1

INTRODUCTION

1.1 Background to the study

This chapter provides an over view on the use of sand dam technology in water conservation, a description of the need for this research, the objectives and hypothesis that guided this study.

1.2 Sand dams and water supply

In Kenya 80% of the land is classified as arid and semi-arid and therefore suffer from water shortage (Puttemans, 2004). The annual rainfall (500 to 1050 mm/yr) is considerable but is limited to two rainy seasons. Most of the ASALs in Kenya experience rainfall in short high intensity events that hardly infiltrate into the ground. Between these rainy seasons, communities in the rural areas in ASALs encounter drought with severe water shortages. In Kitui County for example rain disappears as runoff into ephemeral rivers that stand dry for the rest of the year. Given the expected increase in climate variability (Huntingford et al., 2005; Aerts et al., 2006; Boko et al., 2007) and the massive potential of rainwater harvesting in Africa (UNEP, 2006), studying techniques of small scale water storage such as sand dams becomes increasingly important. In the recent past, there has been a growing recognition of the importance of sand dams as a low cost and robust means to enhance water availability in ASALs.

In the recent past, initiatives have been taken to introduce sand dams in arid and semi-arid lands of Kenya.For instance, sand dams in Kitui and other south eastern parts of Kenya dates back to the 1980s (UDO, 2016). Since the introduction of sand dams in Kenya, other countries in Africa have also adopted the technology for example in Ethiopia, Tanzania and Mozambique (SASOL and ACACIA, n.d.; Rempel et al., 2005).Sand damsare also common in the drylands of India for example in Rajasthan and Gujarat (Sankar, 2002; Rao et.al., 2009; Kheirkhah et al., 1980). Sand dams in Kenya are constructed by both government and non-government organizations where SASOL has the longest history in Ukambani areas. Over 700 sand dam projects have been completed in Kitui County by SASOL in a period of more than two decades as documented in CGoK (2016). The Kitui County government has also embraced the technology and supported mapping of suitable sites for sand dams across the County. In June 2016, the County Government in collaboration with the South Eastern Kenya University mapped a total of 2,029

Sand dam sites in Kitui County. In early 2017, the County Government had already commissioned the first phase of the construction of the sand dams in every ward across the County.

Despite great interest in the construction of sand dams in ASALs, there is still a challenge in identifying sites that can enable maximum performance of sand dams. In this study, we explore the extent to which sand gradation determine suitable sites for construction of sand dams. We also considered factors that affect sand gradation in seasonal rivers found in Kitui South.

1.3 Identification of suitable sitesforsand dams

One of the limitations of sustainable rural development especially in ASALs in Kenya is the lack of access to portable water (Kuria, 2012). Environmental degradation, diseases and continued dependence on rain for cropping has led to water, food, and economic insecurity. The solutions to these problems begin with the conservation of water. Although most of the ASALs receive reasonable amount of rainfall, the spatial-temporal distribution of rainfall does not provide opportunity for continuous water supply to rural communities. Kitui County receives long rains during March and May and short rains between October and December (UNEP, 2006). The challenge is how best to conserve water received during rainy seasons (Maddrell, 2016). Sand dams provide the practical solution of increasing water availability to rural communities in drought periods.

Sand dams have been recognized as one of the appropriate technologies for conserving seasonally available water in ASALs for many years (Maddrell, 2010; Aerts et al., 2006). The dams can be constructed and maintained using the locally available materials and human resources. The performance and sustainability of these dams is however linked with the suitability of the site where they are constructed (Nissen-Petersen, 2007). Locating the suitable sites for sand dams in arid and semi-arid lands in Africa has in the past been based on the traditional methods (Rempel et al., 2005). This traditional method involved identification of sites along the seasonal rivers where there is a substantial accumulation of sand and an impervious bedrock. However this method has been found to be ineffective and unsustainable (Beimers et al., 2001b). Some of the challenges arising from this method included siltation of the previously constructed sand dams, failure of the sand dam during heavy floods and also poor designs which did not match the environment where they were constructed. In other cases, lack of data and ineffective methods of data collection resulted in improper location of sand dams in ASALs.

The criteria proposed in this study for locating sand dams in suitable sites will play a big role in alleviating water scarcity in Kitui South. Proper selection criteria and construction of sand dams in suitable sites will bring about sustainable water and soil conservation measures in Kitui South. Sand dams are proven as an effective method for water conservation that allows recharge of the aquifer (Hoogmoed, 2007). Sand dams located in suitable areas will increase the amount of water available for abstraction; empower local communities to utilize water as they require without the need for any complicated operational or management processes. Moreover, if the water table increases because of dam construction, the local communities will have an opportunity to grow more plants and trees, both increasing the soils drainage capacity and slowing surface run-off. According to Pauw et al., (2008) sand dam can play a great role in controlling soil erosion.

The method proposed in this study attempts to integrate assessment on soils to determine their vulnerability to erosion so that necessary precautions are taken before one decides to locate a sand dam at a given point along the riverbed. Previous studies show that sand dams have a positive impact on water availability in Arid and Semi-Arid Lands (ASALs) (Munyao et al., 2004; Pauw et al., 2008). Sand dams not only increase the volume of groundwater that can be accessed during dry seasons but they also prolong the abstraction period in groundwater wells and boreholes located near sand dams.

Women and children bear the primary responsibility for household water provision in most rural communities. This is done by gathering water from long distances and most often what they get is largely contaminated water. This is usually a time consuming task which farces time away from other more productive activities and therefore resulting in an enormous economic cost for poor families. Sand dams provide a lifetime local access to clean and reliable source of water for domestic use, crops, and livestock in areas that are mostly within 30 to 40 minutes of people's homes in water scarce environments (Nissen-Petersen, 2007; Maddrell, 2016). The method proposed in this study allow one to consider the distribution of both human and livestock in the study area. Priority is given according to the population density and the settlement patterns as the primary considerations when locating a sand dam in arid and semi-arid lands.

1.3.1 Multi-criteria for locating suitable sites for sand dams

In this study we are proposing a new approach for the selection of suitable sites for sand dams. The proposed criteria integrates both morphological and environmental factors that are deemed essential for assessing suitable sites for sand dams. This technique involves the use of Geographic Information Systems (GIS) and Remote Sensing (RS) including the evaluations of the sand gradation and uniformity.

Determining a suitable location for a sand dam involves evaluating the favourability of both the physical and environmental conditions (Nelson, 1985). The physical conditions includes a number of factors. One is the availability of coarse sand supplied by the runoff along the river (Nepal, et al., 2014). Coarse sand is preferred in this case because it allows water infiltration into the sand which is then stored for a given period and can be abstracted for both livestock and domestic uses (Gijsbertsen, 2007). Medium sands are also applicable when there is minimal supply of coarse sands (Maddrell, 2016). Fine sands are not recommended due to their limited storage capacity. The availability of an accessible bedrock below the accumulated sand along the riverbed is also important (Hoogmoed, 2007). The bedrock acts as the foundation and anchoring point for the sand dam. The bedrock also ensures that the water that infiltrate into the sand matrix does not leak away from the subsurface storage (Nissen-Petersen, 2007). This means that the bedrock must also be impervious and without fractures.

Another physical condition that must be fulfilled is the nature of the stream gradient. The recommended stream gradient is between 1.5% and8% (Maddrell and Neal, 2012). At this gradient, the stream has enough room for the sands to accumulate as the water infiltrate into the sand. This condition is mostly observed at the transitional plains (Janardhana-Raju and Reddy, 2005). Some studies have shown that completely flat terrain is not suitable for sand dams due to high rate of siltation in such points. This means that a slope gradient below 1.5% can be avoided when necessary.

The geology and soils are also important determinants for suitability of the sand dams (Burger et al., 2003). The role of geology is to supply the sands to the river courses. Some rocks do not erode easily while others erode and break into smaller particles which end up as different grades of sands which are then transported and accumulate at different points along the river channel. Metamorphic rocks which are rich in quartz are normally preferred because they result into coarse sands. Compact rocks are suitable for anchoring the foundation of the sand dam (Hoogmoed, 2007). Rocks which easily dissolve in water are not recommended since they can generate underground drainage and sink holes which can lead to water losses stored in sand dams.

The distribution of sand particles along the streams varies from one point to the other. This is attributed to several factors namely the parent rock, geology, distance from the origin, and size of the sediments (Van Haveren, 2004). Riverbed dominated with substantial amount of sand can be reclassified to show the distribution of the particle sizes within a given point along the river. This assessment can be done through particle separation procedures in the laboratory. Respective portions denoted as D_{10}, D_{30}, D_{50} and D_{90} are commonly used to show the distribution of sand particle sizes. This represent the first decile, third decile, fifth decile and the ninth decile respectively. The median size is represented as D_{50} which means that half portion of the sand that accumulate at any given point along the river is larger than the particle size at that D_{50} and half of the sand is dominated with particles less than the value indicated at D_{50} (Alderlisten,1990). A normal distribution curve would be attained when the dominant particle size is at D_{50} (median size). The median size varies from one point to the other along the seasonal rivers but if the size is between 0.4 to 2mm (coarse sand), then the site would be taken as suitable for a sand dam.

The distribution of sand particle size is important but in order to maximize the storage capacity of the sand dams, assessment of uniformity and gradation of sand is also important. Uniformity of sand is defined by the Coefficient of Uniformity (Cu) and sand gradation is defined by the Coefficient of gradation (Ck). These coefficients are influenced by changes in the particle size distribution mainly D_{10}, D_{30} and D_{60}.If the ratio between the particle size D_{60} and D_{10} is less than 3 then the sand will be considered uniform and when the ratio is greater 5, it will considered as well-graded (Hutet al., 2008). Uniform sand are preferred due to high surface area for water storage in the sand dams.

The environmental factors are also essential in selecting suitable sites for sand dams. These include factors such as the availability of road infrastructure, presence of human settlements (Pauw et al., 2008). The population size and distribution is an important determinant of the location of a sand dam since the overall aim is to provide water for various uses by the local communities. Thus, it is normally desirable to locate sand dams in areas where local communities can benefit from increased water availability throughout the year. The ideal site should therefore be located near human settlements. Locations near market centers and within towns are not ideal because of high possibility of contamination of water stored in sand dams. Also, thinly populated areas are not suitable because the site will not serve the purpose of supplying water to the people. Thus, field surveys on population size and distribution must be undertaken when determining sites for construction of sand dams. These factors are also considered essential when prioritizing different sites for sand dam as well as evaluating cost effectiveness of the sand dam projects. Sand dams are meant to be cost effective therefore they ought to be located close to the people at the nearest site as much as possible (Munyao et al., 2004). The road infrastructure should also be clear and usable for all the potential users. The location of the sand dam should also be agreed by all the water users to minimize conflict between the communities (Nissen-Petersen, 2007).

In this study, land use within the vicinity of the sites that are considered suitable for the construction of sand dams was assessed through field observations and surveys. Some land uses may be considered to be incompatible with the sand dams. As mentioned in the previous sections, sites that are near markets or those located within urban areas are not suitable due to high possibility of contamination of water in the sand. Also, heavily cultivated areas with high soil erosion rates may not be suitable due to potential for supply of unsuitable sediment materials into the sand dams- materials that may eventual affect the water storage volume within the dam.

1.4 Statement of the Problem

Like in any other countries in the Sub-Saharan Africa (SSA), Kenya agricultural sector has witnessed a minimal growth over the last decade (SIWI, 2001). One of the key cause of this scenario is inadequate water for irrigation. This is partly attributed to lack of effective rainwater conservation methods. In Kitui County, limited rainfall and scarce surface water sources limits socio-economic development. Rivers only hold water during and shortly after rainfall events, especially in more upstream parts of catchments. Due to the often short and intense rainfall events in combinations with certain soil types like silt and clay, a large part of the rainfall tend to leave the catchment as surface runoff instead of infiltrating into the soil and recharging the groundwater. Runoff coefficients of the order of 70% are common in ASALs (Borst and De Haas, 2006). Apart from the perennial rivers such as River Tana and Athi River that runs at the north western and south western boundary of Kitui County respectively, the other major sources of water are seasonal rivers such as Tyaa, Thunguthu, Mwania, Enziu,Thua, Tiva, Kalundu, Nzeeu, Mikuyuni and Mwitasyano that flow only during rainy seasons. Streams generally become dry within one month after the rainy season (Borst and De Haas, 2006).

There is need to promote methods which can ensure that there is optimal storage and or conservation of the available rainwater in the ASALs. Sand dams are considered appropriate technology of conserving rainwater and providing adequate potable water to the local communities in the ASALs

(Borst and De Haas, 2006: Beimers et al., 2001a-b; Burger et al., 2003; Munyao et al., 2004; Puttemans, 2004).However, most of the sand dams in ASALs dry up quickly during extended dry seasons due to location in unsuitable sites (Borst and De Haas, 2006). In Kitui County, several sand dams have failed due to high rate of siltation(CGoK, 2016).

In order to ensure good performance and sustainability, sand dams should be located in suitable sites with appropriate sand gradation. The factors influencing suitability of a site for a sand dam are geology, soil type, riverbed gradient and the rate of coarse sand accumulation on the riverbed (Kheirkhah et al., 1980). These factors are essential in the evaluation of a site for a sand dam. It is from this perspective that this study attempts to come up with a model that can be used to determine site suitability for sand dams in Kitui South by integrating all the essential factors.

1.5 Research Objectives

1.5.1 Goal of the Study

The goal of this study is to develop an approach for determining the suitable sites for sand dams in arid and semi-arid lands based on a multi-criteria that integrates geomorphological characterization and sand gradation along the riverbeds in seasonal rivers.

1.5.2 Specific Objectives

The following specific objectives were formulated:

i) Determine factors that contribute to changes in the particles sizes of sediments along a seasonal stream and how these influence the suitability of sites for a sand dam
ii) Establish relationships in the spatial variability of particle-sizes of stream sediments
iii) Develop a criteria for locating suitable sites for construction of sand dams in arid and semi-arid lands using a multi-criteria approach
iv) Provide recommendations for the development of sand dams in Kitui South

1.6 Hypotheses of the study

The following are the hypothesis of this study:

Null Hypothesis (H_{01}): The rate of accumulation of fine sands is different from that of the coarse sands along the riverbeds in arid and semi-arid lands

Alternative Hypothesis (H_{A1}): Alternative

Null Hypothesis (H_{02}): The riverbed gradient does not affect the rate at which different grades of sands accumulate on the riverbed

Alternative Hypothesis (H_{A2}): Alternative

Null Hypothesis (H_{03}): The rate at which sands accumulate on the riverbed does not increase with the decrease in the elevation

Alternative Hypothesis (H_{A3}): Alternative

Null Hypothesis (H_{04}): There is no significant relationship between the elevation and sand gradation at different points along the riverbed

Alternative Hypothesis (H_{A4}): Alternative

1.7Justification of the Study

Minimal work has been undertaken in Africa and specifically in Kenya on how geospatial technique can be used in the location of suitable sites for constructing sand dams. Although sand dam technology has existed in Kitui County since 1950s, much of the work done have examined the efficiency of the traditional methods in the identification of suitable sites for sand dams without considering the key environmental and the physical factors. The criteria used in the traditional methods for identification of the suitable sites for sand dams has been limited to only two key spatial components. These components are a seasonal river with sufficient coarse sands and an accessible bedrock in the riverbed where the sand dam wall could be anchored (Nissen-Petersen, 2007; Maddrell and Neal, 2012). The sand dams sited using this method have been reported with cases of failure as a result of heavy siltation (Gijsbertsen, 2007).

Increased human and livestock population in most parts of Kitui County has considerably increased the demand for water (UNEP, 2006). There is increased demand for the domestic water needs, irrigation, and livestock watering requirements. This increased demand can partly be met by constructing sand dams that can help increase access to water. The construction of sand dams however needs to be done in the most suitable sites. This study proposes a new approach where multiple spatial components (both environmental and physical characterization of a site) are integrated to establish the best sites for sand dams.

The global and regional studies show that due to climate change, it is anticipated that most countries in the Sub-Saharan Africa will experience severe water shortage as a result of depletion of the available surface water resources. This shortage is attributed to the prolonged droughts that lead to accelerated drying in most parts of the region (Hutet al., 2008). Although sand dam technology have been used for the longest time in Africa and especially in Kenya, there is very minimal application of the proposed approach in the identification of suitable sites for sand dams. The key challenge here seems to be the lack of technical skills and information on how this method can be applied. This is because for the longest time, sand dams have been constructed and maintained by the local self-help groups which in most cases have not had people to train them on the new technologies to enhance the traditional method.

Sand dams have played a very important role in improving water supply in the County but the criteria applied in the past in the identification of appropriate sites for the construction of sand dams did not apply the spatial modelling techniques. There is need to encourage mapping and data collection to ensure that enough data is available for both the local communities and interested organizations to promote cheap sustainable water conservation practices especially in Kitui County. Sand dams are considered as one of the most economical and appropriate methods of rehabilitation of arid and semi-arid areas and adaptation to climate change due to their capability of improving environment and livelihoods of the local communities (Hutet al., 2008)

The criteria proposed in this study attempts to improve performance and success of sand dams which also would bring the following benefits;

i) Sand dams located in suitable sites will provide sustainable water and minimize conflict between communities in water scarce areas. Farmers will also have opportunities to invest in more advanced farming activities for example inter-cropping, diversification of crops and small scale irrigation

ii) There will be minimal wastage of resources when sand dams are constructed in suitable sites

iii) Sand dams will be located at the sites where contamination of water is minimal hence the local communities will have access to good quality water and in return contracting waterborne diseases will be reduced. The availability of water from sand dams will open up other farming activities such as small holder irrigation of high value crops along the riverbeds hence improve food security and income for the local communities.

iv) The information gathered on the technical conditions necessary for successful sand dam will be put in a database that can always be refereed by other interested parties in future when they want to establish areas of improvement and adjustments.

v) Equitable distribution of water available in the sand dams will be achieved since from the proposed approach, priority for sand dam construction will be given to areas having relatively higher population than in areas with low human and livestock population. Accessibility and availability of water resources from short distance location of fully installed sand dams will allow the local communities engage in other income generating activities.

vi) Sand dams will provide another alternative for reliable and clean sources of water for both domestic and cropping activities. Properly sited sand dams will provide natural filter to clean and improve the quality of the water.

vii) Sand dams will promote sustainable land management practices and promote natural regeneration.

1.8 Conceptual model

The conceptual model is based on the hydrological principles and functioning of a sand dam. The physical processes and characteristics of the riverbed contributes more in the generation of material suitable for sand dams. The environmental factors such as the rainfall, land use and ecological zonation greatly influence the surface runoff and the overall effectiveness of the sand dams. The socio and economic factors contributes more in the consumption and the rate at which water is abstracted from the sand dams. All these factors will generally lead to varied degree of suitability of a site for a sand dam. The identification and evaluation of suitability of sites for sand dams is controlled by the favorability of the environmental conditions and the general physical characterization of a site. Based on the literature review and the field observations, the conceptual model of this study was as shown in Figure 1.1. The influence of each of the spatial components describing the physical characterization of sites, environmental factors, and socio-economic factors plays a big role in the overall suitability of sites for a sand dams.

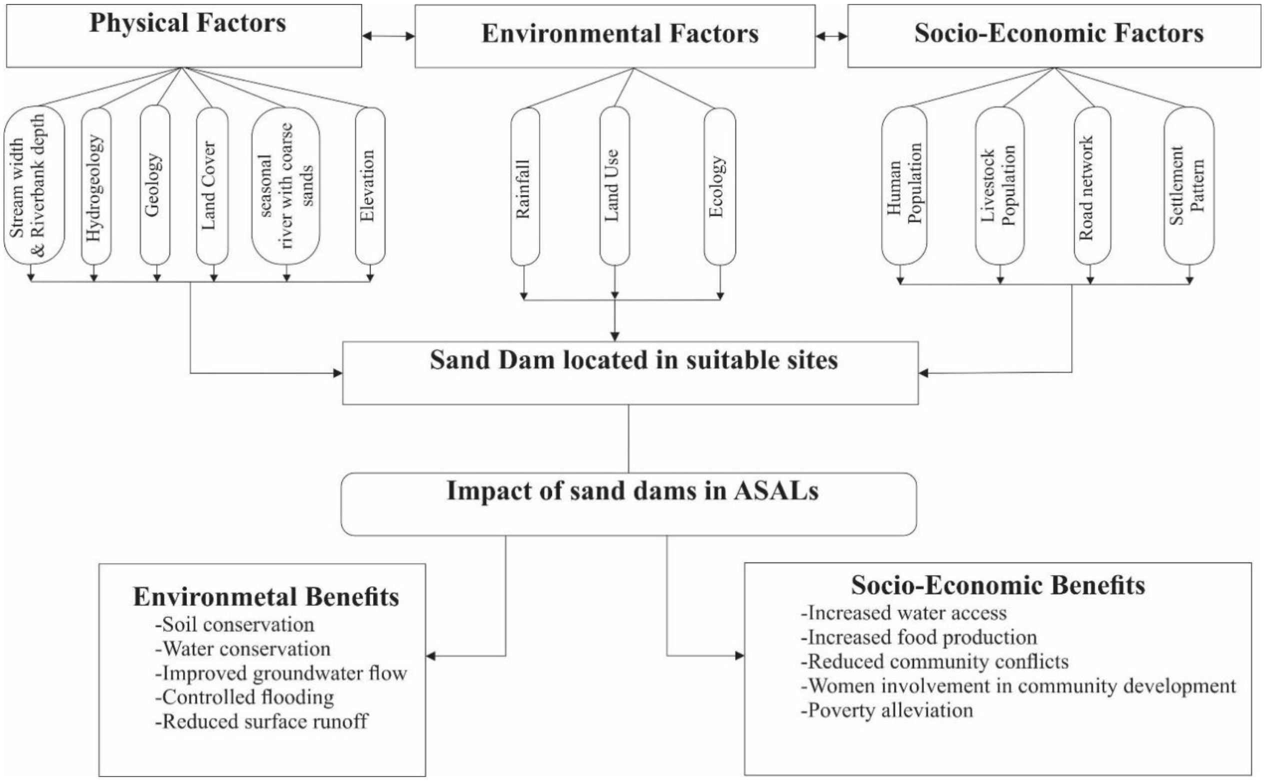

Figure 1.1: Conceptual model of the study

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is focused on the review of literature on the different criteria that has been used to locate sand dams in various parts of the world, Africa and in Kenya. The focus is on the scientific and technical methods applied to evaluate suitability of sites for construction of sand dams and enhancement of their performance. The chapter also provides some details on the knowledge gaps established from the literature review.

2.2 Global existence of Sand Dams

Sand dam is a structure normally developed across a sand river channel for water harvesting and holding coarse sand on the riverbed (Nissen-Petersen, 2007). Sand dams are based on structures that have been built since 400 BC (Maddrell, 2016). Normally, sand dams are built in the transition zone between hills and plains where the gradient of the riverbed is between 1.5% and 8% that is, the upper-middle sections of a river catchment. When river flows contain sand, it has been observed that coarse sand can produce up to 350 litres of water per meter cube of sand (Nissen-Petersen, 2007). This represents an extraction rate of 35% of the volume of the sand (Hut et al., 2008). The value as well as the rate of water infiltration is however lower in finer sands (Nissen-Petersen, 2007).

Sand dams have been used extensively for supplying water to communities in various parts of the world. The construction and utilization of sand dams in the world is observed since the mid-1800s. The history shows that structures similar to the sand dams were used during the Roman times and spread into the Middle East and the US especially in the south-western parts as well as in the northern parts of Mexico. Particularly sand dams have been utilized in India, South Eastern parts of the USA, NE Brazil, Mexico, Middle East countries such Iran, Jordan, Turkey, Yemen, India, Nepal, Northern parts of Thailand and Australia. Several good examples are also observed in many drylands of Africa such as Kenya, Tanzania, Ethiopia, Burkina Faso, Mozambique, and Angola (Kheirkhah et al., 2008).

Organizations such as the UK charity Excellent Development has been actively involved in the construction of sand dams in both Africa (including Zimbabwe and Mozambique) and Asia (Rajasthan- India).Sand dams in Kenya started in the 1950s and 60s when the colonial Kenyan government built the first dams in Kitui District the current Kitui County. Due to favorable environmental suitability for the sand dams' development, much of the effort from the Excellent Development is focused in Machakos and Makueni Counties in South East Kenya.

2.3 Stream morphological influence on suitability of a site for a sand dam

The traditional method applied in the identification of suitable sites for sand dam is the same across the world (Haveren, 2004). Site survey for sand dams are preferably carried out towards the end of a dry season when the water level is at the lowest along the riverbeds. However, suitability of a site for a sand dam is affirmed with the general characteristics of the geology, soil, stream dimensions, and firmness of the river banks, accumulation of sediments, and availability of coarse sands. Suitable soil conditions are recommended to ensure that during the rainy seasons, the selected sites are capable of yielding substantial sediments along the river channel to fill the sand dams (Quillis and Lange, 2009).

Practically, rivers exhibit characteristic changes as it extends down its course. These changes show a recognizable pattern and variation in terms of the energy, discharge, velocity, channel characteristics and load on the riverbed (Love and Singh 2011). Since the rivers are in continuous interaction with the physical environment as well as climate and human factors considerable changes in varied temporal and spatial scales are observed in both the landforms and processes of rivers. Wide stream increases transport of water from the source in the headwaters to the mouth (Bouwer, 2000). The river channel becomes wider and deeper and as a result its cross-sectional area increases. The nature of bedload also changes downstream. In the upper course of the river bedload is larger and more angular. As we track the river downstream bedload becomes much smaller and smoother. In the lower course bedload can only really be found in the form of fine sediments and muds, known as alluvium (Bouwer, 2000).

Erosion results to mass movements hence promoting sand production and movement along the riverbed. The river has greater potential energy to erode in the upper course of the river. This is due to the height difference between its altitude and the base level. In the middle and lower course the river has increased in discharge as well as suspended load. As a result, the river erodes laterally on it banks. The consequence is a wider river channel. Constructing sand dams in very wide river channels beyond 30 meters is not recommended due to possibility of failure and high initial cost (Borst and Haas, 2006). The nature of river banks is an important determinant in the siting of a sand dam. Sites with high riverbanks and lower slopes are also desirable.

2.3.1 The influence of Particle-size and depth of the riverbanks

The sediment characteristics play an important role in enhancing water storage in a sand dam. Sand dams work excellently in rivers that are well supplied with coarse sands (Nissen-Petersen, 2007). High accumulation of coarse sands creates room for subsurface storage of water that infiltrate through the sand and therefore can be tapped during the dry periods of the year in arid and Semi-Arid Lands. The grade of sand particles as well as their uniformity are equally important factors of consideration when locating the suitable sites for sand dams. The coarser sand has the highest settling velocity and deposits upstream of the sand dam while suspended material with smaller grain sizes, such as silt, will wash over the top of the dam and continue downstream

Analysis of sediments on the riverbed is an important step to ensure that the appropriate sands are available for storage of water in sand dams. The analysis of sediments involves determination of the particle-sizes, porosity and depth of the accumulated sediments. The sediments with high content of coarse sands and medium sands are deemed suitable for high storage capacity sand dams. Normally stream channels with high accumulation of coarse sand are the most suitable for sand dam (Nissen-Petersen, 2007). High percentage of coarse and uniform sands will result to a high storage and abstraction potential from the sand dam. The river channels with clay sediments are not suitable due to low permeability (Maddrell, 2010). The ideal sites should consist of consolidated rocks forming the base of the sand dam as well as the riverbanks. The river banks that consist of loose soil materials may not be suitable due to increased possibility of erosion of the banks and subsequent collapse of the sides of sand dams rendering the whole structure unstable.

The ephemeral rivers consist mainly of high infiltration sands (Jansen, 2007). Such streams allow some portion of the water flowing in the river to infiltrate into the riverbed. An impervious layer that exhibits very low or no permeability (weathered or fresh hard rock) near the base of the river allows the infiltrated water to remain within the riverbed sands. Because the infiltration capacity of the coarse sand in the riverbed is very high, the amount of infiltration depends mainly on the available space in the riverbed (Jansen, 2007). This available space is determined by the thickness and width of the riverbed and by the porosity of the material in it. Water can move between the river bed and the river banks, which usually consist of silt and clay with a lower permeability than the river bed. Water in the riverbed storage will flow to the lowest point as well as downstream, until it is obstructed by a natural barrier (rock outcrop) or a sand dam. According to Hutet al., (2008) the rate at which the stored water in the riverbed flows down the stream is dependent on the riverbed gradient and permeability of the river sands. On the other hand water in the riverbanks is lost through evapotranspiration especially where the vegetation cover is present (Domingo, 2001). The amount of water lost through evapotranspiration will depend on the extent of vegetation cover, the depth to the water table and also the factors that define the climate of a given area.

2.3.2 Accumulation of sand on the riverbeds

According to Kirkby and Morgan (1980), hydrological performance of a given sand dam site is also influenced by soil erosion and the physical characterization of the sediments available along the riverbed. According to Foster et al. (1977) water is the most dominant agent of erosion that triggers detachment, transportation, and deposition of individual particles or sediment by raindrop impact and flowing water. This process is therefore deemed fundamental when trying to understand the history and physical characterization of the sediments that are suitable for sand dams. Geertsmaet al. (2010) noted that erosion processes and sediment yields can be related to the interaction between erosive energy and vegetation density even if climatic seasonality, relief, basin lithology and the extent of human activity combine to influence the global pattern of erosion processes. Wolman and Gerson (1978) noted that the estimation of the sediment transport during several events is necessary for the calculation of long-term sediment yields from basins, as one single event may represent the transport of several 'normal' years.

Foster et al. (1977) noted that detached particles are laterally transported to the rills by a thin overland flow and this process is called sheet erosion or inter-rill erosion. Most downslope sediment transport is carried through flow in the rills. Bank erosion leads to channel meandering which results in excessive erosion and deposition within the floodplain. It should be noted that if the amount of detached soil is more than the transport capacity, only the transportable amount will be carried down-slope and the rest will be deposited on the riverbed. The process of soil erosion supports the generation of sands that are transported downstream along the river channel leading to substantial amount of sands to accumulate to the river channel. These sites can be suitable for water storage.

2.3.3 Geological influence on suitability for sand dam

To avoid costly failures and disappointment of the communities who contribute free labour and local construction materials, it must be verified in advance whether the river-bed can actually hold water. A sand dam should, preferably, be constructed on an underground dyke. The underground dyke which dams-up water for the water-holes, can also be in the form of a clay or rock barrier protruding upwards from the floor of the river-bed. The highest point of the underground dyke can be a suitable site for constructing a sand dam with minimum materials and labour.

The correct siting is important for minimizing the construction work and maximizing the storage capacity of sand rivers. Other factors to consider when determining potential sand dam sites should be; locations on ephemeral sandy riverbed (Beimers et al., 2001a) which is periodically flooded during a normal season. The riverbeds should be comprised of coarse sand (Neessen, and June, 2004), with large voids for maximum storage of water – the finer the sand, the less water it can store. Sites with large boulders, fractured or saline rocks should be avoided (Neessen, 2004). If saline deposits are situated in or upstream of a reservoir, its water will be saline or brackish.

Constructing a sand dam at site where water stored in the sand can be retained for about a month are recommended. Whenever possible, it is desirable to build the dam wall at the narrowest point where basement rock with low permeability makes a gorge with a vast aquifer upstream (Rempel et al., 2005). Sand dams should not be located where waste from villages and other places can contaminate the riverbed. For soil conservation purposes, the sand dam should be built as close as possible to the head of the stream as this is where the water begins to erode the soil. For water supply augmentation and soil conservation purposes, it might be better to build a series of small dams along the same stream, rather than building one large dam. A sequence of small dams increases deposition of silt in the water and improves infiltration more than a single large dam (SASOL and ACACIA, n.d.).

2.4 The influence of precipitation on sand dams

According to Jothityangkoon et al. (2001), the most important factors controlling the rainfall-runoff relation in semi-arid regions are the spatial distributions of soils, vegetation, and climate. Maddrell (2016) noted that it is very important to study how a river has flowed at least for a period of 25–50 years before designing a sand dam. From these perspective sand dams and their performance would be associated with the physical characteristics of the river sands accrued from the past rainfall events such as the grain size, rate of infiltration, porosity and permeability, soil types, stability of the river banks, slope, potential runoff, resistance to particle detachment, and availability of underground dyke/ rock. In addition, land use, rainfall amount and intensity, and vegetation cover are other factors that would influence the suitability and sustainability of a sand dam. The interactions of these factors vary from one area to another thus the spatial variation of the sand dam performance and site suitability.

Precipitation is a fundamental factor that initiates sediment transport from the source points. The amount of precipitation determines the amount of sediments that can be transported by the resulting surface runoff. According to Walling and Fang (2003) analyzing flood events is an important step in evaluating the peak period for maximum sediment yield. Additionally, actual evapotranspiration represents an important feature and it is recognized as the main hydrologic loss (50-60 % of mean annual rainfall). In the semi-arid for instance, they experience a spatial temporal climatic variability due to the high variability of rainfall patterns including the influence of topography and the spatial distribution of geology, soil, and land-use. General sediment load is generally high and it reaches maximum values at the beginning of the flood season and after dry periods.

According to Wolman and Gerson (1978) the relationship between rainfall, runoff and soil loss are of critical in nature and hence more studies have been undertaken on these relationships. Since runoff transports sediment particles, its seasonality, and peak value affects the high sediment load in rivers. Maximum sediment yield occurs at an annual precipitation of approximately 300 mm. When the precipitation exceeds 300 mm, increased vegetation growth protects the surface. Other studies have demonstrated the role of intensity of rainfall in sediment detachment and transport.

Several studies have focused on the performance of sand dams in terms of water storage and influence on groundwater flow. Borst and De Haas (2006) has documented the hydrological performance of sand dams. From this study Borst and de Haas studied on the contribution of rainfall as the main recharge of the sand dams, assessed on how infiltration in different soils and evapotranspiration influences the quantity of water stored in the sands and the fluctuation of the groundwater level in the area located near the sand dams. Hoogmoed (2007) also studied on the impacts of sand dams in groundwater flow by focusing on the local groundwater dynamics on one sand dam (Kwa Ndunda sand dam).

Dunne (1979) investigated sediment yields on a broader area of southern Kenya and concluded that land use was the dominant control, although the influence of surface runoff and topography was also recognized. He proposed equations to determine yield for four land use categories: (a) forested; (b) forest > 50%; remainder cultivated; (c) agricultural land > 50%, remainder forested; (d) rangeland. Yield from the agricultural land and grazed land was significantly greater than from partially or completely forested basins. However, there was great variability within each land use class and especially in cultivated catchments.

2.4.1The influence of stream channel height and discharge

According to Maddrell and Neal (2012) before any site is considered for sand dam construction, it is recommended that the water level and the maximum flood level remain below the riverbanks after construction of the dam. If the flood level exceeds the riverbanks (Bh) the construction of the sand dam is not worthwhile. The sand-height therefore is determined by the considerable maximum discharge and the maximum flood height.

The scenario shown in Figure 2.1 means that flooding and thus severe erosion of the riverbanks (eventually causing failure) will not occur. In order to calculate maximum discharge, the correct measurements for example flood levels are gathered from the field. The maximum discharge can also be calculated by measuring the highest flood level or by using a certain return period or by using a rainfall-runoff model or a mathematical formula for rainfall runoff. However, the most practical way to calculate maximum discharge is by using field measurements.

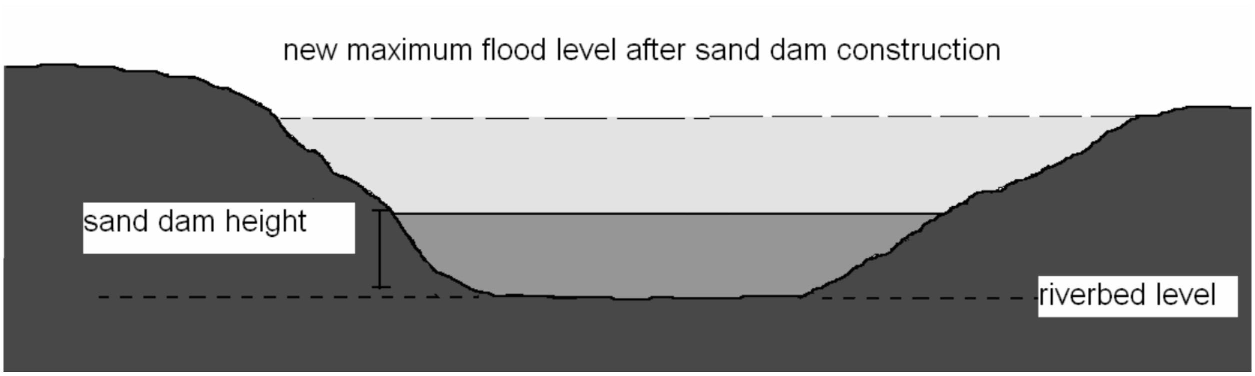

Figure 2.1: Recommended sand dam height based on the maximum flood level and the riverbank depth.

Figure 2.2 shows the cross-sectional view of sand dam located across the riverbed. The indicated parameters are measured to calculate maximum discharge at that site.

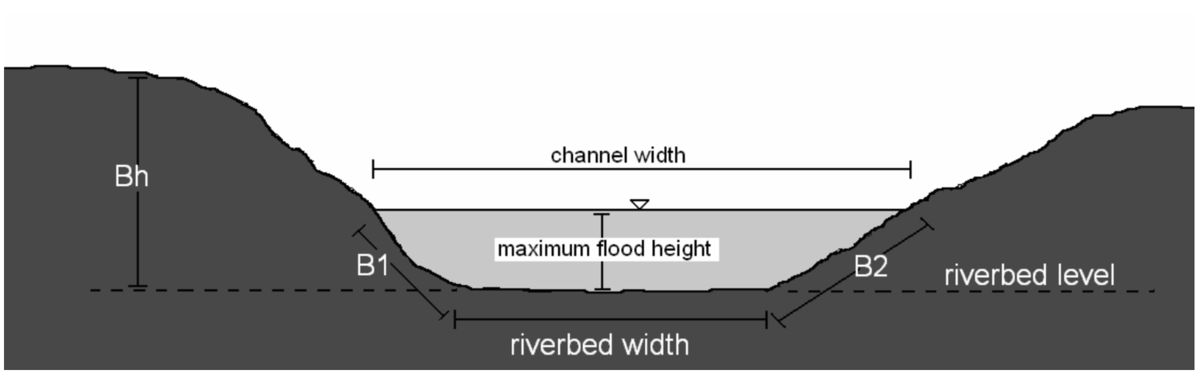

Figure 2.2: Sand dam site cross-section

The Maximum discharge (Q) can then be calculated using the following equation;

$$Q = {}^{1}/_{n} * A * R^{2/3} * S^{1/2} \text{.. (Equation 2.1)}$$

Where:

Q = maximum discharge in riverbed section (m^3/s)
n = Manning roughness of riverbed
A = wetted cross-sectional area (m^2),
A= ½*(channel width + riverbed width)* flood height) …………………… (Equation 2.2)
P = wetted perimeter (m), (where P = B1 + riverbed width + B2)
R = hydraulic radius (m), (where R= A/P)
S = slope of riverbed (m/m)

Generally, water storage capacity within a given cross-section is an important consideration since it determines the ability of a sand dam to satisfy the desired local water needs. Thus, the sites should provide an opportunity for storage of adequate amount of water to meet various water use needs within a given locality. The water storage capacity is normally based on the determination of the potential sand volume within the stretch of the river channel that is considered suitable. This is based on the maximum dimensions of the sand dam that can be constructed at the site. The volume of water held in a sand dam is a function of the volume of the sand and the portion occupied by pore spaces. A substantial volume of the sand dam (approximately 25-30%) is normally occupied by sand and the rest of the volume is occupied by water (Borst & Haas, 2006).The volume of water that can be extracted from a correctly constructed sand dam depends on the coarseness and volume of sand that is contained in the dam. The maximum volume of extractable water is equivalent to 35% of the total volume of the sand (Maddrell, 2016).

2.4.2 Stream order and infiltration level

Infiltration and runoff generation are closely related since the amount of water which cannot infiltrate into the ground generates runoff which is also known as Hortonian overland flow (Horton, 1933). Tate (1996) noted that this Hortonian overland flow is the main runoff generating mechanism in semi-arid regions. The first amount of water that cannot infiltrate into the ground will accumulate in small depressions on the surface causing depression storage. This is also evident at the river head where the gradient is high and low volume of water accumulated. The actual runoff commences when these depressions are filled. The infiltration capacity of the ground depends on soil characteristics, such as porosity and grain size distribution, and on the water content of the soil (Ward and Robinson, 2000). However, Castillo et al. (2003) state that antecedent soil moisture does not influence runoff response in semi-arid regions with short precipitation events with a high intensity. Another important factor which controls the infiltration capacity of the soil is the formation of crusts. The limited vegetation cover in semi-arid areas leaves large parts of the soil unprotected from raindrop impact which can cause this crusting of the soil (Wheater, unpublished). Crusting of the soil can drastically decrease its infiltration capacity, increasing surface runoff. According to RilleHis Lambers et al. (2001) vegetation can greatly improve the infiltration capacity of a soil.

Areas with a potential of high rate sand accumulation are commonly found in depressions or lowlands where more deposition takes place. These points are the most suitable for construction of high-yielding sand dams since there is minimal runoff and high likelihood of water infiltration through the sands. Based on this view, various sites can be categorized as “very high”, “high”, “moderate”, “low”, or “very low” rate of sand accumulation. Areas with very low sand accumulation rates and/or high clay and silt deposits were rated as being unsuitable for construction of sand storage dams due to the high potential of siltation.

2.4.3 Loss of water in the riverbed

Evaporation occurs from open water surfaces (sheet and concentrated flow) and from the groundwater at shallow depths. The amount of evaporation from open water surfaces depends on the local meteorological conditions (Domingo et al., 2001). The amount of evaporation of underground water depends on the depth of the water table, the grain size of the sediment in which the water is stored and the potential evaporation, which depends on the local meteorological conditions. Evapotranspiration occurs throughout any catchment. The amount of evapotranspiration of water from the channel bed storage depends on the potential evaporation, the amount of vegetation present near the channel, the zone of influence of the vegetation and the availability of water in the channel storage. On the riverbanks, evapotranspiration by vegetation is considered as a depletion mechanism (Domingo et al., 2001 and Dahm et al., (2002). However the nature of sediments occurring along the riverbanks may influence the rate of evapotranspiration depending on whether the vegetation are shallow or deep rooted (WWD, 2000).

A study conducted in the arid and semi-arid lands in the Saudi Arabia and Arizona shows that a large portion of the precipitation is lost through evaporation (Wheater et al., 2002). However Andersen et al. (1998) and Parrisopoulos et al. (1991) indicate that the percentage of precipitation lost through evaporation maybe low and would not lead to any significant influence in water balance especially after some water infiltrates through the sediments into the water table. Biamah et al. (2004) on the other hand stated that high rates of evapotranspiration is observed in the soil-water zones but negligible impact on the riverbanks.

Water in the riverbanks is very susceptible to evapotranspiration since there is usually a relatively large amount of vegetation present in these parts of the catchment. The amount of evapotranspiration depends on the amount of vegetation present, the depth of the water table and on local climatological factors (Dahm et al., 2002). According to Dahm (2002) and Domingo (2001), evapotranspiration by vegetation along channels accounts for a large part of water losses from rivers in semi-arid regions. Water which is stored in the riverbanks can also flow back to the riverbed when the water level in the riverbed is lower than in the river banks. The riverbank storage might also be replenished by water which infiltrates the upslope areas. Most of this water will be lost through evapotranspiration (Kinama, 2005), but a small amount might percolate to the deep groundwater or flow to the riverbank storage.

2.5 Spatial modeling for sand dam site suitability

Geospatial technologies have been applied in mapping water resources. Rao et al. (2009) carried out hydrogeological mapping coupled with hydrogeological investigations for evaluating groundwater potential in Madhurawada, India using GIS. Ganapuram et al. (2009) mapped ground water potential zones in the Musi basin using remote sensing data and GIS. Kamaraju et al. (1996) performed an evaluation of groundwater potential of a district in India using GIS approaches. Shahid et al. (2000) used GIS in the analysis of hydrogeological data acquired from remote sensing and surface geophysical techniques in the assessment of groundwater condition of a soft rock terrain in Midnapur District of India.

Aliet al. (2014) embraced the art of remote sensing technique where satellite data was used to map and evaluate the suitable sites for subsurface dam construction in Isayi watershed which is located in Garmiyan area in Kurdistan region. From this study the potential sites for subsurface dams were evaluated in terms of the landforms that were identified from the satellite images. Further investigation on the identified suitable landforms in the study area was done using ground penetrating radar techniques to enhance on the subsurface observations for identification of faults and fracture zones. From this method it was possible to tell the level of groundwater table fluctuations from different lithology and geological formation by monitoring the drop down from selected boreholes. The advantage in this method is that there is high assurance on the concluded productivity of the identified sites for the sand dam however this method is limited to one catchment and the procedure is relatively expensive. The art of locating suitable sites for sand dams and the general management of water abstracted from sand dams is meant to be cheap for the local communities in ASALs and therefore the procedure may not be very viable when assessing more than one catchments.

2.5.1 Spatial Analytical Hierarchy Process

The AHP is a GIS tool that is used for suitability analysis by integration of different spatial components through a Multi-Criteria Decision Making (MCDM) approach. The Spatial Analytical Hierarchy method was introduced by Saaty in the mid-1970s and developed in 1980s (Satty, 1980). AHP is one of the most comprehensive models designed for decision using a multiple criteria. This technique allows formulation of a problem hierarchically and also provides the possibility to consider various qualitative and quantitative criteria (Jafari and Zaredar, 2010). This process involves different options in the decision and allows the sensitivity analysis on criteria and sub-criteria as well. Moreover, pairwise comparison built to facilitate judgment and calculations are superior benefits of this technique in multiple criteria decision (Table 3.6). In addition, the approach is built based on a strong theoretical basis and clear principles (Satty, 1980).

The combination of Spatial AHP method as one of the commonly used methods of Spatial Multi Criteria Analysis (SMCA) with GIS is a new trend in land suitability analysis (Jafari and Zaredar, 2010). Analytic Hierarchy Process is also recognized as the fastest growing decision-analytic techniques (Bello et al., 2009). Cell-based Multi-Criteria Evaluation (MCE) method is also used in suitability analysis on land for uses such as arable farming or irrigated agriculture. Land suitability evaluation is a prerequisite for land-use planning and development (Sys, 1985). The aim of Multi-Criteria Decision Analysis (MCDA) with Geographical Information Systems (GIS) is to provide more flexible and more accurate decisions to the decision makers in order to evaluate the effective factors. Furthermore, by changing the parameters in this type of method, a wide range of decision strategies or scenarios can be generated in some procedures (Mokarram & Aminzadeh, 2010).

Mendoza (2000) identified five benefits of the Analytic Hierarchy Process (AHP) over the other site suitability analysis techniques: it breaks down the suitability analysis problem into hierarchical units and levels for better understanding; AHP relies less on the completeness of the data set, and more on “expert” opinions or observations about the different factors and their perceived effects on site suitability. The approach is more transparent and hence more likely to be accepted especially when the suitability analysis will ultimately serve as a basis for land allocation. AHP also allows both experts and stakeholders in providing the suitability measure of a site relative to a proposed land use. Such framework allows the incorporation and accommodation of both qualitative and quantitative criteria for assessing site suitability. Although many of the GIS-based land suitability analysis approaches such as Boolean overlay and modelling for land suitability analysis have been developed, the approaches lack a well-defined mechanism for incorporating the decision-maker's preferences into the GIS procedures (Malczewski, 2006).

The main steps in AHP include developing comparison matrices in each level of the hierarchy to compare the weight of each component of them and to estimate the compatibility rate of decision. The eigenvector method is a common way to achieve the parameters weight of a pairwise comparison matrix, where the eigenvalues of a pairwise comparison matrix obtained from the following equation.

$$|A - \lambda I| = 0 \text{……………………………………………. (Equation 2.3)}$$

where, A is a comparison matrix, λ matrix eigenvalue A and I is the identity matrix. Final weight (W) of putting the maximum eigenvalue in the following equation will be calculated.

$$(A - \lambda_{max} *) * W = 0 \text{…………………………………. (Equation 2.4)}$$

In order to measure the incompatibility rate, at first the Consistency Index (CI) is calculated as follows.

$$CI = \frac{\lambda_{max} - n}{n-1} \text{……………………………….…………… (Equation 2.5)}$$

In this formula, n is the number of criteria with A matrix dimensions, and then the incompatibility rate is determined as follows.

$$CR = \frac{CI}{RI} \text{…………………………………………….. (Equation 2.6)}$$

where RI is random index based on Satty (1980) which is dependent on the number of compared components (Table 2.1)

Table 2. 1: Incompatibility index used in the pairwise comparisons

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1,24	1.32	1.41	1.45

The compatibility ratio (CR) is designed so that if it is less than 10% then it can be concluded that there is a desirable level of compatibility in pairwise comparisons and otherwise represents incompatibility judgment (Satty, 1980).

2.6 Research Gaps

Despite the wide application of sand dam technology in the supply of water for communities in the arid and semi-arid lands, there is little work done to assess the factors that determine the suitability of the sites for the construction of sand dams in arid and semi-arid lands. Poor performance of sand dams has been attributed to inadequate evaluation of their location characteristics against a well-tested site selected criteria. A lot of studies have been undertaken on the characterization of sands in sand dams (Neessen, 2004; Borst and de Haas, 2006; Quillis and Lasarge, 2009; Rampel et al., 2005). Studies on the general socio-economic and environmental benefits associated with the sand dams have also been undertaken (Munyao et al., 2004; Ryan and Elsner, 2016). However, there is little information on how sand gradation influences optimum performance of sand dams.

Afifi and Fuladipanah (2015) used GIS to study suitable sites for subsurface dam in Chamasiab plain, a semi-arid region with surface water crisis in Khuzestan province, Iran. For this study, feasibility study was done using GIS based on nine parameters namely: topography, unsaturated zone, hydraulic conductivity, electric conductivity, specific yield, alluvium thickness, water table depth, hydraulic gradient, surface drainage density. After assigning weights for each parameter, suitable sites were determined through an overlay procedure using GIS.

Ryan and Elsner (2016) investigated on the effectiveness of sand dams in the adaption to climate change in the East African drylands. From their findings they noted that by using a time series satellite image analysis, the normalized difference vegetation index (NDVI) is reliable in monitoring the impact of sand dams in the maintenance of vegetation biomass during prolonged drought periods. This study however did not make any conclusions on the appropriate procedure that should be applied in selecting the best sites for sand dams with vegetation biomass deficiency nor pointed out areas where sand dams is most applicable in controlling vegetation biomass.

Literature shows that the AHP technique has been very successful in the assessing the suitability of land for different cropping activities. The benefits associated with GIS and RS technique in the agricultural sector are evident in several parts of the world for example wheat and rice production. Several studies show this technique being widely applied in the Middle East countries, Asia and Far East and some parts of Kenya. However this technique has been applied by few researchers in

Kenya in mapping the potential zones for groundwater (Gachari et.al, 2011; Chebet, 2012; Kuria, 2012).

Barkhordari (2015) used the Analytical Hierarchy Process to establish the influence of various spatial component in the determination of suitable sites for sand dams. Barkhordari included the component of territorial analysis using satellite images, hydrological and climatological information. The study concluded that this technique is relatively cheap compared to the tradition method where much money and time is spent in field work. However the method he applied is an approximation of the suitable sites for sand dams. The study also utilized the median sand particle sizes (D_{50}mm) as a parameter in the quantitative analysis of spatial distribution of appropriate sands particle sizes suitable for sand dams. Using the median size (D_{50}) does not exactly show the distribution coarse sands and is therefore not reliable where sand gradation is spatially varied.

Previous studies do not show the influence of the uniformity and gradation of sands in the determination of suitable sites for sand dams. This study attempts to use the concept of varied particle sizes represented as D_{10}, D_{30}, D_{50}, D_{60}, and D_{90} in the proposed criteria to show how distribution of particle sizes influences sand uniformity and gradation. Uniformity and gradation of sands for the sand dams are two important parameters that should be evaluated to establish the storage capacity of sand dams and how it varies from one site to the other along the riverbeds. This is an added value in the determination of suitable sites for sand dams using the GIS based Analytical Hierarchy Process.

CHAPTER 3

MATERIALS AND METHODS

3.1 Introduction

This chapter is focused on the presentation of the methodology that was applied in this study. The chapter also presents the details on the key features of the study area. Most of the data and information used to prepare this study was collected from the field and various departments from the national and county governments.

3.2 Description of the Study Area

The study was carried out in Kitui South which is located in the southern parts of the Kitui County. The Kitui County extends roughly 200 km from north to south and 120 km from east to west with a surface area of 30,496 km^2. The Southern part of Kitui South which is approximately 20% of the Kitui County land cover is occupied by the Tsavo East National Park (Figure 3.1). Kitui South is divided into six administrative wards namely, Mutomo, Mutha, Ikanga, Athi, Kanziko and Ikutha (Figure 3.1). Major hills in this area are Mutha, Mutomo and Nguuni hills. The seasonal streams found in the study area flow for over a distance of 30km which allow runoff from different land use and land cover to interact with varied geology and soil types plus transportation of sediment from the first order up to seventh order.

Based on the data generated from Digital Elevation Model of the study area, Mutha hills is the highest point in Kitui South with an elevation of 1303m above sea level. The lowest point is at the eastern lowlands of Kitui South with an elevation of 136m above sea level. This gives the hydraulic gradient (dh/dL) of about 0.032 as compared to other sub-counties with almost similar characteristics such as Kitui Rural where dh/dL is 0.042 and average river channel length of 23km. Kitui West dh/dL is 0.031 with an average river channel length of 26km.

Kitui South Sub-County exhibits a suitable topography where erosion of outcrops and the seasonal streams drain from the western margin and deposition of sediments on the eastern parts of the area. This gives a relatively adequate stretch of the seasonal streams traversing over a long distance. The occurrence of these seasonal streams also gives a favourable platform for analysis of the stream sediments to establish their suitability for sand dams.

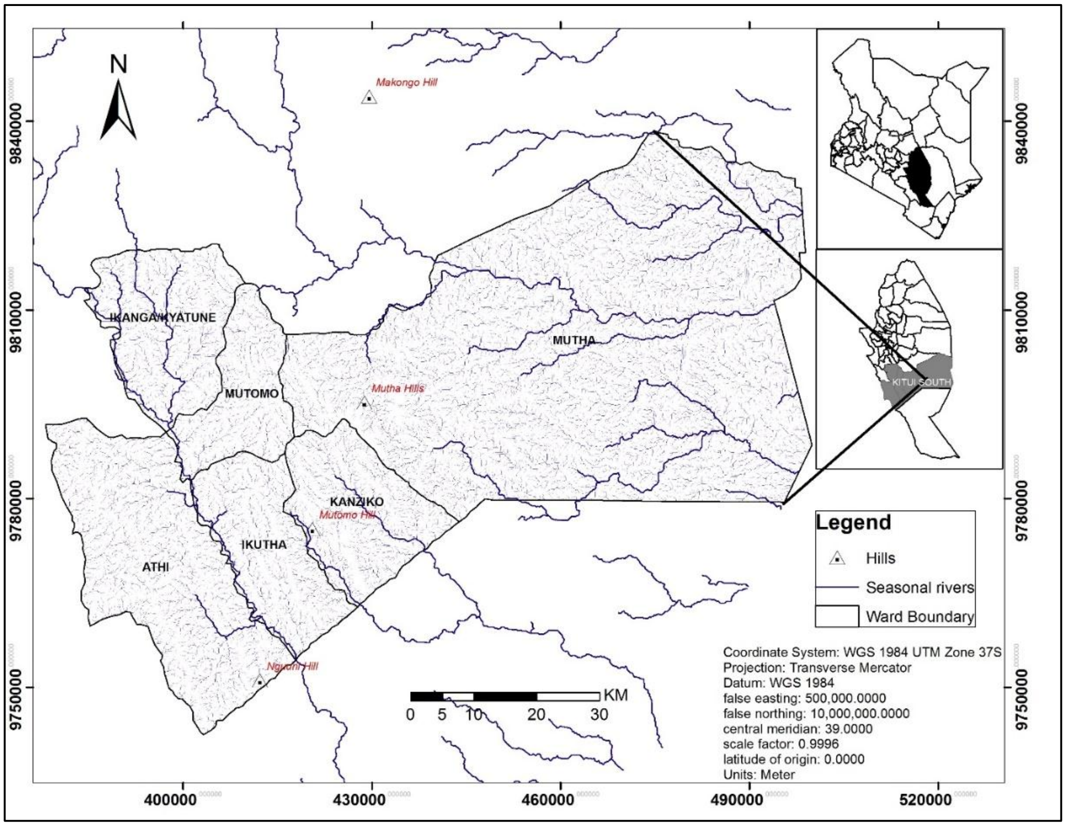

Figure 3.1: Location of Kitui South Sub-County in Kitui County in Eastern Kenya

3.2.1 Climate

The climate of Kitui South is generally hot and dry with erratic and unreliable rainfall typical of arid and semi-arid climatic zones in Kenya (Borst and de Haas, 2006). Erratic rainfall in combination with poor drainage of the soil results in scarce surface water and groundwater resources. The area experiences two rainy seasons with two peaks in April-May (long rains) and November-December (short rains). The rest of the year is hot and dry. The total annual rainfall ranges between 750 and 1150 mm with 40/60 percent reliability (Burger et.al, 2003). Annual rainfall totals in the eastern lowland areas bordering Tana River County are usually less than 500 mm. The average annual potential evaporation is approximately 1800 mm per year, implying most areas of the county experiences water deficit in most periods of the year (Nissen-Petersen, 2007). Air temperature ranges between 16^{o}C and 34^{o}C with mean maxima of 28^{o}C and minima of 22^{o}C (Borst and De Haas, 2006). Relatively lower temperatures are experienced between June and August while high temperatures are experienced in January-March and September-October periods (Borst & de Haas, 2006). The highest temperatures (of the order 34^{o}C) are experienced in February. The prevailing winds are the north and south easterly monsoon winds. The direction of monsoon winds in the area is often influenced by Kitui Mountains found in the central region of the county (UNEP, 2006).

3.2.2 Hydrology and drainage

The study area is well covered with seasonal streams as shown in Figure 3.2. The river discharge is characterized by high flows in April-May and November-December and extremely low or no discharge in the dry periods between January – March and July - October. This strong seasonal contrast in combination with immediate run-off from the hills caused by the poor drainage of the soil, often results in flash floods, transporting large amounts of sand and silt. Most of the ephemeral rivers in Kitui (Figure 3.2) generally dry up within a month after the rainy season (Borst and De Haas, 2006). This study investigated sand gradation in several seasonal rivers in Kitui South namely; Mwila, Kakya, Wiitu, Nguni, Ngunyumu, Muvuko, Kanzilu, Masaa, Katiliku, Ngulungu, Nzeeu, Koma and Katitika.

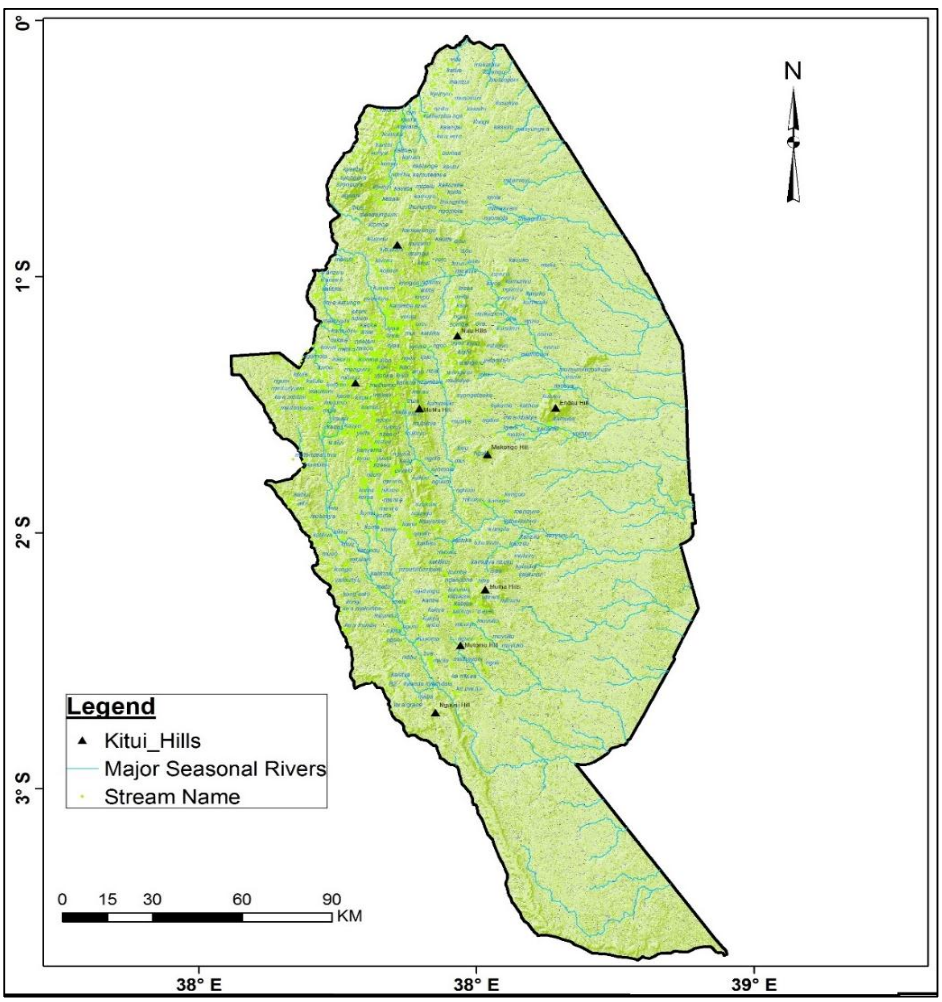

Figure 3.2: Location of the major hills and distribution of the seasonal streams in Kitui County

There are four main groups of aquifers in Kitui South namely; Quaternary superficial deposits, Tertiary rocks, Paleozoic sedimentary rocks and Precambrian crystalline rocks (Louis Berger International Inc., 1983). Tertiary volcanic rocks, forming poor aquifers, and sandstones of Paleozoic age, forming good aquifers, are present (Borst et al., 2006). However, metamorphosed crystalline Precambrian rocks (schists and gneisses) are poor aquifers, although locally water can be stored in fractures, faults, joints and weathered zones. Gneisses are intersected by quartzite veins, forming good aquifers, which can provide water for both domestic and livestock uses.

The Precambrian aquifer is not accessible for manual groundwater abstraction as performed by small communities throughout Kitui South (Borst et al., 2006). For these communities, Quaternary sediments and the weathered zone of the Precambrian rocks are the primary water sources. The alluvial aquifers of Quaternary age form good shallow aquifers. At locations where basement is at shallow depth, natural barriers against groundwater flow through the riverbed are formed. Upstream of these barriers, shallow groundwater reservoirs are formed from which water is extracted through scoop holes. Sand dams are preferably built at these locations (Nissen-Petersen, 2007). Unconsolidated deposits on the riverbanks are less good aquifers, consisting predominantly of silt and clay.

3.2.3Elevation and topography

The elevation of the study varies between 130 and 1300m above sea level (Figure 3.3). Ridges and hills are observed on the western and central parts especially in Athi, Mutomo and Mutha areas. The entire eastern parts of the area is characterized with low terrain with elevation dropping to as low as 130 m above sea level. The Yatta Plateau in the western parts of the area is part of the high terrains in Kitui South.

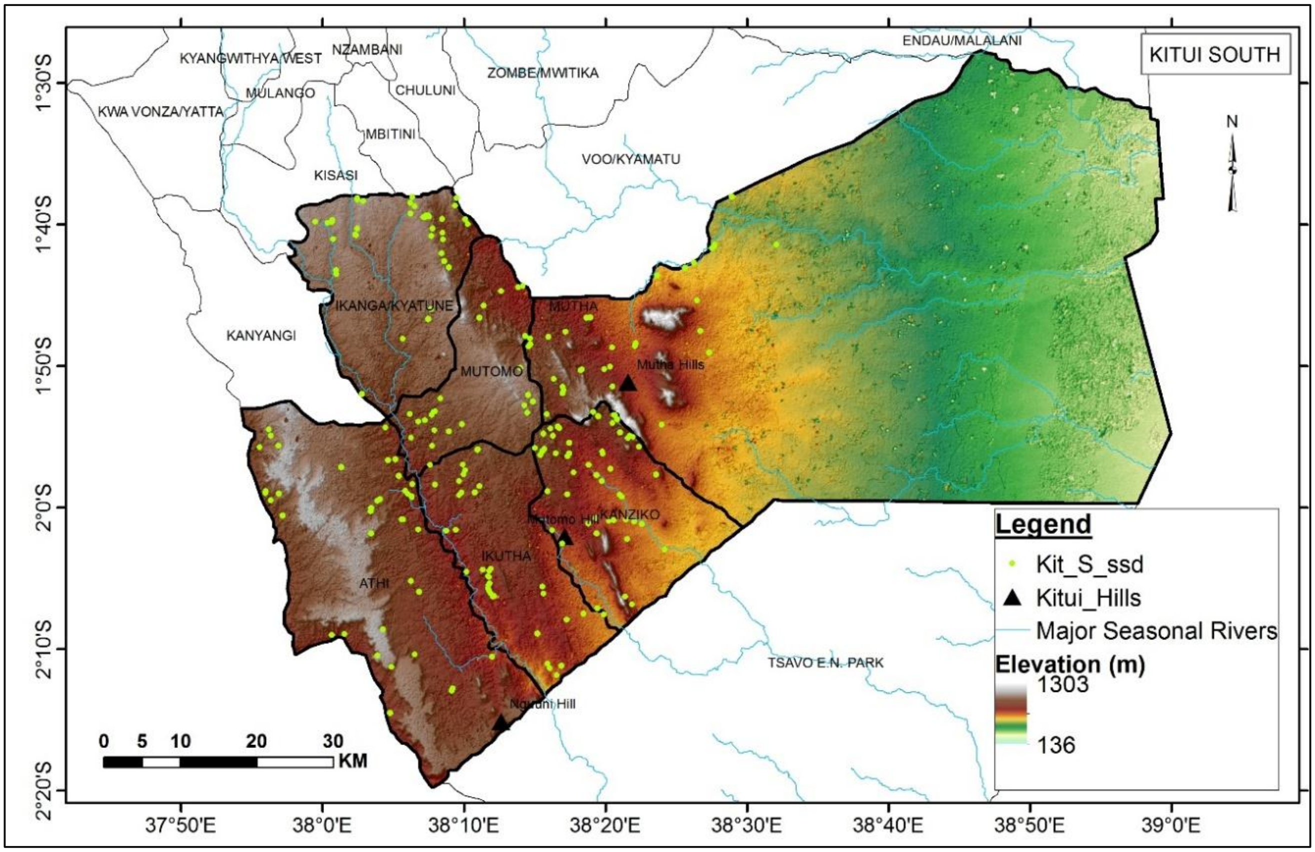

Figure 3.3: The elevation map of Kitui South

3.2.4 Geology

The geology information was important in this study in the identification of the appropriate rocks which could be used as foundation the sand dams. Previous experience shows that sites located on firm rock, less fractured and less weathered are best for anchoring the sand dams. This parameter was therefore important to be included in the evaluation to determine the suitable sites for construction of sand dams in Kitui South.

Generally Kitui County is dominated with three major rock types namely; metamorphic rocks which are overlaid by sedimentary and some pockets of igneous rocks (Saggerson, 1957) (Figure 3.4). The basement consists of the Precambrian gneisses, granitoid gneiss and schists occurring as outcrops and some pegmatitic and quartzite veins which formed at least 540 Ma with a regional North-South trend in foliation. This corresponds to the geology of the Mozambique belt, which is of Proterozoic age (2,500 Ma – 540 Ma BP) and is found in large parts of East Africa (Saggerson, 1957).

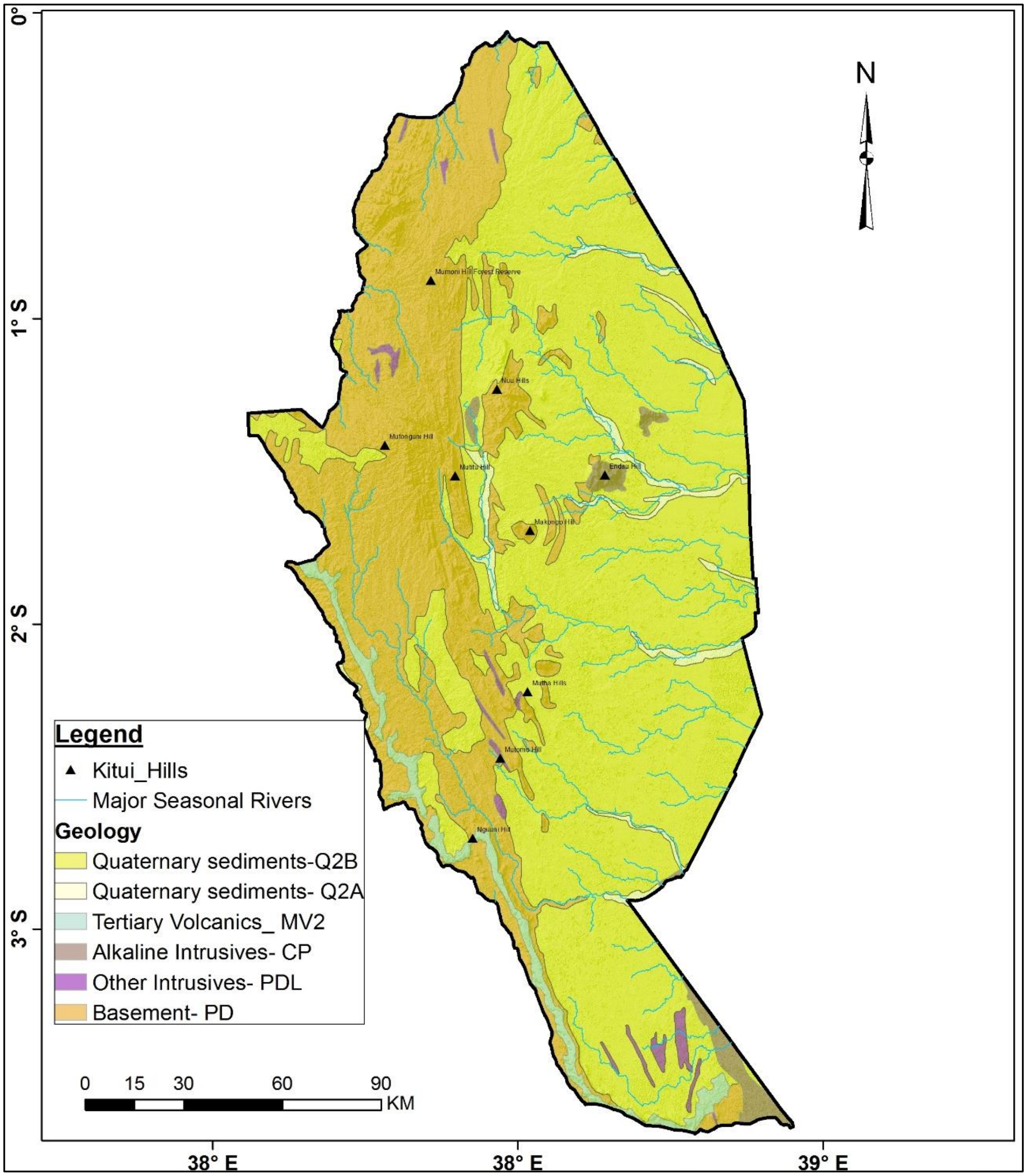

Figure 3.4: Geology map of Kitui County

The geology of Kitui South is spatially varied with different lithological units (Figure 3.5). Quaternary sediments are primarily alluvium, limestone, sand, clay and silt occurring on the hill slopes and on the riverbeds. The basement complex rocks are fractured and weathered and eroded to their current shape. A basement complex of metamorphic and igneous rocks, whose weathered mantle is of varying thickness, occupies much of the western and central parts of Kitui South (Nyamai et al., 2003) (Figure 3.5).

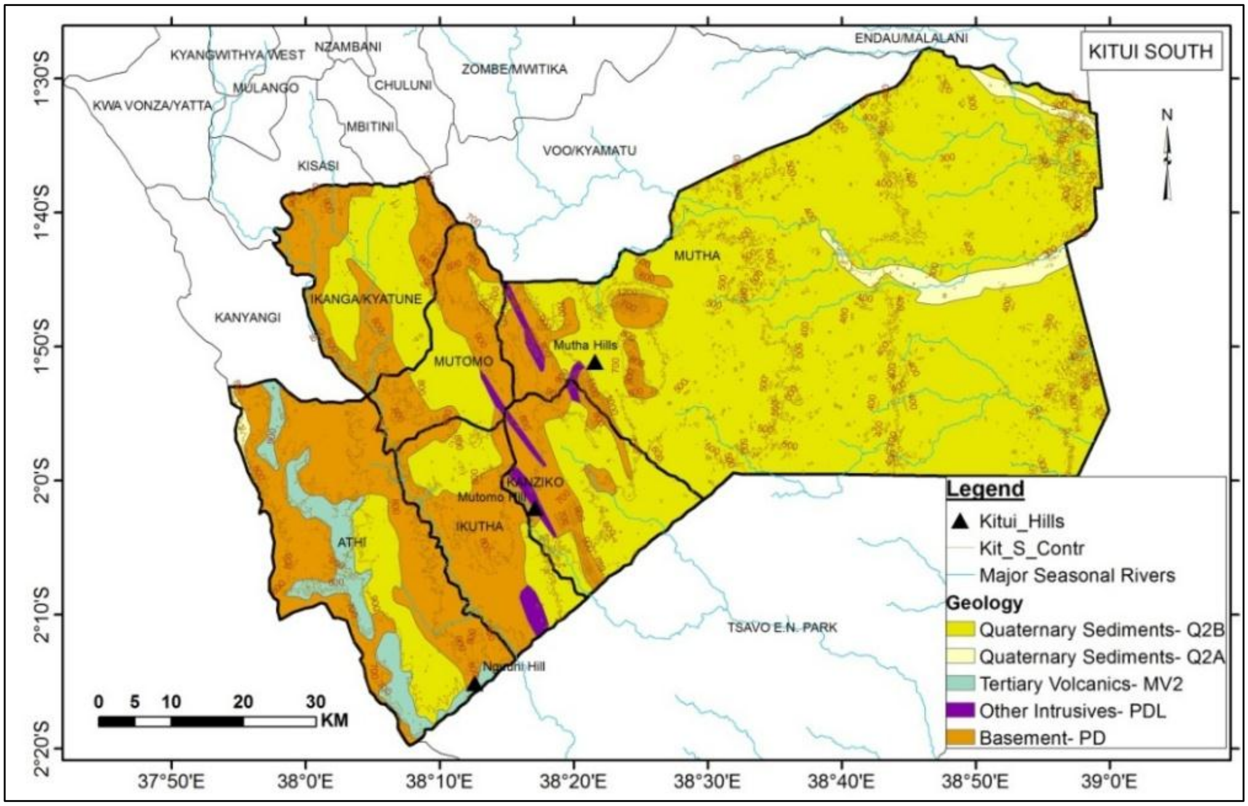

Figure 3.5: Geologic map of Kitui South (Source: Modified after Saggerson 1957)

A large section of the eastern parts of the Kitui South especially in Mutha and some parts of Kanziko ward are dominated with Quaternary sediments (Saggerson, 1957). Intrusive rocks are observed in the central regions stretching from the western parts of Muthato Ikutha-Kanziko areas. Tertiary volcanic and Basement rocks are observed in the western parts of Kitui South.

Black cotton soils occur in the eastern part of Kitui South, but elsewhere distinctive red sandy soils of low fertility are present. The Metamorphosed Precambrian rocks in the western parts of Kitui South form poor groundwater aquifers. The superficial deposits which overlay the basement consist of alluvium (sands, silt and clay soils) and Quaternary deposits. Both form very good aquifers as they consist of usually coarse material with lot of pore space (regolith). Sands occurring at the river beds mostly act as a shallow aquifer. The highly fractured basement rocks also serve as aquifer for groundwater (Borst and de Haas, 2006).The aquifers in this region are only recharged by rainfall. The underground water sources often supplement scarce surface water sources through drilling boreholes (Bruijn and Rhebergen, 2006).

3.2.5 Soils

Based on FAO (1976) international soil classification system, Kitui South is well covered with different types of soils associated with the local geology and occurring in different landforms

(Nyamai et al., 2003). Calcic Cambisols are found on the extreme western parts of the area particularly occurring on dissected erosional plains in Athi ward (Figure 3.6). Chromic vertisols soils are associated with the basement rock predominantly the gneisses which have eroded in the area and commonly deposited in the lowlands of Mutha, Athi and Ikanga areas. The soils classified as complex soils are common in the actively tiled land for agriculture and the larger percentage of land in Ikanga, Mutomo and Ikutha. Eutric Fluvisols are the common soils observed in the floodplains particularly on the eastern part of Mutha. From the field observations, these soils were observed near the stream channel. The occurrence of silt and clays were also observed overlaying the weathered basement rock along the river banks (Borst and de Haas, 2006). The eutric regosols occur in pockets especially on Mutha, Mutomo hills and other minor scarps in the area while the Solonetz are loamy and fine grained soils observed in the lower floodplains (Figure 3.6). Ferric acrisols are the common red to brown soils found in the sedimentary plains in Kitui South also as a result of erosion on the basement rocks found in the area (Nyamai et al., 2003). Rhodic Ferralsols are the common soils found in the transition zone between the erosional plains and depositional plains in Kitui South especially on the larger western parts of Mutha and the southern Kanziko area.

Table 3.1 shows the distribution of sand, silt and clay composition in the soils found in Kitui South. Based on these description, different classes of soils exhibit different physical behavior especially when used for engineering purposes.

This was an important factor of consideration when evaluating the suitable soils for sustainable sand dams in this study (Baniya, 2008). The composition of the respective soils indicated in Table 3.1 is closely associated with the origin and occurrence of the various soils. For instance the calcic cambisols are observed in the erosional plains and this also relates with their high composition of sands (60%) as compared to the chromic vertisols which are found in the lowlands with high percentage of clays (70%). The soils classified as the complex have relatively equal mixed compositions of clay, silt and sands (see Figure 3.6). The Eutric Fluvisols exhibit about 60% of sand occurring on the levees or in the floodplains of the study area.

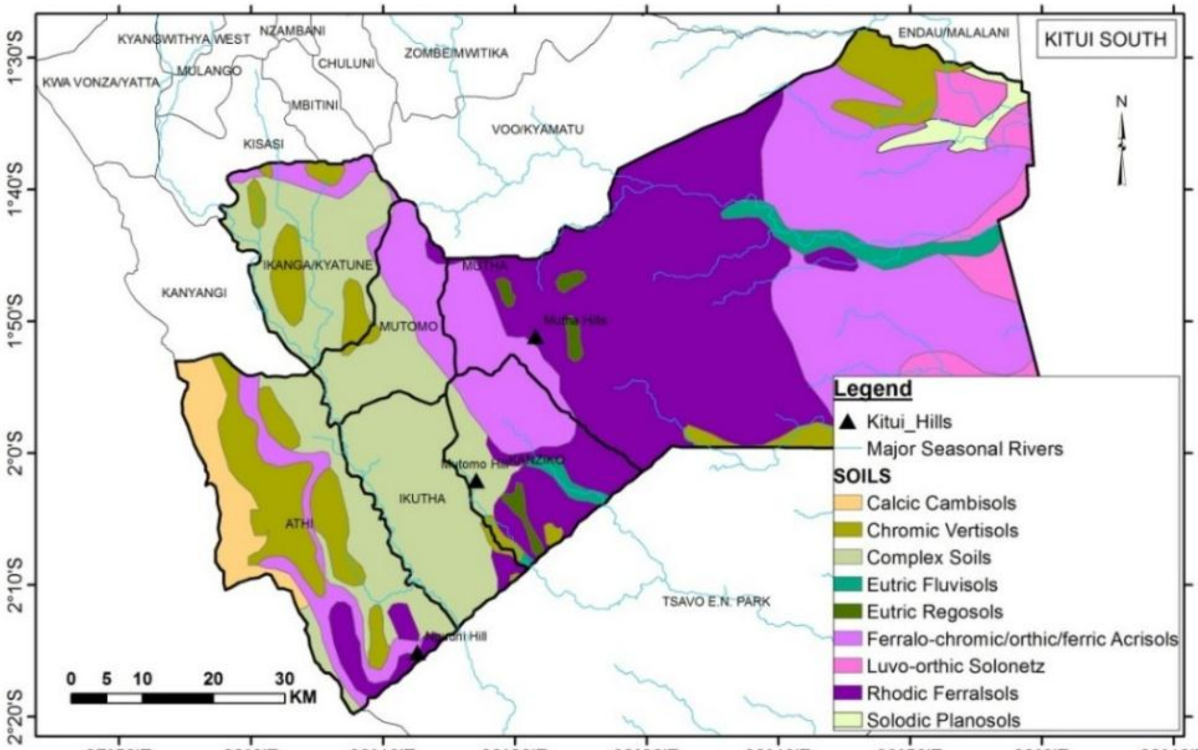

Figure 3.6: Soil map of Kitui South

Table 3. 1: Classification of soils in Kitui South

Type of soil	Clay (%)	Silt (%)	Sand (%)
Calcic cambisols	25	15	60
Chromic vertisols	70	12.5	17.5
Complex soils	99.9	99.9	99.9
Eutric fluvisols	25	15	60
Ferric acrisols	17.5	20	62.5
Luvo-orthic-solonetz	35	30	35
Rhodic ferralsols	57.5	10	32.5
Solodic planosols	35	30	35

3.2.6 Land Use and Land cover

According to the report by the CGoK (2016) Kitui South is clustered in several land use categories where about85% of the land is covered with bushland, grassland, forest and woodlandwhich is widely observed on the eastern region (Figure 3.11).The western parts of the area is covered with the agricultural landwhere the main crops are mainly maize, beans, cow peas, green grams, fruits and irrigated horticultural crops are grown along river valleys. The herding of goats, cattle, and sheep is also common in Mutha, Athi and Kanziko wards. Charcoal burning is widely practiced in

Kitui South leading to degradation of the semi-arid bushlands. This has also made the land bare and unproductive (Jansen, 2007). Most of the area is covered by natural semi-arid vegetation such as the acacia trees, shrubs and bush and a variety of grass cover. Charcoal burning and overgrazing have left most of the land bare exposing it to high soil erosion. Cultivation takes place on steep slopes which has also led to serious soil erosion problem. Shifting cultivation is also common in the area. There is uncontrolled harvesting of sand in major seasonal rivers which reduces the river water retention capacity during dry seasons.

3.2.7 Human and Livestock Population

Kitui South is divided into six (6) administrative wards namely Ikanga, Athi, Mutomo, Kanziko, Ikutha and Mutha. Table 3.2 shows the livestock and human populations in the respective administrative wards in Kitui South. Based on KNBS (2017) Ikanga and Athi wards are highly populated with a human population of 36,185 and 35,437 respectively. The population in Mutomo is 24,450 while that of Kanziko ward is 18,664. Mutomo and Kanziko are the least populated wards in Kitui South

Table 3. 2: Human and livestock populations in Kitui South

Name of Ward	Human Population (2009)	Population (livestock) (2009)	Area (km^2)	Persons per km^2	Livestock per km^2
1) Ikutha/Kasaala	26,176	87,234	433.90	61	201
2) Mutomo/Kibwea	24,450	78,567	325.40	75	241
3) Mutha	25,138	95,670	3,477.10	8	28
4) Ikanga/Kyatune	36,185	67,890	491.60	74	138
5) Kanziko/Simisi	18,664	84,780	453.40	42	187
6) Athi	35,437	86,120	952.30	38	91
TOTAL	**166,050**	**500,261**	**6,133.70**	**-**	**-**

Ikanga, Mutomo and Ikutha wards are located at the central region of Kitui South with high population density of 61 to 75persons per km^2. Mutha ward located on the eastern parts of Kitui South has the lowest population density of 8 persons per km^2 (Figure 3.7). Mutomo is recorded with the highest human and livestock population density in Kitui South (75 person per km^2 and 241 livestock per km^2, respectively). Mutha is the largest ward in Kitui South covering an area of 3,477 km^2. Mutha has the lowest human and livestock population density of 8 persons per km^2 and 28 livestock per km^2, respectively (Figure 3.7).

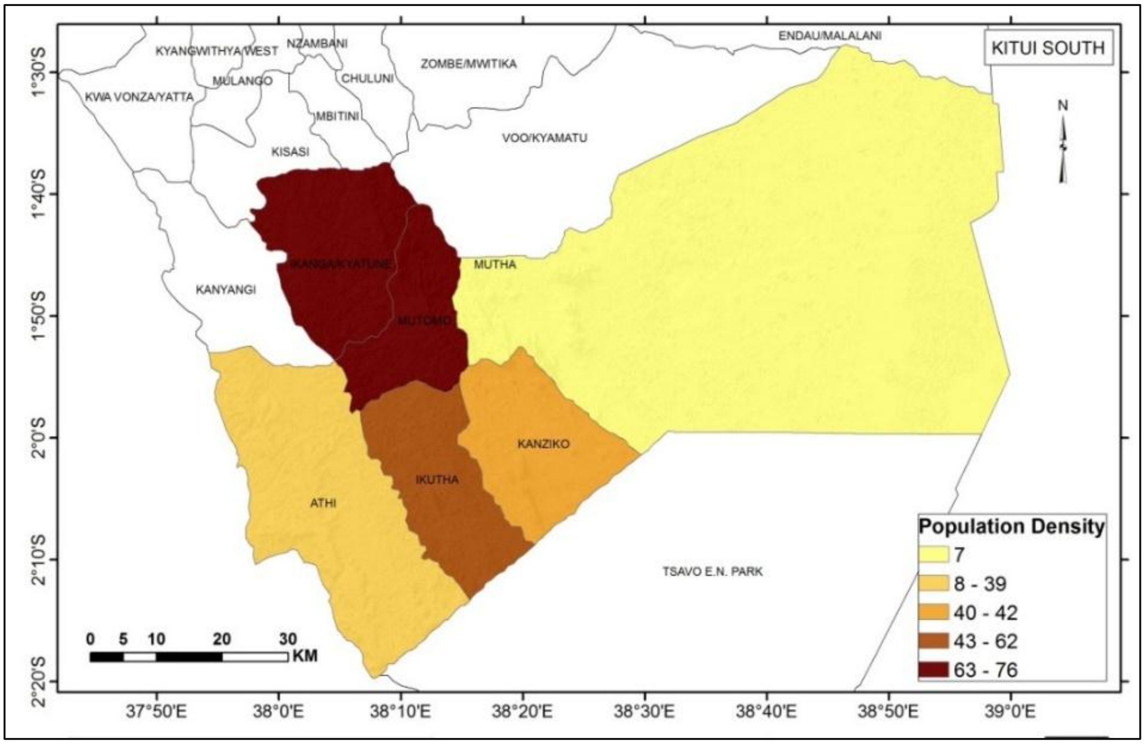

Figure 3.7: The population density map of Kitui South

3.2.8 Socio-economic activities

Kitui South falls in Mutomo-Ikutha Economic and Investment Zone as one of the eight economic zones demarcated in Kitui County (KNBS, 2017). In this area, land is used for cultivation of crops such as maize, beans, cow peas, green grams, fruits and irrigated horticultural crops are grown along river valleys. The herding of goats, cattle, and sheep is important in the area particularly in Mutha, Athi and Kanziko wards. Except for some few rural areas, most of the settlement is permanent. Charcoal burning is widely practiced leading to degradation of the semi-arid bushland. This has also made the land bare and unproductive.

Most of the land in Kitui South is low lying grazing and farming plains covered with seasonal water courses. There are a number of hilly outcrops such as in the Mutomo ward which have been protected and extended to form good rock catchments for water harvesting. These serve the surrounding communities with water especially during the dry seasons. Cultivation takes place on steep slopes. Shifting cultivation is also common in the area (Kuria, 2012). Uncontrolled harvesting of sand in the major rivers has been observed resulting to reduced river water retention capacity during dry seasons.

3.3 Data Collection

There were two categories of datasets used in this study. The first category was the field data which was acquired through field-based surveys in the study area and the other category involved the spatial data which was used in the mapping exercise. The collected datasets were integrated and evaluated appropriately to generate the suitability map for sand dams in Kitui South. The spatial data included the land use/land cover map that was derived from Landsat imagery, soil types, stream gradient, geology map, elevation map, and rainfall data.

3.3.1 Field data collection

The field data used in this study was based on the fieldwork that was undertaken in the period between July 2015 and April 2016. Identification of the potential sand dam sites in Kitui South was done through the involvement of the Kitui County Officials and local community representative members. A number of steps were taken prior to the actual data collection process. A list of proposed sites with exact stream location and names were submitted to the Sub-County Water Officers who forwarded them to the County Director of Water Resources and Services. A total of 344 sites were assessed in Kitui South. This included 60 sites in Mutomo, 52 in Athi, 60 sites in Kanziko, 70 in Ikanga, 42 in Ikutha and 60 sites in Mutha ward. Accumulation of sand at a given site and exposure of outcrops were considered essential in determination of appropriate sites for sand dams. The photo presented in Figure 3.8 shows sample site with high accumulation of uniform sands.

Figure 3.8: Kwa Ngombai (a) site with uniform sand and Ngunini site (b) with rock outcrop in Ikanga ward sampled during field data collection

The data collected from the field included the stream morphology (width, fetch distance and the depth of the river bank -measured in meters using a tape measure). Assessment of the stream morphology was done through measurement of the riverbank height, riverbed gradient and computation of the capacity of the reservoir to be constructed at the site. Rocky river-banks and firm riverbanks plus the particle-size and the volume that accumulated on the riverbed were also noted. The distance to the road and the land use near the potential sand dam site was also recorded. The GPS coordinates and elevation of each site were recorded using a Garmin mobile GPS. The coordinates were important during spatial modelling in the determination of suitable sites for sand dams.

The data collected and generated from sand particle-size analysis were utilized to characterize sands and to establish their influence on suitability, and the storage capacity of sands. This method reduces the field workload and is most appropriate unlike the traditional method where a lot of time and money was spent trying to determine the best location for the sand dams. This study will also provide recommendations on effective measures that should be adopted in order to locate sand dams in appropriate sites and therefore provide water on sustainable basis. The recommendations from this study are important for the government, stakeholders, and funding agencies involved in development of sand dams in ASALs of Kenya and Africa at large.

3.3.2 Sampling sites for sand particle-size analysis

The variation of the factors such as the topography, soil types, land use differences, geology, ecological factors, differences in vegetation cover were taken into consideration in locating sites for sand dams. Section 3.2 demonstrates the variation in these factors across the study area. The areas dominated with coarse sands especially at the low terrain were given high priority due their suitability in allowing water infiltration into the sand for storage in the sand dams. Land use pattern and land cover were important factors for the research in determining vulnerability of the land and suitable land use practices near the potential sites for sand dams. Mapping and understanding the geology of the study area was also very important for identification of suitable rocks that can generate huge amounts of coarse sand which is very essential in sand dam development.

The selection of the sampling sites in seasonal streams was based on sites that were earmarked for the construction of sand dams. Sampling along streams was done at an interval of 500 meters to maximize comparison of sediments variation along a single river channel. Sample collection from specific sites shown in Figure 3.9 was done in a triangle pattern (see Figure 3.10) such that a 1kg of the test sample comprised of sand material from four different positions of the sampling site. The numbers indicated in Figure 3.10 represent the pattern used to collect each sample from the riverbed at a potential sand dam site. The representative samples were collected on the upstream side of the sand dam wall within the riverbed. A total of 80 samples were collected for multi-stage analysis in this study as indicated in Figure 3.9.

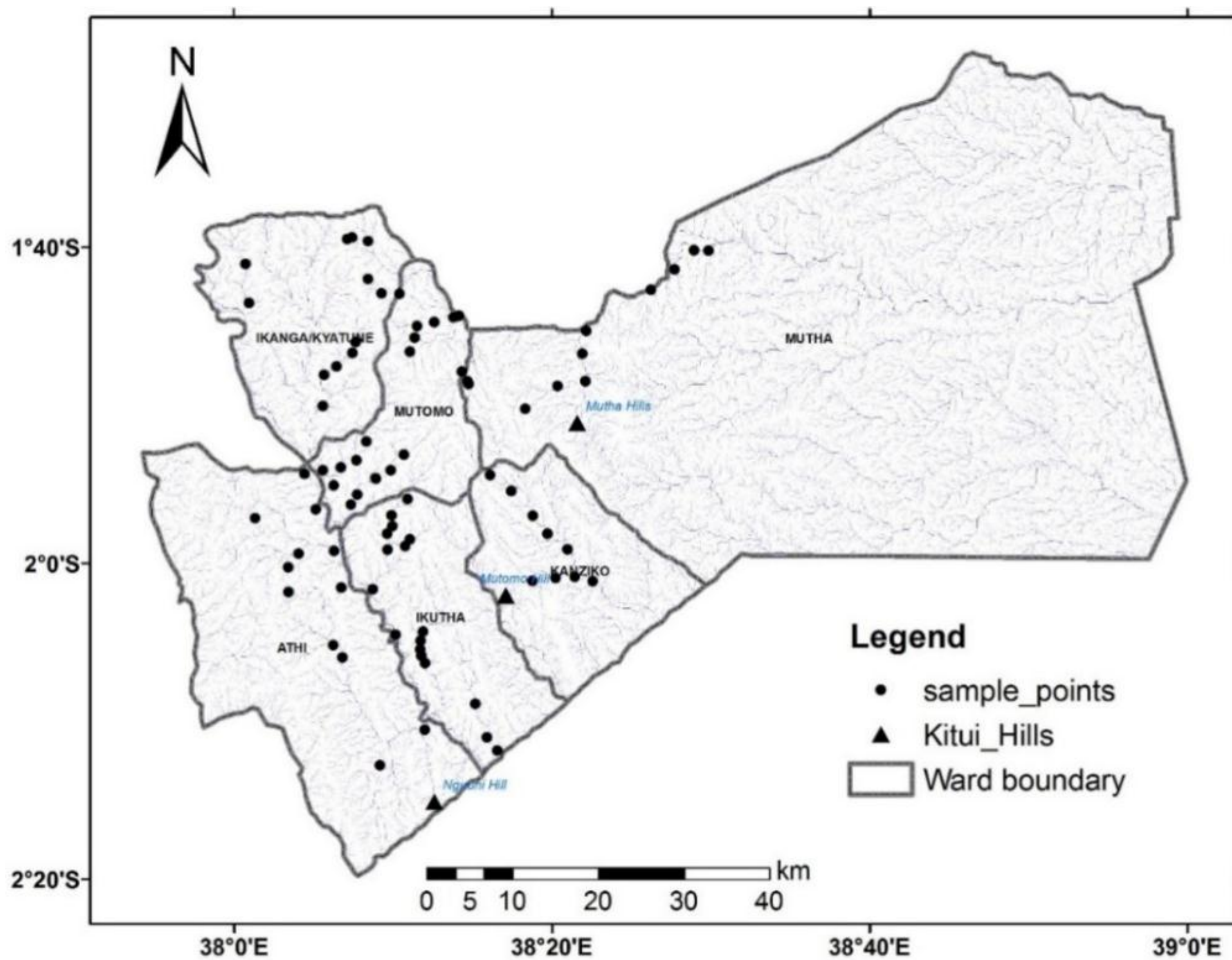

Figure 3.9: Sampling sites located along seasonal rivers in Kitui South Sub-County

The weather conditions were favourably dry and sunny throughout the fieldwork period. This allowed the researcher to collect relatively dry samples with manageable load to carry from the fieldwork. The average mass of the collected samples was one (1) kg per sample packed in clear airtight containers. The samples were well labeled and then transported to the University of Nairobi soil laboratory for particle-size analysis using series of sieves.

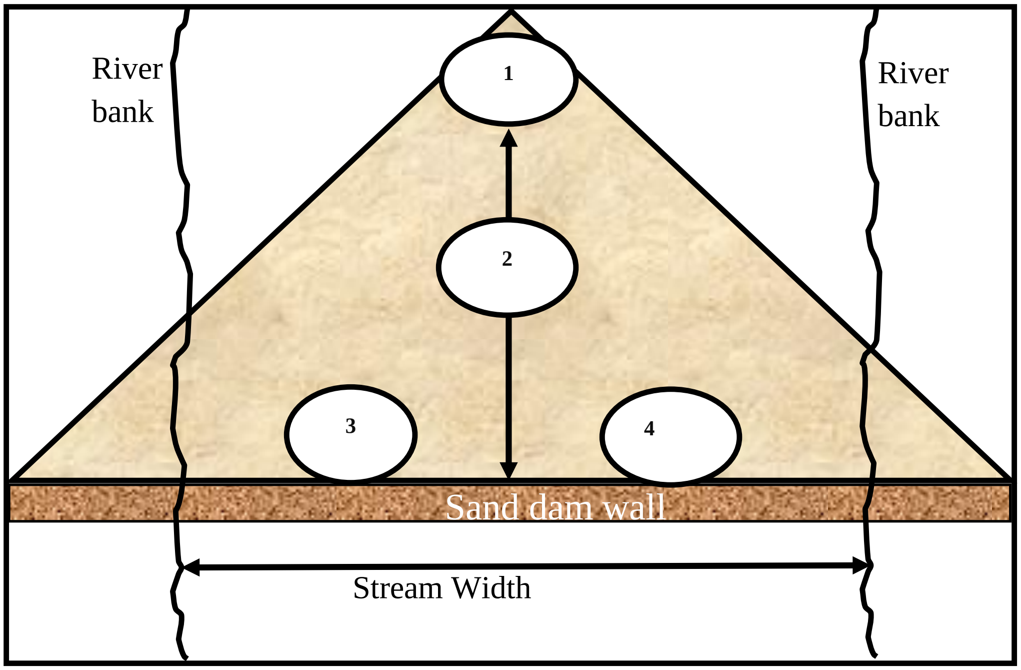

Figure 3.10: The pattern applied during sample collection from the river channel

3.3.3 Spatial data acquisition and analysis

The mapping of sites for sand dams using GIS and satellite image analysis required data in the digital format. Some data were only available in analogue format and others had to be acquired from the satellite imagery. These data were processed in order to generate maps based on the objectives of this study. The overlay analysis in GIS platform needed integration of various spatial data as shown in Table 3.3.

Table 3. 3: Summary of the datasets acquired in this study and their respective sources

Dataset	Source
1) Digital Elevation Model (DEM) 30m resolution)	Shuttle Radar Topography Mission (SRTM)
2) Geological Map	International Livestock Research Institute (ILRI) online archive
3) Soil Map	FAO online database-www.fao.org/soils
4) Satellite data (Landsat)	USGS Global visualization Viewer-glovis.usgs.gov/
5) Rainfall and Temperature data	Kenya Meteorological Department- Kitui office
6) Field data	County Government of Kitui - Ministry of Agriculture, Water and Irrigation
7) Borehole data	County Government of Kitui - Ministry of Agriculture, Water and Irrigation

Digital Elevation Model (DEM) with a spatial resolution of 30m was used to determine the general terrain of the study area. Stream network was then derived from the DEM followed by digitization in order to generate a map showing the drainage network in the study area. The derived stream network in Kitui South shows the rivers and streams from an elevation of 1303m as the highest and 136m as the lowest point above the sea level. The topographical gradient map was also derived from the DEM.

Soil map was also produced to show the general distribution of the soils in Kitui South and the extent to which they can influence site suitability for sand dams. The sites which were found with minimal bedrock exposure were evaluated based on the suitability of the available soils. The field observations were accompanied by the evaluation on soil data which was obtained from the International Livestock Research Institute (ILRI) online archive. The geological report by Saggerson (1957) that was obtained from the Geological Survey of Kenya was used to generate the geological map of the study area. The geology of Kitui South was digitized from this report and updated from the field observations.

Land use and land cover maps were prepared from satellite images. Landsat satellite images were obtained from the online archive provided at Global Visualization System (GLOVIS). GLOVIS is managed by the United States Geological Survey (USGS).The classification of land cover in Kitui South was based on the land cover classification scheme applied by the Department of Resource Surveys and Remote Sensing (DRSRS) in 2014.Supervised image classification was done in order to assign different spectral signatures on the features observed from the Landsat datasets. This was done on the basis of reflectance characteristics of the different LC types. Different color composites were utilized to improve visualization of different objects on the imagery. For example Infrared color composite NIR (4), SWIR (5) and Red (3) was applied in the identification of varied levels of vegetation growth and separating different shades of vegetation. Other color composites such as Short Wave Infra-red (7), Near Infra-red (4) and Red (2) combination which are sensitive to varied degrees of moisture content was applied to identify the built-up areas and bare soils. Supervised classification scheme with Maximum Likelihood Classifier (MAXLIKE) decision rule (Hualou et al., 2006) was used by following three stages, assignment of training sites, classification, and generating vegetation cover map as shown in Figure 3.11.

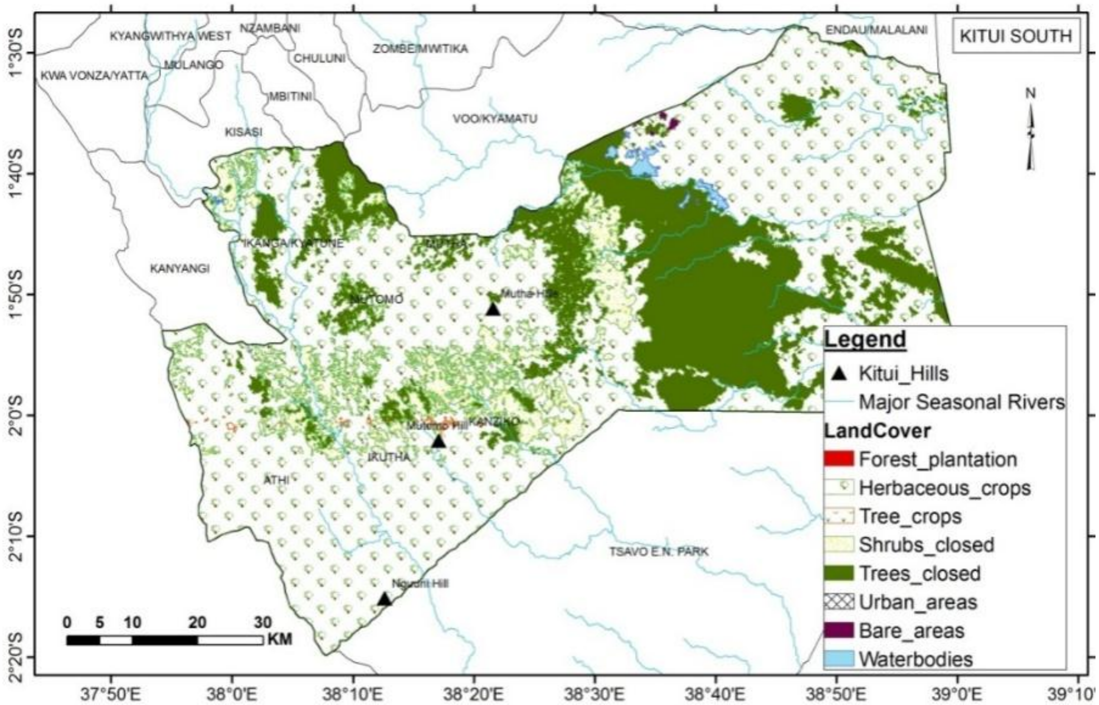

Figure 3.11: Vegetation cover in Kitui South Sub-County

The land use map was generated by digitizing the Landsat satellite images. Google Earth was used for confirmation and verification of land uses in the study area. Several categories of land use were found in Kitui South as shown in Figure 3.12. The other important information required was human and livestock population and settlement patterns.

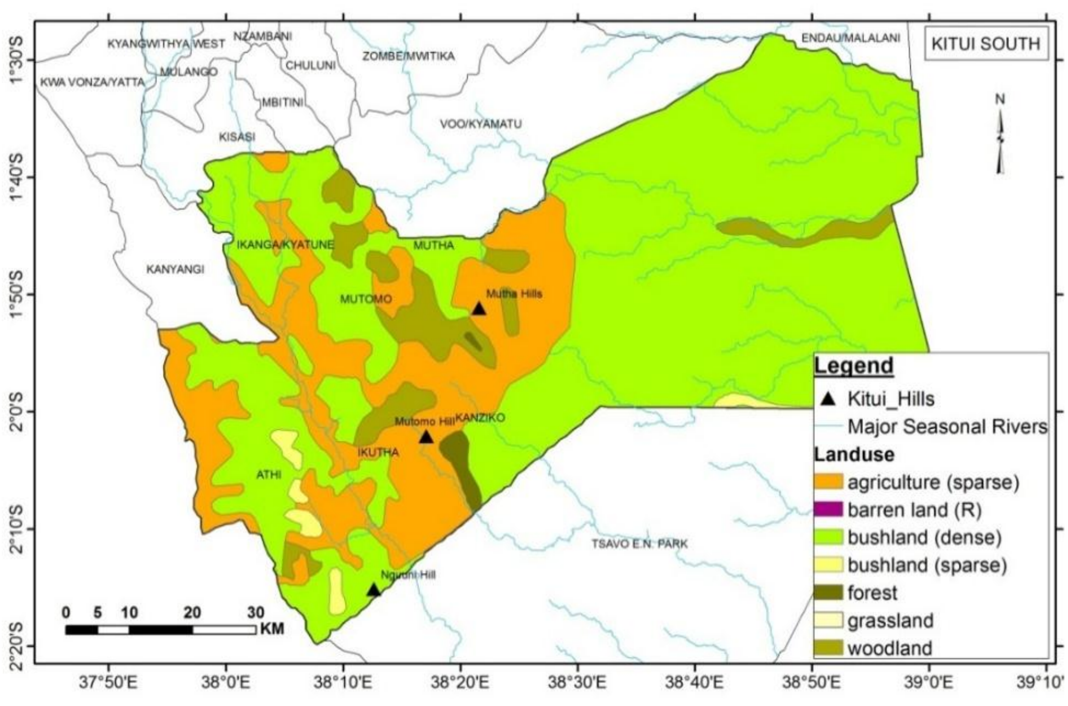

Figure 3.12: Land Use map of Kitui South Sub-County

The population data was obtained from the Kenya National Population Census report of 2009. An assessment was also made on the distribution of accessible roads and footpaths leading to the sites earmarked for construction of sand dams.

3.4 Particle Size Analysis process

Sieve analysis was done using a set of manual soil sieves performed at the University of Nairobi Geology laboratory. The assumption in this study was that sand gradation along the riverbeds is influenced by changes in the elevation (height above sea level). Fluvial morphology and processes are the key factors that guide sand gradation. It was assumed that larger grains of sands were likely to be observed upstream while the small grains would occur at the flood plains. In order to establish the truth in this assumption representative samples were taken from different sites along the selected seasonal streams namely Nzeeu, Katiliku, Memboo, Kanzilu, Kavuti, Muvuko, Tiva, Mwila, Mitanda, Nguuni, Ndiliu and Ngunyumu. Eighty (80) samples were collected from the field for the particle-size analysis. The laboratory work started in mid-April 2017. Sieve analysis was used to separate different grades of sand from the collected stream sediment samples. The coarse sands (2mm-60mm) and sands (0.06mm-2mm) were very important sizes in this study as these are considered most ideal for sand dams.

Dry sieving was done on particles greater than 60µm based on American Standard Test Method (ASTM) (Walling and Fang, 2003). The samples were dried in an oven up to a temperature of 105^0C for 3hrs. At this point, each sample was spread on a tray at a thickness of about 1cm to maximize surface areas for drying. It was important to make sure that the sand grains were not disintegrated between fingers or exposed to tension from any object. This was critical to ensure that there was no disturbance on the samples before they were subjected to sieving. It took eight (8) hours during the day time to dry each sample and then cooling overnight as recommended in Retsch (2009).

After drying, each sample was subjected to sieving using a series of sieves. Each sample was first weighed using a digital weighing balance and recorded on a sieve analysis data sheet as a dry mass. The standard sieves considered for sieve analysis based on ASTM were #2 (4.75mm), #10 (2mm), #20 (0.85mm), #40 (0.43mm), #60 (0.25mm), #100 (0.15mm), and #200 (0.075mm). A series of sieves arranged from very coarse mesh (on top) to the fine mesh (placed at the bottom of the other wider sieves) and all put on top of the collection pan. The number of sieves that were used and their arrangement was determined based on the anticipated maximum grain size of the sample (Walling and Fang, 2003). The test sample was placed on the top sieve, the lid put on, then the set of sieves were manually agitated for 5 minutes for each test sample to achieve a substantial grade separation

(Retsch, 2009). Recording of the mass retained on every sieve and calculation of other parameters was done on a data sheet for further analysis of each sample. The results of the particle-size evaluation were presented graphically and in tabular form.

Different grades of sand particles were then established from each sample and the percentages of each grade computed to know the distribution of fine gravel, coarse sands, medium sands and fine sand in each sample. The loss in the accumulated mass after the sieve procedure was expressed as an error calculated using Equation 3.1. This was defined as the difference between the original dry mass and the total mass of the individual fractions of the sample retained on the sieves after the sieving procedure. The results were acceptable with an error margin of less than 1% (ISO 9276-2:2001).

$$[(O_m-\Sigma M_R)/ O_m]*100\% \quad \text{.. Equation 3.1}$$

3.4.1Interpretion ofthe Soil Grading Curves

Using the percentages of mass passing through the sieves, the grading curves were generated by plotting the log of the particle diameter against the percentage mass of finer particles passing though the sieves (see Figure 3.13). The shape of the grading curve was applied to determine gradation of each sample (Ward and Robinson, 2000).

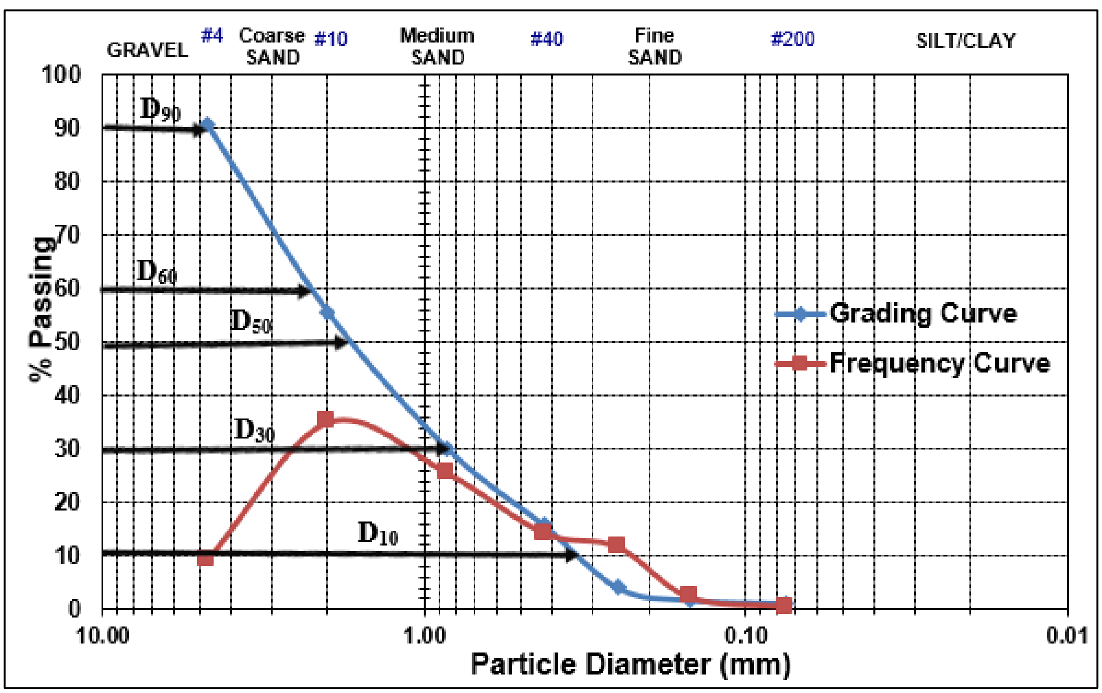

Figure 3.13: Sample grading and frequency curves showing the distribution of soil particle-sizes

A horizontal or near-horizontal shift, like a landing, meant that the sample comprised of some intermediate particle sizes (Ward and Robinson, 2000).When a large part of the sample was made up of uniform-size particles, graph appeared as a near vertical drop. A gradation chart that appeared closer to the origin implied a large percentage of finer particles and was therefore described as a finer gradation (ISO, 2001). Similarly, when the graph shifted away from the origin, a large percentage of more coarse particles were observed from the test sample and therefore described as a coarser gradation.

The other parameters derived from the graphs included the arithmetic mean which is also referred to as the effective particle-size denoted as (D_{10}) (Alderlisten, 1990). The graphs were subdivided into 10 deciles such that the effective particle-size is denoted as the first decile (D_{10}). This was done to determine sand particle-sizes distribution at any given sand dam site. The third, fifth, sixth and the ninth deciles were denoted as D_{30}, D_{50}, D_{60}, and D_{90}, respectively. This parameters were used in the determination of soil Uniformity Coefficient (C_u) and Coefficient of gradation (C_k) (Alderlisten, 1990). The C_u and C_k were computed using the following formulas based on Retsch (2009);

$$C_u = [D_{60}/D_{10}] \quad \text{……………………………………………Equation 3.2}$$

$$C_k = [D_{30}^2/ (D_{60}*D_{10})] \quad \text{………………………………………Equation 3.3}$$

For the single-sized (uniform) soils, C_u and C_k is equal to 1. If C_u is greater than 5 then it implies that the soil is well-graded. When C_u is less than 3, it means that the soil is uniform in size. C_k ranging between 0.5 and 2.0 indicates a well-graded soil but if less than 0.1 then the soils is possibly gap-graded (Van Haveren, 2004). The other attributes computed from the sieve analysis results included the median, and standard deviation refereed here as ‘span’ in the table presented in Appendix II.

3.5 Statistical methods

The statistical analysis of data was performed on the data derived from soil particle-size analysis. The statistical methods applied in this study were regression analysis, ANOVA and correlation analysis. Descriptive statistics were also generated to establish the mean, mode, median as well as the standard deviations, range, maximum and minimum values to explain various observations.

3.5.1 Regression analysis

In this study the influence of various parameters in the suitability model were evaluated through regression analysis. Regression models enables one to evaluate the influence of various variables in a model (Santhi et al., 2001). For example the study tested the influence of the riverbed gradient in the rate of sand accumulation along the river channel. The study also assessed the influence of change in the elevation in the variation of stream sediments particle-sizes. Regression coefficients were generated through a simple regression model (Equation 3.4) to determine the influence of various parameters in the suitability of sites for sand dam.

$$y = \propto + \beta x_n + \varepsilon_i \text{..} \quad \text{(Equation 3.4)}$$

Where y is the dependent variable, $\propto$ is the y-intercept, x is the independent variable and ε_i is the error term in the determination of the y-value. The variation in the dependent variable,$y$is explained by the independent variablesx_n. The variation in the independent variables is defined by the coefficient of determination (R^2) (Devore, 2011).

3.5.2 Coefficient of determination (R^2)

The coefficient of determination R^2 describes the proportion of the variance in measured data explained by the model (Devore, 2011). The R^2can also be derived from the regression analysis where it refers to the amount of variation explained by the independent variable/variables (Santhi et al., 2001).R^2 ranges from 0 to 1, typically values greater than 0.5 are considered acceptable (Santhi et al., 2001). If the value is close to 1 it means that there is good fit of the independent variables. The significance F-value and P-values were used to check if the multiple variables used in the multiple correlations were correct and statistically reliable. If the significance F-value and P-values are less than 0.05, then the variables were considered significant (Gujarati et. al., 2009).

3.5.3 Correlation analysis

Correlation analyses were performed to assess the relationships between different variables that influence suitability of sands along riverbeds for sand dams. The Pearson's correlation coefficient (r) was applied for example in the determination of the relationship between the rate of sand accumulation on the riverbed and the riverbed gradient (Karl, 1895).The correlation coefficient ranges between -1 and +1. When the coefficient is -1 it means that there is a strong negative correlation for which Y variable decreases as X variable increases while +1 means that there is a strong positive linear correlation where Y variable increases as X variable increases. For instance in this study the relationships between the sand gradation and the rate of sand accumulation on the riverbed was evaluated using the Pearson correlation coefficient (r) (Nikolić et al., 2012).

The equation for computing the Pearson Correlation Coefficient, *r* is as follows:

$$r = \frac{\Sigma xy - \frac{(\Sigma x)(\Sigma y)}{n}}{\sqrt{(\Sigma x^2 - \frac{(\Sigma x)^2}{n})(\Sigma y^2 - \frac{(\Sigma y)^2}{n})}} \quad \text{(Equation 3.5)}$$

Where;

r = Correlation coefficient, *y* = independent variable (example sand accumulation), *x* = dependent variable (example sand particle-size), and *n* = total number of values/variables.

3.5.4 Measures of Central Tendency

The measures of central tendency on the data used in this study were determined using mean, mode and median (Dodge, 2003). The data that was used in this case was derived from the sieve analysis results. The mode value for the sand particle-sizes was determined from the peak of the histograms to show the dominant particle-size in a soil sample.The assessment on the measures of central tendency was done to determine the spatial relationships between the variation in sand gradation and sand particle-sizes. These relationships were established using parameters such as D_{10}, D_{30}, D_{50}, D_{90} derived from the grading curves illustrated in Figure 3.13.

These parameters were also used in the determination of the averages and the median values to establish the relationship between the overall rates of accumulation of different grades of sands along the riverbeds and also the relationships in the occurrences of different grades of sand. The distribution of the different particle-sizes at any given sampling site was defined by the particle-sizes represented by D_{10}, D_{30}, D_{50}, and D_{90} derived from the grading curves (Retsch, 2009).

The study also used the median values (D_{50} in mm) which represented the corresponding sand particle-size in millimetres that splits the grading curve into two halves (Figure 3.13). The particle diameter at D_{50} as well as at D_{10}, D_{30}, D_{60}, and D_{90}were applied in determining the distribution of particle-sizes and generating the coefficients of uniformity in each sample (Retsch, 2009). These values provided more meaningful and representative statistics in terms of particle-size distributions unlike when using simple ‘mode’ and ‘mean’ to show the same. However, the significance of using the median as (D_{50} in mm) is upheld in other related studies (Alderlisten, 1990; Barkhodari, 2015).

3.5.5 ANOVA and Hypothesis Testing

The analysis of variance was utilized to establish whether there is any significance difference between the means of two or more variables used in this study (Freud and Simon, 2000). One-way analysis of variance was applied to determine whether there is any significant differences between sand gradation and the changes in the elevation. This for example was examined by looking at the significance of each variable generated from the sieve analysis to establish how sand gradation and their spatial variations influence their suitability for sand dams. The hypotheses tests was assessed by setting 0.05 significance level (95% level of confidence) so if the computed F-value was less than the critical value, then the null hypothesis was accepted. The null hypothesis was rejected if the condition F>F-critical, was true (Saunders, 1990).

3.6 Mapping of suitable sites for sand dams

The Digital Elevation Model (DEM) (30 m) was derived through remote sensing technique (Tweed et al., 2007). The land use data was derived from the Landsat dataset which are also freely accessible online at the United States Geological Survey (USGS) website (https://glovis.usgs.gov/). Landsat 7 archive was used as the main source of the Land use data which was later be processed in Erdas Imagine 2015 Remote Sensing Tool. Preprocessing of the satellite images for example data gap filling, masking, mosaicking, and creating data sub-sets was done to prepare the datasets for farther procedures. Supervised classification using maximum likelihood algorithm on the satellite images was done to create the landuse map using Erdas Imagine 2015 (Baniya, 2008).

ArcGIS 10.3 was used for spatial analysis, preparation of GIS data, performing overlay analyses and producing maps (Ali, 2014). A database was created in ArcGIS in order to configure the required data and data structures in the appropriate layers for the analysis. The organization of datasets greatly helped in performing the overlays in the determination of suitable sites for sand dam construction. Spatial analysis was also performed to assess suitability of different sites for the sand dams at different stream regimes and characterization. The Digital Elevation Model (30m resolution) was used to generate the slope map of the study area (Ali, 2014). Data integration and spatial analysis was done using ESRI Geographic Information System (GIS) (ArcInfo). Hexagon Geospatial remote sensing software, Erdas Imagine 2015 (Baniya, 2008) was used to generate the land cover and land use maps of the study area (Figure 3.11 and Figure 3.12 respectively) through an intense image processing of the Landsat Satellite data (30m resolution) which was acquired in January 2017.

The integration of different datasets was done to establish the suitable sites for sand dam construction through the Analytical Hierarchy Process (AHP) approach based on Saaty (1980). The AHP approach enables the decision-maker to select the 'best' alternative from the number of feasible choice-alternatives under the presence of multiple choice criteria and diverse criterion priorities (Jankowski, 1995). The integration of model parameters were based on scientific principles and relative weight of various parameters applied in the suitability model as described in Table 3.4.

Table 3.4: Point scale used in AHP to prioritize variables used in suitability model

Definition	Relative Importance
Extremely Preferred	9
Very Strongly Preferred	7
Strongly Preferred	5
Moderately Preferred	3
Equally Preferred	1
For compromises between the above	2,4,6,8

Using the AHP approach the parameters were put in a pairwise comparison matrix for multi-criteria assessment on their influence in suitability model. Pairwise comparisons were utilized to facilitate judgement and calculations as well as checking compatibility in the decisions. The parameters of the model included land use and land cover, soil types, slope, geology, sand accumulation, and sand gradation. The assigned relative weights in the individual criteria were ranked based on their importance in the model as described in Table 3.4. This ranking was done based on expert knowledge and through literature review.

The influence of each factor was interdependent. The relative weightage assigned to each factor was used to compute the total score for each of the influencing factors and later applied in the overlay analysis in GIS mapping. The priority vectors for each parameter of the model were determined by getting the average of the normalized relative weights in the model. Factors with higher weight value meant that it had a greater influence while the factor with a lower weights meant minimal influence in the determination of suitable sites for construction of sand dam. GIS was used in the demarcation of suitable sites in a scale of five categories namely 1=‘not suitable’, 2=‘least suitable’, 3=‘fairly suitable’, 4=‘suitable’, and 5=‘very suitable sites’.

CHAPTER 4

RESULTS OF THE STUDY

4.1 Introduction

This chapter presents the results of the study. The chapter presents the results of sand particle-size analysis including the determination of spatial distribution of the sand along the seasonal rivers in Kitui South and how different factors influence their suitability for sand dams. The key outputs from this study were used to establish the suitable sites for sand dam construction through a multi-criteria approach.

4.2 Gradation of stream sediments

Gradation of the stream sediments was determine through sieve analysis on the collected samples. Table 4.1 shows sample results obtained from sieve analysis for a sample collected along Makongoni River at Kwa Teresia Joseph in Mutomo Ward. The distribution of different particle sizes in a sample was determined by calculating mass retained on the corresponding sieves as tabulated in Table 4.1.

Table 4.1: Sample sieve analysis data sheet

Sample name: Makongoni Kwa Teresia Joseph		Fine GRAVEL%	Coarse SAND%	Medium SAND %	Fine SAND%	
		3.1	9.8	83.2	4.0	
Sieve Size (mm)	**Mass of Sieve + soil (g)**	**Mass of Sieve (g)**	**Mass of Soil retained (g)**	**Cu. mass retained(g)**	**% of soil retained**	**% of soil passing**
#5	631	626	5	5	0.50	99.50
#12	491	465	26	31	2.59	96.91
#22	513	415	98	129	9.77	87.14
#36	1045	410	635	764	63.31	23.83
#72	561	362	199	963	19.84	3.99
#100	406	379	27	990	2.69	1.30
#150	330	321	9	999	0.90	0.40
Pan	**486**	**482**	**4**	**1003**	**0.40**	**0.00**

Mode=0.43, Median=0.57, D_{10}=0.32, D_{30}=0.47, D_{60}=0.6, D_{90}=0.9, C_u=1.88, C_k=1.15, error=0.0%

The example shown in the table indicates that the total mass of the medium sand (retained on sieve #36 and #72) was 834g. This is 83.2% of the accumulated mass of the sample. The total mass retained on sieve #100 and #150 was 36g implying that only 4% of the sample was fine sand. The total mass retained on sieve #22 was 98g which represented 9.8% coarse sand. The sieve #5 and #12 retained an accumulative mass of 31g which represented 3.1% fine gravel in the analysed sample. This example of the analysis results showed that the sample collected at Kwa Teresia Joseph was dominated with medium sand which is the same as the mode value from the results and negligible amount of fine gravel and fine sands. In terms of the uniformity of the particle sizes the Coefficient of Uniformity (C_u) was 1.88 which is less 3 implying a uniform graded medium sand. This kind of analysis was done on the 80 samples collected from the study area and the compiled resulted presented in Appendix 2.

59% of the studied sites exhibited sediments with uniform grades and appropriate particle sizes suitable sites for sand dam (Figure 4.1). For instance River Nzeeu in Ikanga Ward at an elevation of 848m had 23% fine gravel, 42% coarse sand, 30% medium sand and 4% of fine sand (see Table. At a lower elevation of 841m, Memboo River in Mutomo Ward had 0.7% of fine gravel, 8.1% coarse sand, 80.3% of medium sand and 10.5% of fine sand which shows a great impact of the change in elevation along the seasonal river.

Table 4.2: Stream sediment particle size distribution

Site Name:	**Seasonal River**	**Elevation (m)**	**Fine GRAVE**	**Coarse SAND%**	**medium SAND %**	**Fine SAND%**	**mode**	**Median (D50)**	**C_u**	**C_k**
Indangani	River Nzeeu	848	0.7	1.1	75.8	21.5	0.25	0.31	1.89	1.28
kwa nyamai memboo	Memboo River	841	0.7	8.1	80.3	10.5	0.43	0.47	2.08	0.92
Makutano Kivili	Kanzilu	580	44.3	25.5	26.1	3.4	2.00	1.7	7.06	0.89
Kwa Kikuyu	Kanzilu	498	2.6	8.6	75.3	13.3	0.43	0.45	2.26	0.91
Kwa Musyimi	Kanzilu	476	13.9	41.8	41.6	2.6	0.85	0.95	3.51	0.83
Kwa Katu Kilonzo	Kanzilu	468	0.7	8.9	85.0	5.0	0.43	0.5	2.04	0.95

Another river that showed suitable sites was Kanzilu in Mutha Ward where the accumulation of fine gravel was quite high (28%) at an elevation of 580m near Makutano Kivili, 41% of coarse sand, and 28% of medium sand. Along the same river were other suitable sites for example Kwa Kikuyu along Kanzilu River at an elevation of 498m with 2.6% fine gravel, 8.6% coarse sand, and

75% medium sand. At Kwa Musyimi with elevation of along Kanzilu River the composition of fine gravel was 14%, 42% coarse sand, 42% medium sands and 2% fine sands. Another site along the same river at Kwa Katu Kilonzo with an elevation of 468m, had 0.7% fine gravel, 8.9% coarse sand and high accumulation of medium sand (85%).

In general, the particle-size distribution along the seasonal rivers in Kitui South ranged from 8% fine sands (0.08mm-0.15mm), 66% medium sands (0.25mm-0.43mm), 21% coarse sands (0.85mm), and 5% fine gravel (2mm-4.75mm). 2.5%% of the studied sites along the seasonal rivers in Kitui South were found to be composed of 'gap graded fine sands, 6.3%% were 'well-graded fine sands, 13.8% 'uniform graded medium sands', 2.5% 'uniform graded fine sand', 27.5% 'well-graded coarse sands, and 47.5% 'well graded medium sands' (Table 4.3). The results show that most of the investigated sites were dominated with medium and coarse sands in that order (see also Figure 4.9).

Table 4.3: General gradation of stream sediments in Kitui South

	Count	**%**	**Criteria**
gap graded fine sands	2	2.5%	Cu>5
well-graded fine sand	5	6.3%	Cu>3
uniform graded medium sand	11	13.8%	Cu<3
uniform graded fine sand	2	2.5%	Cu<3
well-graded coarse sands	22	27.5%	Cu>3
well graded medium sands	38	47.5%	Cu>3
Total	**80**	**100%**	

Uniform coarse sands are deemed the best for sand dam (Nissen-Petersen, 2007). Uniform particle-sizes give high porosity hence high potential storage capacity. Sites with these kind of sands are more appropriate for sand dams. Figure 4.1 was generated to show how uniformity of sands vary with the particle sizes from one point to the other along the seasonal rivers in Kitui South. The parameters C_u and C_k were used to assess uniformity and gradation of the sands along the seasonal rivers in Kitui South. Cu<3 indicates uniform soils while $C_u>5$ indicates well-graded soils. Out of the 80 samples that were analysed, 47 (59%) of them were categorized as uniform sands (Cu<3), 24 (30%) were intermediate and only 9 (11%) were well graded ($C_u>5$).

Out of the 47 sites observed with uniform sands, 86% were dominated with the medium sands and the rest were coarse sands. The Coefficient of Uniformity (Cu) varied between a maximum of 16.67 and a minimum of 1.74 resulting to a range of 14.93 and a mean of 3.42 (Figure 4.1). The results also showed that the coefficient of gradation, Ck varied between 2.55 and 0.33, a range of 2.22 and a mean of 0.94. These results imply that 47 (59%) of the 80 sites are highly potential and suitable for sand dams.

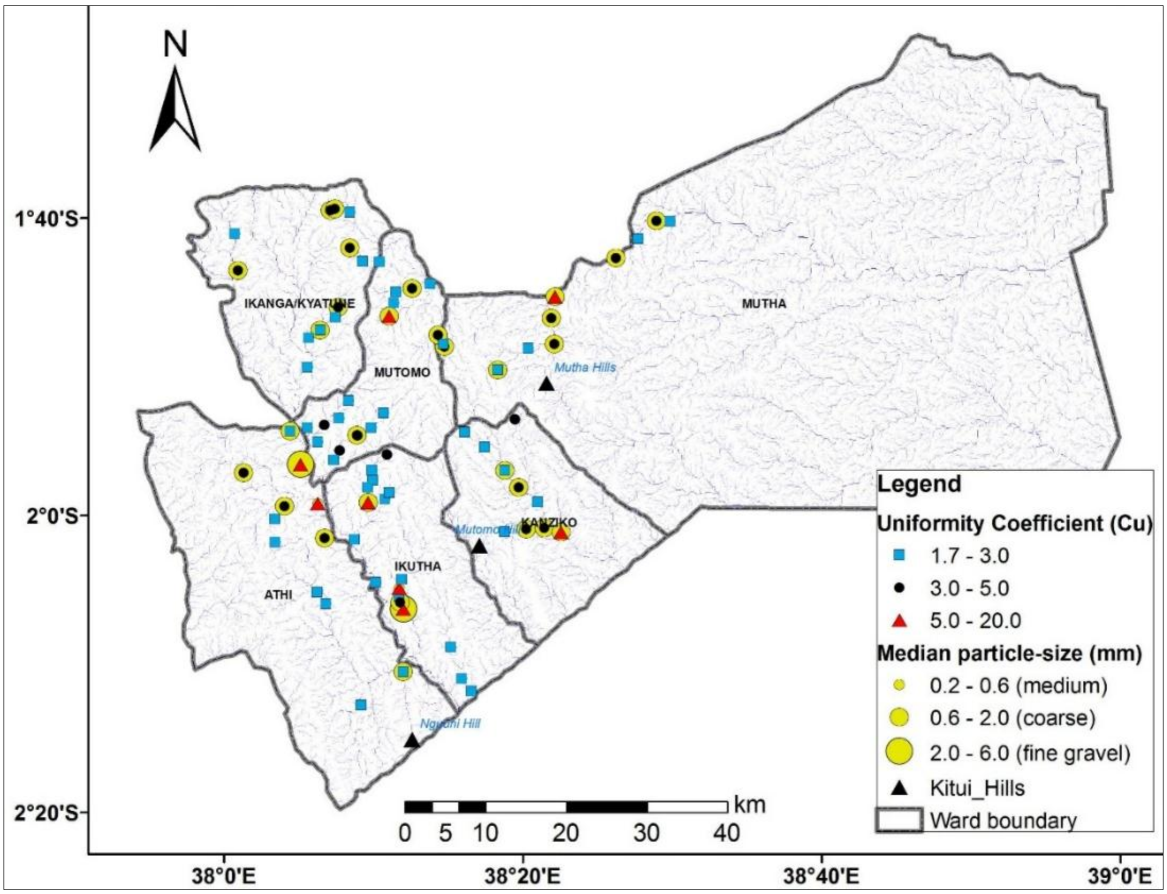

Figure 4.1: Relationship between the sand uniformity (Cu) and the spatial distribution of median particle-size of sand in Kitui South at the potential sand dam sites

4.3Sand accumulation and the dominant particle-sizes

The results derived from the frequency and grading curves show that fine gravels (2-6mm) are the largest particle-sizes of sand available in the seasonal rivers in Kitui South while the smallest grade ranges between 0.06mm and 0.2mm (fine sands). The distribution of different grades of sand namely; D_{10}, D_{30}, D_{50}, and D_{90}were used to explain the variation of accumulation of fine gravels at different points along the riverbeds in the seasonal rivers. The relationship between the accumulation of fine gravels and the distribution of different grades of sands as mentioned here was established and the results are presented in Figure 4.2.

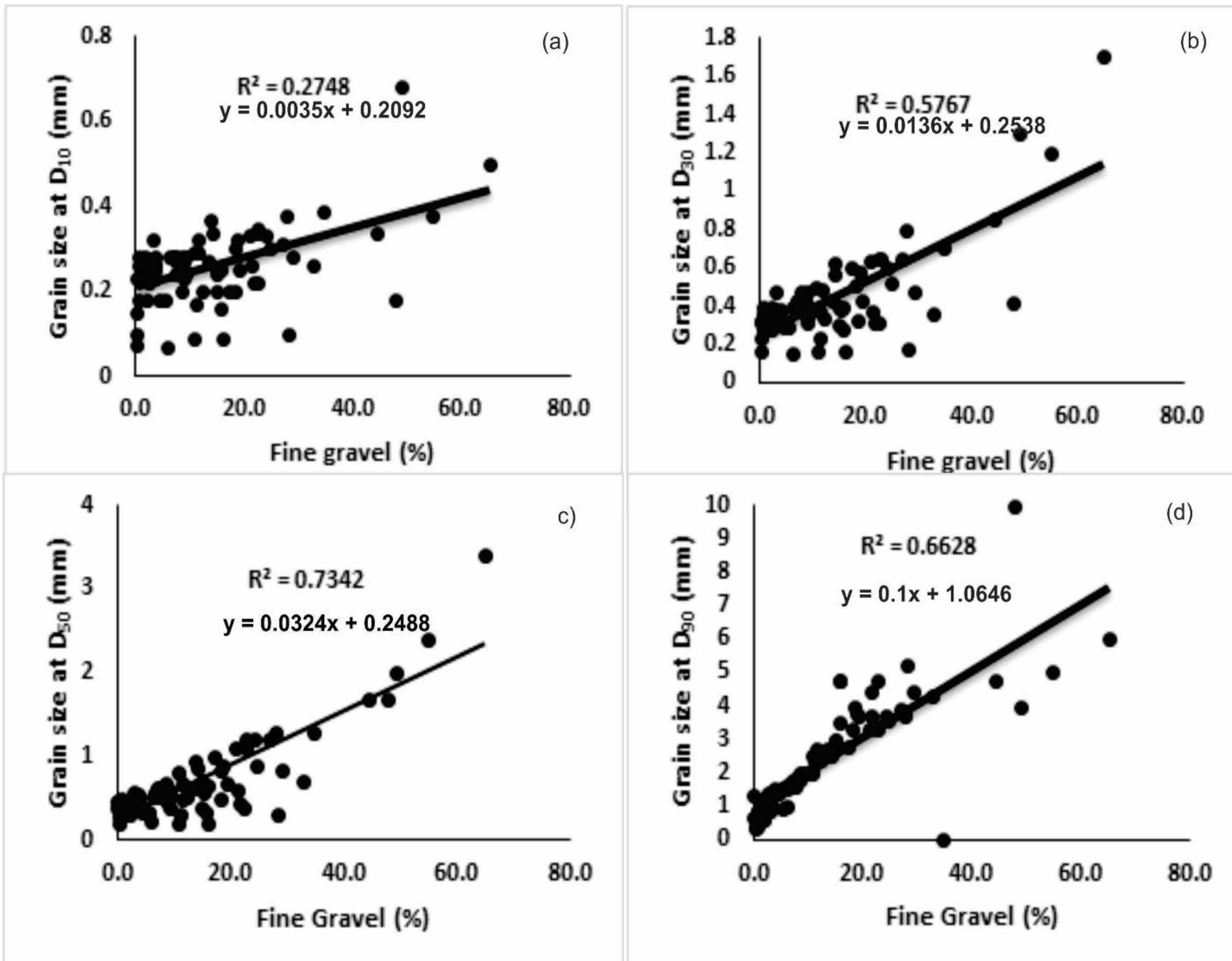

Figure 4.2 (a-d): The relationship between the rate of fine gravels accumulation and the distribution of D_{10}, D_{30}, D_{50}, and D_{90} sand particle-sizes in the riverbeds in Kitui South Sub County

Figure 4.2 (a-d) shows the relationship between accumulation of fine gravels and the distribution of other sand particles represented as D_{10} D_{30} D_{50} and D_{90}. The particles represented as D_{10} show a moderate relationship with a coefficient of determination, $R^2$of 0.27 and a correlation coefficient of 0.52. The distribution of particle size represented as D_{10} ranges between 0.1 and 0.4mm (fine to medium sands). In Figure 4.2 (b), the distribution of the particle-sizes represented as D_{30} ranges between 0.2 to 0.6mmwhich suggests the occurrence of medium sands. The relationship between the occurrence of medium sands and accumulation of fine gravel is significant with a coefficient of determination, R^2 of 0.58 and a correlation coefficient, r of 0.76.

Figure 4.2 (c) shows that an increase in the accumulation of fine gravels was strongly influenced by the distribution of the median particle-sizes (D_{50}) along the riverbeds. This relationship was significant with the coefficient of determination, R^2 of 0.73 and a correlation coefficient, r of 0.85. The distribution of the median size (D_{50}) sand ranges between 0.2 to about 1.4mm which imply presence of medium to coarse sands.

It was also observed that increase in the gravelly sands along the riverbed was closely related with increase in the D_{90} of the particle sizes. This relationship was significant with a coefficient of determination, R^2 of 0.66 and a correlation coefficient, r of 0.81. The distribution of particle sizes at D_{90}ranged between 0.1 to 5mm in diameter. This suggested that the accumulation of fine gravel was not influenced by the accumulation of other particle sizes from fine sand to very coarse sands.

Figure 4.2showed that accumulation of fine gravel varied between 0% and 40% of the total volume of sediments that accumulated on the riverbeds in Kitui South seasonal rivers. The median size particles seems to have more influence in the variation of the amount of fine gravels that accumulate along the riverbed. For example along river Ngulungu in Mutomo, this relationship was observed at Kwa Musingila site where the accumulation of fine gravel was 9% when the median sand particle-size (D_{50}) was 0.45mm and at Kwa Joseph Mulatya, the accumulation of fine gravel was 1.8% when the median sand particle-size was 0.38mm.

In another example along Memboo River at Kwa Nyamai, accumulation of fine gravel was at 0.8% while the median sand was 0.47mm. At Kwa Nguute the median size sand was 0.28mm when accumulation of fine gravel was 0.3%. Another example that showed significant relationship between the median sand particle-size and the accumulation of fine gravel was at Kwa Mwendwa along Muvuko seasonal river in Kanziko ward. Fine gravel accumulation at this site was at 11.6% while the median particle-size was 0.69mm. At Kwa Mula along the same seasonal river, the accumulation of fine gravel was 2% while the median sand particle-size at (D_{50}) was 0.32mm. The trend showed that as the accumulation of fine gravel increased, the median particle-size also increased.

In order to determine the relationships established in Figure 4.2, a regression analysis was done to establish the contribution of different grades of sand in the accumulation of fine gravels. The results displayed in Table 4.4show that the distribution of medium to coarse sands (D_{30} D_{60} and D_{90}) combined has a significance influence in the accumulation of fine gravels which is evident with a coefficient of determination, R^2 of 0.911, and a correlation coefficient, r of 0.95. This relationship is statistically significant since the F-value is less than 0.05 and the P-Values for D_{30} D_{60} and D_{90} is 0.04, 0.00 and 0.00, respectively (Table 4.4).Given that the P-value is equal to 0.13, there is no significant influence of the distribution of the medium sands (0.2-0.4mm) represented by the particle size D_{10}in the accumulation of fine gravels along the riverbeds (Figure 4.2-a). The results showed that the occurrence of fine gravels is well associated with the distribution of sand particles ranging between 0.4mm and 4mm (coarse sands).

Table 4. 4: Sand characteristics that influence the occurrence of gravelly sands

ANOVA	df	SS	MS	F	Significance F
	5	12736.60	2547.32	151.04	**2.3E-37**
	74	1248.02	16.87		
	79	13984.62			
R^2= 0.911					
	Coefficients	Standard Error	t Stat	P-value	Lower 95%
Intercept	-7.58	1.83	-4.14	0.00	-11.23
Median (D50)(mm)	-15.36	10.16	-1.51	0.13	-35.62
D10(mm)	-6.77	11.25	-0.60	0.55	-29.18
D30 (mm)	25.77	12.24	2.10	0.04	1.38
D60 (mm)	15.19	5.18	2.93	0.00	4.87
D90 (mm)	3.58	0.47	7.64	0.00	2.65

This study also established that accumulation of coarse sand is significantly influenced by the distribution of other particles sizes of the streams sediments. The accumulation of coarse sands is moderately influenced by the distribution of the particles of sand at$D_{10,}$ D_{30}, D_{50} and D_{90}. Figure 4.3 (a) shows that sand particles ranging between 0.1 and 0.3mm (fine to medium sands) at$D_{10,}$ have a moderate influence in the accumulation of coarse sand along the riverbeds. This is reflected with a coefficient of determination, $R^2$of 0.296 and a correlation coefficient, r of 0.54 (Figure 4.3 –a). The results also showed that sand particles ranging between 0.1 and 0.5mm had a moderate influence in the accumulation of coarse sand along the riverbeds. This is evident with a coefficient of determination, $R^2$of 0.269, and a correlation coefficient, r of 0.52 at D_{30} (Figure 4.3- b).

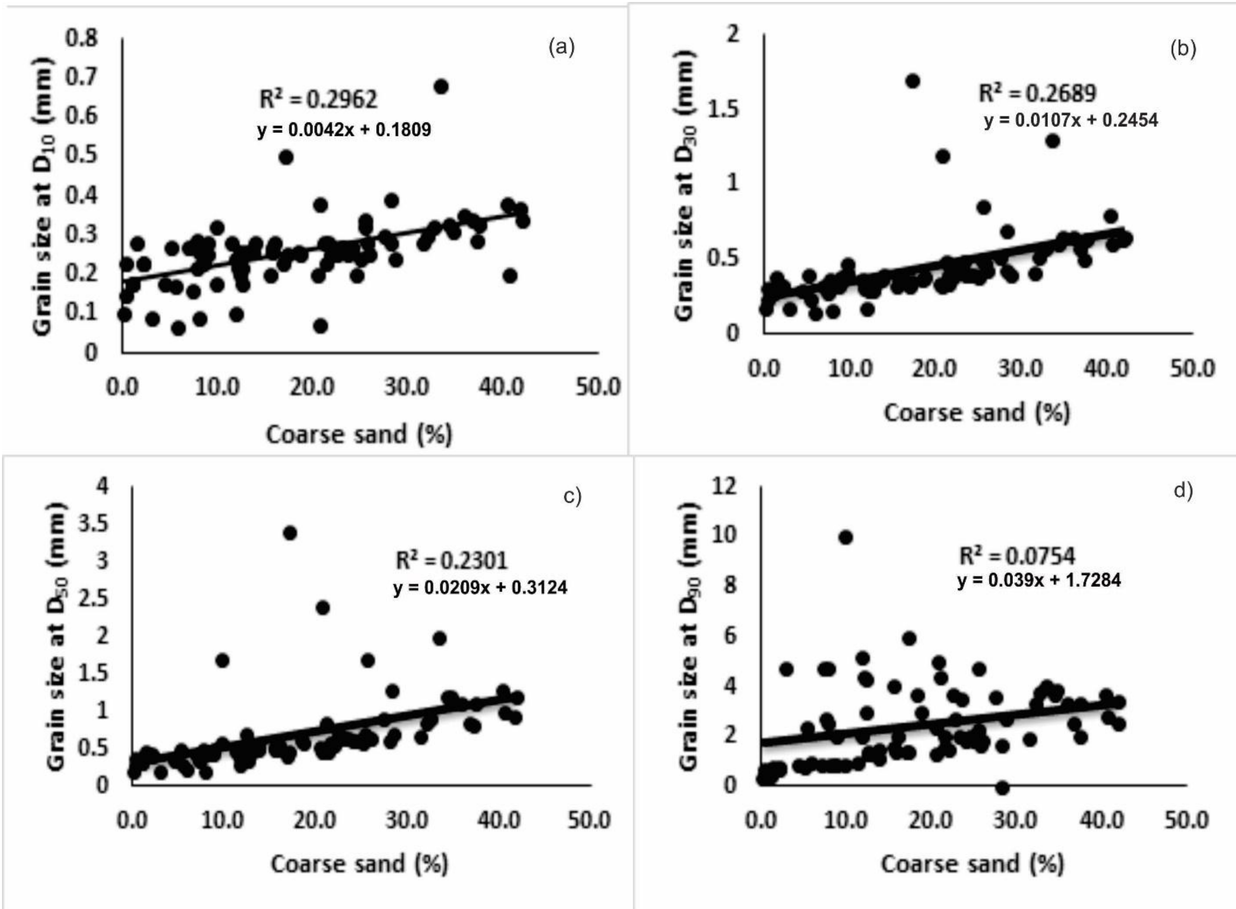

Figure 4.3 (a-d): The relationship between the rate of accumulation of coarse sands and occurrence of other particle-sizes

The accumulation of coarse sand was fairly influenced by the occurrence of median particles of sand. Figure 4.3 (c) shows that upto 40% accumulation of coarse sand is partly influenced by the occurrence of median sand at (D_{50}) with a coefficient of determination, R^2 of 0.23 and a correlation coefficient, r of 0.48. However the occurrence of sand particles ranging between 0.2 and 4mm shows no significant influence in the accumulation of coarse sands (Figure 4.3 – d). The coefficient of determination, R^2 of 0.08 and correlation coefficient, r of 0.27 were generally low suggesting minimal influence.

The results in Table 4.5 shows similar observations where the particle diameter at D_{10} indicates a significant influence in the variation of accumulation of coarse sands with a significance F-value less than 0.05 and a P-value of 0.04. The other particles represented as D_{30} D_{50} D_{60} and D_{90} do not show any significant influence in the accumulation of coarse sands as indicated with P-value 0.73, 0.91, 0.70 and 0.13, respectively (Table 4.5). The 34% of the variation in the accumulation of coarse sands is explained by the changes in the distribution of D_{10} particle sizes along the riverbeds. This shows that the medium sands (0.2-0.4mm) have a great influence in the accumulation of coarse sands on the riverbeds (Figure 4.3 -a). The occurrence of the median sand particle-size did not show any significant relationship with the accumulation of coarse sands in seasonal rivers found in Kitui South.

Table 4. 5: Site characteristics that influence the occurrence of coarse sands

ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	5	3506.21	701.24	7.45	1.05E-05
Residual	74	6969.20	94.18		
Total	79	10475.41			
R^2= 0.34					
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-2.45	4.33	-0.57	0.57	-11.08
Median (D50)(mm)	2.71	24.02	0.11	0.91	-45.15
D10(mm)	55.97	26.57	2.11	0.04	3.02
D30(mm)	10.20	28.93	0.35	0.73	-47.45
D60(mm)	-4.80	12.24	-0.39	0.70	-29.18
D90(mm)	1.71	1.11	1.54	0.13	-0.50

Influences in the accumulation of medium and fine sands were also assessed. The accumulation of medium and fine sands were negatively influences by the occurrence of other particle sizes. The results showed that the accumulation of medium sands increased as the overall sand particle sizes decreased (Figure 4.4).This relationship had a low coefficient of determination, R^2 of 0.02 and a correlation coefficient, r of 0.15 (Figure 4.4 – a). A moderate relationship was observed between the increase in the amount of medium sands and the decrease in particle sizes at(D_{50}) with coefficient of determination, R^2 of 0.3087 and correlation coefficient, r of -0.56 (Figure 4.4-b). The median size sand particles in this case ranged between 0.2 and 1mm.

The distribution of particle size represented as D_{60} showed a moderate relationship with the accumulation of medium sands in Figure 4.4-c). This study found that as the volume of medium sand increased the occurrence of sand particles between 0.2 and 1.5mm which is also represented as D_{60} (medium to coarse sands) decreased with a coefficient of determination, R^2 of 0.37 and correlation coefficient, r of -0.61. A decrease in the size of coarse sand particles (0.5 to 4mm) which was represented as D_{90} (Figure 4.4-d) significantly contributed to the increase in the accumulation of medium sands on the riverbed with a coefficient of determination, R^2 of 0.48 and correlation coefficient, r of -0.69. The results suggest that a decrease in coarse sand particle sizes (0.6-4mm) resulted to an increase in the accumulation of medium sands (Figure 4.4, b- d).

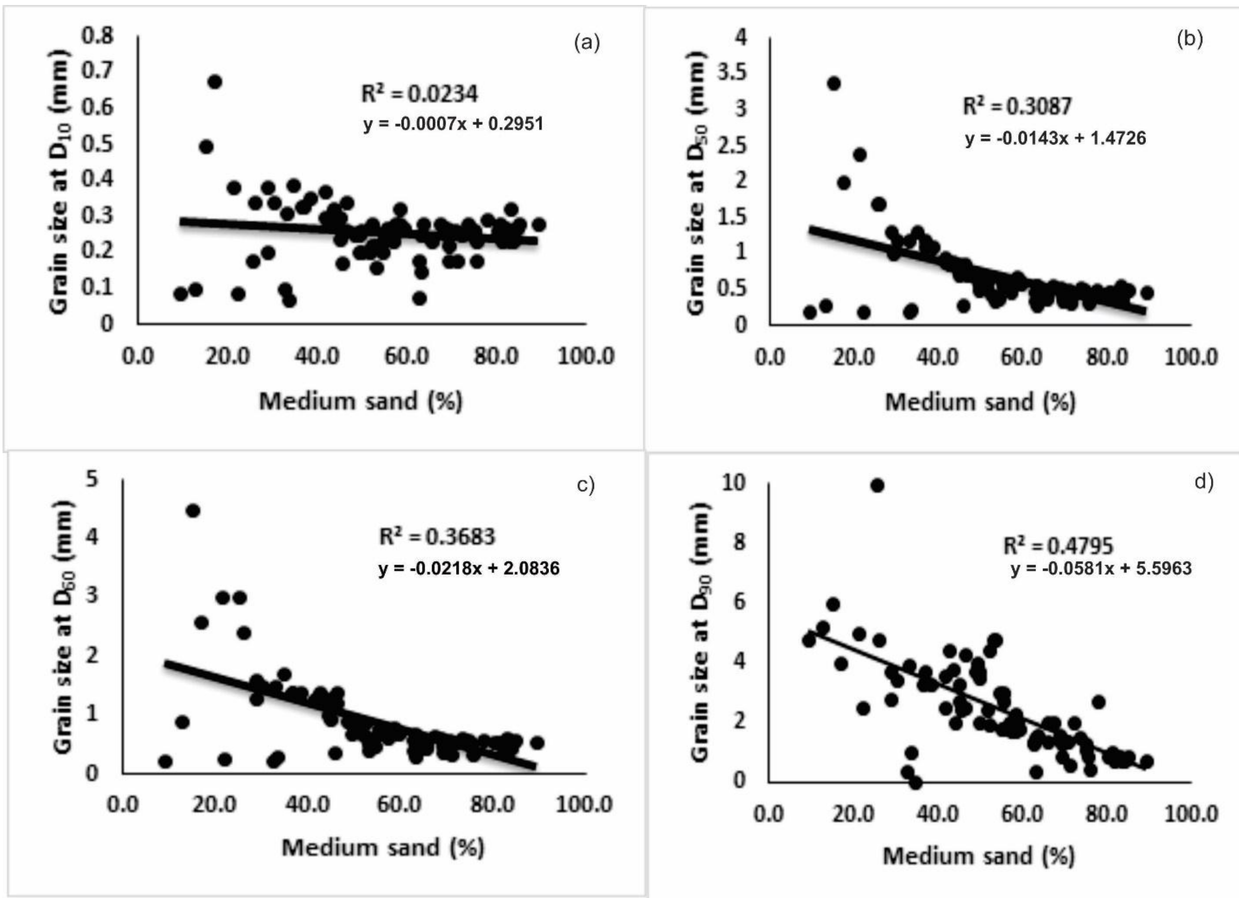

Figure 4.4 (a-d): The relationship between the accumulation of medium sands and occurrence of other particle-sizes

Similar observations were made in the results presented in Table 4.6 where accumulation of medium sands was strongly attributed to the changes in the distribution of sand particles above the average sizes at (D_{90}) or the occurrence of coarse sands. A significant variation was contributed by the changes in the coarse sands (D_{90}) as the P-value was 0.001. Although D_{10} and D_{30} particle-sizes (less than 0.5mm) showed a weak relationship, the results showed that the distribution of these particles also contributes to some extent in the overall accumulation of medium sands as the P-values was in the range of 0.00 and 0.01 respectively (Table 4.6).

Table 4. 6: Site characteristics that influence the occurrence of medium sands

ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	5	17912.44	3582.49	22.03	1.89E-13
Residual	74	12032.23	162.60		
Total	79	29944.67			
R^2= 0.60					
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	66.55	5.69	11.70	0.00	55.22
Median (D50)(mm)	44.01	31.56	1.39	0.17	-18.88
D10(mm)	130.89	34.92	3.75	0.00	61.31
D30(mm)	-103.11	38.01	-2.71	0.01	-178.85
D60(mm)	-17.91	16.08	-1.11	0.27	-49.95
D90(mm)	-6.10	1.46	-4.18	0.00	-9.00

86% of sand accumulated along the seasonal rivers in Kitui South showed 0% to 20% composition of fine sand (Figure 4.5).The study determined the relationship between the occurrence of fine sand and the accumulation of other sediments. The results showed a reverse relationship similar to the one observed in the accumulation of the medium sands in Figure 4.3. The occurrence of find sands was strongly related to the decrease in the corresponding distribution of finer grades of sand at (D_{10}). From Figure 4.5 (a), it was noted that an increase in the accumulation of fine sands was strongly related to the overall decrease in the distributed particle sizes along the rivers in Kitui South. This relationship existed with a coefficient of determination, R^2 of 0.51 and a correlation coefficient, r of 0.71. The accumulation of fine sands was moderately influenced by the decrease in particles less than 0.5mm (Figure 4.5 a-b). It was concluded that the accumulation of fine sand was probably attributed to the decrease in the sand particle-size ranging between 0.2 and 0.4mm (medium sands).This implies that more accumulation of fine sands would occur where the accumulation of medium sediments is minimal.

The distribution of particle sizes represented as D_{30}, D_{50} and D_{90} did not show any significant relationship with the increase in the accumulation of fine sands. Figure 4.5 (c) showed a weak relationship between the decreases in the median size particles (D_{50}) and the increase in fine sand accumulation with a coefficient of determination, R^2 of 0.19 and correlation coefficient of 0.43. There was no significant relationship established between accumulation of fine sands and the decrease in size of coarse sands (Figure 4.5–d).

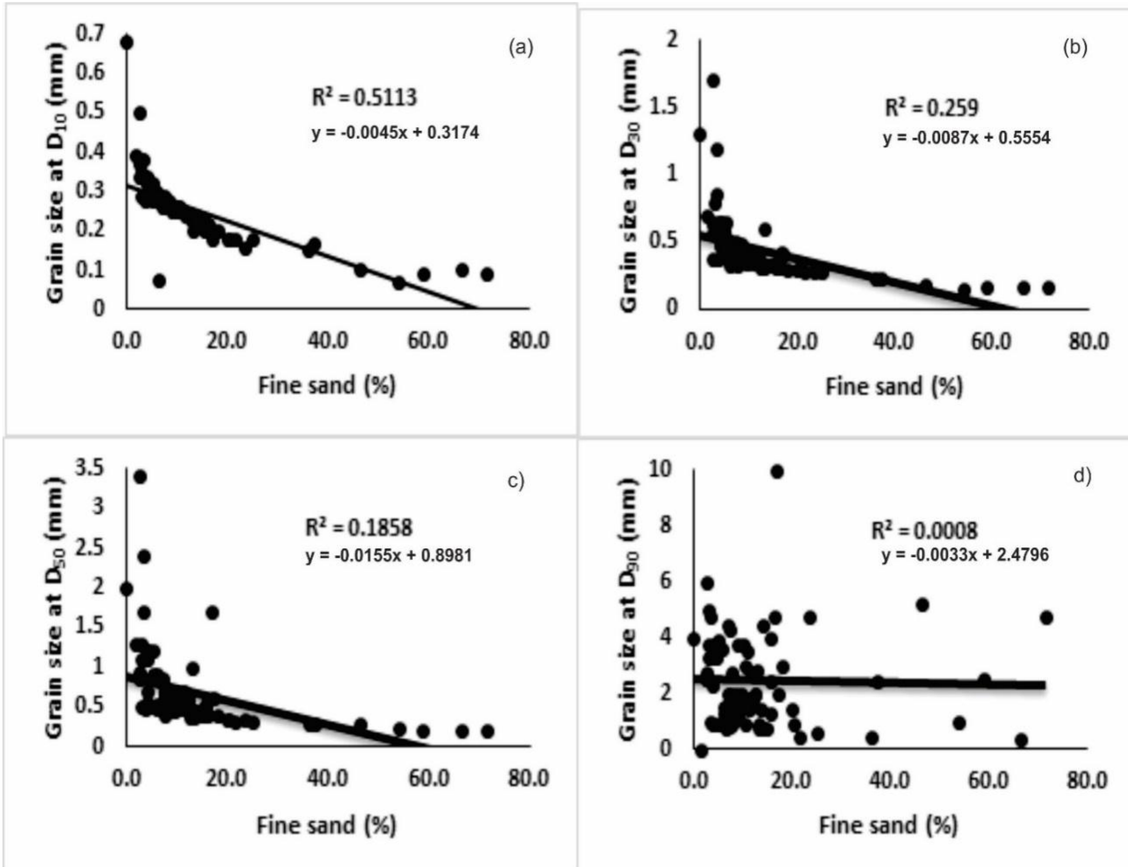

Figure 4. 5 (a-d): The relationship between the accumulation of fine sands and the occurrence of other particle-sizes

The influence of the low grade particle-sizes in the accumulation of fine sands is evident from the results shown in Figure 4.5 where the particles represented as D_{10} and D_{30} showed a significant contribution (56%) in the observed variation (Table 4.7).

Table 4. 7: Site characteristics that influence the occurrence of fine sands

ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	5	8572.75	1714.55	18.59	6.45E-12
Residual	74	6826.26	92.25		
Total	79	15399.01			
R^2=0.56					
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	41.62	4.28	9.72	0.00	33.09
Median (D50)(mm)	-28.19	23.77	-1.19	0.24	-75.56
D10(mm)	-169.73	26.30	-6.45	0.00	-222.13
D30(mm)	61.20	28.63	2.14	0.04	4.15

D60(mm)	6.11	12.11	0.50	0.62	-18.02
D90(mm)	0.98	1.10	0.89	0.38	-1.21

The significance of these low grade particle sizes was reflected with P-value of 0.001 and 0.04 for D_{10} and D_{30}, respectively. This suggest that the accumulation of fine sands was somehow associated with the accumulation of low grade particle-sizes as compared to the coarse sands.

4.4 Relationship between elevation and the rate of sand accumulation

This study attempted to establish whether the rate at which sands are deposited on the seasonal rivers has any significant relationship with the changes in the elevation. The results generated from the sieve analysis shows two key observations. One is that there is no relationship between the amounts of different grades of sand that can accumulate along the riverbed and the changes in the elevation (Figure 4.6).

The second point is that there is significant variation in the distribution of different grades of sands along the seasonal rivers in Kitui South. For example in Memboo seasonal river, at Kwa Nyamai which is located at an elevation of 841m the accumulation of coarse sand was 8.1% and median sand particle-size of 0.47mm while at Kwa Nguute site which is located downstream on the same river at an elevation of 759m the accumulation of coarse sand was 0.4% and the D_{50} was 0.28mm. Along Muvuko seasonal river at Kwa Mwendwa Kilatya (638m), the accumulation of coarse sand was 26% with median size of 0.69mm and at an elevation of 602m the accumulation of coarse sand was 1% with median size of 0.32 at Kwa Mula. Similar observation was made on Nguluni seasonal River in Mutomo Ward at Kwa Musingila and Kwa Joseph Mulatya sites.

Figure 4.6 (a-d) also showed that accumulation of sands on the riverbed was mainly at an elevation ranging between 600 and 900 meters above sea level. The accumulation of fine sands occurred in small quantities (less than 20%) as indicated in Figure 4.6 (a). This was observed especially on Koma-Kwa Mbithi River in Ikanga Ward, Kanzilu in Mutha ward, Kakya in Ikutha ward and Muvuko seasonal river in Kanziko Ward. More accumulation of medium sands (20 to 80%) was observed at an elevation between 600 and 900m above sea level (Figure 4.6 – b) occurring in 66% of the potential sand dam sites in Kitui South. Only less than 30% of fine gravels and 10 to 40% of coarse sands accumulated within this range of elevation. Accumulation of coarse sands and the fine gravels was more at an elevation above 700m (Figure 4.6 c-d). However the sand accumulation varied between less than 20% of fine sands and 20 to 80% of the medium sands at the sites located above and below 700m.

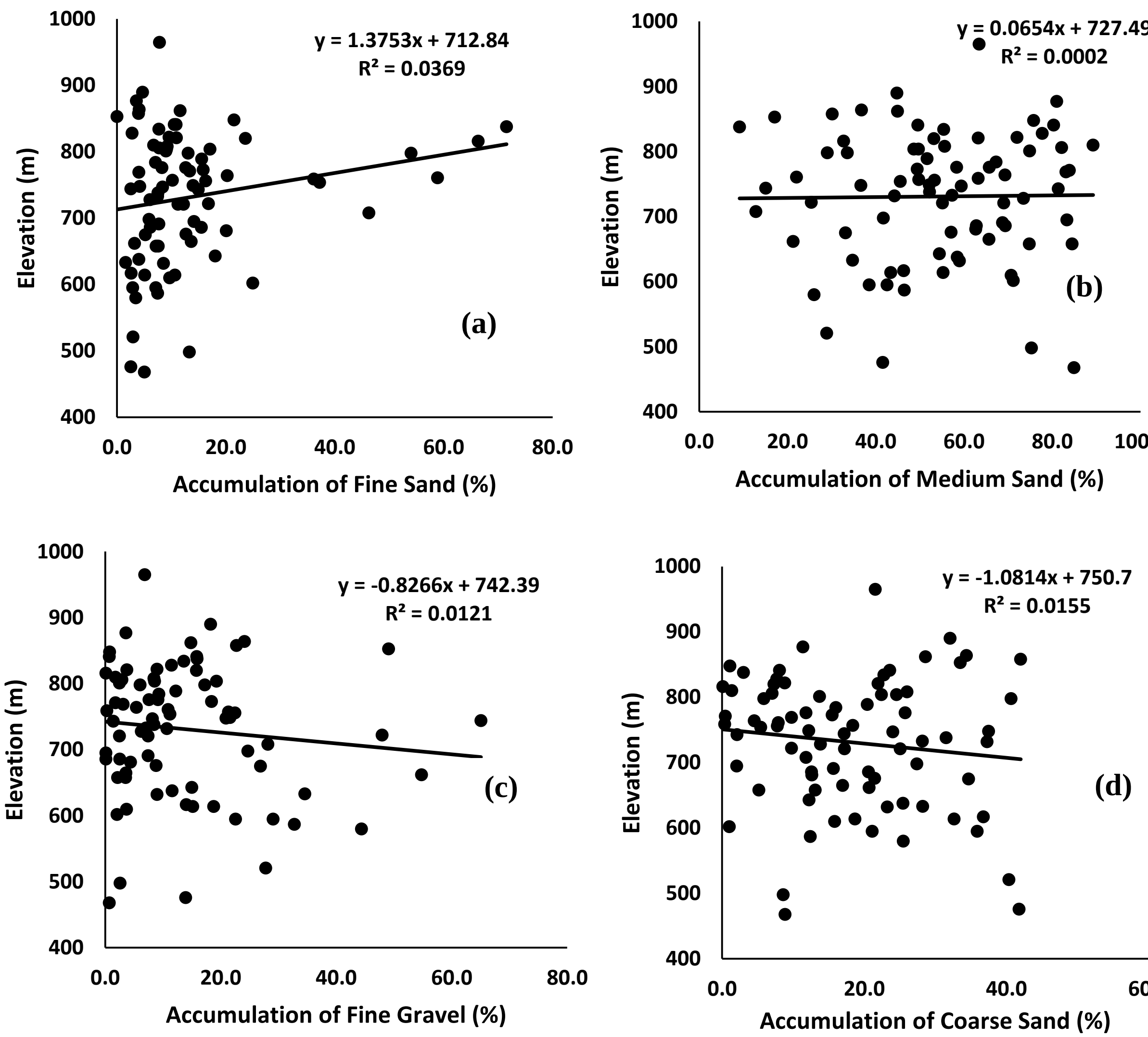

Figure 4.6 (a-d): Relationship between elevation and the rate of sands accumulation on the riverbed

4.5 Relations between sand gradation and stream elevation

Sites located upstream from the potential sand dam sites were dominated with larger particle-sizes as compared to the sites located downstream where sediments due to the impact of erosion. Figure 4.7 shows that sand particle-sizes at different sites significantly varied based on elevation along the streams in Kitui South.

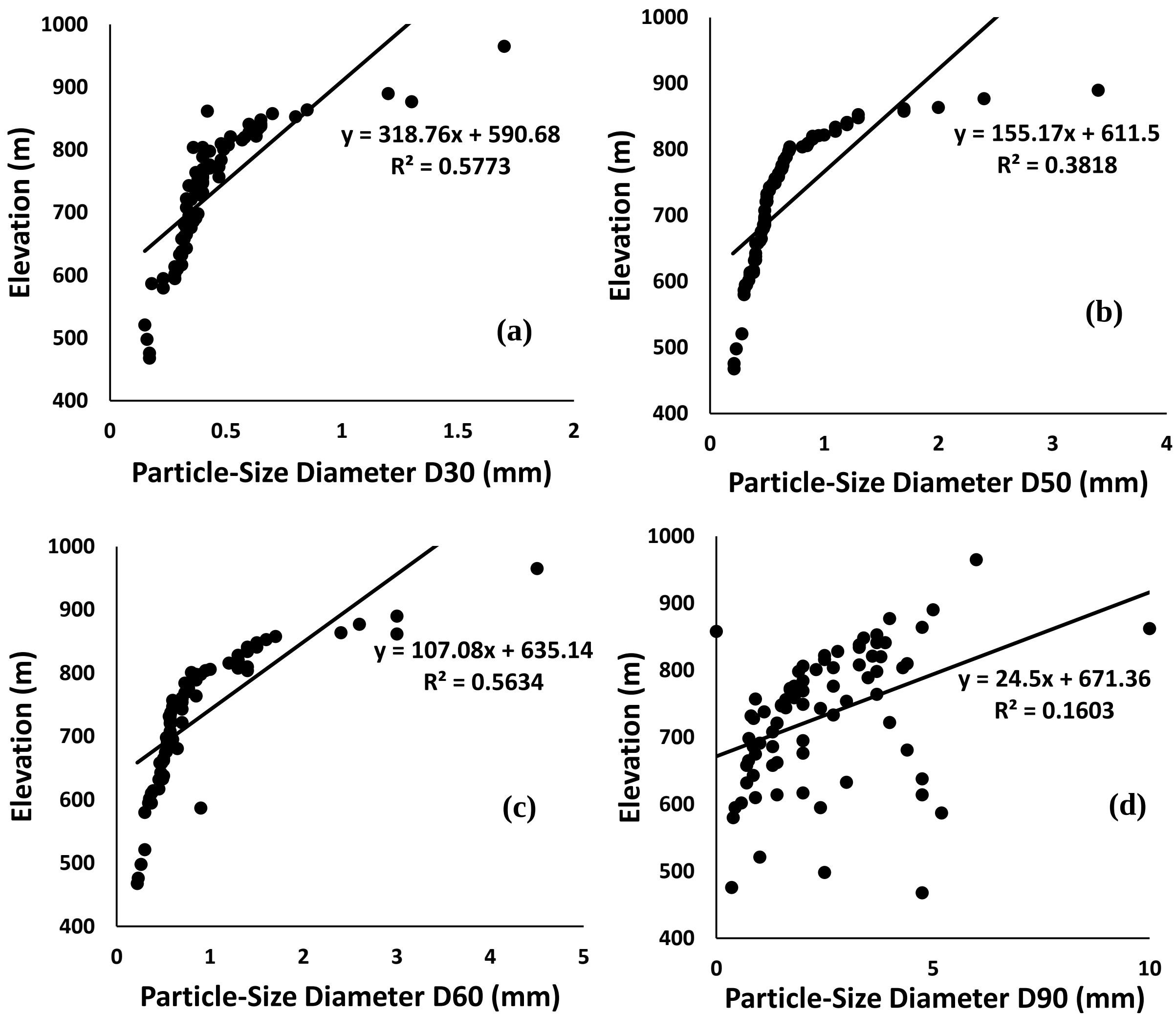

Figure 4. 7 (a-d): The relationship between elevation and sand gradation along the seasonal rivers in Kitui South Sub-County

The particle-sizes atD_{30}, D_{50}, D_{60} and D_{90} were applied to determine the particle-size distribution along the seasonal streams at different elevation. Figure 4.7 (a) shows that changes in the sand particles-size ranging between 0.2 to 0.8mmat (D_{30}) was significantly influenced by the changes in the elevation along the seasonal streams in Kitui South. Sand particle-sizes increased from 0.2mm at an elevation of 600m to 0.8mm at an elevation of 860m. This implies a strong relationship between elevation and sand gradation especially for the medium and coarse sands (0.2-0.8mm) with a coefficient of determination, R^2 of 0.58 and correlation coefficient, r of 0.76 at D_{30} particle size distribution (Figure 4.7-a). Figure 4.7 (b) showed similar trend where the median size (D50) also increased from about 0.2mm to 1.5mm at an elevation between 470m and

850m. The influence of elevation was significant in this case with a coefficient of determination, R^2 of 0.38 and a correlation coefficient, r of 0.61.

Figure 4.7also showed that sand particles which were slightly larger than the average size (i.e medium to coarse sand (0.2-2mm) showed a decreased particle diameter from upstream to downstream along the seasonal rivers in Kitui South (Figure 4.7- a and c). A similar trend was observed on coarse sands (0.2-2mm) atD_{60}, whereR^2 is0.56 and r is 0.75 between an elevation of 450m and 900m. Sand particles sizes larger than 2mm (gravels) at D_{90}did not show any significant influence by the changes in the elevation along the seasonal streams in Kitui South (R^2=0.1603, r= 0.40) (Figure 4.7-d).

4.6 Relationship between riverbed gradient and sand accumulation rate

The general terrain in Kitui South ranges between 0^0 and 72^0 (Figure 4.9). This also implies a gradient ranging between 0 to 70%. It was also observed that more accumulation of sands occurred at the low gradient points along the seasonal rivers. There is clear evidence that accumulation of sands on the riverbeds occurred within the recommended riverbed gradient ranging between 0% and 6%. The mean gradient was 4.1% while the minimum and maximum accumulation of sands would occur at 8% and 1% respectively. Figure 4.8 shows that there is no significant relationship between the riverbed gradient and the rate of sand accumulation along the seasonal rivers. This relationship had a correlation coefficient, r ranging from -0.15 to 0.13 (Figure 4.8).

Different grades of sand are distributed along the seasonal rivers in Kitui South where the accumulation of coarse sand to medium sand is between 30% and 80%. The accumulation of coarse sands and fine gravels ranged between 0% and 40% at a riverbed gradient ranging between 1% and 5% (Figure 4.9). Sites located at high riverbed gradient were less considered as potential suitable sites for sand dam construction. Such sites include Kwa Mbivu along Kyaangu River in Mutomo Ward, Kwa Mutheki along Isaa seasonal river and Kwa Musyimi on Kanzilu seasonal river in Mutha ward, Kwa Kisangau along Mwila River in Ikutha, and Kwa Nyamai on river Nguni in Athi Ward among others.

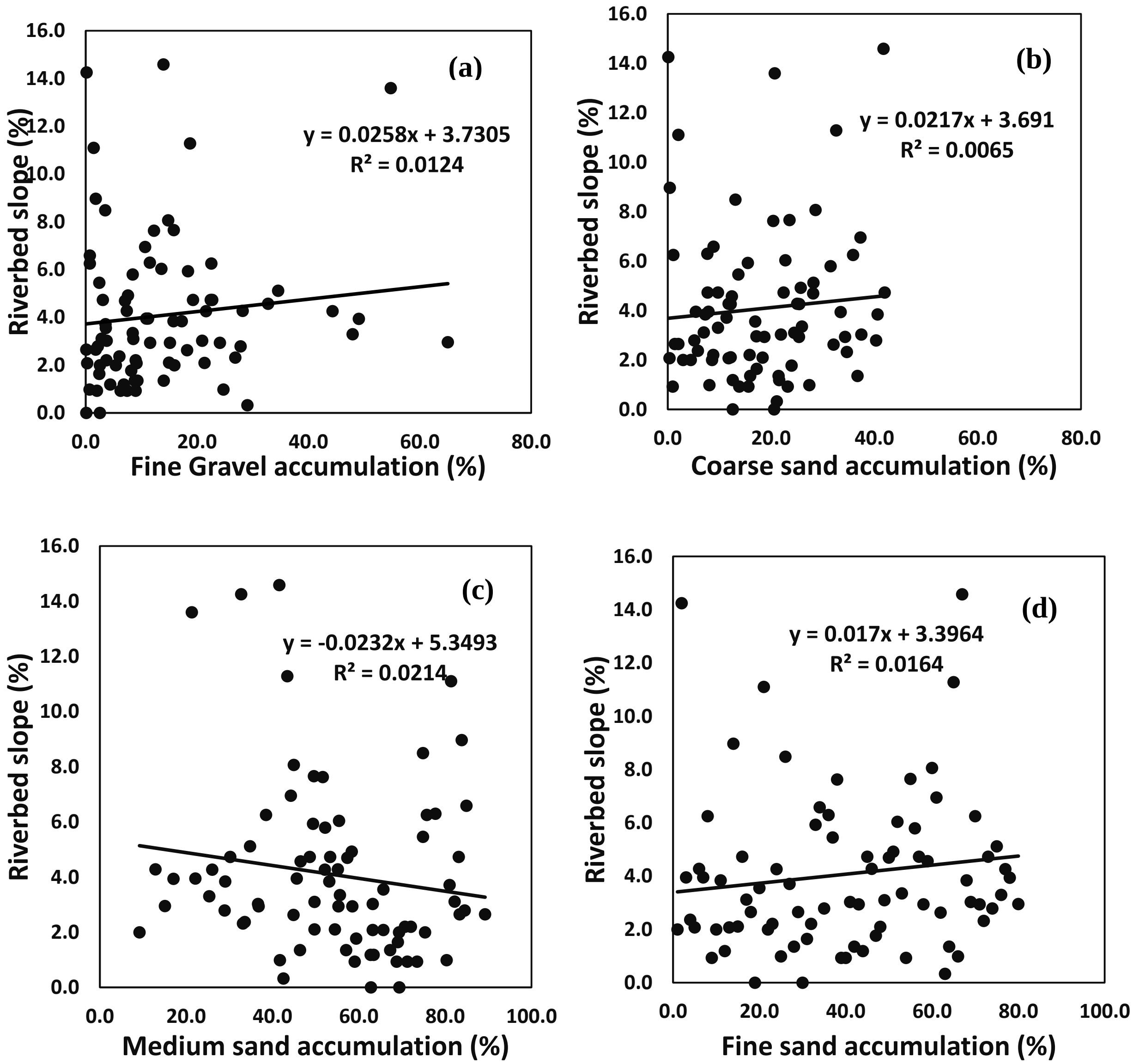

Figure 4. 8 (a-d): Relationship between the accumulation of different grades of sand and riverbed gradient

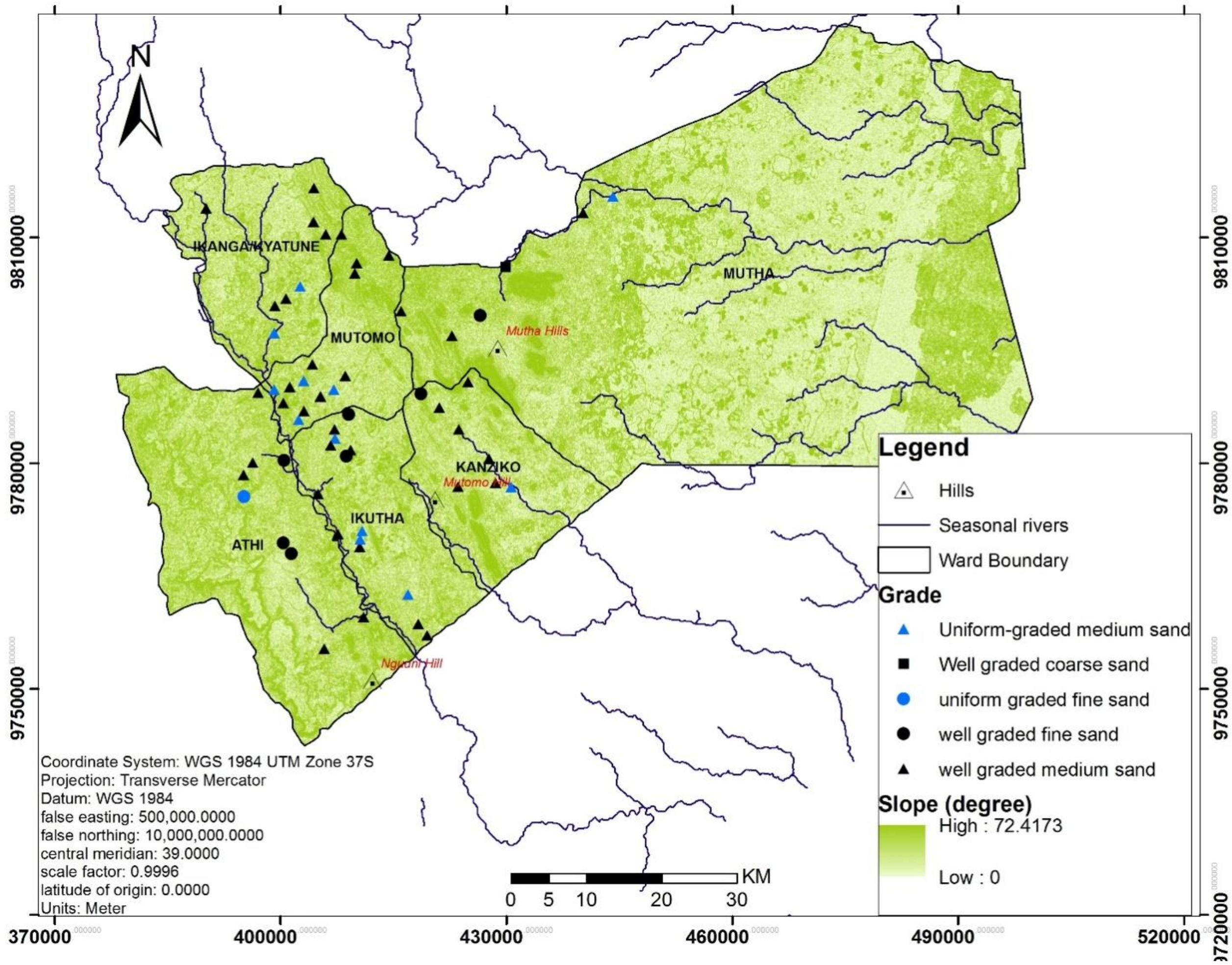

Figure 4. 9: The general terrain of Kitui South Sub-County and gradation of stream sediments

4.7 The influence of riverbank depth and stream width

Although not well defined, the seasonal rivers in Kitui South were observed to have shallow bank depths although the stream width increased downstream (Figure 4.10). These two parameters did not show any significant relationship with changes in the elevation. This could be an indication that changes in elevation does not influence stream morphology in seasonal rivers found in Kitui South.

According to Sasol and Acacia (n.d.), very wide streams (more than 25m) are not recommended for sand dams. This is because reinforcing very wide riverbed is not cost effective. The minimum and the maximum stream widths observed in the study area were 8m and 48m, respectively.

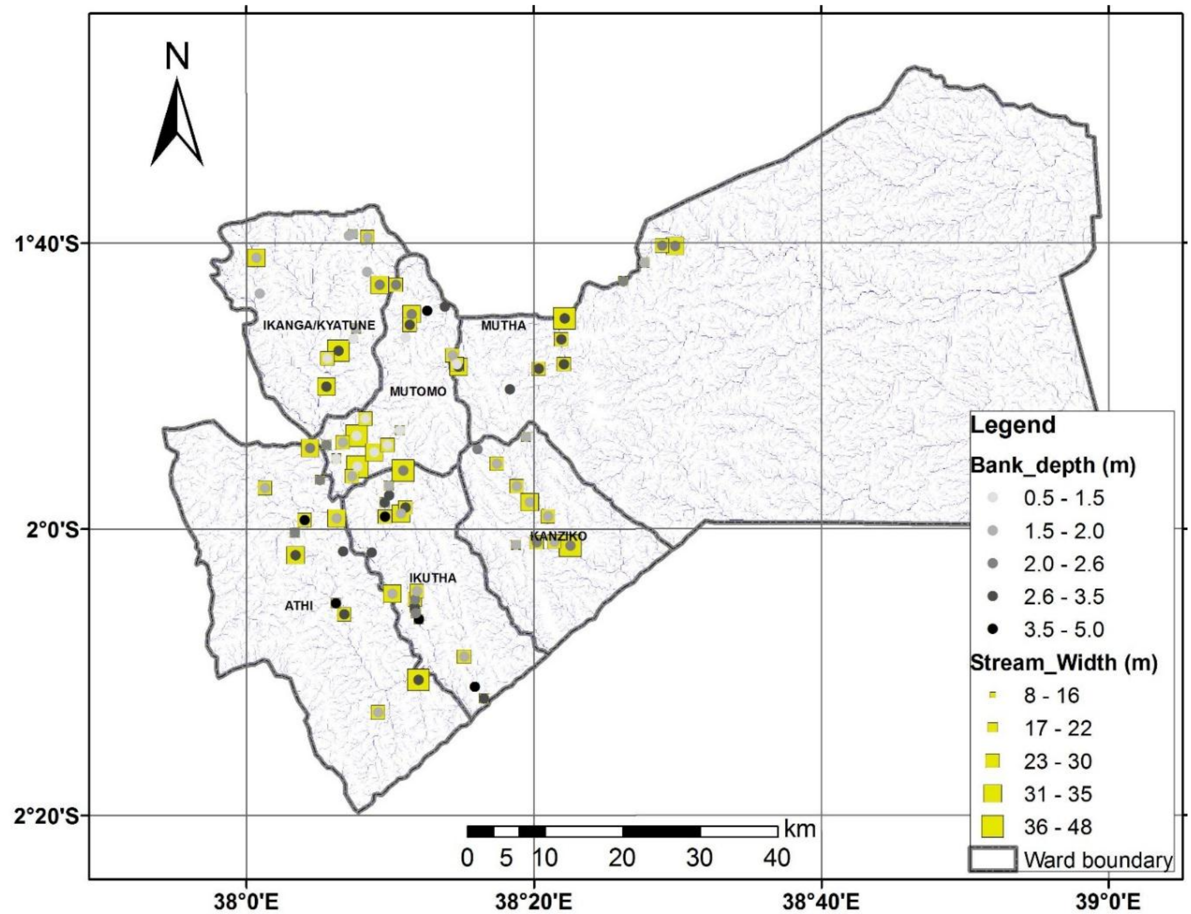

Figure 4.10: Variation of the stream width and bank depths along the seasonal rivers in Kitui South at the potential sand dam sites

The stream width in 55% of the streams that were studied in Kitui South were less than 25m wide while 45% had a width ranging from 28m to 48m. Suitable sites on the seasonal rivers with stream width less than 25m were sited on the hilly areas in Kitui South. Some of the site were identified in Ikanga Ward for example at Kwa Mbithi, Kiangwa along Manzee river, and and Kwa Ngambai along Nzeeu river. Other sites were distributed in the hilly areas of Mutomo and Ikutha wards. There were few sites on the eastern hilly areas of Athi ward for example at Kwa Matheka along Nguni River and Mukue Ndiliu and northern parts of Kanziko Ward.Mutha Ward were least dominated with sites having streams width of less than 25m.

Kitui South is well distributed with deep riverbank streams. About 80% of the seasonal streams have riverbank ranging between2to 5m. Suitable sites were observed with deep riverbanks for example in Mutha ward at Kwa Katu Kilonzo where the riverbank depth was upto 2.6m, Kwa

Mwendwa Kilatya in Kanziko ward the riverbank depth was 2m and Nzeveni in Ikutha the riverbank depth was 3m.Deep riverbanks ranging between 4 to 5m were common in the seasonal streams in Athi and Ikutha wards namely Makue Ndiliu and Kwa Meshack Mutua in Athi and Kwa Kiluu, Kwa Kisangau and Kwa Kinene in Ikutha ward. Deep riverbanks are vital during flood events to ensure that water is maintained within the riverbed. This condition should be maintained to avoid erosion on the riverbank which might lead to failure during high flood events.

4.8 Hypotheses testing

The analysis of variance (ANOVA) was used to test the hypotheses. F-test was used to determine the significant differences between the rates at which fine sand accumulates at a given site as compared to the rate for the coarse sand. Using the mean differences, single factor analysis of variance was used to test hypothesis $H0_2$, $H0_3$ and $H0_4$. The 0.05 significance level was set to accept or reject of the defined hypothesis.

The study tested the hypothesis that the rate of accumulation of fine sands is different from that of the coarse sands at different points along the riverbed. The following model was adopted in testing the null hypothesis; $\mathbf{H0_1: \mu_1 = \mu_2}$

Where $\mu_1$and $\mu_2$are the percentage means of the amount of coarse and fine sands respectively. Analysis of variance on the means was run to confirm this assumption. Table 4.8 displays the results of the tested hypothesis. The results show that indeed there is no significant difference between the rate of accumulation of coarse sands and fine sands (P-value=0.04). This result is well reflected in the findings presented in Figure 4.2 where it was indicated that the occurrence of fine gravel corresponded with the average coarse particle-size of the sand on the riverbed.

The results displayed in Table 4.8 show that the critical value is 1.45 which is slightly lower than the F-ratio of 1.47 (F≥F-critical). We therefore reject the null hypothesis that the rate of accumulation of fine sands is different from that of the coarse sands.

Several morphological factors have a great role in the accumulation of sands. This study attempted to determine whether the variation in the riverbed gradient has any significant influence on the rate at which different particle-sizes of sand are deposited on the seasonal riverbeds. To achieve this, the hypothesis that riverbed gradient does not have any significant influence in the rate at which different grades of sands accumulate on the riverbed was tested.

Table 4. 8: Analysis of the relationship between the rates of accumulation of fine sand and coarse sand

	Fine SAND (%)	*Coarse SAND (%)*
Mean	13.24257	18.17325
Variance	194.9242	132.6001
Observations	80	80
df	79	79
F	1.470016	
P(F<=f) one-tail	0.044419	
F Critical one-tail	1.451152	

The results presented in Figure 4.8 showed no significant relation between the accumulation of different grades of sand and the increase in the slope along the riverbed. The coefficient of determination, R^2 ranged between 0.0065 and 0.0164 and correlation coefficient, r ranged from -0.15 to 0.13. It was however noted that although more accumulation of sand fall within the recommended riverbed gradient range (0-8%), the rate at which different grades of sand would accumulate at any point along the river is not dependent on the riverbed gradient. This means that at the steep gradient, minimal or no sand would accumulate but as you down the stream, high accumulation is observed in streams with the optimum gradient ranging between 1.5% and 5%. Any size of the sand particles would settle along the riverbed at the favourable stream gradient.

Most of the sites located on the erosion plains were found at high elevation land particularly on the erosional plains while large volumes of sand deposition was observed on the lowlands. It was assumed that more accumulation of sands would occur at the lowlands due to the influence of low terrain than at the erosional plains in hilly areas. The hypothesis stating that the rate at which sands accumulate on the riverbed increases with a decrease in the elevation was therefore accepted.

The following model was adopted in testing the null hypothesis; **$H0_3$: $\mu_1 = \mu_2 = \mu_3 = \mu_4$**

Where **μ_1**and **μ_2**are the percentage means of the fine and medium sands while **μ_3** and **μ_4** are the amount of coarse and gravelly sands respectively.

The established relationship between the rate at which sands accumulated on the riverbed and the changes in elevations along the seasonal streams was found to be weak (Figure 4.6). The coefficient of determination R^2 ranged between 0.0002 and 0.037. This suggested that accumulation of different grades of the stream sediments was not influenced by the change in elevation. The accumulation of coarse sand and the fine gravels increased at the higher elevations. Table 4.9 shows that there is no significant difference in the rate at which both the coarse and fine sands would accumulate at any point based on varied elevation (P-Value=0). The F-ratio (3949.07) was far greater than the critical value (2.39) and therefore the null hypothesis which states that the rate at which sands accumulate on the riverbed increases with the decrease in the elevation was rejected. This was confirmed from the field observation where some points located at high elevation along the rivers were observed with high accumulation of sands due to the favorable gradient level at such points. However majority of the suitable sites were not found in the lowlands areas with low riverbed gradients.

Table 4. 9: Analysis of the relationship between the rates of accumulation of different grades of sand and the change in elevation

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	33153575	4	8288394	3949.069	0	2.394533
Within Groups	829034.8	395	2098.822			
Total	**33982610**	**399**				

The null hypothesis in this study states that the particle-sizes along the riverbed decrease downstream. Since the F-values for the selected variables namely D_{30} and D_{60} are far greater than F-Critical values we accepted the null hypothesis that there is a significant relationship between the elevation and sand gradation at different points along the riverbed.

The following model was adopted in testing the null hypothesis; $\mathbf{H0_3: \mu_1 = \mu_2 = \mu_3 = \mu_4}$

Where μ_1, μ_2, μ_3 and μ_4 are the respective D_{30}, D_{50}, D_{60} and D_{90} particle-sizes expressed in millimeters. This comprise the medium and median sizes (D_{30} and D_{50}) and the coarse particles-sizes (D_{60} and D_{90}) which were adopted in this study.

The medium sands were observed in the transitional plains while the fine sands dominated the depositional plains in the study area. Coarse sands were significant at the erosional plains. This trend confirms the hypothesis that there is a significant relationship between sand gradation and changes in the elevation along the riverbed. We therefore accept the null hypothesis.

4.9 Suitable sites for sand dams

The AHP approach was applied in ArcGIS to integrate the spatial components in the evaluation of different sites for sand dams along the seasonal streams in Kitui County. The spatial components involved geology, soil, slope, sand accumulation, landuse and landcover. The relationship between various components contributing to the suitability for sand dam was determined through a pairwise comparison and assigning weights through analytical hierarchy process as described in Table 4.10. A comparison scale with values from one (1) to (9) describes the intensity of importance of each of the factors used in the suitability model (Saaty 1980 and Saaty 1995).

Table 4.10: Pairwise Comparison Matrix as a criteria for determining the weightage of each parameters used in the suitability model

	Slope	**Land Use**	**Land Cover**	**Soil**	**Geology**	**Sand accumulat**	**Sand gradation**	**Sum of relative weights**	**Priority Vector**	**% Weight**
Slope	1	3	3	0.33	0.33	1.00	5	0.92	**0.13**	**13.0%**
Land Use	0.33	1	0.33	0.2	0.33	0.14	0.2	0.24	**0.03**	**9.0%**
Land Cover	0.33	3.00	1	0.2	0.33	0.14	0.2	0.34	**0.05**	**3.0%**
Soil	3.00	5.00	5	1	1.00	0.33	0.33	1.21	**0.17**	**2.0%**
Geology	3	3	3	1	1	3.00	7.00	1.86	**0.27**	**10.0%**
Sand accumulation	1	7	7	3	0	1	5	1.54	**0.22**	**46.0%**
Sand gradation	0.2	5	5	3	0.14	0.20	1	0.89	**0.13**	**17.0%**
Sum	**8.87**	**27.00**	**24.33**	**8.73**	**3.48**	**5.82**	**18.73**		**1.00**	**100.0%**

λmax= 7.674, CI= 0.112, CR= 8.5% <10% (acceptable)

From the results stipulated in Table 4.10 sand accumulation was identified as the key determinant of a suitable site for a sand dam given the priority of 46% influence. The other components that showed great influence in the model were sand gradation and the slope of the riverbed given priority of 17% and 13% respectively. The influence of geology was 10% while that of the land use was 9%. The result showed that influence due to land cover and soil types was relatively low given priority of 3% and 2% respectively. The consistent ratio in thisjudgement wasat 8.5% which is less than 10% and therefore acceptable. The results obtained from this pairwise comparison were distributed in the respective components to run the suitability model as shown in Table 4.11.

Table 4. 11: Classification of weighted factors influencing suitability of a site for construction of sand dam

Factor	**Domain of Influence**	**Relative weight**	**Weightage (Priority Vector) (%)**
Slope (degrees)	0-5	7	**13**
	5-15	9	
	15-25	5	
	25-35	3	
	35-45	1	
Landuse	Bushland (dense)	5	**9**
	Agriculture (sparse)	7	
	Woodland	9	
	Bushland (sparse)	5	
	Barren land (R)	1	
	Forest	3	
	Grassland	5	
Land Cover	Herbaceous crops	3	**3**
	Tree crops	5	
	Trees closed	7	
	Shrubs close	9	
	Urban areas	3	
	Bare land	1	
	Water bodies	1	
	Forest plantation	5	
Soils	Calcic Cambisols	7	**2**
	Rhodic Ferralsols	5	
	Eutric Regosols	3	
	Ferric Acrisols	9	
	Chromic Vertisols	5	
	Luvo-orthic Solonetz	1	
	EutricFluvisols	1	
	SolodicPlanosols	1	
	Complex soils	3	
Geology	Basement	9	**10**
	Other Intrusives	7	
	Older Quaternary sediments	3	
	Younger Quaternary sediments	1	

	Tertiary Volcanic rocks	7	
	Alkaline Intrusive	5	
Sand accumulation	Very high	9	**46**
	High	9	
	Moderate	7	
	Low	5	
	Moderately low	5	
	Very low	3	
Sand gradation	Gravel	2	**17**
	Coarse sand	9	
	Medium sand	5	
	Fine sand	2	
Σ			**100**

The suitability model consisted of six (6) key spatial components each with different domain of influence (Table 4.11). Every component and its domain contributes differently at a given scale in suitability model. For example the slope gradient across the study area varied between zero (0) to 45 degrees. The recommended slope falls between 0 to 8 degree but flat terrains are mostly not preferred therefore slope between 0-5 degree were assigned a relative weight of 7 while the most important domain between 5-15% was assigned a relative weight of 9 as shown in the Table 4.11. The steeper terrain which fall between 25 to 40 degrees were also not considered for sand dam therefore given lower weights. The resultant contribution of the slope in the suitability model was set at 13%.

Land use and land cover were also important components in the model given an overall scale of influence of 9% and 3% respectively. The land categorized as woodland and bushlands are considered important since minimal erosion is experienced from such lands hence reduced rate of soil erosion and in return low rate of siltation into the sand dams. Agricultural land was also given a relative weight of 7 since the distribution of water abstracted would start with the farmers located near the sand dam.

The soil types played a minimal role in the suitability model given priority of 2% influence since they have minimal contribution in the development of sands on the riverbed. The suitability of different soils types was however important in the evaluation for the best riverbanks for anchoring the sand dam wall. Soils rich in clay given low weight between 1 and 3 while the soils type with low expansion capacity were given high weight for example Ferric Acrisols which are found on erosional plains.

Geology was also very important in the suitability model. The production of sands was observed from the basement rocks and some intrusive rocks in the study area. This happened mainly from the quartz rich rocks which when eroded produced sand particles. The accumulation of these sand particles along the riverbed is important for an effective sand dam. Therefore the rocks with these characteristics were given high weightage and the overall influence factor of geology in the suitability model was at 10%. The points observed with high and moderate accumulation of sand along the riverbed were given relative weights of 9 and 7 as shown in Table 4.11. The overall role of sand accumulation in the model was considered high with a scale of 46% while that of the sand gradation was 17%.

Various points in Kitui South were found relatively favourable for sand dams since most of the ephemeral rivers are well supplied with sands. Some areas are classified as “more suitable” than others.The suitability model was used to generate the map showing sites with different levels of suitability for sand dams in Kitui South (Figure 4.11). The results showed that 16% of the analyzed sites in Kitui South were found ‘fairly suitable’ (shaded in light green points), 79% were ‘suitable’ (dark green points) and 5% were categorized as ‘very suitable’ (shaded in dark blue points) for sand dam construction (Figure 4.11).

The seasonal rivers located in the central and the entire eastern parts of Mutha Ward were found not suitable for sand dam construction due to poor conditions such as the lack of bedrock on the riverbeds, flat terrain, very shallow stream banks, and weak soils on the riverbanks. The western and central areas of the study area are dominated with favorable sites for sand dam due to high accumulation of coarse sands and bedrock exposure along the riverbeds. The areas near Mutomo hills and the rocky areas in Ikanga wards were found with excellent sites.

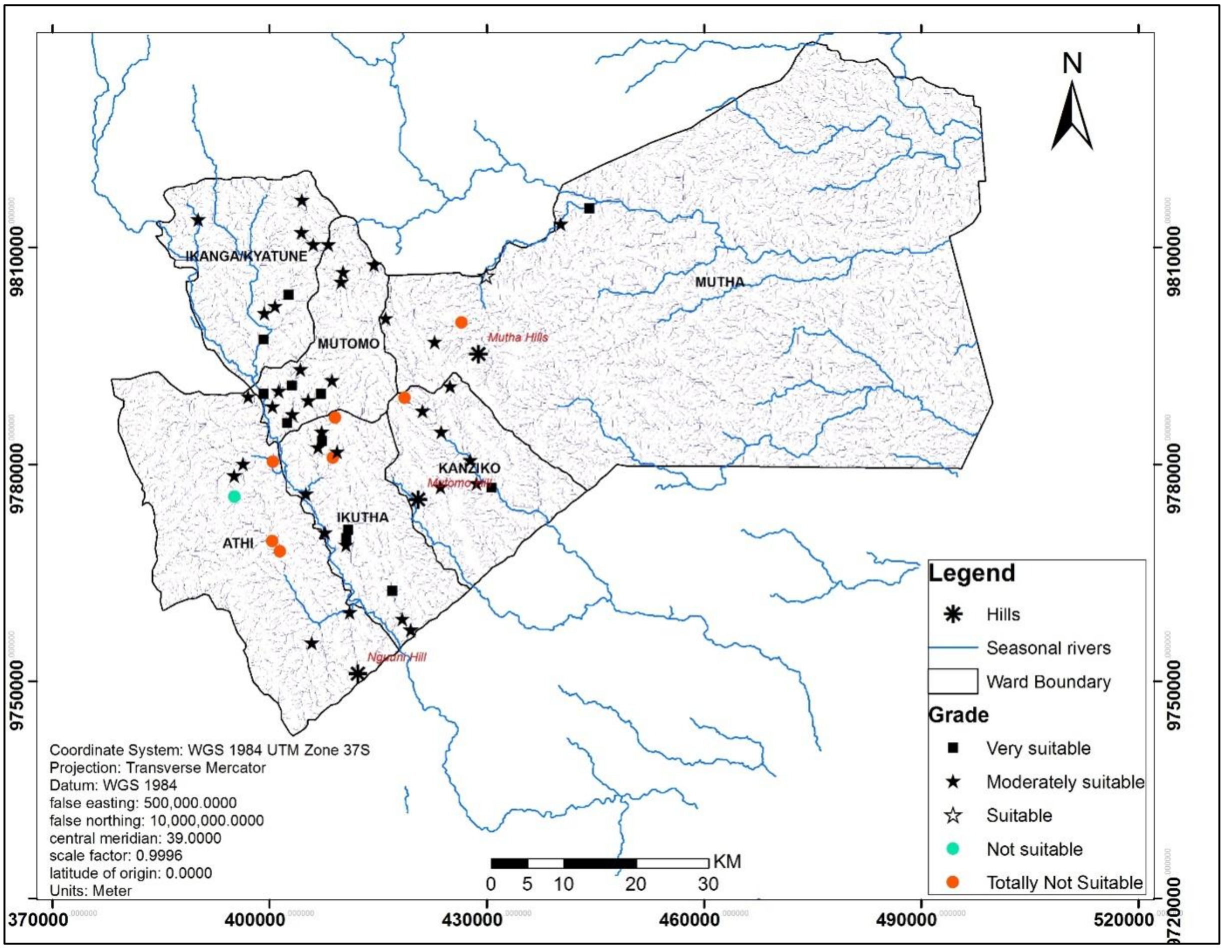

Figure 4. 11: Sand dam suitability map for Kitui South Sub-County

Excellent sites were identified in the sites where the supply of coarse sands is sufficient. Very suitable sites in the study area are indication of excellent qualification in terms of the preconditions required for a sand dam. Such excellent sites are however few in the study area. This observation was attributed to the existence of the basement rocks which dominate in the western parts of the study area. Fairly suitable to poor sites that were observed in the western parts of Mutha ward were commonly identifiedin the lowlands. Such sites included Kwa Kilonzo Kivoo along Kaviuni seasonal river, Kwa Katu Kilonzo, Kwa Musyimi, Kwa Kikuyu, Kwa Kithuku and Kiminza along Kanzilu River, and Kavyuni on Kavyuni seasonal river.Sites located near markets and urban areas were not considered suitable due to high possibility of water contamination in the sand dams. These sites included Also, heavily cultivated areas with potential high rate of soil erosion were not suitable due to supply of unsuitable sediments that may eventually limit water storage in the sand dam (Kirkby and Morgan, 1980).

Suitable sites were concentrated at the north eastern parts of Ikanga ward (especially along Thua-Syotwii river, Manzee-Ngunga, Nzeeu and Koma-kwa Mbithi. The southern parts of Mutomo ward was also dominated with suitable sites for sand dam construction especially along Ngulungu and Memboo seasonal rivers. There were few sites on the western parts of Mutha ward that were found suitable for sand dam construction especially along Katuluvi-Kanzilu and Kavuti seasonal rivers. In Kanziko ward, suitable sites for sand dam were also well distributedespecially at the northern parts for example along Ikungute-Muvuko, Ikutanzale-Muvuko and Muliluni seasonal rivers at the southern parts of the ward. Ikutha ward was found with suitable sites along Mwila-Tiva, Masoma-Tiva, and Ke Mwaa-Muliluni seasonal rivers. Suitable sites for sand dams in Athi Ward were established along Mitanda-Nguni seasonal river which is found near the border to Ikutha Ward and Ndiliu-Ngunyumu seasonal river at the south eastern parts of Athi Ward.

CHAPTER 5:

DISCUSSION OF THE RESULTS

5.1 Introduction

The chapter is focused on the discussions of the results of the study presented in various sub-sections. The discussions are presented in to two major sections. The first section discusses the results obtained from the spatial modeling in GIS environment to establish the suitable sites for sand dam. The second section discusses the results of statistical analysis and testing of the hypotheses defined in this study.

5.2 Factors influencing accumulation and gradation of sandsalong the riverbeds

A number of factors influence the rate of sand accumulation along the riverbed and their characterization in terms of sand gradation and uniformity of sand particles. This section discusses the findings on gradation of sand and the relationships between sand accumulation along the riverbeds, the role of slope and elevation in the variation of sand characterization which resulted to the final conclusion on suitable sites for sand dam construction in Kitui South.

Gradation describes the distribution of particle sizes in a sand sample. According to Maddrell and Neal (2012), high sediment load in the seasonal rivers promote sand dams fill with sand and mature more quickly where seasonal rivers have the greatest sediment load. Sand gradation along the seasonal rivers in Kitui South is spatially varied. Majority of the streams in Kitui South are dominated by medium sands (66%) and coarse sands (21%). The uniformity coefficient (Cu) and coefficient of gradation (C_k) were applied in the classification of sands based on their particle size distribution.59% of the investigated sites in Kitui South were found to have uniform sands, 30% had intermediate and only 11% had well-graded sands. Out of the 47 sites, 59% had uniform sands, 86% were dominated with uniform medium size sands and hence are suitable for sand dam. Only 10% of the sites were dominated with fine sands while the rest, 4% of the sites were dominated with coarse and gravelly sands.

26.3% of the sites were found to be 'well-graded coarse sands' distributed in Athi 3, 3 in Ikutha, 2 in Kanziko, 3 in Mutomo, 6 in Mutha and 4 in Ikanga Ward, 6.3% were 'well-graded fine sand' distributed in small quantities along the streams on the hilly areas of Athi and Ikutha wards. 48.8% of the sites were dominated by 'well graded medium sands' which were equally distributed in Ikanga, Mutomo, Ikutha and Kanziko wards and few sites in Athi and Mutha. Thestudy also found that 59% of the potential sand dam sites are dominated with uniform sands while 30% are intermediate. The sites accumulated by the uniform sands were categorized as suitable for sand dams construction in Kitui South.These sites were 6 sites in Athi at Kwa Mutunga,Kwa Matheka, Kwa Nyamai, Mukue, Kwa Kasuku, and Kwa Sila Mutiso, 12 sites in Ikutha ward along Ke Mwaa, Nzeveni and Masoma-Tiva seasonal rivers, 5 sites in Kanziko ward one on Ikutanzale seasonal river and the rest along Ikungute-Muvuko river, 5 in Mutha along Katuluvi-Musila-Kanzilu seasonal river, 12 in Mutomo ward distributed in three streams name Memboo, Ngulungu and Katiliku-Masaa seasonal river, and 8 sites were found in Ikanga Ward along Koma-Kwa Mbithi, Manzee-Katitika, and Nzeeu seasonal streams.

Other parameters that were found significant in the determination of sand gradation along the seasonal streams included the particle sizes at D_{10}, D_{30}, D_{60} and D_{90} (expressed in millimeter) as explained in section 3.4.1. The advantage of using this parameters is that they give a more representative statistics derived from the sieve analysis results as also observed in (Retsch, 2009). These parameter were found significant in the determination of the distribution of sand particle sizes along the riverbeds unlike when only the median grain size as a parameter is applied (Retsch, 2009 and Barkhordari, 2015).

Kitui South is widely distributed with uniform medium and coarse sands (Table 4.3). Most of the seasonal streams in Kitui South are potential of having high capacity sand dams especially those with uniform sands which account to about 14%. This is observed in Athi, Ikanga, Mutomo, Kanziko, and Ikutha wards. Mutha ward has sparsely distributed sites exhibiting uniform sands especially on the western parts of the ward. Well-graded sands are observed in Ikutha and Athi wards. This can be attributed to the enormous exposure to suitable rocks that are easily eroded and sediments transported on the existing long distance running river at the boundary between the three wards. Uniformity of sand is however influenced by the increase in size of the sand particles. Areas dominated with very coarse sediments showed less uniform and well graded sands while those dominated with finer sediments were largely uniform.

5.2.1 The influence of accumulationof the dominant particle-sizes of sand

Limited studies have been undertaken to explain if there is any spatial relationships that exist on the characteristics of the potential sand dam sites. However, Maddrell and Neal (2012) and Munyao et. al. (2004) confirmed that the occurrence of coarse and uniform medium sands is critical for high performance of sand dams.It is therefore important to make sure that any sites selected for sand dam construction has a considerable accumulation of the appropriate sands for a sustainable good performing of sand dam. The higher the percentage of uniform coarse sands, the greater the storage capacity of that dam (Nissen-Petersen, 2007 and Rempel, 2005).The first objective of this study was to find outthe factors that contribute to changes in the physical characteristics of sands and their location at different points along the seasonal rivers in Kitui South. This involved evaluation on different grades of sands that accumulate along the riverbeds.From the field observations and results presented in chapter four, accumulation of different grades of sand varies from one point to the other along the riverbed depending on their particle-sizes.

Coarse sands are deemed the best for sand dams (Borst and de Haas, 2006). Unlike the fine gravels which give an average drainable porosity of 25%, uniform and unconsolidated coarse sand gives an average drainable porosity of 27% for the accumulation and storage of subsurface water (Johnson, 1967). Most of the investigated sites in Kitui South dominated with coarse and medium sands. The accumulation of medium sands also corresponded with the accumulation of coarse sands (Figure 4.6) which concur with Barkhodari (2015) findings. This occurrence of coarse sands is an indication of high erosion rates along the seasonal streams and presence of metamorphic rocks greatly contributes to the production of coarse sediments for sand dams.

In areas where limited accumulation of coarse sands was observed, medium sand was also considered suitable for sand dam (Maddrell and Neal, 2012). Accumulation of medium sands in the seasonal rivers in Kitui South is relatively higher than the other grades of sand occurring along the riverbeds. The results shows that accumulation of medium sand ranged between 20% and 80%

(Figure 4.4). This represents 62% of the sites which were observed to have accumulated medium sand.

The results showed unique relationship between the distribution of different grades of sand and the accumulation medium and fine sands. Both medium and fine sand accumulation showed a negative relationship with the distribution of other particle sizes. This study found that high accumulation of medium sands occurred when the dominating sand particles were less than 0.6mm in diameter. The distribution of different grades of sands along the riverbed showed a significant association with other grades of sands that have a close measure in particle sizes. For example the accumulation of fine gravels and the occurrence of coarse sands showed very strong relationship. The accumulation of coarse sands showed a strong relationship with the distribution of medium sands on the riverbed. Previous studies have shown that medium sand are more likely to accumulate in the transitional plains (Kheirkhah et al., 1980; Retsch, 2009 and Ali et al., 2014). This concurs with the findings of this study where the majority of the sites with suitable sites for sand dam construction in Kitui South were also found in the transitional plains at an elevation ranging between 500 to 800m above sea level.

It was also found that accumulation of medium sand on the riverbed was negatively influenced by the occurrence of decreasing particle sizes of the coarse sand. It was found that accumulation of medium sands was equally influenced by the occurrence of particles below and above the average sizes but is relatively highly influenced where the coarse sands are minimal (Figure 4.4- d). Although the median sizes (D_{50}) was found important in a previous study (Barkhordari, 2015) in the determination of sand particle-size distribution on the sand dam sites, in this study, (D_{50}) as well as D_{60} did not show any significant influence in the accumulation of medium sands along the riverbed (P-value= 0.17 and 0.27 respectively).However, the occurrence of fine sands showed a strong relationship with the decrease in the medium size particles of sand ranging between 0.2 and 0.4mm.

5.2.2 Uniformity of sands and their suitability for sand dam

Particle-size distribution was done through an intensive sieve analysis. The procedure helped in separating the different grades of sands from the test samples. A parameter was computed to show the uniformity of the sand particles defined here as the coefficient of uniformity (Cu). The coefficient of uniformity was applied to show how uniformity of the sands varies across the study area. The study area is well distributed with sands that are suitable for sand dam (Figure 4.10).

Maddrell and Neal, 2012 generalized that high accumulation of uniform coarse sands would result to increased storage capacity and the abstraction potential from a sand dam. This study found out that all these observations are spatially varied irregardless of the dominated particle-sizes of the sand available on the riverbed. In order to maximize the extractable water from a sand dams it is important to construct sand dams at the sites with uniform-sands (Borst and de Haas 2006; Burger et.al, 2003; Maddrell and Neal, 2012; Nissen-Petersen, 2007).

The two important parameters namely the Uniformity Coefficient (Cu) and Coefficient of Gradation (Ck) were derived to evaluate on the uniformity of sands in Kitui South seasonal rivers. Results show that Uniformity Coefficient (Cu) varied between 16.67 and 1.74 with a mean of 3.42. The coefficient of gradation (Ck) varied between 2.55 and 0.33 and a mean of 0.94. Based on the assessment on uniformity of sands (Cu) found on the riverbeds, most of the sites located along the seasonal streams in Kitui South (86%) were accumulated by uniform medium sands ($Cu<3$). The rest of the sites (14%) were dominated with coarse and gravelly sands. This means that 86% of the investigated sites in Kitui South are suitable for sand dams. Other studies found that medium sand are also applicable in sand dams (Nissen-Petersen, 2007) but the evaluation on their uniformity was not done. This study established that uniform medium sand have higher storage capacity graded sands. These observations are likely to be more at the transition between the erosional plains and flood plains at an elevation of 700m and below. This study assumes that any future rainfall in the study area would have no significant influence in terms of sand gradation, sand uniformity, sand composition and the rate at which the river sands would be accumulated at any given site along the riverbed. The results generated from this study are reliable and can be used by any group of people or an individual unless a major flooding event occurs.

5.2.3 The influence of geology

Suitability of sites for sand dams vary throughout the study area. The central and western parts of Kitui South are promising with good performance in sand dam technology. There is a vast area dominated with rock outcrops along the riverbed which are very suitable as an anchorage for the sand dam wall across the riverbed. Most of these rocks are metamorphic. Quartz grains are the main components of the river sands generated from the metamorphic rocks therefore there is an adequate supply of sands in the area (Saggerson, 1957). Kitui South is well distributed with rocks that easily erode to coarse sands and which get deposited at the low laying terrain where the gradient is between 0% and 7%. This is an added advantage in this area (Jansen, 2007) since most of the sand dam can be constructed on stable foundation and high accumulation of sands can equally be achieved. However, a detailed probe into the existence of fractures and joints along the riverbed where suitable sites are found should be done to avoid leakage from the sand dam.

The geology on the eastern parts of Kitui South is dominated with Quaternary sediments (Saggerson, 1957). The terrain in this area is almost flat and the riverbanks are very shallow and wide hence relatively not suitable for sand dam. Sand gradation in this area is however characterized with uniform medium to coarse sands (C_u = 1.7-3.0). Future studies should examine the availability of groundwater in this area. The excellent sites were concentrated on the western parts of Kitui South where the basement rocks are dominant unlike in the western parts of the area where the dominant bedrock are sedimentary. The suitable sites identified in Kanziko, Ikutha, Mutomo Ikanga, and some parts in Athi are located on firm and none fractured bedrock hence good for anchoring the sand dam wall. This is contrary to the eastern region (flood plains) especially in the larger parts of Mutha where the geology does not favor siting of sand dams. Most parts in the western region of the study area are characterized with medium and coarse sands which are favorable for excellent sand dams.

5.3 The relationship betweenriverbed gradient and the rate of sand accumulation

The river bed gradient determines the rate at which sands accumulate at a given site (Maddrell and Neal, 2012). Grounds located on gentle slope (0-10 degrees) along the riverbed are recommended for sand dam because they provide maximum potential for water storage. The low gradient also gives enough time for river flow to infiltrate into the sands, thus increasing the water storage volume in the sands. Previous studies show that high gradient accelerates the movement of riverbed sediments down the stream due to high influence of gravity and high energy of the river (Beimers et al., 2001a and Beimers et al., 2001b).

From the field observation, several sites located at the steep slopes were observed with low rate of sand accumulation hence categorized as not suitable for sand dam. Results show that the diameter of the sand particles increased upstream along the riverbeds. Areas along the riverbed where slope is between 0 to 6% are disposed to high accumulation of sand hence suitable for sand dam. Low to very high accumulation of sand was observed at constant slope range (1.5-8%). Medium sands ranged from 20 to 80% of the total volume of the available sand from different points along the seasonal rivers in Kitui South. The accumulation of the coarse sands ranged between 0% and 40% while that of the fine gravels ranged between 0% and 30% at riverbed gradient ranging between 1 and 5%. The fine sands seems to occur all through the riverbed but in small quantities (less than 20%). The results showed that86% of the investigated sites in Kitui South were suitable for the sand dam with a gradient ranging from 0% to 8%which fall within the recommended range for the slope of a potential suitable site for sand dam (Maddrell and Neal, 2012). .

The stream slope from 18% of the potential sand dam sites in the study area are 1.5% and below. 73% of the sites show a stream slope between 1.6 and 8%. Only 9% of the sites are observed with relatively steep slopes (8 to 15%). However according to SASOL and ACACIA (n.d.) the riverbed slope below 1.5% can easily have problem of siltation. From this insight some of the sites with a gradient of between 1.5 to 6% rises were considered relatively suitable for sand dams. This findings are consistent with those of Gezahegne (1986) who also noted that there is an optimum slope where sediments accumulate in large volume along the riverbed. High riverbed gradient will decrease water infiltration (Afifi and Fuladipanah, 2015). High volume of fine grained sands were observed at the lowlands far from the erosional plains.

5.4 The relationship between elevation and sand accumulation along the streams

The accumulation of sands along the riverbed is influenced by several factors along the river which include both physical and human related factors (Nepal et.al, 2014). The variation of sediment transport capacity as the sediments are carried downstream along the river is a key factor that contributes to the deposition of sediments downhill. Potential suitable sites for sand dams with well graded coarse sands and fine gravels were observed in the metamorphic rich areas for example Makutano Kivili which was dominated with coarse sands rich in quartz and feldspars. Sites such as Kwa Ngombai in Ikanga Ward, Kwa Beth Mutinda in Ikutha Ward, Kwa Kasilu in Mutomo and Itumba B in Mutha were characterized with very minimal silt composition of less 5%.

This study confirmed that there is no significant relationship between the change in elevation and the rate at which sand accumulate on the riverbeds (Burger et al., 2003). Particles larger than 2mm (gravels) were not influenced by the change in elevation along the streams. Moreover, the difference in the dominant grade size of sand at a particular point along the river varied with changes in the elevation. Coarse sands occurred at high elevation riverbeds while fine sands accumulated in the depositional areas with low gradient. However, majority of the suitable sites for sand dams are in Kitui South were found in the transitional zones where the medium sand were dominant.

Substantial accumulation of sand accumulate up to an average of50%medium sand at an elevation between 600 and 900 m above sea level. This implied that sand accumulation along the seasonal rivers depended more on the stream gradient than the elevation at any site along the stream. The favourable stream gradient was between 0.5 and 4%. This imply that even if the elevation is high, other attributes such as favourable slope would encourage sand accumulation at the site located in such site and therefore considered suitable for sand dam.

5.5 The relationship between elevation and sand gradation

Sand gradation along stream channels is associated with changes in the river morphology (Maddrell and Neal, 2012). More erosion occurs upstream while the deposition occurs at the floodplainswhere the river energy and erosional activities are minimal. Vertical soil erosion occurs at the upstream when the river energy is still high while lateral erosion occurs at the depositional plains due reduced energy of the river under the influence of low terrain (Borst and de Haas, 2006).The assumption in this study was that sites located upstream along the stream were likely to be dominated with larger particle-sizes than the sites located downstream. The analysis on the particle-size distribution played major role in determining the relationships between sand gradation and their suitability for sand dams in the seasonal rivers found in Kitui South. This study applied the particle-sizes at D_{30}, D_{50}, D_{60} and D_{90} to determine the particle-size distribution along the streams in Kitui South. The findings show that changes in the elevation has a strong influence on the dominant sand particles-sizes found on the riverbed. This is attributed to the distance travelled by the sediments down the stream whereby smaller particles imply that they have been transported over a longer distance to the point of deposition than the coarse sediments which occur at the higher elevation near the river head (Alderlisten, 1990).

Sand particles larger than 2mm (gravels) were observed at several sites along the seasonal rivers in Kitui South. This observation is attributed to the continued generation of fresh particles that break from the bedrock due to human and livestock activities along the streams (Munyao et al., 2004). It was observed from the field that both human and livestock walk along the streams in search for water from the scoop holes.

5.6 Suitability of sites for sand dams based on multi-factor criteria

Sand dams continue being the most cost-effective method to harvest and conserve water and particularly the technology has provided an improved, local, and reliable source of water for the people, plants and livestock in the rural communities in the ASALs. The technology has been in existence for more than five decades now. The sustainability of good performing sand dams was not witnessed in the past due to poor location of the dams and poor designs. This study came in to fill the knowledge gap by introducing the AHP approach based on GIS which allowed evaluation of various spatial components in the identification of suitable sites for sand dams. The AHP approach has been applied before in the determination of suitable sites for sand dam in Yazd-Ardakan watershed (Barkhordari, 2015). The approach allowed integration of climatological, hydrological and satellite data to come up with potential sites for sands. Kheirkhah, et al. (1980) also showed that the AHP approach is reliable when evaluating the influence of both spatial and non-spatial data in the decision making process to establish suitable sites for underground dams. The new method introduced in this study is more inclusive and it allows integration of various environmental and morphological factors in selecting the suitable sites for sand dams.

The scale used to rank the suitability of different sites was governed by several spatial components described above. The suitability of sites for sand dams was ranked in a scale of 1 to 5 where 1 represented "not suitable", 2 =”fairly suitable", 3 =”moderately suitable", 4 = "suitable", and 5 =”very suitable” The sites classified as "very suitable" and "suitable" sites were characterized with high accumulation of coarse to medium sands with good exposure of the bedrock across the riverbed.

Excellent sites are concentrated where the supply of medium to coarse sands is adequate and where the riverbed is nearly flat (slope=0-6^0). This is the case observed especially on the western parts of the study area where the basement rocks are dominant unlike in the regions covered with sedimentary rocks in the east. The riverbanks in this region are firm and rocky hence good for anchoring the sand dam wall. This is contrary to the eastern region (flood plains) especially in the larger parts of Mutha where the geology does not favor siting of sand dams. Most parts in the western region of the study area are also characterized with occurrence of relatively coarse sand which are recommended for excellent sand dams. The lowlands in Mutha is covered with relatively finer particles which originate from the erosional plains in the west and are deposited after long distance hence the reduction in grain size. The eastern region of the study area shows unfavorable and unsuitable sites for sand dam due to weak riverbanks, minimal exposure of bedrock where the sand dam wall can be constructed and common occurrence of shallow riverbanks. Very suitable sites were observed in sparsely different distributed areas Makutano Kivili, Kwa Ngombai in Ikanga Ward, Kwa Beth Mutinda in Ikutha Ward, Kwa Kasilu in Mutomo and Itumba B in Mutha. However this ward can be supplemented with underground water. Shallow wells can also be dug in this area since there is possible enough recharge

Runoff from the adjacent active farms carries large amount of silt which leads to accumulation of unsuitable material running into the sand dam (Jothityangkoon et al. 2001). From the field it was observed that soils erosion especially from the farms located near sand dam sites were found to greatly influence their suitability. This was observed at Ndiliu-Athi, Kwa Matheka- Athi where red soils were dominant, while silty sands observed with in Kwa Kyeva in Kanziko ward and Mutulu in Ikutha wards. The variations in the intensity of precipitation, variation in the soils infiltration capacity, and the time lapse for sheet flow were also attributed to the differences in landcover and landuse as well as the total amount of water available as runoff flows into the rivers. The sites located near the tilled and bare lands were observed with extensive soil erosion hence negatively influencing sustainability of the sand dam sites located near such lands.

The use of water from the sand dam is influenced to a certain extent by the nature of infrastructure at or near the sand dam. Sites that are located far from villages may not be useful sources of water to the local communities and this will defeat the whole purpose of constructing sand dams. The sites located near settlements have higher priority and to ease accessibility for water. The sites located in heavily populated areas such as markets or within towns were considered not suitable because of high possibility of contamination of water in the sand dam.

CHAPTER 6:

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

Poor performance of sand dams is majorly attributed to lack of adequate evaluation of the sites where they are constructed. Previous studies focused on characterization of sands that are suitable for sand dams and the general socio-economic and environmental benefits associated with the sand dams. This chapter offers conclusions linking the results and findings to the research problem, general literature and objective of the study. The chapter also presents the key findings of the study and recommendations for actions.

6.2 Conclusions of the study

The goal of this project was to develop an approach for determining the suitable sites for sand dams in Kitui South based on the geomorphological characterization and sand gradation on seasonal rivers. This involved evaluating both the physical and environmental suitability across the study area. The Analytical Hierarchy Process (AHP) was the procedure applied in allocating the scale of influence in each of the different components that were used in the suitability model. This was done by the help of a spatial tool in ArcGIS platform to allow integration of multiple factors and evaluate them in the determination of suitable sites for sand dams.

ArcGIS was used to integrate the spatial components, environmental data and the details of the sediments particle-size to identify the suitable sites for sand dams in Kitui South. The outcome was a suitability map for sand dams in Kitui South. However the process was tedious and needed a lot of time to produce a correct suitability model. Data acquisition, data conversion, the pairwise comparison process, and tabulation of results required a high power computer and a lot of time.

The key findings from this study were as follows;

i) These findings imply that 59% of the sites located along the seasonal rivers in Kitui South are highly potential and are suitable for sand dams.
ii) The results showed that 86% of the investigated sites in Kitui South were suitable for the sand dam with a riverbed gradient ranging from 0% to 8% which fall within the

recommended slope range and that majority of the sites were potential of having high capacity for water storage due to occurrence uniform graded sands.

iii) 16% of the sites that were investigated in this study were fairly suitable for construction of sand dams while 79% are classified as suitable and 5% are categorized as very suitable for sand dam construction. The other sites classified as fairly suitable and not suitable were compromised with poor exposure of the bedrock across the streams, poorly defined riverbanks, lack of coarse or medium soils, and generally low accumulation sands.

iv) Several sites in the central and the entire eastern parts of Mutha Ward were found not suitable for sand dam construction due to poor conditions such as the lack of bedrock exposure on the riverbeds, flat terrain, very shallow stream banks, and weak soils on the riverbanks. The western and central areas of Kitui South are dominated with favorable sites for sand dam due to favorable rocks and high production and accumulation of coarse sands along the seasonal rivers. The areas near Mutomo hills and the rocky areas in Ikanga wards are characterized with few excellent sites for sand dams.

v) 59% of the investigated sites were found dominated with uniform sands, 30% were intermediate sands and only 11% were well-graded sands. Spatial variation in terms of sand particle-sizes, 86% of the sites were characterized with medium sands while 10% were dominated with fine sands and the rest (4%) dominated with coarse and gravelly sands. From the results this study concludes that 59% of the 80 sites that were investigated in this study are high capacity potential sites for sand dams in Kitui South.

vi) The optimum accumulation of different grades of sand in the seasonal rivers was commonly found on the riverbed gradient ranging between 1.5 and 6% dominated with 0 to 40% coarse sands, 0 to 30% fine gravels, 0 to 20% fine sands, and 20 to 80% medium sands.

vii) The accumulation of fine gravels was found to be closely related to the distribution of D_{30}, D_{60} and D_{90}particle-sizes (0.4-4mm) while accumulation of coarse sands showed good relationship with the distribution of the medium size sand (0.2-0.4mm). The accumulation of medium sands was equally high where the occurrence of coarse sands was minimal. Different grades of sand were found to be strongly associated with changes in the elevation along the riverbed especially in the accumulation of the medium sands ($r= 0.76$)and coarse sands($r=0.75$). Accumulation of finer grades of sands was identified in the lowlands at a slope ranging between 1.5 and 6% while the coarse sands and gravelly sands was common on the erosional plains near the source rocks. This resulted to more suitable sites located within the erosional plain of Kitui South.

The height of the riverbanks and uniformity of sands were found to be very important parameters in the determination of the storage capacity of the potential sites for sand dams. Uniform coarse and medium sands were dominate in most of the seasonal rivers (66%)which imply potential of high storage capacity sand dams unlike in the sites dominated with well-graded sands. The erosional plains exhibited optimum width of the riverbed where sustainable sand dams can be located. This was not observed on the flood plains where the riverbed width is between 30 and 48m which was beyond the recommended width of 25m. On the other hand rivers located upstream beyond the erosional plains were characterized with very narrow streams widths of upto 8m.

6.3 Recommendations of the study

This study presents an approach for locating suitable sites for sand dams in Kitui County. The results were generated through integration of different spatial components to generate suitability map for locating sand dams in Kitui South. The results are reproducible with high accuracy and can be applied by anyone. However this procedure is not well embraced by many NGOs and community groups that have been constructing sand dams in the Kitui County. The traditional procedure which lasted for decades was very simple. The only important factor which was considered in that criteria was the availability of accessible bedrock across a stream and coarse sands on the riverbed. The assessment on different grades of sands and their suitability was not done in the traditional method. This resulted to unsustainable construction of sand dams which did not serve the communities as expected.

The proposed new method allows one to integrate all the important spatial components that are useful in mapping out the suitable sites for sand dams plus one time field work for data collection and ground trothing. We therefore recommend future individuals, county governments especially in ASALs, groups and organization that are interested in the sand dam technology to embrace the method proposed in this study to ensure that identification of sites, designs for sand dams, and monitoring is done in the most cost effective way to ensure their sustainability and efficiency for the overall benefit of the local communities.

The study also recommends similar analysis to be conducted in the remaining sub-counties in Kitui County. By doing so, the behavior of sand dams will be well understood in different parts of the county and in return improve efficiency and reduce misallocation of funds in sites that may be suitable for construction of sand dams.

The western parts of Kitui South is characterized with uniform medium sands to coarse sands. This puts the western parts of Kitui South more preferable for construction of sand dams than the eastern parts of the area. The major part of Mutha is a lowland and the stream banks in this area are not well defined. Thus this area is not suitable for construction of sand dams. However, the area receives more surface and groundwater recharge from the west. This suggests that the area is likely to have a high potential for groundwater. The study therefore recommends geophysical and hydrogeological surveys to be carried out in the area to explore the availability of groundwater in this area. This is important given that this area suffers from serious water scarcity. Groundwater can provided water to the communities in this area. Porosity plus the hydraulic conductivity are important parameters that control the potential storage capacity of sand dam and any other groundwater reservoir. The analysis on these parameters was beyond the scope of this study due to limitation of data. There is need for further studies to determine how hydrological characterization is related to sand gradation and hence suitability of different sites for sand dams.

6.3.1 Recommendation for further studies

i) We recommend for further study to evaluate the influences of sand gradation on the quality of water abstracted from the sand dams and how this varies with time at different sites. This study will be significant in the assessment of the quality of water abstracted from the sand dams for domestic, irrigation and livestock uses.

ii) Future research can focus on the influence of land use and land cover change in the overall performance of sand dams in arid and semi-arid lands. Most of the farmers have neglected their cropping lands which has led to land degradation and this is negatively influencing sustainability of sand dams.

iii) There is need to review cost effectiveness of sand dam technology in arid and semi-arid lands. This in relation to the length of period taken for the water stored in the sand dams to be supplied to the communities compared to availability of other water resources in the county

REFERENCES

Aerts, J., Lasage, R., Beets, W., De Moel, H., Mutiso, G., Mutiso, S. & De Vries, A (2006). Robustness of sand storage dams under climate change. *Vadose Zone Journal, 6*, 572-580.

Afifi, S & Fuladipanah, M (2015). Subsurface Dam Site Selection Using GIS (Case Study: Chamsiab Plan, Masjedsoleyman, Iran), *Indian Journal of Fundamental and Applied Life Sciences ISSN: 2231– 6345*

Alderlisten, M (1990). Mean Particle Diameters, Part 1: Evaluation of Definitions Systems, 7, pp. 233-241

Ali, S.S., Al-Umary, F.A., Salar, S.G., Al-Ansari, N. and Knutsson, S. (2014) Evaluation of Selected Site Location for Subsurface Dam Construction within Isayi Watershed Using GIS and RS Garmiyan Area, Kurdistan Region. *Journal of Water Resource and Protection, 6*, 972-987. http://dx.doi.org/10.4236/jwarp.2014.611092

Andersen N. J., Wheater H.S., Timmis A.J.H., Gaongalelwe D (1998). Sustainable development of alluvial groundwater in sand rivers of Botswana. *Sustainability of Water Resources under Increasing Uncertainty, IAHS* No. 240, pp. 367-376.

Baniya, N (2008). Land suitability evaluation using GIS for vegetable crops in Kathmandu Valley, Nepal. Berlin, 13 p.

Barkhordari, J (2015). The pre-selection of suitable sites for small underground dams in arid areas using GIS. A case study in Yazd _ Ardakan watershed, *6*(1), 18–27.

Beimers, P. B., Eick, van, A. J., Lam, K. S., & Roos, B (2001a). Improved design sand-storage dams, Kitui District, Kenya, Project report, Delft University of Technology, 125 p.

Beimers, P. B., Eick, van, A. J., Lam, K. S., & Roos, B (2001b). Building sand-storage dams, SASOL Foundation Kitui District, Kenya, Practical work report, Delft University of Technology, 100 p.

Biamah E.K., Stroosnijder L., & Omuto C.T (2004). Watershed conservation in semi-arid Kenya. University of Nairobi, Kenya.

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R. &Yanda, P (2007). Africa. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In Parry, M.L., Canziani, O.F., Palutikof, J.P., Linden, P.J. van der & Hanson, C.E. (Eds.). Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge UK, pp. 433-467.

Borst, L and de Haas, S.A (2006). Hydrology of Sand Storage Dams - A case study in the Kiindu catchment, Kitui District, Kenya. Free University of Amsterdam, the Netherlands. 146 p.

Bouwer, H (2000). Integrated water management: emerging issues and challenges, Agricultural Water Management, v.45, pp. 217-228.

Bruijn, E. de & Rhebergen, W (2006). Socio-economic impacts of the construction of sand dams on communities in Kitui District, Kenya. VU University Amsterdam. 45 p.

Burger, A. S., Malda, W., & Winsemius, H. C. (2003): Research to Sand-storage dams in Kitui district, Delft University of Technology, 94 p.

Castillo, V. M., Gomez-Plaza, A., & Martinez-Mena, M (2003). The role of antecedent soil moisture in the runoff response of semi-arid catchments, *Journal of Hydrology*.

Chebet, C (2012). Suitability Analysis of Watersheds in Keiyo District, Kenya. *Journal of Emerging Trends in Educational Research and Policy Studies*, *3*(5), 762 p.

County Government of Kitui (2016). Identification of suitable sites for surface and sand dams in Kitui County: Sub-Surface and sand dam development project (Report 13 June 2016). Kitui, Kenya

Dahm, C. N., Cleverly, J. C., Allred Coonrod, J. E., Thibault, J. T., McDonnel, D. E., & Gilroy, D. J (2002). Evapotranspiration at the land/water interface in a semi-arid drainage basin, Freshwater Biology (2002) 47, pp. 831–843

Devore, J. L (2011). Probability and Statistics for Engineering and the Sciences (*8th Ed*.). Boston, MA: Cengage Learning. pp. 508–510. ISBN 0-538-73352-7.

Dodge, Y (2003). The Oxford Dictionary of Statistical Terms, OUP for International Statistical Institute. ISBN 0-19-920613-9

Domingo, F., Villagarcia, L., Boer, M. M., Alados-Arboledas, L., Puigdefabregas, J., (2001). Evaluating the long-term water balance of arid zone stream bed vegetation using evapotranspiration modelling and hillslope runoff measurements. *Journal of hydrology 243*, pp 17-30

Dunne, T., & Ongweny, G. S (1976). A new estimate of sedimentation rates on the upper Tana River. *The Kenyan Geographer, 2*(2), pp. 26-109.

FAO (1976). A framework for land evaluation: Soils Bulletin 32, Food and Agriculture Organization of the United Nations, Rome, Italy.

First County Integrated Development Plan (CDIP) 2013- 2017 report, planning for Sustainable Socio-Economic Growth and Development. (2013). Kitui County Economic and Investment Zones.

Foster, G. R., Meyer, L. D., & Onstad, C. A (1977). A runoff erosivity factor and variable slope length exponents for soil loss estimates. Transactions of the ASAE [*American Society of Agricultural Engineers*]. USA.

Freud, W.L. & Simon, J.D (2000). Educational research: Competencies for analysis and application (6th ed.). Upper Saddle, N.J.: Charles Merrill Publishing Company

Gachari, D. N. K. M. K., Mary, W., & Mungai, E (2011). Mapping groundwater potential in Kitui District, Kenya using geospatial technologies. *International journal of water Resources and Environmental Engineering, 4*(1), 15-22.

Gash, J. H. C (1979). An analytical model of rainfall interception by forests, *Quarterly Journal of the Royal Meteorological Society Vol. 105*, No. 443, pp. 43-55

Geertsma, R., Wilschut, L., & Kauffman, J. H (2010): Review for the Green Water Credits Pilot Operations in Kenya. ISRIC-World Soil Information.

Gezahegne, W (1986). Sub-surface dams for rural water supply in arid and semi-arid regions of developing countries, Department of Civil Engineering, Tampere University of Technology;

Gijsbertsen, C (2007). A study to upscaling of the principle and sediment transport processes behind sand storage dams. Kitui District, Kenya. Vrije Universiteit, Amsterdam.

Haveren, B.P. van (2004). Dependable water supplies from valley alluvium in arid regions. *Environmental Monitoring and assessment, 99*, 259-266.

Hoogmoed, M (2007). Analyses of impacts of a sand storage dam on groundwater flow and storage. VU University, Amsterdam. 165 p.

Horton, R. E (1933). The role of infiltration in the hydrologic cycle, *Trans American Geophysical Union. Issue 14*. Pp. 446-460

Hualou, L., Guoping T., Xiubin L., & Gerhard K. H (2006). Socio-economic driving forces of land-use change in Kunshan, the Yangtze River Delta economic area of China. Journal of Environmental Management 83 (2007) 351–364.

Hut, R., Ertsen, M.W., Joeman, N., Vergeer, N., Winsemius, H., & Van de Giesen, N.C (2008). Effects of sand storage dams on ground water levels with examples from Kenya. *Physics and Chemistry from the Earth 33,* pp. 56-66.

ISO 9276-2 (2001). Representation of results of particle size analysis – *Part 2: Calculation of average particle sizes/diameters and moments from particle size distributions.* Available online at *hsevi.ir/RI_Standard/File/7455*

Janardhana Raju, N., & Reddy, T. V. K (2005),Subsurface dams to harvest rainwater— a case study of the Swarnamukhi River basin, Southern India, *Hydrogeology Journal (2006) 14:* pp.526–531

Jankowski, P (1995). Integrating geographical information systems and multiple criteria decision-making methods. *International Journal of Geographical Information Science 9*: pp. 251-273.

Jansen, J (2007). The influence of sand dams on rainfall-runoff response and water availability in the semi-arid Kiindu catchment, Kitui District, Kenya. Vrije Universiteit, Amsterdam.

Jothityangkoon, C., Sivapalan, M., & Farmer, D. L (2001). Process controls of water balance variability in a large semi-arid catchment; downward approach to hydrological model development, *Journal of hydrology 254*, pp. 174-198

Karl, P (20 June 1895). "Notes on regression and inheritance in the case of two parents," *Proceedings of the Royal Society of London, 58*: pp. 240–242.

Kenya National Bureau of Statistics (2017). Population Distribution by Sex, Number of Households, Area and Density by County and District. Available online at: https://www.knbs.or.ke/publications/, Date accessed: February, 21 2017

Kheirkhah, M. M. Sharifi, E., & Azizi, S. H (1980). "Suitable site selection for groundwater dams construction using spatial and non-spatial analytical hierarchy process methods in the Taft Pishkoh catchment, Yazd, Iran: pp. 1–5.

Kinama, J. M., Stigter, C. J., Ong, C. K., Ng'ang'a, J. K., & Gichuki, F. N (2005). Evaporation from soils below sparse crops in contour hedgerow agroforestry in semi-arid Kenya Agricultural and Forest Meteorology 130: pp. 149–162

Kuria, D. N (2012). "Mapping Groundwater Potential in Kitui District, Kenya Using Geospatial Technologies." *International Journal of Water Resources and Environmental Engineering 4*(1): pp. 15–22.

Lasage, R., Seifu A., Hoogland M., & Vries de, AC (2010). Report on the General Characteristics of the Borana zone Ethiopia. IVM report (R-10/03) Institute for Environmental Studies (IVM) VU University Amsterdam: 36 p

Louis Berger International Inc. (1983) Arid and Semi-Arid Lands Development Project, Kitui District Water Resources Study, Executive Summary. Government of the Republic of Kenya

Love, D., & Singh, A (2011). A water balance modelling approach to optimizing the use of water resources in ephemeral sand rivers, River Research and Applications, v.27, pp.908-925

Maddrell, S (2016). Securing water supply with sand dams. Article retrieved from; www.excellentdevelopment.com, Date: May 16, 2017

Maddrell, S. & Neal, I (2012). Sand dams: a Practical Guide, Excellent Development, London

Maddrell, S. (2010). “The miracle of sand dams.” Appropriate Technology, 37. 2 (Jun 2010): pp. 26-27

Malczewski, J (2006). GIS-based multi-criteria analysis: a survey of the literature. *International Journal of Geographic Information Science, 20:* pp.703–726.

Mokarram, M., & Aminzadeh, F (2010). GIS-based multi-criteria land suitability evaluation using ordered weight averaging with fuzzy quantifier: a case study in Shavur Plain, Iran. The International Archives of the Photogrammetry, *Remote Sensing and Spatial Information Sciences, 38* (part 2)

Morgan, R. P. C., Quinton, J. N., & Rickson, R. J (1992). EUROSEM Documentation Manual. Silsoe College: Silsoe.

Munyao, J.N., Munyoki, J.M., Kitema, M.I., Kithuku, D.N., Munguti, J.M., & Mutiso, S (2004): Kitui sand dams: Construction and operation, SASOL foundation, 53p.

Neessen, D.J (2004). Regional water balance modelling of a semi-arid catchment in South Kitui District, Kenya, Katholieke Universiteit Leuven Faculteit Land bouwkundigeenToegepaste Biologische Wetenschappen, 109 p.

Nelson, K.D (1985). Design and Construction of Small Earth Dams, Melbourne, Inkata Press, Nepal, S. Wolfgang-Albert, F., & Arun Shrestha, B (2014). Upstream-downstream linkages of hydrological processes in the Himalayan region, *Ecological Processes. 3*(19) DOI: 10.1186/s13717-014-0019-4

Nissen-Petersen, E (2007). Water Supply by Rural Builders. For Danish International Development Assistance (DANIDA). ASAL Consultants Ltd., Nairobi, Kenya

Nyamai C.M., Mathu, E.M., Opiyo, A.N., & Wallbrecher, E (2003). A reappraisal of the geology, geochemistry, structures and tectonics of the Mozambique belt in Kenya, east of the Rift System. African Journal of Science and Technology (AJST) Science and Engineering Series, Vol. 4, No. 2: pp. 51-71

Pauw, W.P., S. Mutiso, G. Mutiso, H.K. Manzi, R. Lasage, & Aerts, J.C.J.H. (2008). An Assessment of the Social and Economic Effects of the Kitui Sand Dams: Community based Adaptation to Climate Change. SASOL & Institute for Environmental Studies

Puttemans, S (2004). Potential for small scale irrigation from groundwater dams in South Kitui, Kenya, Katholieke Universiteit Leuven Faculteit Land bouwkundigeen Toegepaste Biologische Wetenschappen. 177 p.

Quillis, R.Q and Lange, J (2009). Measuring and modeling hydrological processes of sand-storage dams on different spatial scales, Physics and Chemistry of the Earth, v.34: pp.289-298

Rao, P.J, Harikrishna, P, Srivastav, S.K, Satyanarayana, P.V.V, & Rao, B.B.D (2009). Selection of groundwater potential zones in and around Madhurwada Dome, Visakhapatnam District – A GIS approach. J. *Indian Geophy.l Union, 13*(4): pp. 191–200.

Rempel, H., Nyaga, C.W., Manzi, H.K. & Graff, P (2005). Water in the sand: an evaluation of SASOL's Kitui Sand Dams Project. SASOL Foundation, Mennonite Central Committee & Canadian Food Grains Bank. 55p.

Retsch, G. H. (2009). Sieve Analysis in Quality Control, available at www.retsch.com

Ryan, C. & Elsner, P (2016). The potential for sand dams to increase the adaptive capacity of East African drylands to climate change. 16: 2087. https://doi.org/10.1007/s10113-016-0938-y

Saaty, T. L (1980). The Analytical Hierarchy Process. McGraw Hill, New York. 350 p.

Saaty, T. L (1995). Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World. (3rd Ed), RWS Publications, Pittsburgh, PA.

Saggerson, E. P (1957). "Geology of the South Kitui Area." *Report No. 37*, Geological Survey of Kenya.

Sankar, K (2002). Evaluation of groundwater potential zones using Remote Sensing data in upper Vaigai river basin, Tamil Nadu, India. J. *Indian Society Remote Sensing*, *30*(3): pp. 119-129.

SASOL and ACACIA (n.d.). Manual on Sand dams in Ethiopia. Available at www.samsamwater.com

Saunders, J.D (1990). Educational research: Quantitative, qualitative and mixed approaches. Boston, MA: Allynand Bacon.

SIWI (2001). Water harvesting for upgrading of rain-fed agriculture. Problem analysis and research needs. SIWI Report 11. Stockholm International Water Institute (SIWI), Stockholm, Sweden. 97p.

Sys, C (1985) Land evaluation, State University of Ghent, Ghent; The Netherlands

Tate, K. W (1996). Rangeland Watershed Program - A Water Quality Education and Technical Assistance Program for California Rangelands - FACT SHEET - U.C. Cooperative Extension and U.S.D.A. Natural Resources Conservation Service, Department of Agronomy & Range Science, University of California, Davis, CA 95616-8515

The Mathworks (2004). Matlab 7 (R14), TheMath Works, Inc.

Tweed, T.O, Leblanc, M., Webb, J.A, & Lubczynski, M.W (2007). Remote sensing and GIS for mapping groundwater recharge and discharge areas in salinity prone catchments, southeastern Australia. *Hydrogeol. J., 15*(1): pp. 75-96.

UNEP (2006). Harvesting Rainfall a Key Climate Adaptation Opportunity for Africa. http://www.unep.org/Documents.Multilingual/Default.asp?ArticleID=5420&DocumentID=485&l=en.

Utooni Development Organization (UDO), (2016). Website; www.utoonidevelopment.org

Van Haveren, B.P (2004). Dependable water supplies from valley alluvium in arid regions, Environmental Monitoring and Assessment, v.99: pp. 259-266.

Walling, D. E., & Fang, D (2003). Recent trends in the suspended sediment loads of the world's rivers. *Global and Planetary Change, 39*(1): pp. 111-126.

Ward, R. C., & Robinson, M (2000). Principles of hydrology (fourth edition), McGraww-Hill Publishing, 450 p.

Wheater, H.S., and Al Weshah, R.A (2002). Hydrology of wadi systems. In IHP regional network on wadi hydrology in the Arab region. UNESCO, Paris.

Wolman, M. G., & Gerson, R (1978). Relative scales of time and effectiveness of climate in watershed geomorphology. *Earth surface processes*, *3*(2): pp. 189-208.

WWD: Westlands Water District (2000). Water management handbook. http://www.westlandswater.org/wtrcon/handbook/wmh0.htm

Appendix 1: Laboratory procedure for sand particle-size analysis

Purpose:

This test is performed to determine the percentage of different grain sizes contained within a soil. The mechanical or sieve analysis is performed to determine the distribution of the coarser, larger-sized particles, and the hydrometer method is used to determine the distribution of the finer particles.

Equipment:

Balance, Set of sieves, Cleaning brush, Sieve shaker

Sieve Analysis Procedure

i) Write down the weight of each sieve as well as the bottom pan to be used in the analysis.

ii) Record the weight of the given dry soil sample.

iii) Make sure that all the sieves are clean, and assemble them in the ascending order of sieve numbers (#4 sieve at top and #200 sieve at bottom). Place the pan below #200 sieve. Carefully pour the soil sample into the top sieve and place the cap over it.

iv) Place the sieve stack in the mechanical shaker and shake for 10 minutes.

v) Remove the stack from the shaker and carefully weigh and record the weight of each sieve with its retained soil. In addition, remember to weigh and record the weight of the bottom pan with its retained fine soil. You should use the table like the one shown below

Sieve Size (mm)	**Mass of Sieve + soil (g)**	**Mass of Sieve (g)**	**Mass of Soil retained (g)**	**Cumulative mass retained (g)**	**% of soil retained**	**% of soil passing**
#4						
#10						
#20						
#40						
#60						
#100						
#200						
Pan						

Data Analysis: Sieve Analysis

i) Obtain the mass of soil retained on each sieve by subtracting the weight of the empty sieve from the mass of the sieve + retained soil, and record this mass as the weight retained on the data sheet. The sum of these retained masses should be approximately equals the initial mass of the soil sample. A loss of more than two percent is unsatisfactory.

ii) Calculate the percent retained on each sieve by dividing the weight retained on each sieve by the original sample mass.

iii) Calculate the percent passing (or percent finer) by starting with 100 percent and subtracting the percent retained on each sieve as a cumulative procedure.

For example: Total mass = 500 g

Mass retained on No. 4 sieve = 9.7 g

Mass retained on No. 10 sieve = 39.5 g

For the No.4 sieve:

Quantity passing = Total mass - Mass retained

= 500 - 9.7 = 490.3 g

The percent retained is calculated as; % retained = Mass retained/Total mass

= (9.7/500) X 100 = 1.9 %

From this, the % passing = 100 - 1.9 = 98.1 %

For the No. 10 sieve:

Quantity passing = Mass arriving - Mass retained

= 490.3 - 39.5 = 450.8 g

% Retained = (39.5/500) X 100 = 7.9 %

% Passing = 100 - 1.9 - 7.9 = 90.2 %

(Alternatively, use % passing = % Arriving - % Retained

For No. 10 sieve = 98.1 - 7.9 = 90.2 %)

iv) Make a semi-logarithmic plot of grain size vs. percentage of the soil passing through the sieves.

Appendix 2: Results of sand particle-size analysis

No.	Site Name	Elevation (m)	Fine GRAVEL (%)	Coarse SAND (%)	Medium SAND (%)	Fine SAND (%)	Mode (mm)	Median (D_{50}) (mm)	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	D_{90} (mm)	Cu	Ck	% Error
1	Itumba B	748	20.9	37.5	36.7	4.2	0.85	1.1	0.33	0.64	1.4	3.3	4.24	0.89	0.7%
2	Itumbule	821	3.8	22.0	63.3	10.9	0.43	0.55	0.25	0.38	0.65	1.5	2.60	0.89	0.1%
3	Ivuvasoo	776	9.1	11.8	65.7	12.6	0.25	0.38	0.24	0.31	0.45	2	1.88	0.89	0.8%
4	Kamula	708	28.2	11.8	12.9	46.2	0.15	0.3	0.1	0.18	0.9	5.2	9.00	0.36	0.9%
5	Kandumbu	841	15.8	23.6	49.6	10.9	0.43	0.65	0.25	0.4	0.85	3.5	3.40	0.75	0.1%
6	Kanze	820	15.8	7.3	53.2	23.6	0.25	0.35	0.16	0.28	0.39	4.75	2.44	1.26	0.2%
7	kasangu	587	32.7	12.4	46.5	7.4	0.25	0.7	0.26	0.36	1.4	4.3	5.38	0.36	0.9%
8	Kathing'we	773	18.4	15.5	49.4	15.8	0.25	0.5	0.2	0.33	0.7	4	3.50	0.78	0.9%
9	Kavuti	747	8.2	24.0	59.4	8.4	0.43	0.6	0.27	0.4	0.7	1.8	2.59	0.85	0.0%
10	Kiangwa	890	18.2	32.1	44.8	4.7	0.85	0.85	0.3	0.51	1.3	3.3	4.33	0.67	0.2%
11	Kisese	756	22.5	7.8	53.3	16.3	0.25	0.4	0.22	0.31	0.5	4.75	2.27	0.87	0.1%
12	Koma	877	3.6	11.4	81.0	3.6	0.43	0.48	0.28	0.37	0.54	1	1.93	0.91	0.4%
13	kwabenjamin mbuthu	789	12.2	20.4	51.7	15.5	0.25	0.52	0.2	0.34	0.7	2.4	3.50	0.83	0.1%
14	kwa Beth Mutinda	676	8.8	21.5	57.1	12.7	0.25	0.48	0.23	0.34	0.6	2	2.61	0.84	0.0%
15	Kwa joseph mulatya	771	1.8	0.4	83.9	13.3	0.25	0.38	0.23	0.31	0.45	0.7	1.96	0.93	0.6%
16	Kwa Kamuli	691	7.4	15.7	68.8	7.7	0.43	0.52	0.27	0.38	0.6	1.6	2.22	0.89	0.4%
17	Kwa kariuki	595	29.1	21.1	42.6	7.1	0.43	0.85	0.28	0.48	1.4	4.4	5.00	0.59	0.7%
18	Kwa Kasee	757	21.3	18.4	49.7	10.2	0.25	0.6	0.26	0.37	0.85	3.7	3.27	0.62	0.3%
19	Kwa kasilu	738	8.5	31.5	52.2	7.5	0.85	0.67	0.28	0.41	0.85	1.9	3.04	0.71	0.3%
20	kwaKasuku	754	11.2	5.5	45.6	37.2	0.15	0.3	0.17	0.23	0.37	2.4	2.18	0.84	0.5%
21	Kwa Kaswii	810	1.8	1.4	89.3	6.7	0.43	0.48	0.28	0.38	0.53	0.75	1.89	0.97	0.8%
22	Kwa KatuKilonzo	468	0.7	8.9	85.0	5.0	0.43	0.5	0.28	0.39	0.57	0.86	2.04	0.95	0.4%
23	Kwa Kikuyu	498	2.6	8.6	75.3	13.3	0.43	0.45	0.23	0.33	0.52	0.9	2.26	0.91	0.2%

24	kwakiluu	614	15.1	18.7	55.3	10.6	0.43	0.57	0.25	0.38	0.7	3	2.80	0.83	0.2%
25	kwakimuyu	806	2.9	7.0	82.2	7.7	0.25	0.4	0.27	0.33	0.47	0.85	1.74	0.86	0.2%
26	Kwa Kinene	722	47.9	9.8	25.4	16.8	4.75	1.7	0.18	0.42	3	10	16.67	0.33	0.1%
27	Kwa Kisalu	744	65.1	17.2	15.1	2.6	4.75	3.4	0.5	1.7	4.5	6	9.00	1.28	0.1%
28	Kwa Kisangau	662	54.8	20.7	21.3	3.2	2.00	2.4	0.38	1.2	3	5	7.89	1.26	0.0%
29	Kwa KyevaIkungute	838	15.9	3.0	9.2	71.6	0.15	0.2	0.09	0.17	0.22	4.75	2.44	1.46	0.4%
30	Kwa Kyungu	658	2.2	5.2	84.5	7.6	0.43	0.5	0.27	0.4	0.56	0.8	2.07	1.06	0.5%
31	Kwa Makongo	521	27.8	40.4	28.9	2.9	0.85	1.3	0.38	0.8	1.6	3.7	4.21	1.05	0.0%
32	Kwa Mathekaathi	828	11.5	7.7	77.7	2.8	0.43	0.5	0.29	0.37	0.57	2.7	1.97	0.83	0.3%
33	Kwa Mathekakanziko	617	14.0	36.8	46.4	2.6	0.85	0.86	0.34	0.57	1.2	2.5	3.53	0.80	0.2%
34	Kwa Mbithi	864	24.1	34.4	36.8	4.0	0.85	1.2	0.33	0.6	1.4	3.7	4.24	0.78	0.7%
35	Kwa MbithiMutunga	643	15.0	12.2	54.4	18.0	0.25	0.39	0.2	0.3	0.49	3	2.45	0.92	0.3%
36	Kwa Mbivu	743	1.4	2.1	81.4	14.9	0.43	0.44	0.23	0.33	0.5	0.74	2.17	0.95	0.7%
37	Kwa Mbuvi Lokaa	965	6.8	21.6	63.4	7.8	0.43	0.57	0.28	0.4	0.68	1.6	2.43	0.84	0.3%
38	kwaMeshack Mutua	804	19.2	22.4	48.6	9.1	0.43	0.69	0.25	0.43	0.9	3.7	3.60	0.82	0.6%
39	kwaMula	602	2.0	1.0	71.2	24.9	0.25	0.32	0.18	0.28	0.35	0.58	1.94	1.24	0.8%
40	Kwa Musango	633	34.5	28.2	34.8	1.6	0.85	1.3	0.39	0.7	1.7	0	4.36	0.74	0.9%
41	Kwa musingila	822	9.0	8.8	72.0	9.6	0.25	0.45	0.25	0.35	0.53	2	2.12	0.92	0.6%
42	Kwa Musyimi	476	13.9	41.8	41.6	2.6	0.85	0.95	0.37	0.63	1.3	2.5	3.51	0.83	0.1%
43	Kwa musyokaKitungi	801	2.4	13.7	74.9	9.0	0.43	0.5	0.26	0.37	0.58	1.1	2.23	0.91	0.0%
44	Kwa Mutheki	614	18.8	32.7	43.4	5.1	0.85	0.9	0.32	0.58	1.3	3.8	4.06	0.81	0.1%
45	Kwa Mutia	733	7.0	28.2	57.3	7.5	0.43	0.62	0.28	0.43	0.77	1.7	2.75	0.86	0.0%

46	kwamutiemutetei	798	17.3	40.7	29.0	13.0	0.85	1.0	0.2	0.6	1.3	2.8	6.50	1.38	0.0%
47	Kwa Mutile Malombe	686	0.1	20.6	62.8	6.1	0.43	0.48	0.075	0.33	0.57	1.3	7.60	2.55	0.2%
48	Kwa Mutinda	732	10.7	37.3	44.3	7.4	0.85	0.81	0.29	0.5	1	2	3.45	0.86	0.4%
49	Kwa MutukoKitheko	675	26.9	34.7	33.2	5.2	0.85	1.2	0.31	0.65	1.5	3.9	4.84	0.91	0.1%
50	Kwa mutungaKieti	776	7.6	25.8	58.4	8.2	0.43	0.63	0.28	0.47	0.75	1.7	2.68	1.05	0.0%
51	Kwa Mwangu	721	2.4	17.2	69.0	11.2	0.43	0.48	0.25	0.35	0.57	1.4	2.28	0.86	0.1%
52	Kwa MwendwaKilatya	638	11.6	25.5	58.5	4.0	0.43	0.69	0.32	0.49	0.8	2.3	2.50	0.94	0.5%
53	kwaNgombai	858	22.7	42.0	30.2	4.0	0.85	1.2	0.34	0.65	1.5	3.4	4.41	0.83	1.1%
54	kwaNguiMuinde	853	49.1	33.5	17.1	0.0	0.85	2	0.68	1.3	2.6	4	3.82	0.96	0.3%
55	Kwa Nguute	759	0.3	0.4	63.2	36.1	0.25	0.28	0.15	0.23	0.3	0.39	2.00	1.18	0.0%
56	kwanyamaimembo o	841	0.7	8.1	80.3	10.5	0.43	0.47	0.26	0.36	0.54	0.85	2.08	0.92	0.4%
57	Kwa Nyamainguni	816	0.1	0.1	32.7	66.4	0.15	0.21	0.1	0.17	0.23	0.35	2.30	1.26	0.6%
58	kwanzukimutia	695	0.1	2.1	83.3	14.1	0.43	0.4	0.23	0.32	0.46	0.7	2.00	0.97	0.4%
59	Kwa Ruth Kithuku	681	4.4	12.6	62.7	20.1	0.25	0.35	0.18	0.29	0.39	1.4	2.17	1.20	0.2%
60	Kwa Sammy	610	3.7	15.9	70.7	9.7	0.43	0.49	0.26	0.35	0.58	1.4	2.23	0.81	0.1%
61	Kwa SilaMutiso	728	6.3	13.9	73.5	6.0	0.43	0.53	0.28	0.4	0.6	1.5	2.14	0.95	0.4%
62	kwateresia john	769	3.1	9.8	83.2	4.0	0.43	0.57	0.32	0.47	0.6	0.9	1.88	1.15	0.0%
63	Kwa yole	698	24.7	27.4	41.7	5.9	0.85	0.9	0.3	0.52	1.3	3.6	4.33	0.69	0.3%
64	Kyakyi	665	3.6	17.0	65.7	13.6	0.25	0.42	0.23	0.32	0.5	1.4	2.17	0.89	0.1%
65	MakueNdiliu	761	10.9	7.9	22.1	58.9	0.08	0.21	0.09	0.16	0.26	2.5	2.89	1.09	0.2%
66	Makutano	686	2.5	12.6	69.4	15.5	0.25	0.4	0.22	0.31	0.48	1.3	2.18	0.91	0.0%
67	Makutano Kivili	580	44.3	25.5	26.1	3.4	2.00	1.7	0.34	0.85	2.4	4.75	7.06	0.89	0.7%

68	Manzee	862	14.8	28.6	44.9	11.6	0.85	0.7	0.24	0.4	0.95	2.7	3.96	0.70	0.0%
69	Mulilunі	784	9.3	16.0	67.3	7.1	0.43	0.55	0.28	0.4	0.64	2	2.29	0.89	0.3%
70	Mutulu 2	798	6.0	5.9	33.6	54.0	0.15	0.23	0.07	0.15	0.3	1	4.29	1.07	0.5%
71	Mvumbuni	595	22.6	35.9	38.5	2.9	0.85	1.1	0.35	0.65	1.4	3.3	4.00	0.86	0.1%
72	Mwimbi	764	5.4	4.5	69.3	20.3	0.25	0.34	0.18	0.29	0.37	0.9	2.06	1.26	0.5%
73	Ndangani	848	0.7	1.1	75.8	21.5	0.25	0.31	0.18	0.28	0.34	0.43	1.89	1.28	0.9%
74	Ngatiie	632	9.0	23.3	59.0	8.6	0.43	0.64	0.27	0.48	0.73	2	2.70	1.17	0.2%
75	Ngomano	834	13.6	22.8	55.4	7.7	0.43	0.63	0.27	0.43	0.77	2.7	2.85	0.89	0.5%
76	Ngunini	721	7.4	25.1	55.1	12.2	0.43	0.58	0.24	0.38	0.7	1.8	2.92	0.86	0.2%
77	Nzeveni	749	21.6	12.2	52.2	13.9	0.25	0.45	0.22	0.32	0.65	4.4	2.95	0.72	0.1%
78	Nzula B	808	8.4	26.0	55.6	9.2	0.43	0.63	0.25	0.43	0.76	1.8	3.04	0.97	0.7%
79	Nzula C	804	8.5	24.5	49.7	17.1	0.43	0.6	0.2	0.4	0.73	2	3.65	1.10	0.1%
80	Tiva	658	3.5	13.1	74.8	7.2	0.43	0.47	0.26	0.36	0.55	1.3	2.12	0.91	1.4%