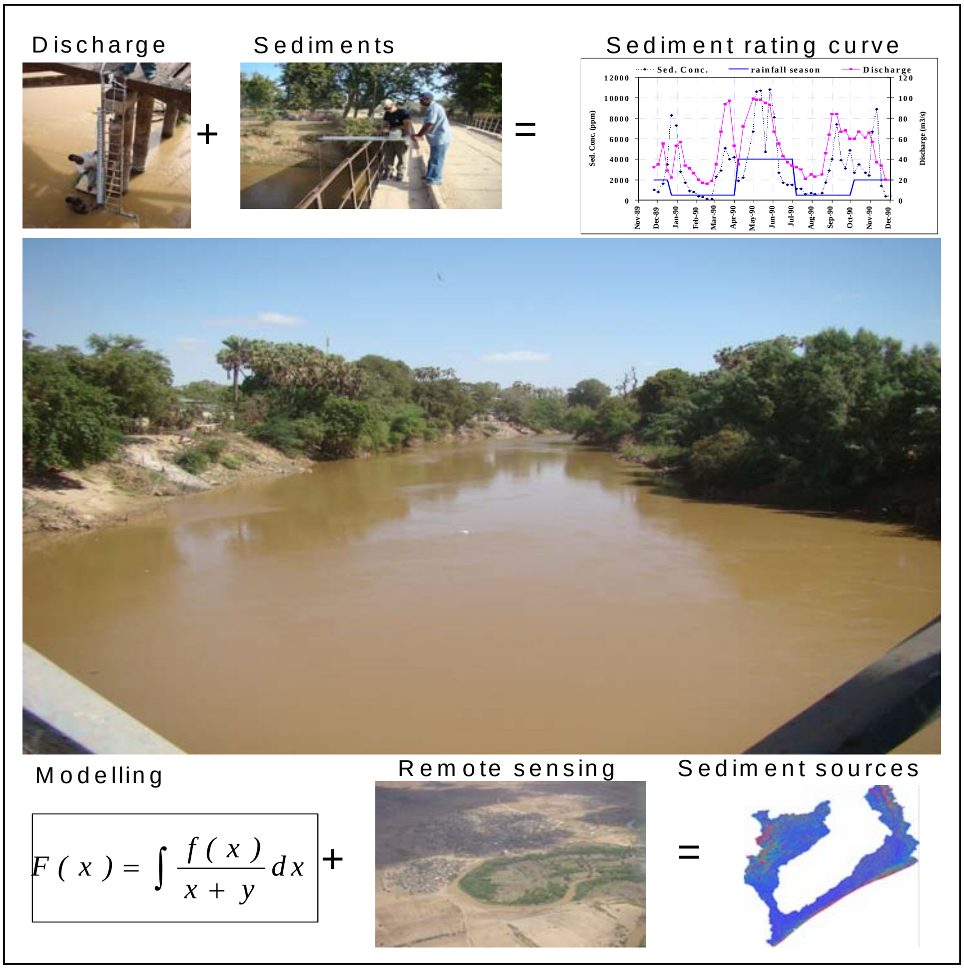
SOIL EROSION AND SEDIMENTATION MODELLING AND MONITORING OF THE AREAS BETWEEN RIVERS JUBA AND SHABELLE IN SOUTHERN SOMALIA



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List of acronyms

CN	- Curve Number
CTA	- Chief Technical Advisor
FAO	- Food and Agriculture Organisation
ITCZ	- Inter-Tropical Convergence Zone
MODIS	- Moderate Resolution Imaging Spectrometer
MUSLE	- Modified Universal Soil Loss Equation
PVC	- Polyvinyl Chloride
RUSLE	- Revised Universal Soil Loss Equation
SDR	- Sediment Delivery Ratio
SCS	- Soil Conservation Service
SSC	- Suspended Sediment Concentration
SWALIM	- Somalia Water and Land Information Management
TSS	- Total Suspended Solids
XRD	- X-Ray Diffractometry

1. INTRODUCTION

1.1 Background

Soil erosion is a complex dynamic process by which the productive soil surface is detached, transported, and accumulated at a distant place. It produces exposed sub-surface where the soil has been detached and the detached deposited in low-lying areas of the landscape or in water bodies downstream in a process known as sedimentation. Soil erosion and sedimentation are concurring environmental processes with varied negative and positive impacts. The negative impacts include the removal of nutrient rich topsoil in upland areas and subsequent reduction of agricultural productivity in those areas. In irrigation projects, soil erosion and sedimentation cause reduction of irrigation conveyance capacities and reservoir storage volumes. They also reduce irrigation water quality by increasing water turbidity. In the lowlands, deposition of soil from eroded uplands causes changes in river channels and subsequent increase in flood vulnerability of the floodplain farmlands and residential areas.

Soil erosion and sedimentation is not also always a negative environmental process. Whenever soil erosion occurs, there may be downstream benefits such as deposition of rich sediments for promotion of agricultural activities. Examples include Nile basin irrigation systems in Egypt, Juba and Shabelle irrigation projects in Somalia, etc.

In south Somalia, rivers Juba and Shabelle are the main rivers supplying irrigation water for many agricultural activities in the region. However, over many years and more specifically in the last 20 years, the irrigation projects have experienced high sediment loads which hamper their operation. Upland soil erosion is believed to be the major cause for this high sediment load [11]. Generally, upland areas with high soil erosion rates tend to contribute more sediment compared to areas with low soil erosion rates. In order to reduce the sediment plume into the two rivers, contributing areas with high soil erosion rates need to be identified and targeted for soil erosion control measures. Many Somalia development partners are currently putting special attention towards rehabilitating irrigation schemes in south Somalia and even initiate soil erosion control in the upland areas. However, this desire and anticipated initiative lack sufficient information on soil erosion and sedimentation rates, potential sediment sources, and sediment flow-rate in the two rivers.

The present study by FAO-SWALIM was initiated with the general objective of preparing an assessment of soil erosion and sedimentation of the riverine areas between rivers Juba and Shabelle and to provide input into soil erosion-sedimentation monitoring framework which will contribute to improved management of the irrigation systems in south Somalia. The study identified areas prone to high soil erosion rates and sediment flux into river Juba and Shabelle in south Somalia. It also proposed a comprehensive monitoring framework which will support routine identification of soil erosion and sedimentation problems for quick and targeted interventions. The methods and main findings of this study are documented in technical report.

1.2 Definition of terms associated with soil erosion and sedimentation

1.2.1 Soil erosion

Soil erosion may be defined as detachment, transportation, and deposition of soil particles from one place to another under the influence of wind, water or gravitational forces. In broad sense, soil erosion process can be classified into two categories: geologic and accelerated erosion. Geologic erosion refers to the simultaneous formation and loss of soil which maintain the balance between soil forming processes and soil loss. It is a natural process. Accelerated erosion includes deterioration and loss of soil by human activities. It is called "accelerated" because it speeds up the geologic soil erosion; thus upsetting the balance between soil forming processes and soil loss. Accelerated soil erosion occurs in various forms (e.g. splash, sheet, rill, and gullies) depending on the stage of progress in the erosion cycle and the position in the landscape. Some types of accelerated erosion may be used to refer to where the erosion process occurs (e.g. trail erosion, riverbank/riverbed erosion, road slope erosion, cropland erosion).

The main factors influencing soil erosion include climate (rainfall/precipitation or wind), landscape relief, soil and bedrock properties, vegetation cover, and human activity [7, 22]. Of these factors, the climate has been used to further define other forms of soil erosion such as erosion by wind, raindrop, wind etc. Erosion by rainfall is induced by when raindrops strike the surface and overcome the forces holding soil particle together. This is commonly referred to as "rain splash" or "raindrop splash"

[27]. As the rainfall process continue, water infiltrates into the soil at a rate controlled by the intensity of the water hitting the surface and the infiltration capacity of the vertical soil profile. Water that does not infiltrate begins to pond on the surface and then flows along the steepest descent after achieving a sufficient ponding depth. This hydrological process is referred to as "overland flow" or "runoff" [22]. In the upland areas of a landscape, overland flow is conceptually divided into rill flow and inter-rill flow mechanisms. As overland flow converges from various portions of the upland area and becomes more concentrated, it becomes sufficiently erosive to form shallow channels, referred to as "rills" (Figure 1.1). Additional soil particles may become detached as water flows through these rills. In the inter-rill areas, runoff may occur as a very thin broad sheet, sometimes referred to as "sheet flow". Both detachment and transport may occur in the rill and inter-rill areas. As erosive power increases, the small rills converge to form a large and deep surface channel known as "gully" [20]. In south Somalia, sheet, rill and gully erosion of croplands and riverbanks have been cited as the most common soil erosion types [11].

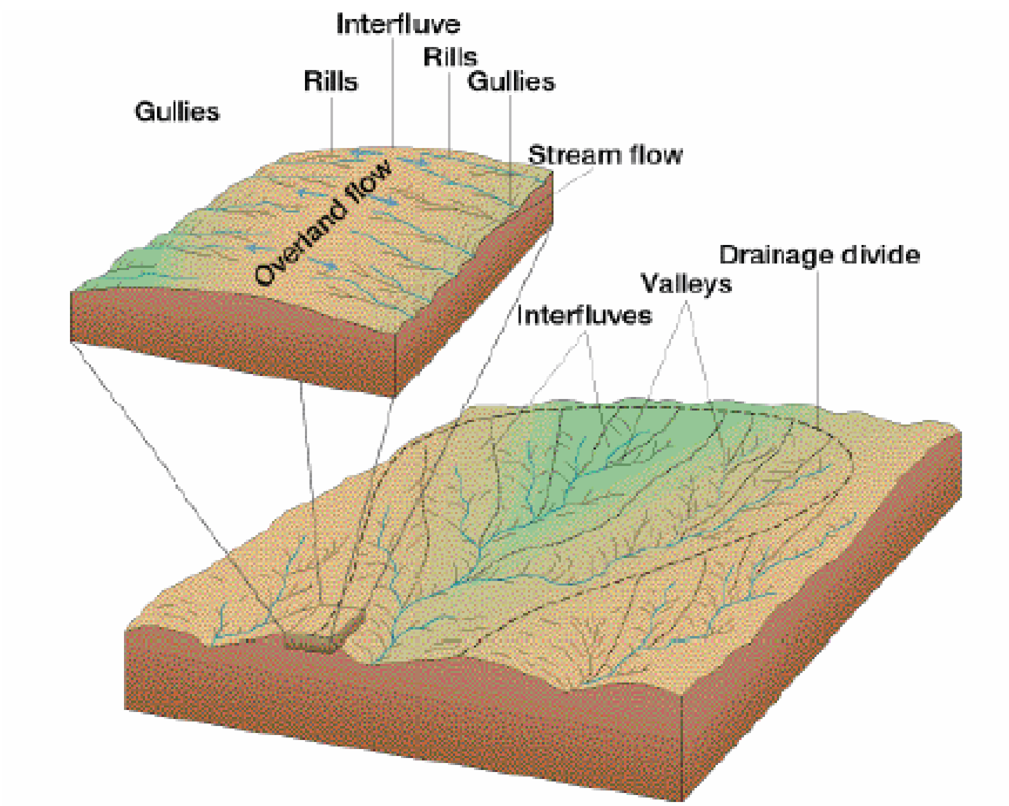


Figure 1.1: Schematic view of soil erosion types in a basin

1.2.2 Sedimentation

The entrained soil materials carried in water or air is known as sediment. The main sources of sediments are soil erosion of upland areas or river channel, mass movement due to landslides, soil creeps etc, and from mining or dumps lefts as waste material. In south Somalia, soil erosion is the major source of sediments into rivers Juba and Shabelle.

Sediment transport is a direct function of water or wind movement. With respect to water movement in a river, during sediment transport, sediment particles become separated into three categories: suspended material which includes silt + clay + sand; the coarser, relatively inactive bedload and the saltation load. *Suspended load* comprises sand + silt + clay-sized particles that are held in suspension because of the turbulence of the water. The suspended load is further divided into the wash load which is generally considered to be the silt + clay-sized material (< 62 µm in particle diameter) and is often referred to as "fine-grained sediment". The wash load is mainly controlled by the supply of this material (usually by means of erosion). The amount of sand (>62 µm in particle size) in the suspended load is directly proportional to the turbulence and mainly originates from erosion of the bed and banks of the river. In many rivers, suspended sediment (i.e. the mineral fraction) forms most of the transported load. *Bedload* is stony material, such as gravel and cobbles that moves by rolling along the bed of a river because it is too heavy to be lifted into suspension by the current of the river. Bedload is especially important during periods of extremely high discharge and in landscapes of large topographical relief, where the river gradient is steep (such as in mountains). It is rarely important in low-lying areas such as lower parts of river Juba and Shabelle in south Somalia. *Saltation load* is a term used by sedimentologists to describe material that is transitional between bedload and suspended load. Saltation means "bouncing" and refers to particles that are light enough to be picked off the river bed by turbulence but too heavy to remain in suspension and, therefore, sink back to the river bed. Saltation load is never measured in operational hydrology [10, 22].

Sediment transport is facilitated when there is sufficient energy to carry the sediments. The mass rate of transport is known as "sediment discharge". If at any point during the transport the velocity of the water is reduced, some sediment will be deposited. The process is known as sedimentation. Sediment yield is the amount of eroded soil that is delivered to a point in the catchment [22].

1.3 Modelling of soil erosion and sediment flux

Soil erosion and sediment yield can be directly measured in the field. The methods include the use of erosion pins, runoff plots, shrub-mounds, pedestals etc for soil erosion and measurement of sediment quantity in reservoirs, sediment concentration in rivers, etc for sedimentation processes. These direct measurements are reliable for determining soil erosion or sedimentation at a specific point in the landscape. However, they do not give much needed information on spatial distribution of sources of sediments and often integral of many complex phenomena in the landscape. In order to circumvent the problems of direct measurements, many researchers preferred combined application of direct measurements and modelling.

In soil erosion, various models have developed by many researchers worldwide. Table 1.1 shows some of these models and their implementation characteristics.

Table 1.1: Soil erosion model selection

Model	Type	Spatial scale	Temporal scale	Data demand	Outputs
AGNPS	Conceptual	Small catchments	Event/ continuous	High	Runoff, peak rate, erosion, sediment yield
ANSWERS	Physical	Small catchments	Event/ continuous	High	Runoff, peak rate, erosion, sediment yield
CREAMS	Physical	Plot/field	Continuous	High	Erosion, deposition
EMSS	Conceptual	Catchment	Continuous	Low	Runoff, sediment load
HSPF	Conceptual	Catchment	Continuous	High	Runoff, flow-rate, sediment yield
IHACRES-WQ	Empirical/ Conceptual	Catchment	Continuous	Low	Runoff, sediment
IQQM	Conceptual	Catchment	Continuous	Moderate	Sediment, sediment load
LASCAM	Conceptual	Catchment/ basin	Continuous	High	Runoff, sediment
SWAT	Conceptual	Catchment/ basin	Continuous	High	Runoff, peak rate, erosion, sediment yield
AGWA	Conceptual / physical	Catchment /basin	Continuous	High	Runoff, peak rate, erosion, sediment yield
GUEST	Physical	Plot / Field	Continuous	High	Runoff, sediment concentration
KINEROS	Physical	Hillslope/ small catchment	Event	High	Runoff, peak rate, erosion, sediment yield

Table 1.1 Cont.

Model	Type	Spatial scale	Temporal scale	Data demand	Outputs
LISEM	Physical	Small catchment	Event	High	Runoff, sediment
EUROSEM	Physical	Small catchment	Event	High	Runoff, erosion, sediment
TOPOG	Physical	Hillslope		High	Erosion hazard
USLE	Empirical	Hillslope	Annual	Low	Erosion
RUSLE	Empirical	Hillslope	Annual	Low	Erosion
USPED	Empirical/ conceptual	Catchment	Event/ annual	Moderate	Erosion, deposition
Thornes	Conceptual / empirical	Hillslope/ catchment	Event	Moderate	Runoff, erosion
WATEM	Conceptual	Catchment	Annual	Moderate	Erosion
WEPP	Physical	Hillslope/ catchment	Continuous	High	Runoff, sediment yield, soil loss
SHETRAN	Physical	Catchment	Event	High	Runoff, peak rate, erosion, sediment yield
SEAGIS	Empirical/ conceptual	Catchment	Annual	High	Erosion, sediment yield
PESERA	Physical	Hillslope	Continuous	High	Runoff, erosion, sediment
SPL	Empirical/ conceptual	Catchment/ river basin	Annual	Moderate	Fluvial erosion, river incision

For sediment flux, the most widely used models are those relating to sediment rating curves and combined use of erosion models and sediment delivery ratio. Table 1.1 shows the common erosion models used which are used to predict sediment yield.

Rating curves are widely used for direct assessment of changes in the suspended sediment delivery process and indirectly for estimating total yields. They are graphical representation of the functional relationships between water discharge and suspended sediment concentration (SSC). They can be used to determine changes in suspended sediment flux by comparing "before" and "after" rating curves. They can also be used to quantify sediment yields between two stations [31, 32]. In spite of their wide application, several researchers have found some problems with them [31]. One of the problems is how to deal with the hysteresis effect. When a series of discharge measurements and sediment samples are taken at intervals throughout a storm event (when flow increases, reaches a peak, and then decreases), the rating curve often takes the form of a hysteresis loop. Figure 1.2 shows an example of this looping effect where samples 1 and 7 correspond to the same discharge rate but sample 7 (taken late in the discharge event) has a lower concentration of suspended sediment than sample 1. The inset graph shows a typical time sequence of sampling in relation to the discharge. This kind of hysteresis may also be observed in plots of seasonal data. It reflects periods of the year when sediment may be more readily available than at other times. Higher concentrations may occur, for example, after a long, dry period or in dry months when vegetation is not able to hold back soil particles that are being eroded. During development of rating curve from data spanning long periods, it is not uncommon to find researchers fitting a single rating curve to the entire data; thus overlooking the hysteresis effect. The resultant effect would reduce the predictive accuracy of the rating curve developed. In order to overcome the hysteresis effects in sediment rating curves, some authors have suggested the use of overland flow component of the total river discharge [31, 32]. This suggestion sound sensible since suspended sediments is yielded and transported principally by overland flows. Alternatively, a family of curves may be developed corresponding to different hydrologic periods.

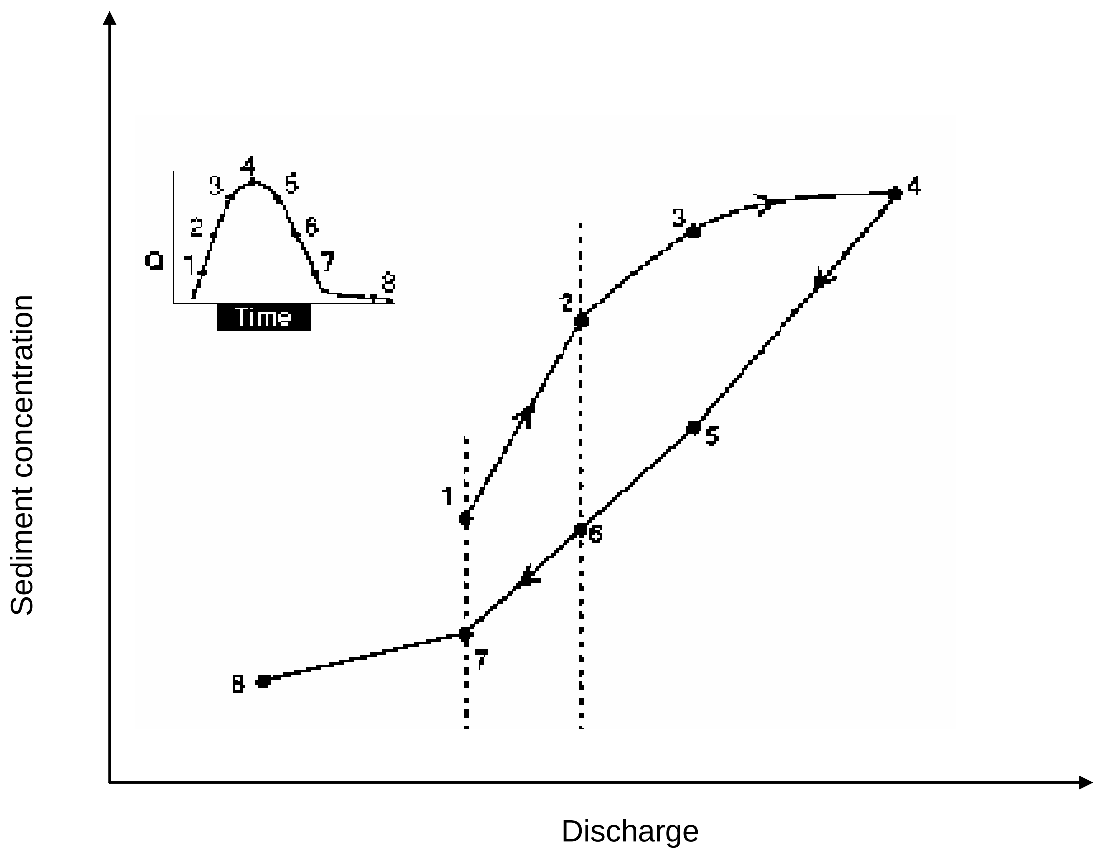


Figure 1.2: Typical hysteresis effect observable in suspended sediments. Sample numbers are those noted in the inset storm hydrograph

1.4 Approach for preliminary study of soil erosion and sedimentation study in south Somalia

Due to the current fragile security situation in southern Somalia which prevented detailed field survey, this study basically focused on desk analysis of soil erosion and sedimentation of the riverine areas along rivers Juba and Shabelle. In addition to lack of field survey, there was also the lack of comprehensive and consistent historical data on sediment concentration of the two rivers. Because of these limitations, this study focused on what could be feasible in designing a monitoring framework for soil erosion and sedimentation into river Juba and Shabelle. Its main thrust was therefore to use the available information in developing a versatile method for assessing soil erosion and sedimentation rates into river Juba and Shabelle in south Somalia. It also developed a framework for obtaining future comprehensive data for guiding decisions on river basin management of rivers Juba and Shabelle. In effect, the study was an input for designing future monitoring of soil erosion and sedimentation into the two rivers. Its results should therefore be seen within this context.

The major inputs for the study were remote sensing and archived data at FAO-SWALIM, on the one hand for erosion, and limited sediment samples and river discharge in 2007 and 2008, on the other hand for sedimentation (Figure 1.2). The approach used included three steps: soil erosion modelling, prediction of sediment flux, and determination of potential monitoring sites and framework for soil erosion and sedimentation (Figure 1.3).

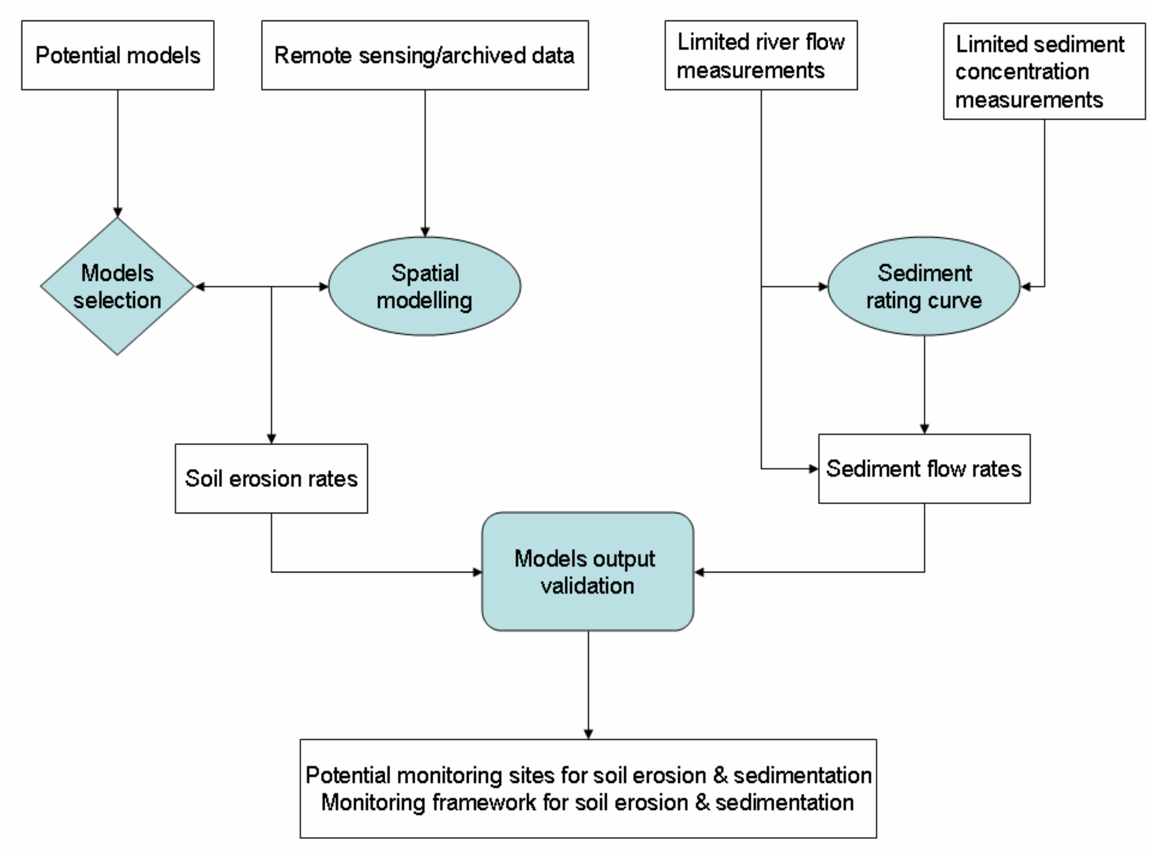


Figure 1.3: Approach for preliminary study of soil erosion and sedimentation

Soil erosion modelling was done to predict the potential sediment sources and erosion rates in the study area. Appropriate models for application were selected depending on their data needs and relevance in predicting necessary soil erosion characteristics such as sheet or rill erosion, runoff, etc [22]. Three models were selected from those listed in Table 1.1 and included: MUSLE, RUSLE, and Thornes models. Due to insecurity which hindered ground observations, soil erosion modelling was based on previous data collected by FAO-SWALIM and remote sensing application. Future opportunities for field verification are recommended when the security situation in the country will improve. Besides predicting of erosion rates and sediment sources, soil erosion modelling was also done to help in construction of a framework which will be followed for future spatial monitoring of soil erosion and changing sediment sources in the study area.

Sediment flux was predicted using sediment rating curve. The rating curve method was adopted due to lack of continuous sediment sampling of river Juba and Shabelle in the study area. The discrete temporal measurements of sediment concentrations were calibrated with daily measurements of river discharge and the resultant relationship used to determine annual sediment flux into the two rivers. This approach was successfully used in this study was to: 1) support the formulation of a framework for assessing and future monitoring of potential sediment flux into the two rivers, 2) give insight into the best soil erosion model for predicting sediment flux in the study area. It is important to note that the focus on the use of sediment rating curves was not to get decimal digits of accuracy but rather to give insight into appropriate monitoring methods and potential rates of sedimentation in rivers Juba and Shabelle in south Somalia.

2. STUDY AREA

This study was carried out in the riverine areas between rivers Juba and Shabelle in south Somalia. The study area lies between the longitudes 41°53' and 46°07' 48" East and between the latitudes 0°16' South and 5°06' North; thus, covering about 88 000 square kilometres (Figure 2.1).

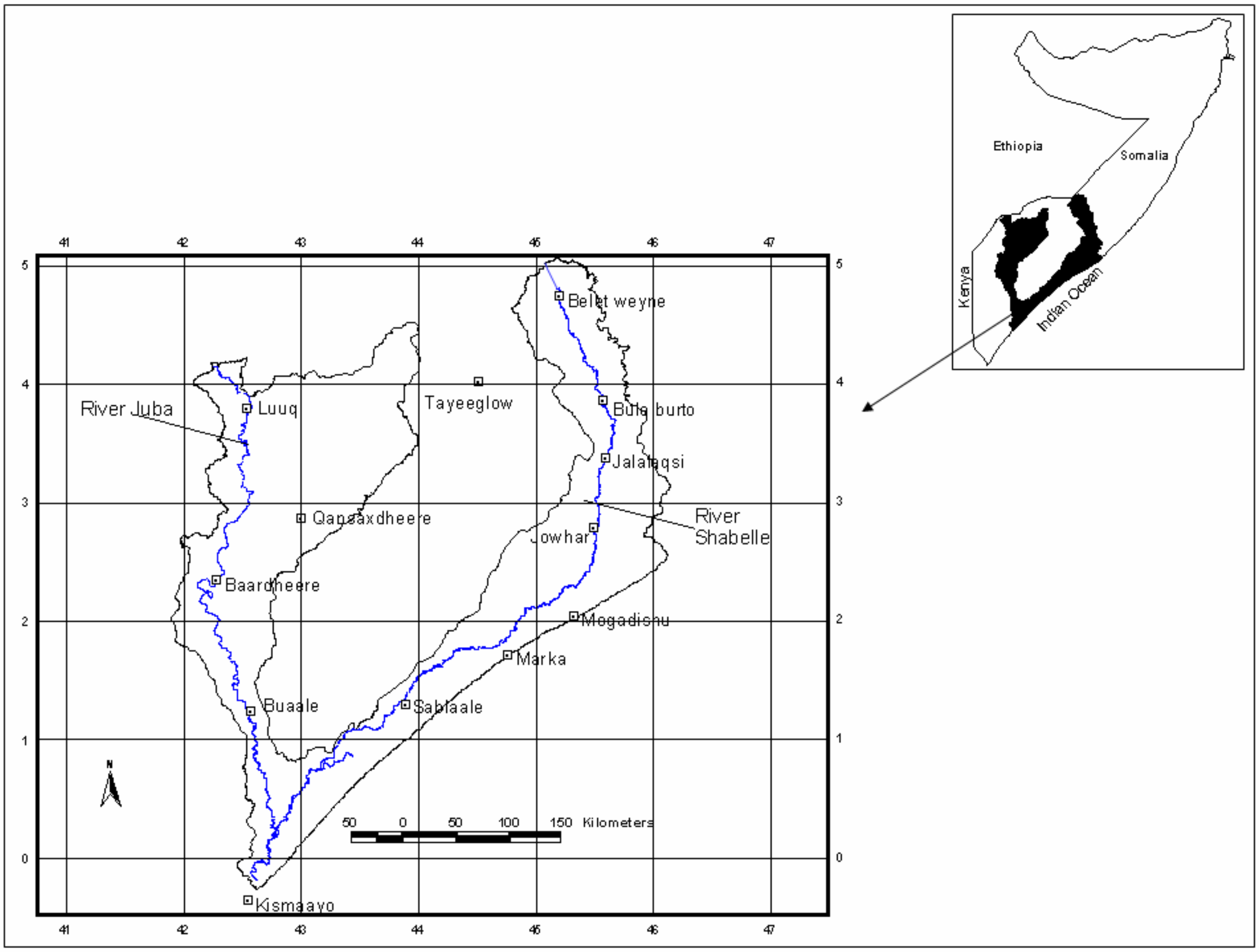


Figure 2.1: Study area

2.1 Rainfall distribution

The climate of the study area is tropical arid to dry and sub-humid, which is influenced by the north-easterly and south-easterly winds of the Inter-tropical Convergence Zone (ITCZ). It has four seasons, namely:

Gu: April to June, which is the main rainy season

Xagaa: July to September, which is dry and cool

Deyr: October to December, which is second rainy season

Jilaal: January to March, which is the longest dry season

Rainfall in the study area is erratic, with a bimodal pattern except in the southern parts close to the Indian Ocean where some showers may occur even during the *Xagaa*. Rainfall varies considerably, with the *Gu* delivering about 60% of the total mean annual rainfall, which ranges from 200 - 400 mm in areas bordering Ethiopia, between 400 - 500 mm in the central areas, and above 500 in the southern areas.

2.2 Geology and soil

The study area is characterized by outcropping of the metamorphic basement complex, which are made up of migmatites and granites. Sedimentary rocks such as limestones, sandstones, and gypsiferous limestones are also present, as well as an extensive and wide system of coastal sand dunes. Basaltic flows are present in the north-western part of the study area. From a tectonic point of view, the study area is characterized by a fault system lying parallel to the coast and by a system of northwest-southeast oriented faults in the metamorphic basement complex.

Some late tertiary fluvio-lagunal deposits also occur on the Lower Juba floodplain and part of the southern Shabelle. This latter part consists of clay, sandy clay, sand, silt and gravel. Recent fluvial deposits are common alongside the two rivers and mainly consisting of sand, gravel, clay and sandy clay. Other recent alluvial deposits in small valleys can be found here. They mainly consist of gravely sand or red sandy loam materials. A wide coastal dune system also occurs along the coast of Indian Ocean.

In terms of the landscape features, the study area can be characterized as follows:

- The two main river valleys (river Juba and Shabelle) that traverse the area.
- Hilly topography in the middle of the study area, which is cut by wadis flowing towards the Indian Ocean.
- A coastal dune complex known as the Marka red dunes, which fringes the coast from beyond the Kenyan border and separating the narrow coastal plain from the Webi Shebeli alluvial plain [3].

In terms of the distribution of soil types, the study area can be characterized as follows: soil along the upper reaches of both the Juba and Shabelle, soil on the floodplain, and soils along the coast of Indian Ocean. Along the upper reaches of the two rivers, the soil is shallow Fluvisols, Arenosols, and Calcisols, the soils in the floodplain are mainly Fluvisols, Vertisols, Stagnosols and Calcisols, while the soils along the coast are Arenosols, Regosols and Calcisols [29].

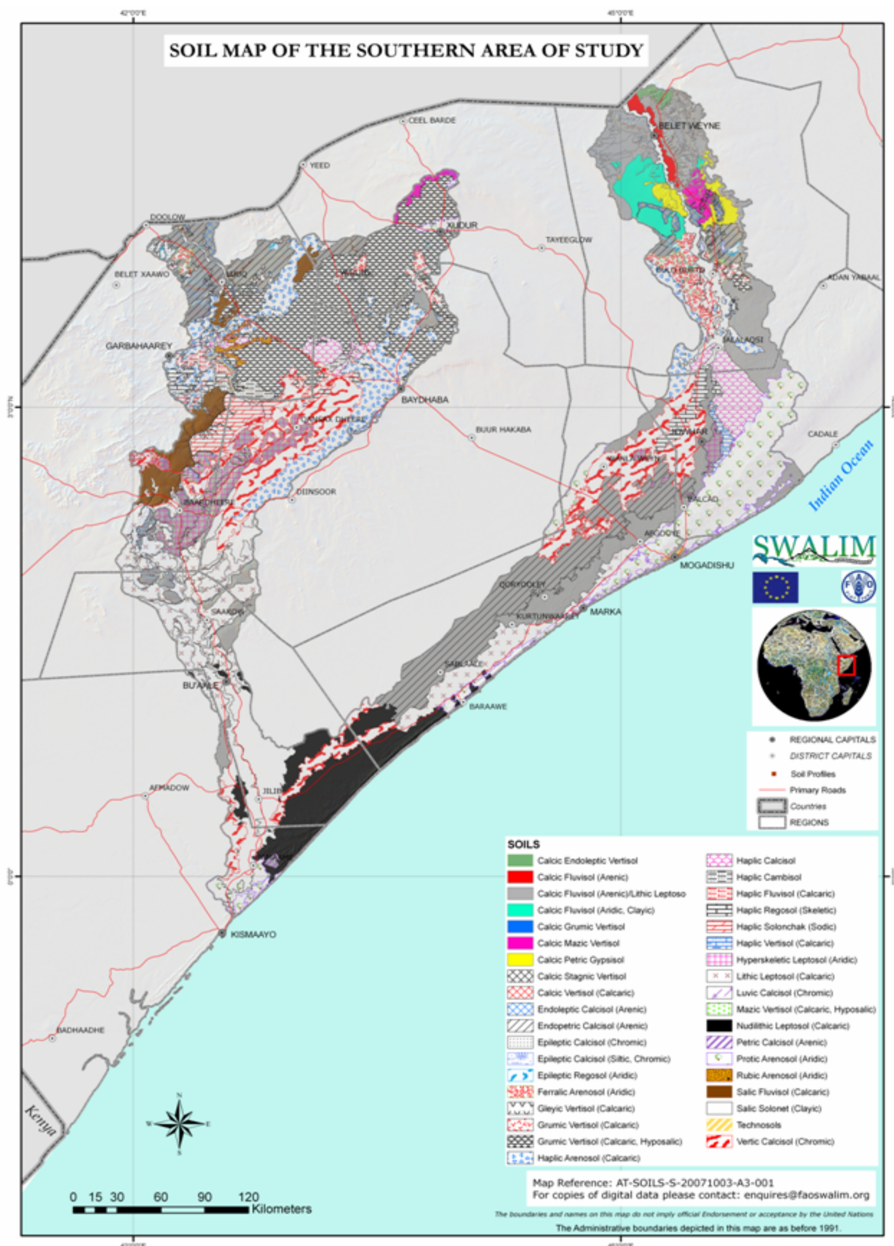


Figure 2.2: Soil map of the study area

2.3 Land cover and land use

Land cover of the study area consists mainly of natural vegetation. Other cover types include crop fields (both rainfed and irrigated), built-up areas (settlement/towns and airport), sand dunes and bare lands, and natural water bodies. The natural vegetation consists of riparian forest, bush lands and grasslands, and woody vegetation. Woody and herbaceous species include *Acacia bussei*, *A. seyal*, *A. nilotica*, *A. tortilis*, *A. senegal*, *Commiphora spp.*, *Chrysopogon auchieri* var. *quinqueplumis*, *Suaeda fruticosa* and *Salsola foetida* etc.

The land use is mainly of grazing and wood collection for fuelwood and building material. Rangelands in the Juba and Shabelle catchments support livestock such as goats, sheep, cattle and camels. Livestock ownership is private but grazing lands have been traditionally communal, making it difficult to regulate the use of rangeland. Rangelands are utilised by herders using transhumance strategies [1]. Land covers associated with this land use include forest, wooded bushland, bushlands, shrubland and grasslands [12].

Most farmers in the study area are sedentary who practice animal husbandry in conjunction with crop production. They tend to keep lactating cattle and a few sheep and goats near their homes while non-lactating animals are kept further away in nomadic life pattern. Along the rivers, there are rainfed and irrigation farms where there are farmers who also keep relatively small numbers of livestock (mainly cattle and small ruminants). Small-scale irrigated fields (some with pumps and some by gravity) are also found along the Shabelle and Juba river valleys. Crops grown include maize, sesame, fruit trees and vegetables. Large-scale plantations sugar cane, bananas were originally found in these areas prior to the civil war in 1990s. These plantations have since collapsed during the civil war. However, remnant large-scale production of guava, lemon, mango and papaya may be spotted in a few places. Flood recession cultivation in *desheks* (natural depressions) on the Juba River floodplain is common. Crops grown include sesame, maize, sesame, tobacco, beans, peas and vegetables, watermelon, sometime groundnuts.

3. MATERIALS AND METHODS

3.1 Data sources

The data used in this study included daily rainfall amounts for 2007 and 2008, sediment concentration (Total Suspended Sediment, TSS) samples for some stations in river Juba and Shabelle for certain periods in 2007 and 2008, and daily river flow measurements at four stations in 2007 and 2008.

3.1.1 Sediment sampling and river discharge measurements

Sediment samples were collected using instantaneous sampling method. In this method, a sampler consisting of a horizontal tube with water-tight doors (Figure 3.1) was lowered into the river. The doors were then opened by triggering an opening mechanism using suspension cords to allow sediments and water to enter the sampling bottle (Figure 3.1). The doors were held open long enough for the flow within the tube to become equal with that outside the tube. They were then suddenly shut to trap the sediment suspensions inside the bottle.

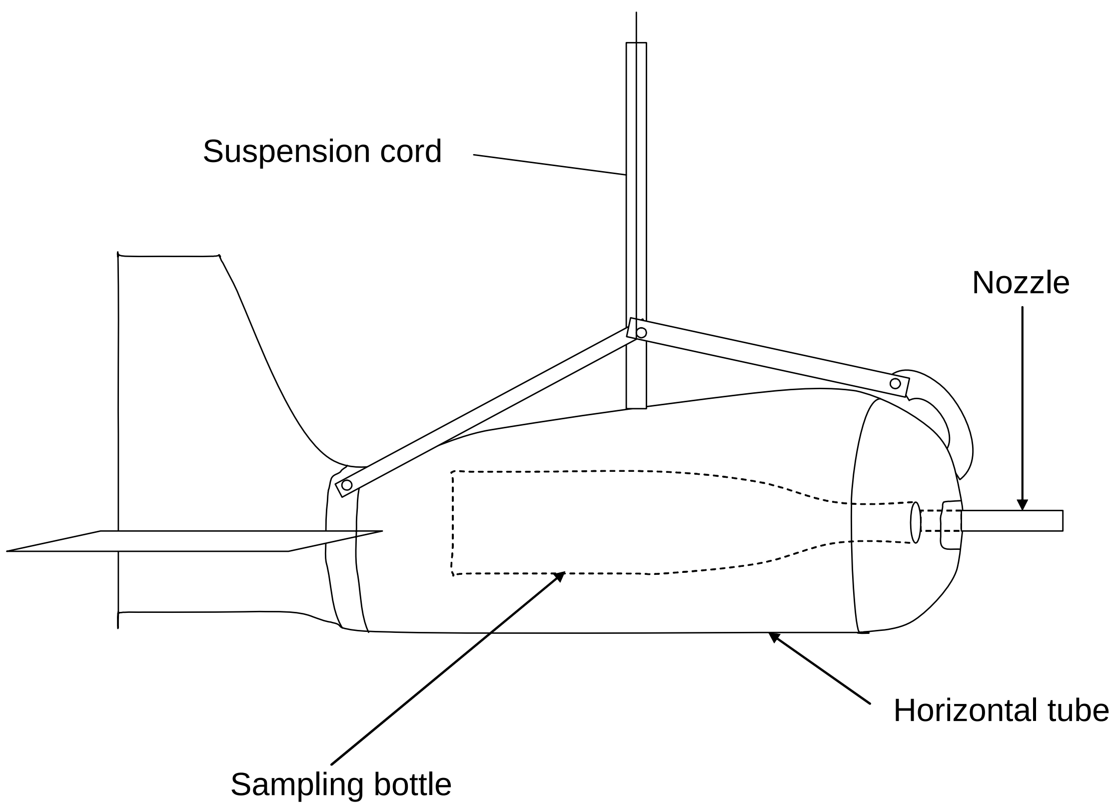


Figure 3.1: Sampler for sediment sampling

Sediment sampling was done in seven locations (Figure 3.2). Three of these locations had river gauging equipment for measuring water discharge. Collection of sediment was done by lowering the sample into the river from the same spot as for river flow-gauge (Figure 3.3).

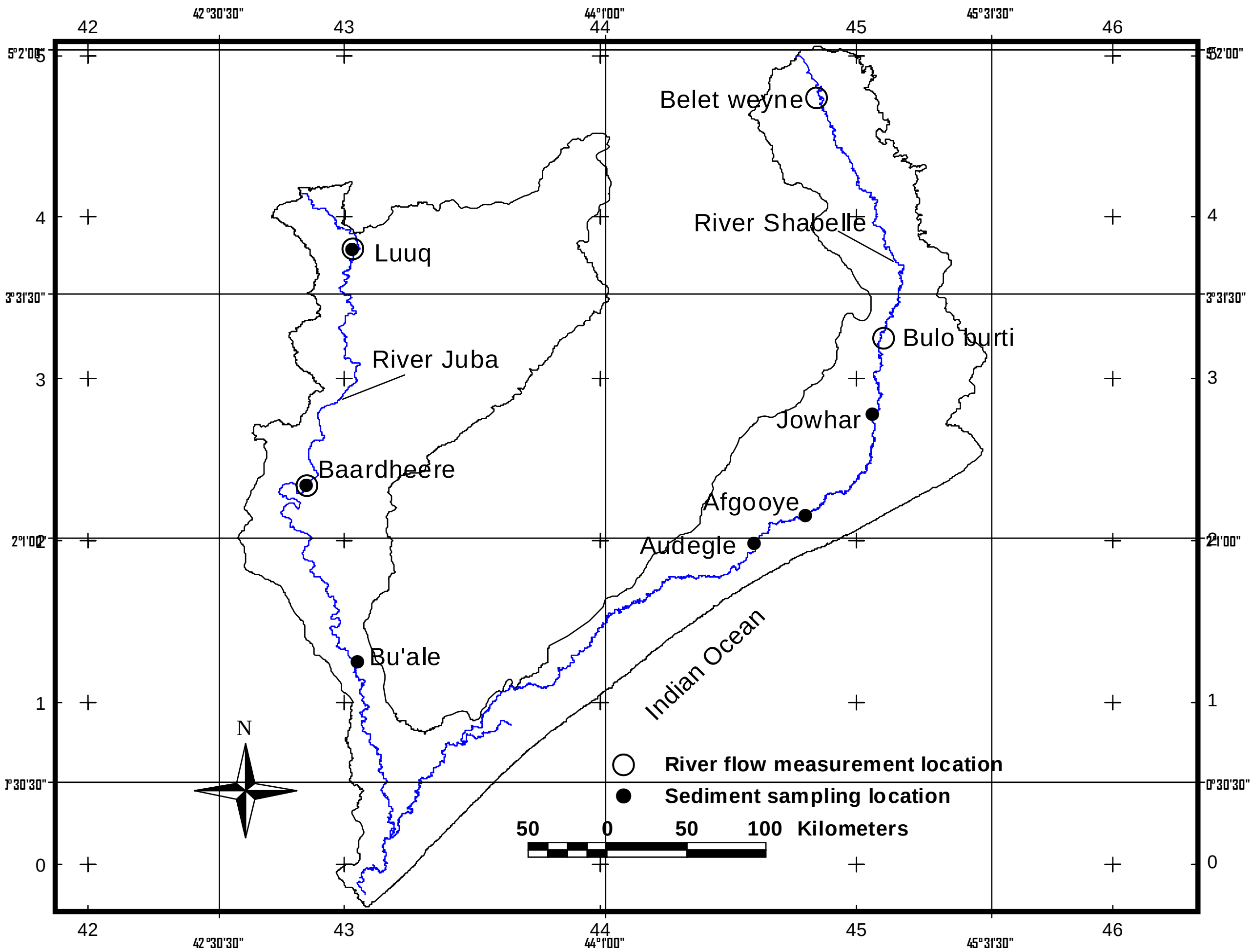


Figure 3.2: Location of sediment and river discharge measurements in 2007 and 2008

Figure 3.3: Sediment and river discharge sampling in Jowhar, south Somalia

The sediment samples were then transferred into PVC bottles and sent to Nairobi where they were checked and logged in for laboratory analysis. The analysis was done at Crop Nutrition Laboratory Service in Nairobi (http://www.cropnuts.com) and included comprehensive water quality analysis. Comprehensive water quality analysis was done because sedimentation and water quality studies were both joint activities carried out by FAO-SWALIM. Figure 3.4 is an example of the output from the laboratory, where TSS results at the bottom of the lab report was of interest in the sedimentation study.

Water Analysis Report

Total suspended soils (CNS), Irrigation Water Analysis (CNS)

Crop Nutrition Laboratory Services
The Power of Knowledge

Customer:	SWALIM	Water purpose	Irrigation (FAO)	Date received:	11-Apr-08
Farm name	Shabelle river project			Report date:	18-Apr-08
Contact person:		Comments:	31.06.08	Sample ID:	CS044WACO20

Water source: JOWHAR

Important: To maintain the correct history ensure the next sample sent from this water source is labeled: JOWHAR

Parameter	Unit	Result	Guide low	Guide high	Low	Normal	High	Symbol	current
pH		7.63		8.40				pH	7.63
Electrical conductivity	mS cm-1	1.55		<1.5				EC	1.55
Total dissolved solid	ppm	776		<450				TDS	776
Ammonium	ppm	0.00		<5.00				Al	0.00
Calcium	ppm	137		<60				Ca	137
Magnesium	ppm	34		<25				Mg	34
Potassium	ppm	13		<20				K	13
Sodium	ppm	136		<60				Na	136
Nitrate, N	ppm	0.22		<15				N	0.22
Phosphorous	ppm	0.18		<0.4				P	0.18
Sulphur	ppm	60.99		<27				S	60.99
Iron	ppm	0.03		<5				Fe	0.03
Manganese	ppm	0.00		<0.2				Mn	0.00
Zinc	ppm	0.21		<2				Zn	0.21
Copper	ppm	0.05		<0.2				Cu	0.05
Boron	ppm	0.00		<0.6				B	0.00
Chlorides	ppm	257		<140				Cl	257
Bicarbonate	ppm	150		<91				HCO_3	150
Total suspended solids	mg/L	204		<45				TSS	204

Figure 3.4: Example of laboratory report of analysis of sediment sample from Johwar sampling station

The data for river flow measurements was obtained from FAO-SWALIM. It consisted of daily river discharge for four stations in 2007 and 2008 (Figure 3.2). Table 3.1 shows summary information from this dataset.

Table 3.1: River discharge for river Juba and Shabelle in 2007 and 2008

River	Station	2007			2008		
		Mean	Minimum	Maximum	Mean	Minimum	Maximum
Shabelle	Belet Weyne	119.3	29.2	315.7	82.2	21.9	383.6
	Bulo Burti	116.9	29.9	316.4	85.1	23.2	312.0
Juba	Luuq	185.1	13.3	734.2	207.5	4.4	1229.2
	Baardheere	289.6	85.1	914.8	305.2	38.6	1549.5

The summary shows that the flow rate in river Juba was higher than the flow rate in river Shabelle in 2007 and 2008. Also, on average river Juba had higher flow in 2008 than in 2007 while river Shabelle had higher flow rate in 2007 than in 2008 (Table 3.1).

Preliminary plot of the sediment concentration and river discharge showed that peak discharge and sediment concentrations coincided and occurred in the last quarter of 2007 and 2008 (Figure 3.5). This was slightly different from the rainfall distribution, which peaked in May-July and September-October with mid-year peaks being the highest (Figure 3.6) [15]. Although there could be many possible reasons for this difference (e.g. sediment flux from Ethiopia where the rainfall causing the peak discharge could have been high in the later part of the year), more comprehensive data is needed to explain the difference.

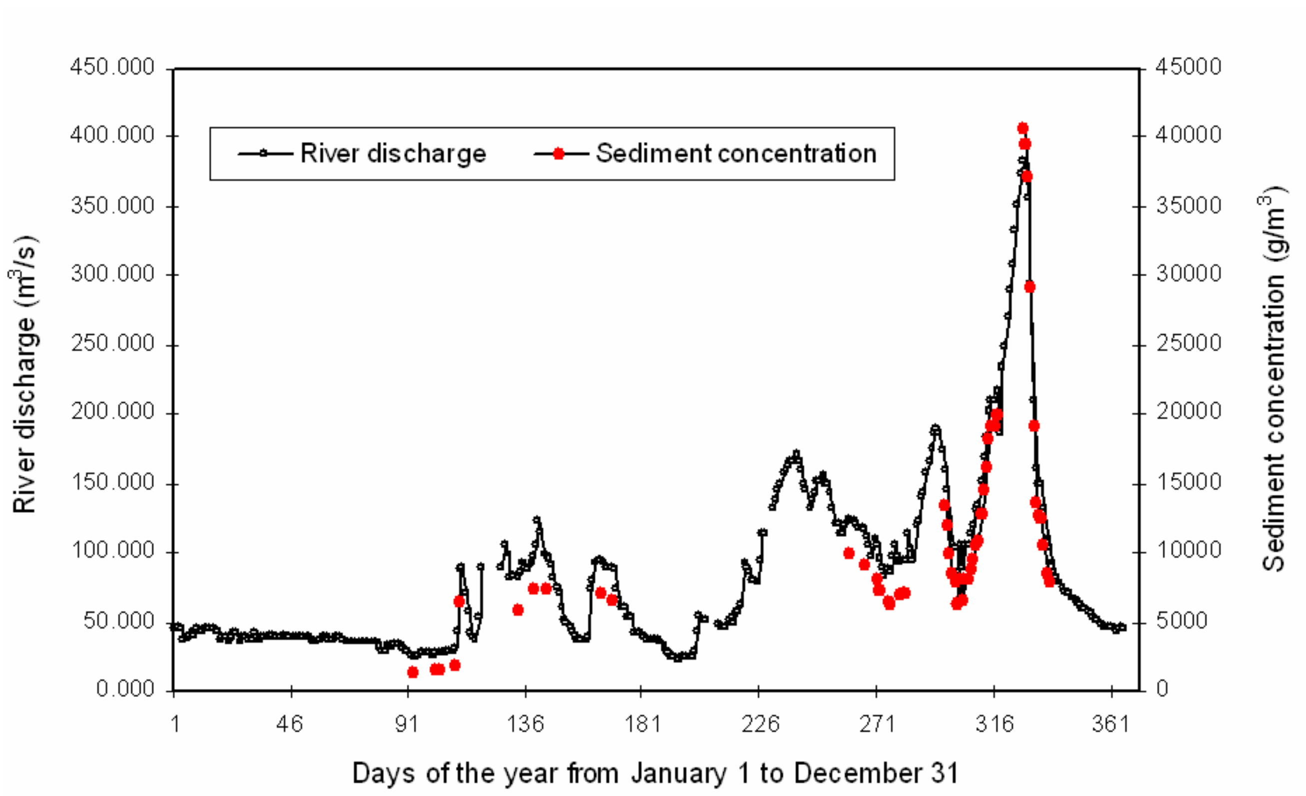


Figure 3.5: Example of sediment and discharge patterns in Belet Wyne in 2008

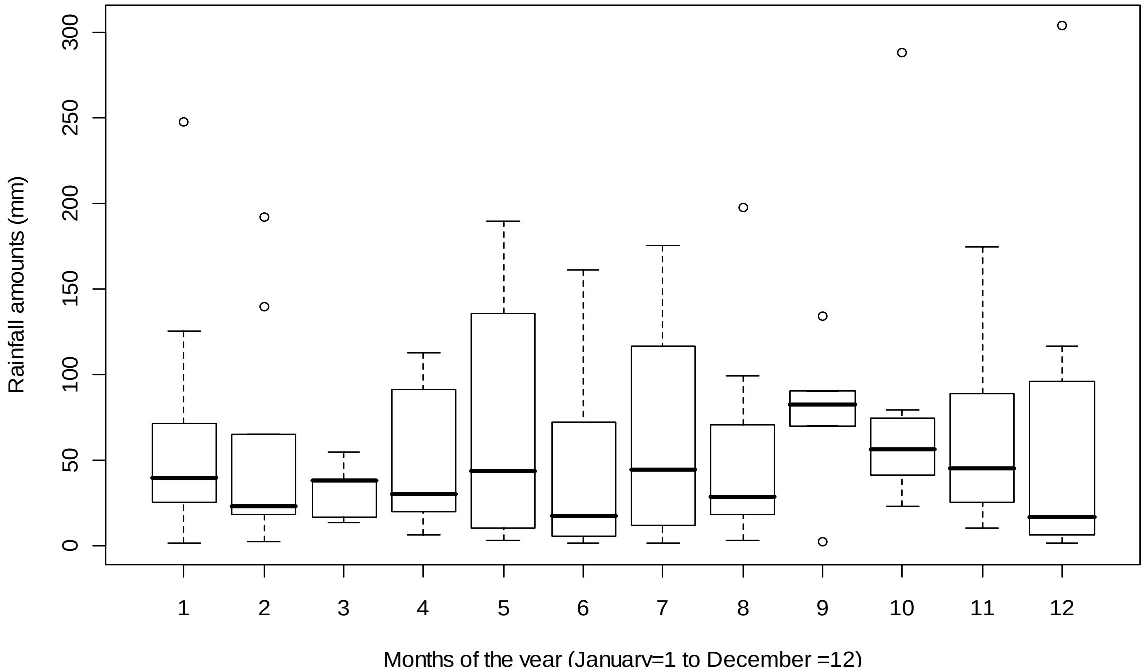


Figure 3.6: Average monthly rainfall for 19 stations in the study area in 2008

3.1.2 Other datasets

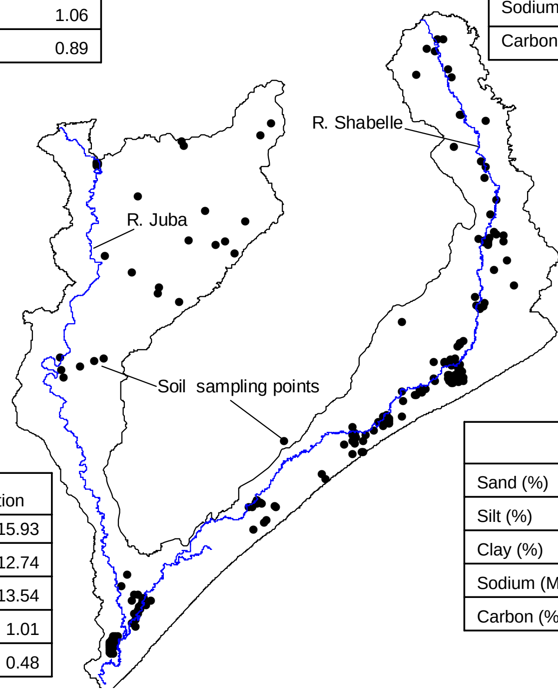
Other data used in this study included land use and land cover maps [12, 18], 90-m DEM which was downloaded from http://srtm.usgs.gov, 16-days 250-m composite maximum MODIS NDVI images from January 2007 to December 2008. They were downloaded from http://pekko.geog.umd.edu/usda/apps on 20th February 2009. In addition to these datasets, soil samples from 166 locations in the study area were also used. The soil samples were collected by FAO-SWALIM between 2006 and 2007 [29]. The data contained soil physical properties which were used to determine soil erodibility in the study area. Figure 3.7 shows summary of these soil properties according to different regions of the study area. The Juba side of the watershed seem to have had higher silt and clay contents; which imply that it could be more erodable than the Shabelle side. According to Morgan [13], a combination of high silt and clay content translates into high soil erodibility.

Upper Juba

	Mean	Std. Deviation
Sand (%)	32.55	10.21
Silt (%)	35.69	9.31
Clay (%)	31.76	8.74
Sodium (Me/100g)	0.63	1.06
Carbon (%)	1.17	0.89

Upper Shabelle

	Mean	Std. Deviation
Sand (%)	48.22	20.77
Silt (%)	25.66	11.88
Clay (%)	26.13	14.89
Sodium (Me/100g)	0.53	1.30
Carbon (%)	0.52	0.37



Middle Shabelle

	Mean	Std. Deviation
Sand (%)	29.75	19.72
Silt (%)	31.91	11.85
Clay (%)	38.38	14.94
Sodium (Me/100g)	0.79	0.88
Carbon (%)	1.06	0.73

Lower Juba and Shabelle

	Mean	Std. Deviation
Sand (%)	30.53	15.93
Silt (%)	30.10	12.74
Clay (%)	38.35	13.54
Sodium (Me/100g)	0.59	1.01
Carbon (%)	1.09	0.48

Figure 3.7: Location of soil samples and summary of soil physical properties

3.2. X-Ray Diffractometry (XRD)

In addition to sediment concentration and river flow measurements, suspended sediment samples were also analysed with X-ray diffractometer to determine their mineral contents. This was done in an attempt to better understand the source rocks of the sediments transported by the two rivers.

Four stations were originally planned for sediment sampling (two in each river) for XRD analysis. However, due to increased insecurity in 2008, only samples from Belet Weyne and Buale stations were consistently received in 2008. Sampling for TSS still continues though for the other stations and they are anticipated to be included in future XRD analysis. The sediment samples received were first dried and then sent to the Department of Geological Sciences, University of Roma TRE (www.italithos.uniroma3.it) in Rome for X-ray diffractometry (XRD).

Generally, XRD analysis involved determination of X-ray signatures from the samples which corresponded to signatures of known minerals. Since suspended sediments are composed of mineral particles eroded from riverbed/upland rocks or soil, their X-ray signatures were construed to imply signatures of their mineralogy. X-Ray is part of the electromagnetic spectrum corresponding to a wavelength region between 10^{-8} to 10^{-10} metres (Figure 3.8). To analyse minerals with the X-Ray Diffractometry (XRD) a sample of almost 3 grams needs to be reduced into powder (by grinding with mortar) and dried-up. The powder is then compressed into a small pellet and placed in a holder at the centre of a goniometer in the XRD machine (see Figure 3.9). Then the sample is radiated with X-rays of fixed wave-length with beams hitting the sample at different angles in subsequent time intervals. After hitting the soil sample, the X-ray beams are diffracted at different angles depending on the minerals present in the soil sample. A scanning detector records the diffracted rays and their intensity measured to determine various inter-atomic diffraction distances (also known as D-spacing) for the test sediment sample. Each type of mineral has unique diffracted intensity and angles. A typical XRD output is shown in Figure 3.10 in which the intensity of diffracted rays is plotted on the Y axis (and expressed in counts per second) and scattering angle on the X axis (expressed with the Greek letter theta, 2θ). Such a plot is called diffractogram.

The peaks in the diffractometer have special linkage with certain minerals. Thus, once a diffractometer of a given sample has been determined its peaks are compared to peaks of known minerals to deduce the mineral composition of the test sample. In this way, XRD helps to determine different minerals of a given soil sample. In this study, XRD method was attempted to test if it could help in identifying sediment sources in the larger river Juba and Shabelle watershed. The analyzed minerals from the samples were checked against the geologic characteristics of the larger river Juba and Shabelle basin.

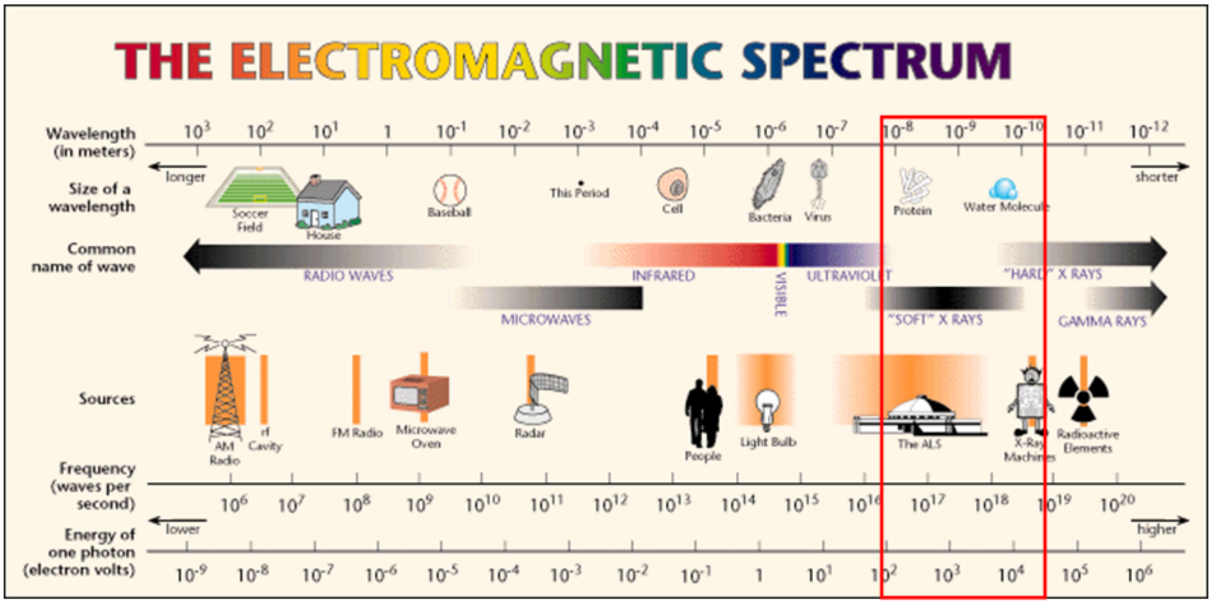
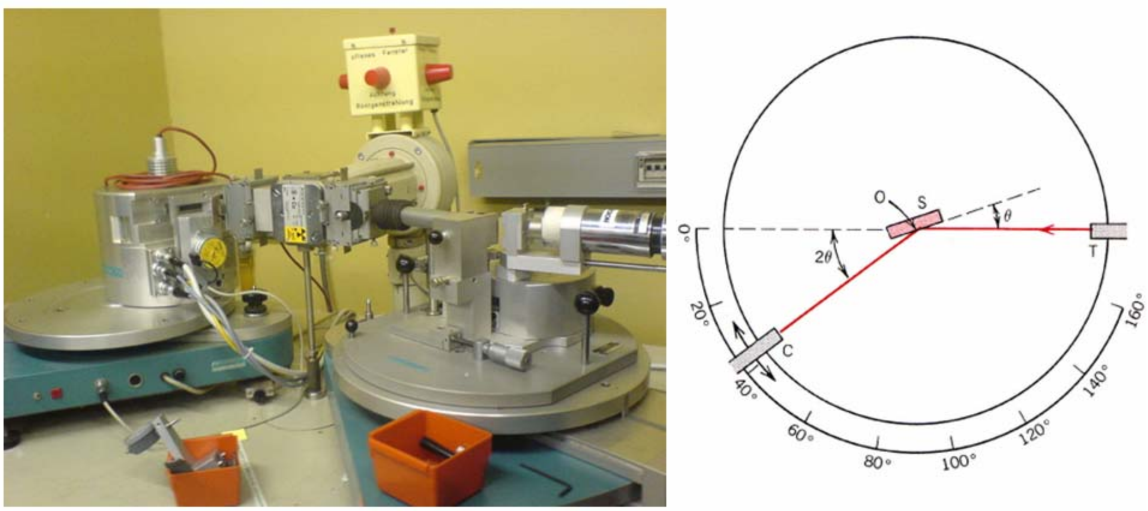


Figure 3.8: Electromagnetic spectrum and X-Ray window.



(a) X-Ray diffractometer

(b) Goniometer principle

Figure 3.9: X-Ray diffractometer and the goniometer principle. T is transmitter of X-Ray and C is cathode detector

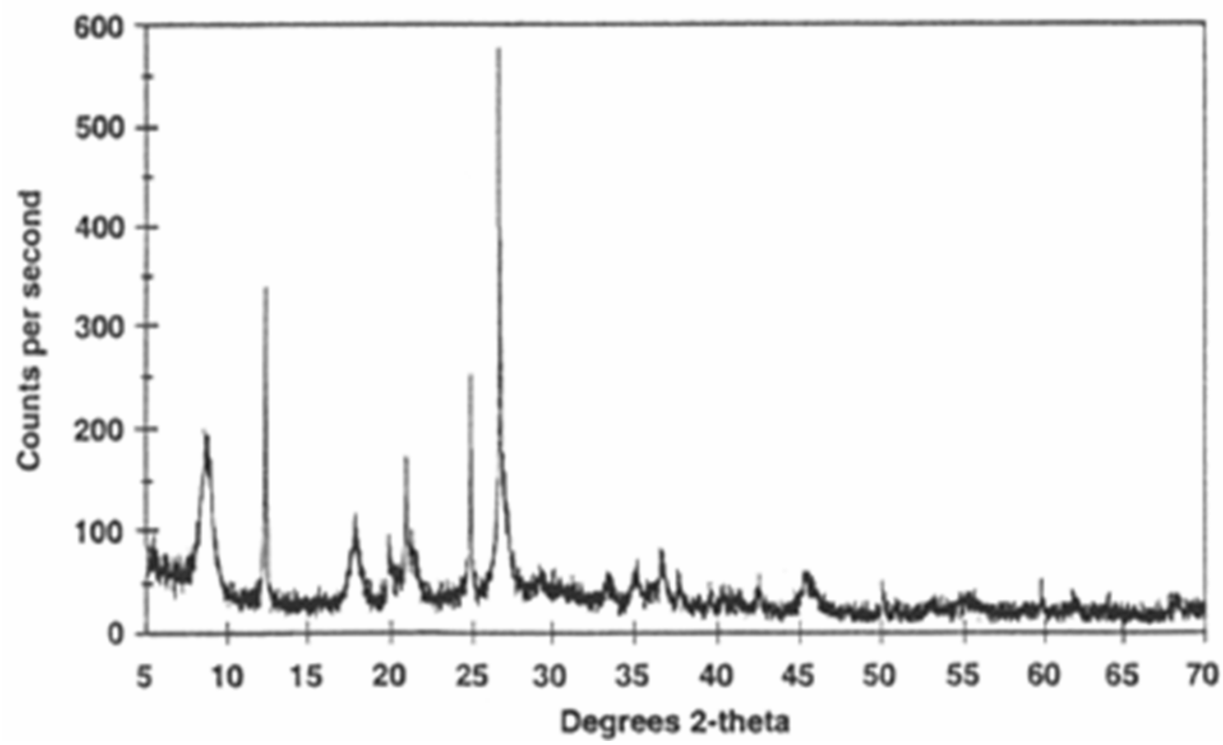


Figure 3.10: A typical X-ray Diffractogram

3.3 Soil erosion modelling and estimation of sediment yields

Soil erosion modelling was done to determine the potential upland soil erosion rates and sediment sources into rivers Juba and Shabelle. The models were tested MUSLE, RUSLE, and Thornes models [21, 26, and 32]. Their input requirements and associated equations (which are also elaborated in Appendix 1) are shown in Table 3.2.

Sediment yield into rivers Juba and Shabelle was determined at specific times in form of sediment concentration (g/m^3). The data was collected between April and July and between September and December in 2007 and 2008. These times also coincided with peak flows (Figure 3.5) and therefore posed little threat of hysteresis effects. Summary results of the sediment concentration data showed that river Juba had more sediment concentration than river Shabelle (Table 3.3). The sediment concentration data was calibrated with water discharge to establish sediment rating curve for the two rivers. Figure 3.11 shows the calibration results from these stations.

Table 3.2: Models for estimating overland sediment yield

Model	Formula	Input parameters
MUSLE	$E = R * K * LSt * C * P$	R = Erosivity (Eq. 8 in Appendix 1) K = Erodibility (Eq. 10 in Appendix 1) LSt = Topographic factor (Eq. 14 in Appendix 1) C = land cover (Eq. 12 in Appendix 1) P = Land management (Wischmeier and Smith monograph)
RUSLE	$E = R * K * LSt * C * P$	R = Erosivity (Eq.1 in Appendix 1) K = Erodibility (Eq. 10 in Appendix 1) LSt = Topographic factor (Eq. 14 in Appendix 1) C = land cover (Eq. 12 in Appendix 1) P = Land management (Wischmeier and Smith monograph)
Thornes	$E = Ru^2 * K * St^{1.66} * e^{-o.77*C}$	Ru = Runoff (Eq.7 in Appendix 1) K = Erodibility (Eq. 10 in Appendix 1) St = Slope C = land cover (Eq. 12 in Appendix 1)

Using least-squares regression analysis, the rating curve was determined from the model in Equation (1).

Sediment discharge (kg/s) $= 0.087 * Q_d^{\ 1.96}$ (1)

where Q_d is the water discharge. The above model gave a coefficient of correlation of about 88% with a residual standard error of 0.93 kg/s (Figure 3.10).

Table 3.3: Summary of sediment concentration in 2007 and 2008

River	Station	Average	Std. Deviation	Range
Shabelle	Belet Weyne	10292	8013.6	41028
	Jowhar	6773.6	1017	11424
	Mahadday Weyne	5752	6780.3	13404
	Afgooye**	587	79.1	172
	Audegle*	528	-	-
Juba	Luuq*	380	-	-
	Bardheere	11784	15167	21795
	Buale	934.4	766.2	2200
	Year	**Average**	**Std. Deviation**	**Range**
Shabelle	2007	9170.5	14564	13332
	2008	7547.8	11027	19200
Juba	2007	14120	10123.1	22123
	2008	8137.7	14380.1	22407

*These stations had only one sample available for analysis
**This station had only four samples available for analysis

Using the sediment rating curve in Figure 3.11, sediment yields were determined for the same period as soil erosion modelling. The two results were then compared to find out the appropriate erosion model for predicting sediment sources in the study area. The comparison was done only for areas between two sediment measurement stations to avoid errors arising from considering sediments emanating from outside the study area. For example, sediment yield difference between Luuq and Bardheere was compared to soil erosion output from the areas between these two stations. The erosion model which gave close prediction to the output from sediment rating-curve was then considered the appropriate model for determining upland sediment sources and soil erosion rates. Areas with high erosion as detected by the chosen model were then earmarked as potential sites for high sediment generation in the study area.

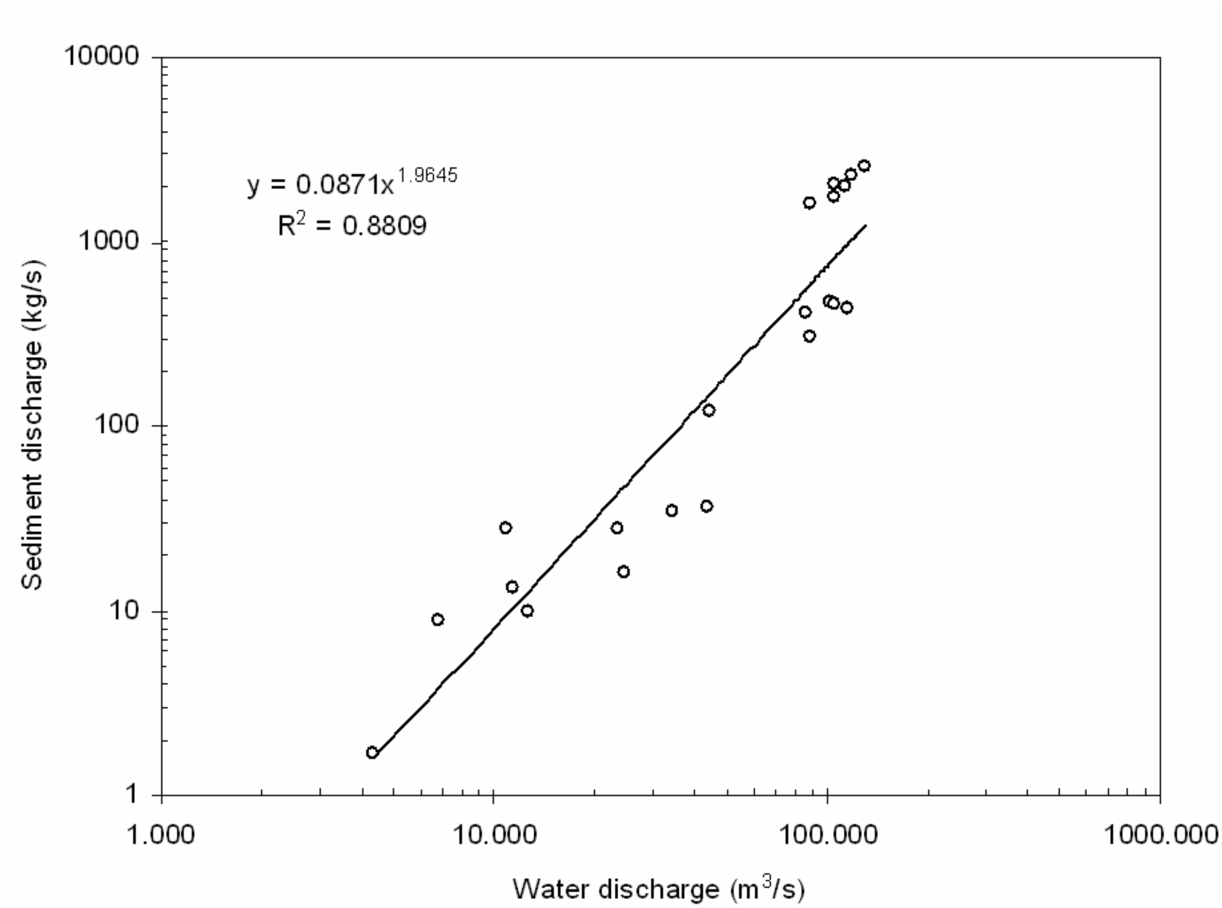


Figure 3.11: Sediment rating curve for river Juba and Shabelle in Somalia

4. RESULTS AND DISCUSSIONS

4.1 Modelling of topsoil loss

Soil loss estimates from the three models showed higher soil loss rate in 2007 than in 2008. On average, the rate of loss of topsoil was predicted at 15.48 ton/ha/year (and standard deviation of 9.11 tons/ha/year) in 2008 and 21.46 tons/ha/year (and standard deviation of 4.7 tons/ha/year) in 2007. Figure 4.1 shows example of spatial distribution of soil loss estimates using MUSLE model for 2007 and 2008.

Although the three soil erosion models tested gave different magnitudes of loss of topsoil, they had nearly the same spatial pattern of loss of topsoil in 2007 and 2008: high soil loss rate in western, north-western, north-eastern parts of the study area and along the coast of Indian Ocean. Soil loss rates from these areas were above 30 tons/ha/year (Figure 4.1).

Table 4.1 shows the soil loss estimates between Luuq and Bardheere and between Belet Weyne and Bulo Burti stations. On average, the three models depicted the areas between Luuq and Bardheere to have had more soil loss than the areas between Belet Weyne and Bulo Burti stations during 2007-2008. This may give an impression of higher sediments into river Juba than into river Shabelle.

Table 4.1: Soil loss estimates between sediment measuring stations

		Soil loss estimates (million tons)		
Between stations	Year	MUSLE	RUSLE	Thornes
Belet Weyne and Bulo Burti	2007	436.1	674.3	515.3
	2008	260.0	157.0	168.4
Total		**696.1**	**831.3**	**683.8**
Luuq and Bardheere	2007	436.6	302.8	451.4
	2008	770.5	536.6	211.3
Total		**1207.1**	**839.3**	**662.8**

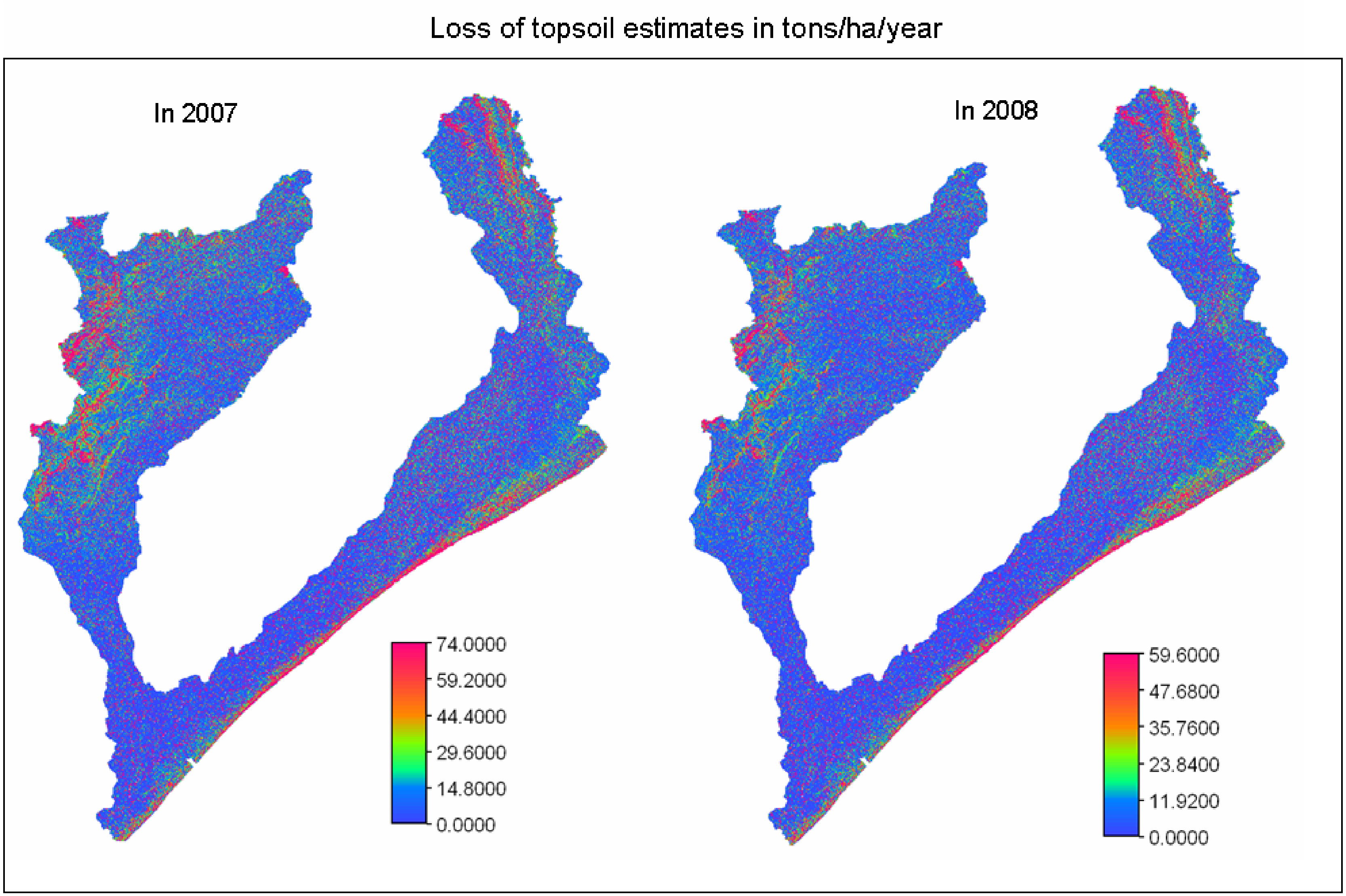


Figure 4.1: Example of MUSLE topsoil loss estimate in 2007 and 2008

4.2 Comparison of modelling and rating curve estimates of sediment yield

Sediment yield from the rating curve was determined every six months from January 2007 to December 2008. In order to try to account for sediment yield within the study area alone, the sediment yield at upstream locations were subtracted from sediment yield at the downstream stations (e.g. sediment yield at Bulo Burti minus sediment yield at Belet Weyne). The outputs were then compared to topsoil loss modelling estimates for the areas between these stations. Table 4.2 shows the results of this comparison.

Table 4.2: Sediment yield from the rating curve compared with modelling

		Estimation method (million tons)			
Between stations	Period	Rating curve	MUSLE	RUSLE	Thornes
Belet Weyne - Bulo Burti	1st half 2007	580.0	256.1	471.2	402.5
	2nd half 2007	211.2	180.0	203.1	112.9
	1st half 2008	182.1	169.8	45.8	101.2
	2nd half 2008	123.8	90.2	111.2	67.2
Luuq - Bardheere	1st half 2007	186.5	44.6	68.0	150.3
	2nd half 2007	534.7	332.1	234.8	301.1
	1st half 2008	951.7	785.5	523.8	118.1
	2nd half 2008	123.7	45.0	12.8	93.2
Sum of Squared Error (SEE)			202166	431780	995277

The sediment yield by rating curve gave higher estimates between Luuq and Bardheere than between Belet Weyne and Bulo Burti. The other three soil loss models also gave similar estimate; thus, corroborating the impression depicted by the rating curve that sediments into river Juba were higher than sediments into river Shabelle. Before concluding that there could be higher sediments into river Juba than Shabelle, a number of possible facts were considered: the area, river flow rate, and topography of the areas between the gauging stations. In terms of areas, the area between Belet Weyne and Bulo Burti was 22% of the area between Luuq and Baardheere; which imply that sediment contributing areas in river Juba was larger than in river Shabelle. In Table 3.1 it was shown that river Juba flow rate was higher than river Shabelle; again indicating that river Juba had potentially more energy to carry more sediment than river Shabelle. In terms of topography, the area between Luuq and Baardheere is flanking to highly eroding plateau and had high content of easily erodable soil material (Figure 3.7). The topography of the area between Belet Weyne and Bulo Burti is mainly rocky ridges on the eastern side of the river with less eroding soil material. These characteristics show that the sediment yield between Luuq and Bardheere should be higher than between Belet Weyne and Bulo Burti. This was in fact confirmed from the sediment yield results (Table 4.2) where the average six-month sediment yield between Belet Weyne and Bulo Burti was 82% of the sediment yield between Luuq and Bardheere.

Comparison of the sediment yield from the rating curve and modelling estimates showed that MUSLE model had the closest estimates to the rating curve outputs (Table 4.2). Figure 4.2 shows the relationship between the estimates from the rating curve and MUSLE outputs. The bold diagonal line in the figure is a 1:1 comparison line (i.e. where the two estimates of sediment yields would ideally fall if they were similar). As it is, sediment yield from the rating curve was higher than sediment yield from erosion modelling. Perhaps this was because erosion modelling did not account for channel erosion and bedload which were already included in the rating curve outputs.

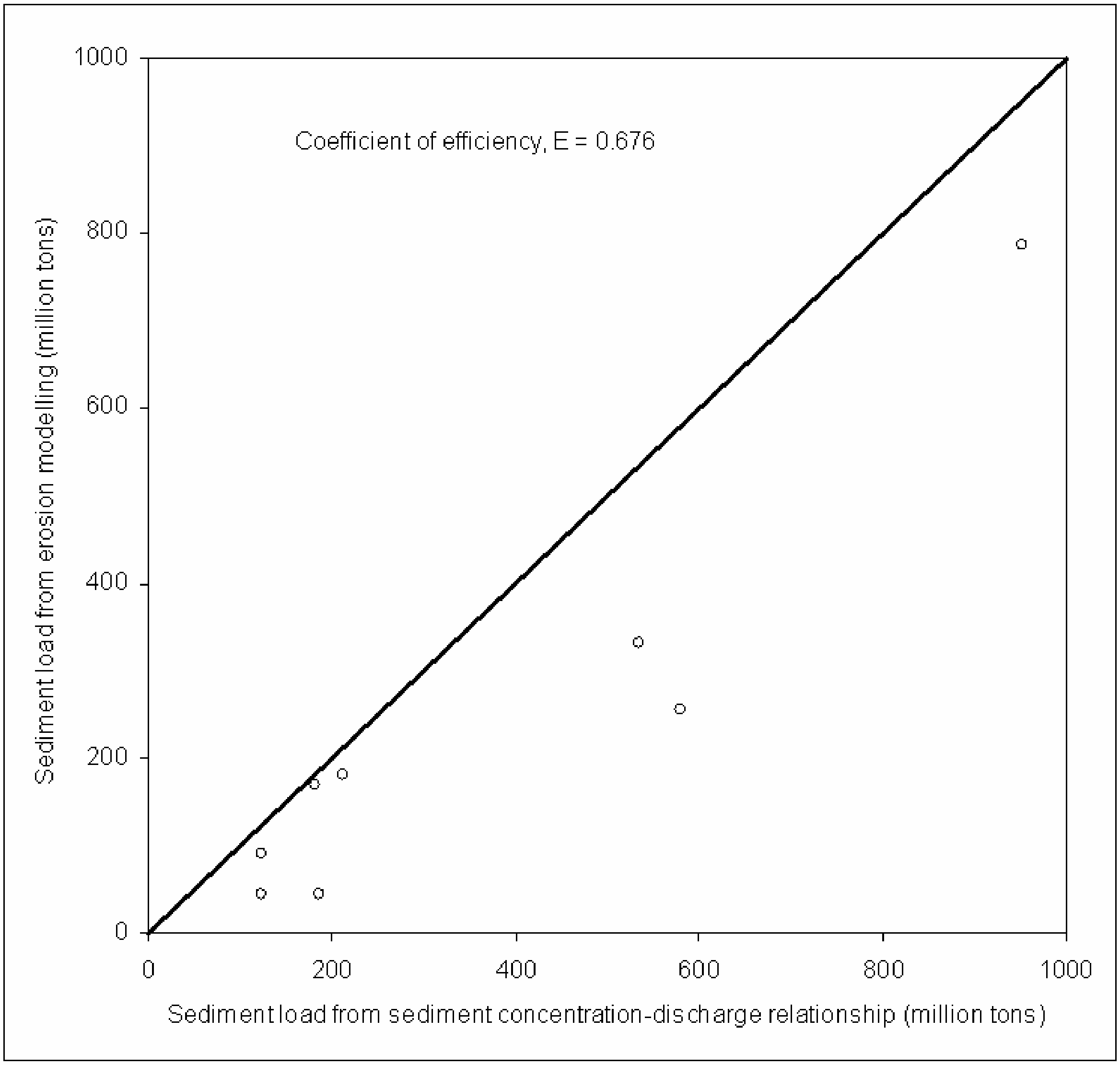


Figure 4.2: Comparison of sediment yield by rating curve and MUSLE model

Although the estimates from the MUSLE model were lower than the estimates from the rating curve, the model consistently predicted sediment yield close to the estimates from the rating curve. Analysis of the agreement between the two outputs using Nash-Sutcliffe coefficient efficiency gave efficiency = 67.6% [16]. Nash-Sutcliffe coefficient efficiency has been used in many studies in the literature to compare modelled and measured sediment yield and river discharge [14, 16]. Coefficient of efficiency of 1 (E=1) corresponds to a perfect match between modelled and observed data. Efficiency of 0 (E=0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty<E<0$) occurs when the observed mean is a better predictor than the model [14]. In the case of sediment yield in rivers Juba and Shabelle, the soil loss modelling by MUSLE can be said to have had fairly close approximation to sediment yield measurements in 2007 and 2008. Hence, MUSLE soil loss estimate could be regarded as a good predictor of sediment yield in the study area.

4.3 X-Ray diffractometry

The results of the XRD on the samples from Belet Weyne (sample number 44, 45, 47 and 49) and Buale (sample number 35 and 37) are shown in Figure 4.3. There was no substantial difference between the analysed samples; which imply that their mineralogic composition was rather the same.

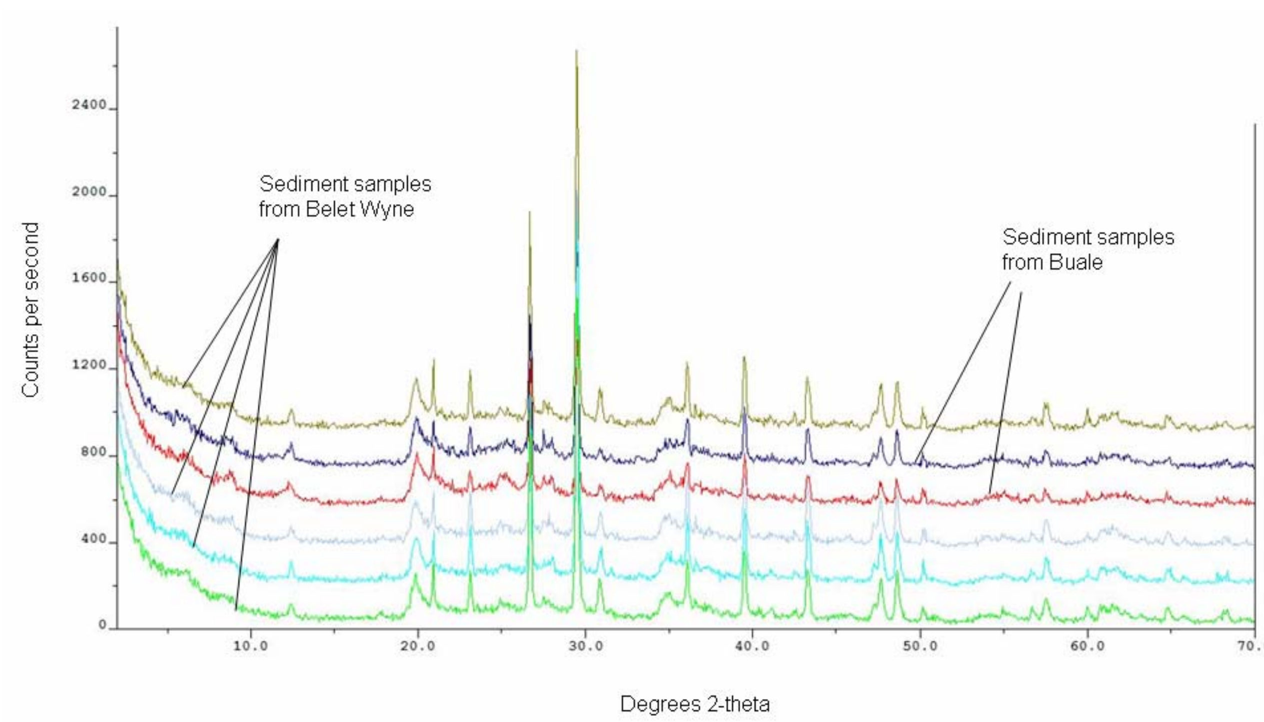


Figure 4.3: spectra of XRD from the samples of Belet Weyne and Buale.

The XRD laboratory report also specified that there was no major difference between the sediment samples analysed. The report also showed that all the sediment samples analysed had residual minerals such as calcite, quartz, and feldspar and neo-formation minerals such as chlorite, kaolinite, smectite, illite. See Appendix 2 for definition of these minerals.

Te XRD results shown in Figure 4.3 were quite uniform since they come from one sample for each river only (due to field inaccessibility). Having one sample at each river means that the suspended sediment contains minerals from most of the rocks outcropping upstream of the sampling point.

In the specific case upstream of the sampling points there are outcrops of sedimentary, volcanic, and metamorphic rocks as shown in Figure 4.4

The two watershed share the same type of rocks over their entire basins. The main distinction is made from the upper (Ethiopia) to the middle/lower (Ethiopia and Somalia) parts of the basins. In the upper portion of the catchments the outcropping rocks are mainly volcanic and metamorphic: Basalts, Rhyolite, Trachyte, Gneiss, Granulite, Migmatite (purple colour in figure 4.4) of very old age (Paleozoic) and some few sedimentary ones (Cenozoic): mainly Sandstone (white colour in figure 4.4). In the middle part of the catchments sedimentary rocks are predominant: gypsiferous rocks (pale yellow colour in figure 4.4) together with Limestones and Sandstones (white colour). In the lower part of the catchments the main rocks outcropping are still sedimentary with scattered volcanic and metamorphic (the latter mainly in the Bur region of Bay and Bakool regions): Limestone, Sandstone, Gypsum, Marls (white colours), and some scattered Basalts (purple colour in figure 4.4).

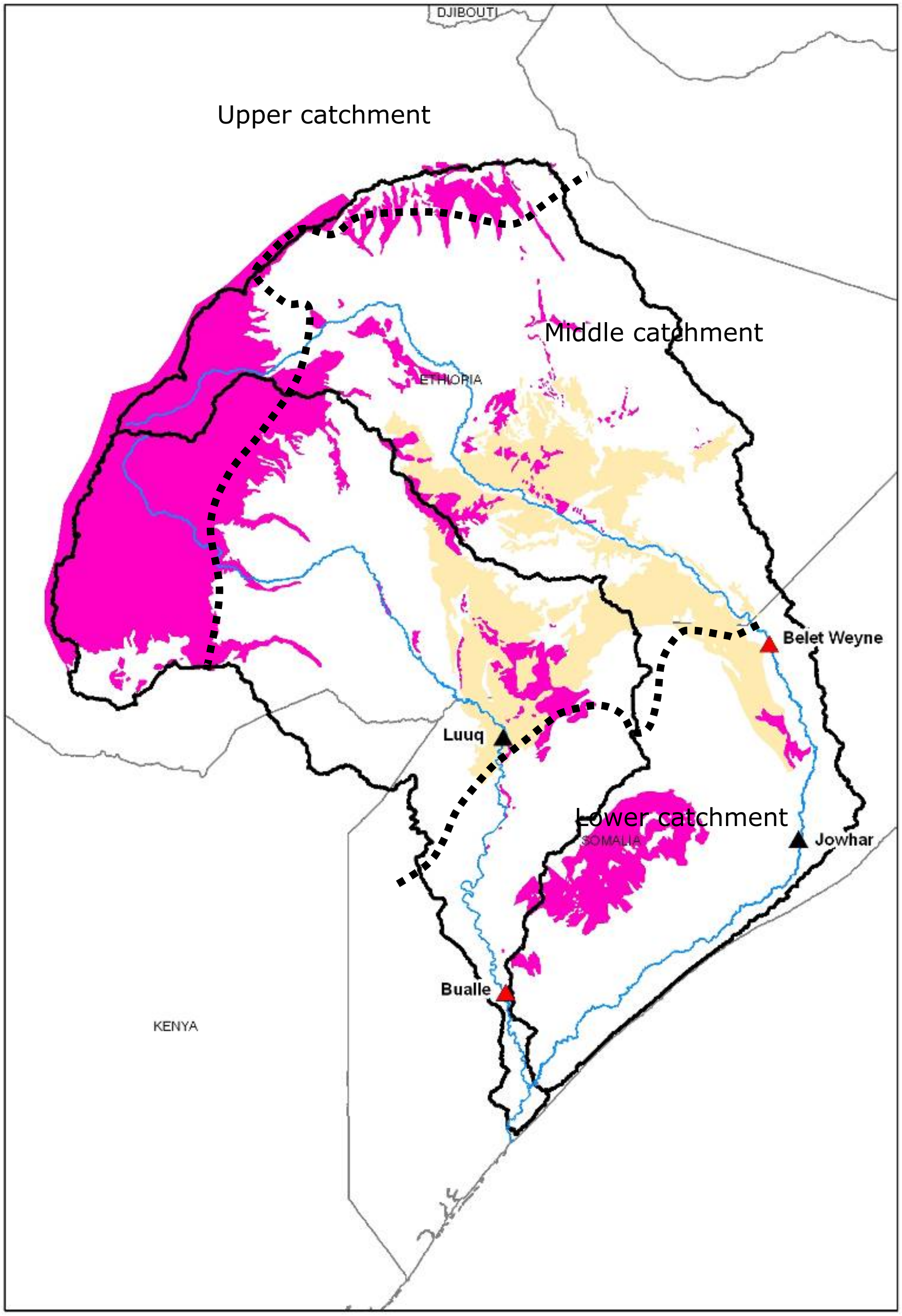


Figure 4.4: Simplified geologic map of the Juba and Shabelle watershed.

In purple are volcanic and metamorphic rocks like basalts, trachytes, granites; in pale yellow are sedimentary rocks rich in gypsum; in white are sedimentary rocks like limestone, sandstone, and recent alluvial deposits. The dotted lines delineate the upper, middle and lower parts of the catchment based on the outcropping rocks analysed samples were few and were collected during low river flows. It was therefore unlikely that they could show major differences with respect to potential geologic composition of upland areas. However, the XRD results carry some potential for scientifically objective method for determining sediments sources in a watershed. It is anticipated that in future more samples will be taken and detailed XRD analysis done for comprehensive identification of sediment sources in the study area.

4.4 Potential sites for monitoring sediments

The potential sources of sediments into river Juba and Shabelle were identified from the MUSLE modelling of upland topsoil loss. Figure 4.5 shows areas which were consistently modelled by MUSLE as having high topsoil loss rates (> 30 tons/ha/year). They were therefore considered as potential sites contributing to high sedimentation of rivers Juba and Shabelle.

Majority of the areas identified with high rate of topsoil loss (Figure 4.5) were also found to belong to areas with low vegetation cover where transhumance pastoralism/wood collection was the dominant type of land use [18]. It was therefore possible to posit that overgrazing and deforestation were the major contributors to high sediment yield from these areas. Along the coastline, sand dunes, pastoralism, and negative effects of urbanization were the dominant land use types in areas with high rates of topsoil loss. Again, the major contributors of high sediment yield from these areas could have been transhumance pastoralism, urban centres, and prevalent sand dunes.

If a quantitative analysis of land cover and land use change over time (at least the last 10 years) would be available then more detailed considerations about the links between land use/cover and soil erosion could be established.

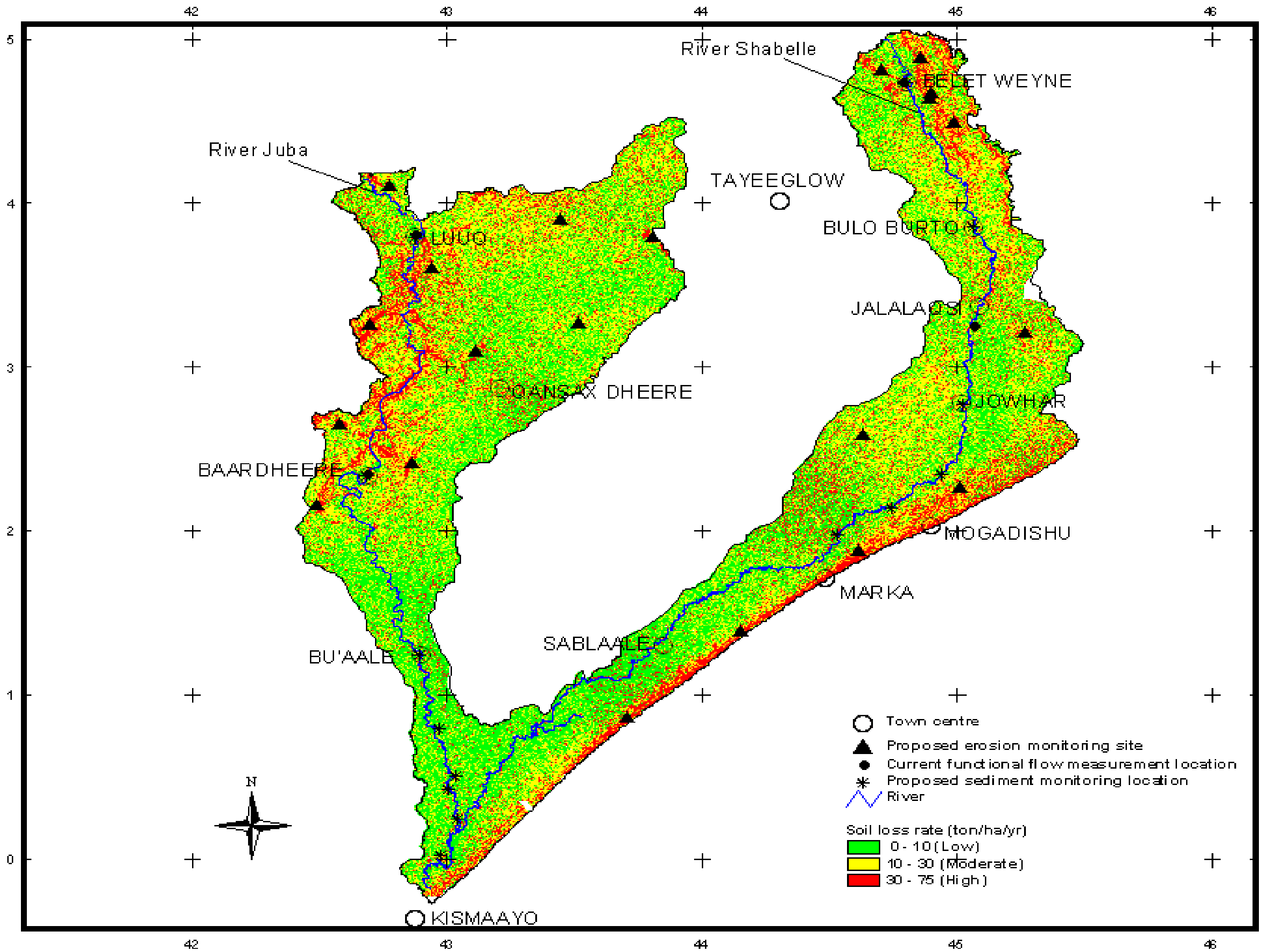


Figure 4.5: Potential sediments sources and monitoring sites in the study area

Further analysis of the landscape near the coastline showed that majority of the areas slope towards the Ocean. Majority of their potential soil lost during erosion could therefore be deposited into the Indian Ocean instead of going into river Shabelle (Figure 4.6). However, to avoid possible doubts and errors of omission, four locations in these areas were also proposed for future monitoring of soil erosion (Figure 4.5).

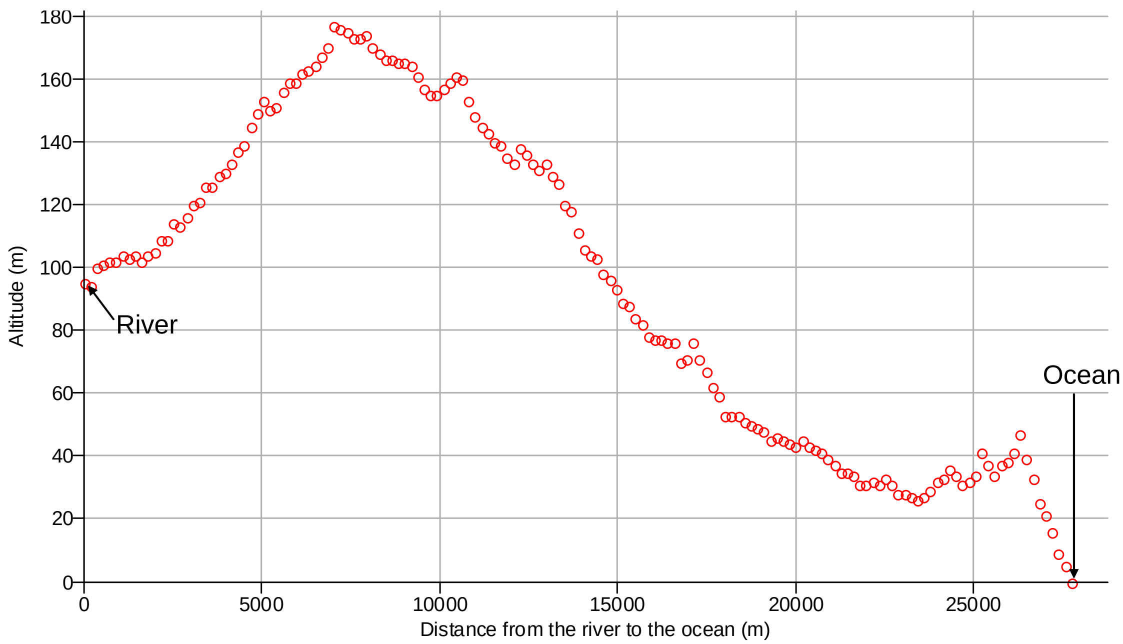


Figure 4.6: Landscape cross-section from river Shabelle to the Indian Ocean near Mogadishu

5. RECOMMENDATIONS FOR MONITORING EROSION AND SEDIMENTATION IN SOUTH SOMALIA

5.1 Theoretical framework for monitoring soil erosion and sedimentation

This study generated some baseline information in 2009 which will form the basis for future monitoring of soil erosion and sedimentation of rivers Juba and Shabelle in south Somalia. Future soil erosion and sedimentation monitoring activities in the study area is recommended to be done through continuous measurement/sampling of soil loss rates (and modelling) in the field and river gauging for sediment samples and river flow rates. These sampling and measurements should be repeated from between daily (for river flow measurements) to seasonally (for sediments sampling) and to six months for soil erosion rates. Figure 5.1 gives a guideline of how these sampling and measurements should link up together to give the general trend of soil erosion and sedimentation in the study area.

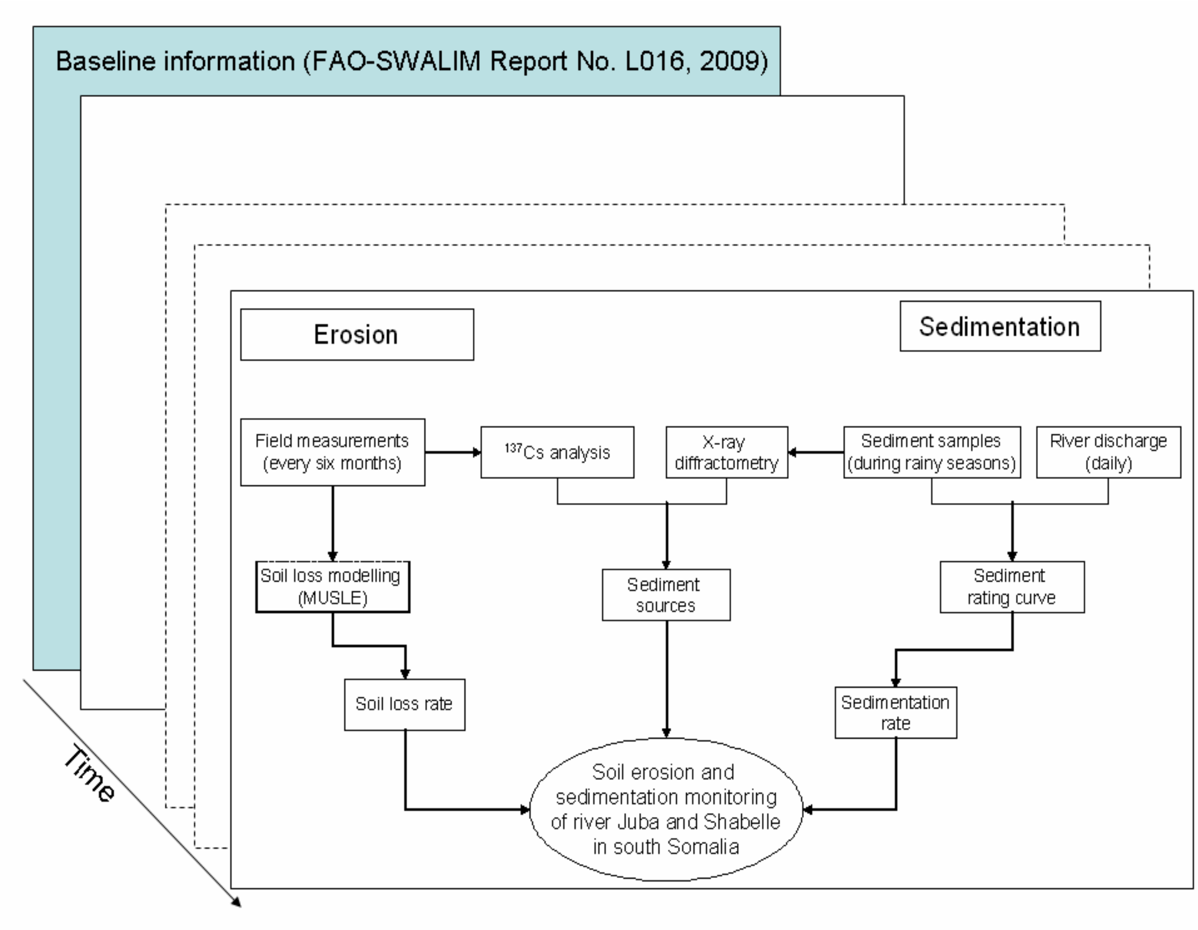


Figure 5.1: Theoretical framework for soil erosion and sedimentation monitoring in south Somalia

5.1.1 Monitoring soil erosion

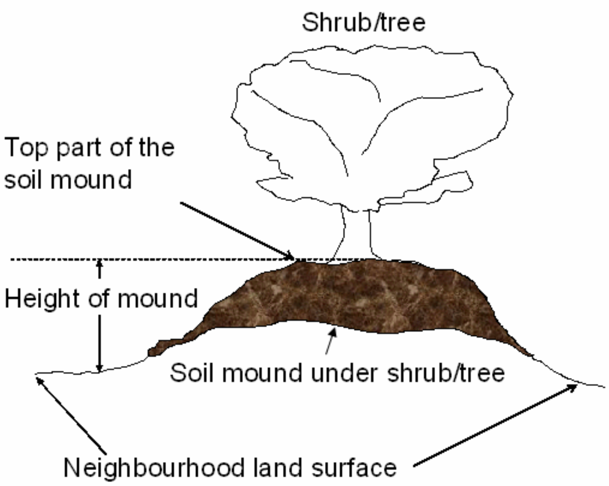
Monitoring of soil erosion is recommended to be done for two reasons: for estimating upland soil erosion rates and sediment sources (Figure 5.1). One of the recommended ways for monitoring soil erosion rates is through the use of Stocking and Murnaghan method [25]. An example of this method is shown in Figure 5.2; where soil erosion rates is determined as the difference between soil protected by trees/shrubs (known as shrub-mound) and the soil in the neighbourhood of the tree/shrub which had been subjected to soil erosion (Figure 5.2). In order to reduce errors in measuring the height of the mound, three replicate measurements is recommended for every tree/shrub and about 19 tree/shrubs sampled in an area (Figure 5.2). Furthermore, it may be necessary to establish a stable reference top-level of the mound for each tree/shrub (e.g. using steel rods/wooden bars) to take care of potential changes on the reference level of the top part of the mound over time.

The determination of rate of soil loss from periodic monitoring can then achieved by dividing the difference of soil loss amounts (obtained from figure 5.2) by time difference between two consecutive measurements. Equation (2) also illustrates how this can be done.

$$Soilloss(ton/ha/yr) = \frac{(soilloss_{i+1} - soilloss_i)ton/ha}{(Time_{i+1} - Time_i)yr} \qquad (2)$$

where $Time_i$ is the time count for field measurements.

Soil erosion measurement using the shrub-mound method



Sample	Height of the mound (mm)				
Trials	Trial1	Trial2	Trial3	Total	Average
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
			Total		
Average		Total/19 =			
Age of the shrub (yrs)					
Bulk density (g/cm³)					

Soilloss (ton/ha/yr)	=	Average height of mound (mm)	X	Bulk density (g/cm³)	X	10	/	Age of shrub (yr)
	=		X		X	10	/	

Figure 5.2: Field-measurement method for monitoring soil erosion

As a starting point, soil erosion monitoring sites identified in Figure 4.4 should be used and measurements of soil erosion rates repeated after every six months. The procedure in Figure 5.2 and other methods by Stocking and Murnaghan [25] and FAO-SWALIM Report No. L01 can be used where appropriate.

Once the soil loss rates shall have been determined, a new MUSLE output should be computed to determine the spatial extent of soil erosion in the study area. The total sum of these steps will be to determine new potential soil erosion sites (Figure 5.3). The whole process should then be repeated to provide adequate monitoring of soil erosion in the study area.

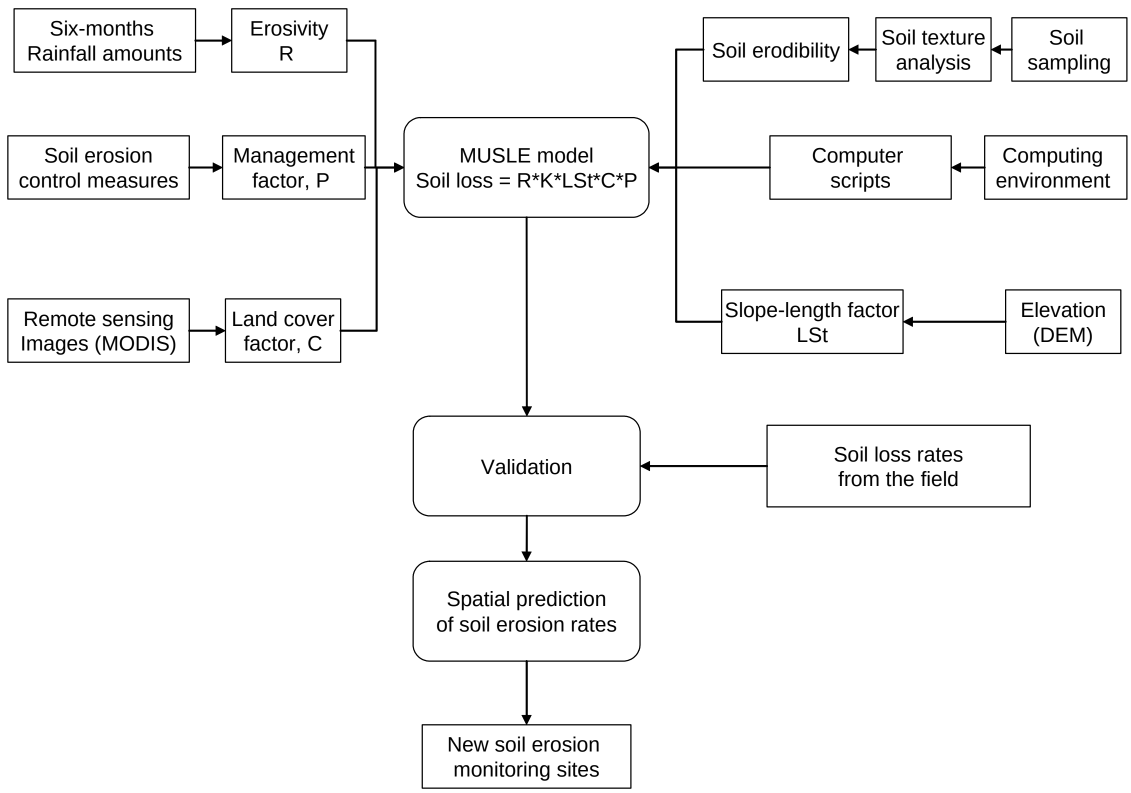


Figure 5.3: Framework for spatial monitoring of soil erosion

5.1.2 Monitoring sediment sources

In addition to monitoring soil erosion rates, monitoring of sediment sources is also recommended in this study. The monitoring framework should entail the use of X-ray diffractometry and Caesium-137 (^{137}Cs) analysis (Figure 5.1). Caesium-137 radionuclide analysis will help in fingerprinting sediment sources by radionuclide counting of ^{137}Cs on soil samples from upland areas and on sediment samples from the two rivers. The technique is based on the fact that during the 1950s to 1970's global fallout after worldwide atomic experiments, some ^{137}Cs accumulated on the soil as they fell from the atmosphere. By radionuclide counting of ^{137}Cs on soil samples from upland areas and on sediment samples from the river, it is possible to link the radionuclide counts on the two samples and potentially identify sediment samples of with their areas of origin in the study area. Walling [32] has described detailed soil sampling methods for ^{137}Cs analysis.

Similarly, XRD may also be done on sediment samples to augment the results from ^{137}Cs analysis. XRD analysis can detect sediment samples from a wider region compared to ^{137}Cs since it relates the minerals in the sediments samples to rock materials in the wider river basin. Co-analysis of sediment samples by XRD and ^{137}Cs is recommended since the same sediment samples can be used for both methods; hence there will be no need for separate sampling for XRD tests. In addition, collaboration between FAO-SWALIM and institutions in Europe with specialized laboratories for XRD and ^{137}Cs is currently underway and is anticipated to benefit sediment analysis by these two methods.

In order to support XRD and ^{137}Cs analyses, sampling for sediment sources is recommended to be done in two ways: soil sample collection from upland areas and sediment sampling of the river bed/floodplain. Soil sample collection from the upland areas will entail auguring of samples from the already identified locations in Figure 4.4. Figure 5.4 shows how soil auguring and sample-collection should be carried out at each sampling location.

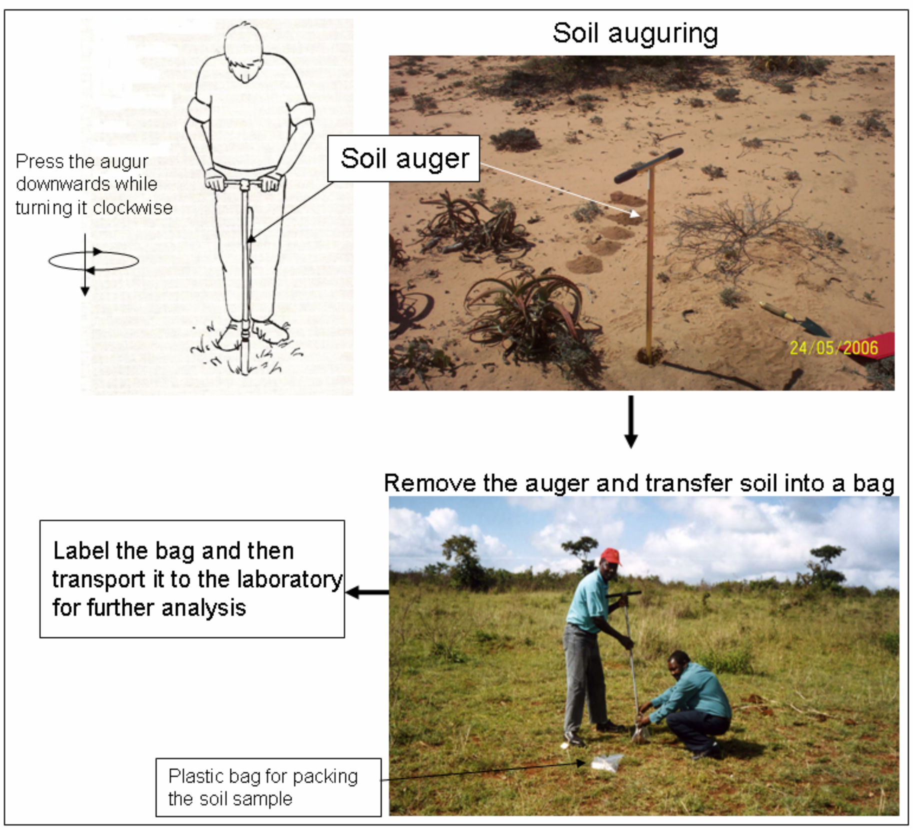


Figure 5.4: Soil-sample collection from the field

Sediment sampling of the river bed/floodplain will involve coring of floodplain and/or river bed up to almost 1 m of depth and collecting samples of at least 50 g every 1 or 2 cm (depending on the rate of accretion). Soil augurs such as shown in Figure 5.4 can also be used for sediment coring. An estimate of the bulk density of the sediment should also be done in the field in order to calculate the soil volume needed to reach 50 g sample. Once the samples are collected, they will be transported to specialized laboratories for XRD and ^{137}Cs analysis.

5.1.3 Monitoring suspended sediment discharge

Due to cost of analysis for sampling and processing suspended sediment samples, targeted sampling is recommended. The proposed locations chosen for suspended sediment sampling in Figure 4.4 were those which coincided with locations for river flow measurements. However, some of the river flow measurement locations have been non-operational (see Figure 5.5) but are currently under consideration for rehabilitation by FAO-SWALIM. It is recommended that the sediment samples from these stations be taken and analysed alongside samples from the other operational stations once the rehabilitation of non-operational gauging stations shall have been completed. This will improve the sediment rating curve developed during this study.

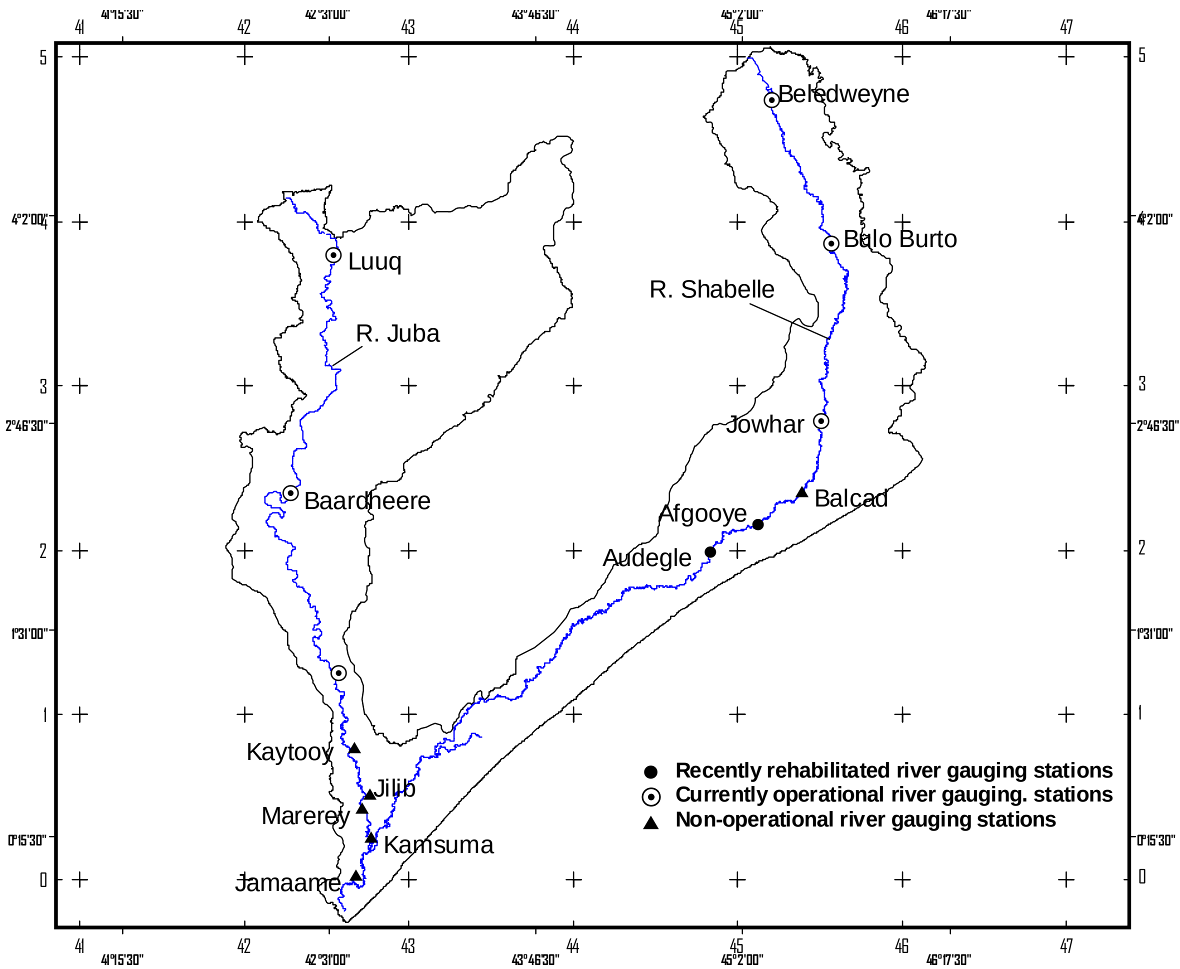


Figure 5.5: River gauging stations in the study area

Periodic sediment sampling is recommended from these stations to cover hydrologic periods of low or high river flow (Figure 5.6). The collected sediment samples will then be sent to the laboratory for analysis of sediment concentration. The process should be taken periodically to monitor any changes in sediment flux in the two rivers. If the cost of sediment analysis is to be minimized, alternatively different sediment rating curves corresponding to different hydrologic times are recommended. Use of different rating curves is recommended to minimise hysteresis-effect which is common in lumped data of mixed flow regimes (Figure 5.6). The rating curves should be developed using the procedure described in this report.

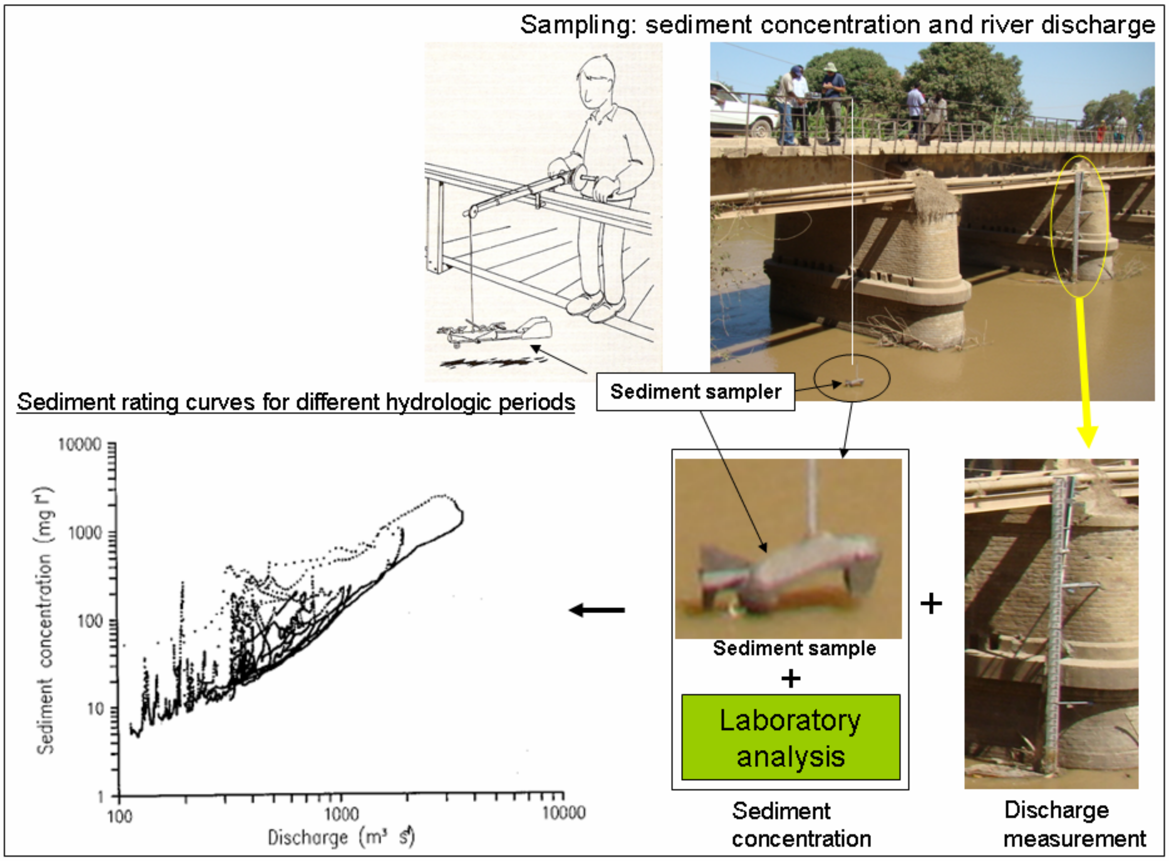


Figure 5.6: Field sampling for periodic monitoring of sediment flux

5.2 Practical steps towards monitoring soil erosion and sedimentation in south Somalia

In order to implement the above theoretical monitoring framework for soil erosion and sedimentation in south Somalia, the following practical steps in Table 5.1 have been suggested. The general assumption for their implementation is that there will be improved security and a central government in south Somalia in future. In addition to the practical steps, the requirements suggested in Table 5.2 will also be necessary. Requirements for scripts for computer models should be overcome through the use of those already developed during this study. They are available at FAO-SWALIM.

Table 5.1: Practical steps towards monitoring soil erosion and sedimentation in south Somalia

Step	Activity	Objective	Time	Institutions
1	Setting up baseline information Preliminary assessment of soil erosion and sedimentation rates	To identify potential sites for monitoring erosion and sedimentation To identify methods for monitoring soil erosion and sediment discharge	2009	FAO-SWALIM
2	Validating identified methods and preliminary assessment results	To improve monitoring methods for soil erosion and sedimentation To establish reference points for monitoring soil erosion using FAO-SWALIM Report No. L01 and Figure 5.2	2010	FAO-SWALIM and Government of Somalia
3	Training field assistants in monitoring soil erosion and sedimentation	To build capacity of staff from the government of Somalia in soil erosion and sedimentation monitoring	2010	FAO-SWALIM and Government of Somalia
4	Carrying out a first monitoring exercise	To begin monitoring of soil erosion and sedimentation	2010	FAO-SWALIM and Government of Somalia
5	Repeat monitoring exercise as indicated in Figure 5.1	To establish a soil erosion and sedimentation monitoring framework for south Somalia	2011	Government of Somalia

Table 5.2: Potential requirements for implementing soil erosion and sedimentation monitoring framework

Activity	Variable to monitor	Requirements		
		Field	Laboratory	Computer models
Soil erosion	Soil erosion rate	Tape-measure, transparent ruler, recording materials		
	Sediment sources	Soil auger, plastic bags, recording materials, rainfall amounts, land cover characteristics, land use	Soil texture analysis	MUSLE model
Sedimentation	Sediment flux	Sediment sampler and river gauge	Sediment concentration	Sediment rating curve
	Sediment sources	Soil auger, plastic bags, recording materials	Radionuclide analysis	
			XRD analysis	

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Potential sources of sediments

This study showed that river Juba which has higher discharge than Shabelle is potentially carrying more sediments than river Shabelle. The sediment load into river Juba in 2007 and 2008 was found to be about four times the sediment load in river Shabelle in the same period. Some of this sediment load was found to originate from the upland areas of the riverine areas of river Juba and Shabelle in south Somalia. Analysis of potential soil erosion rates in the upland areas showed that annual loss of topsoil in 2007 and 2008 was about 18 ton/ha. The major land use types driving this rate of topsoil loss are livestock grazing, fuelwoood collection, and negative effects of expansion of urban centres. These land use characteristics should be further investigated and targeted for proper management to reduce the high soil erosion rates in the study area.

6.1.2 Techniques and opportunities for monitoring sediments yields

Field measurement, modelling of soil erosion, and targeted sediment sampling of river Juba and Shabelle were found in this study to be able to provide reliable estimation of soil erosion and sedimentation rates. Their continuous measurement is one way for monitoring soil erosion and sedimentation of the two rivers in south Somalia. In addition to modelling and measurements, XRD and ^{137}Cs radio-isotope analysis are also potential indicators for identifying upland sediment sources. Their analyses are potentially possible especially with the collaboration and support FAO-SWALIM can get from the specialized laboratories in Europe who normally do such analyses.

6.2 Recommendations

The following recommendations have been proposed as a way-forward for implementing successful monitoring of soil erosion and sedimentation of river Juba and Shabelle:

1. To carry out field validation of erosion modelling baseline generated during this study. This should be done as soon as the security situation improves in south Somalia.
2. To establish soil erosion monitoring reference sites and develop geodetic survey protocol for insuring accuracy in measuring soil erosion rates.
3. Strengthening of the agreement and collaboration between FAO-SWALIM and the government of Somalia and Ethiopia to support soil erosion and sediment sampling of the greater river Juba and Shabelle watershed.
4. Rehabilitation of non-operational river gauging stations and incorporation of sediment sampling alongside river flow measurements.
5. Establishment of routine and structured sample recording and processing steps for sediment and soil samples for future laboratory analysis. A login form is important for samples from the field to detail sample characteristics (e.g. sampling date, georeference, etc).
6. Capacity building for the staff members of the relevant government ministries in Somalia and Ethiopia with respect to soil erosion and sedimentation monitoring of river Juba and Shabelle.
7. Follow up on ^{137}Cs isotope and XRD analysis of more samples from the study area and strengthening of collaboration between FAO-SWALIM, Somalia government and institutions in Europe who are specialized in ^{137}Cs and XRD analysis of sediment samples.
8. More future support for continuation and implementation of soil erosion and sedimentation monitoring within river Juba and Shabelle in Somalia and Ethiopia.
9. Implementation of the proposed monitoring framework proposed in this study.

Although all the above mentioned steps will be needed to put in place a thorough scientific monitoring of soil erosion and sedimentation, some urgent measures to prevent or reduce soil erosion should be adopted as soon as possible. This will prevent further loss of fertile topsoil and increase soil productivity especially in agricultural areas of the lower part of the river catchments.

Furthermore the not regulated tree cutting activity for charcoal production increases the loss of top soil.

For this reason simple and cheap measure of soil conservation should be adopted with immediate effect at least in the agricultural areas. For instance, on a short term, properly designed soil bunds (soil and/or rock bunds) -in both the higher sloping rainfed crop areas of Bay and Bakool regions and the low sloping irrigated areas along the floodplains- should be created to allow accumulation of colluvium and reduction of the erosive power of running waters. On a medium term, intervention for mitigating the floods should be considered, in order to reduce the erosive power of flooding waters over the prevalent clay soils of the study area. On a longer term, and after adequate field assessment, the practice of agroforestry could be introduced in the irrigated areas of the floodplains. In addition to this, in the few mechanized farms of Lower and Middle Shabelle and along the Juba, contour stripping cropping should be adopted to slow down the formation of straight runoff lines.

All the above mentioned counter measures, although probably not the most durable in the long term, are efficient in the short terms, relatively cheap to put in practice and culturally accepted and used in the Somali context as demonstrated by their successful practice in other regions.

A proper flood control management and the rehabilitation of the canal system will also allow for a better management of the moisture in the soil and of its drainage, during both flood times and normal flows.

REFERENCES

1. Alim, A.S. 1997. Inventory report for Somalia. GCP/RAF/287/ITA Internal Report No.1. FAO

2. Alonso, C.V., Bingner, R.L. and Kuhnle, R.A. 1995. Sediment yield from watersheds with eroding channels. In: W.H. Espey and P.G. Combs (Editors), Water Resources Engineering: Proceedings of the First International Conference. American Society of Civil Engineers, pp. 1183-1187

3. Carbone, F. and Accordi, G. 2000. The Indian Ocean coast of Somalia. *Marine Pollution Bulletin* **41**:141-59. (Univ La Sapienza, CNR, Ctr Studio Quaternario and Evoluz Ambientale, Dipartimento Sci Terra, P Aldo Moro, 5I-00185 Rome, Italy

4. Collins, A.L. and Walling, D.E. 2002. Selecting fingerprint properties for discriminating potential suspended sediment sources in river basins. J. of Hydrology, 261(1-4): 218-244

5. Collins, A.L. and Walling, D.E. 2004. Documenting catchment suspended sediment sources: problems, approaches and prospects. Progress in Physical Geography, 28(2): 159-196

6. Collins, A.L., Walling, D.E., Sichingabula, H.M. and Leeks, G.J.L. 2001. Using 137 Cs measurements to quantify soil erosion and redistribution rates for areas under different land use in the Upper Kaleya River Basin, Southern Zambia. Geoderma, 104: 299-323.

7. Foster, G.R., 1982. Modelling the erosion processes. In: C.T. Haan (Editor), Hydrologic Modelling of Small Watersheds. ASAE Monograph, pp. 297-380.

8. GTZ, 1990. Master plan for Juba Valley Development. Main Report. Somali Democratic Republic

9. Hamin, R.S. and Doe, W.W. 2001. Landscape Erosion and Evolution Modelling. Kluwer Academic / Plenum Publishers, New York, USA, 540 pp

10. Lu, X. and Higgitt, D.L. 2001. Sediment delivery to the Three Gorges. 2: local response. Geomorphology, 41: 157-169.

11. McDonald and Partners in collaboration with Institute of Hydrology. 1991. Hydrometry Project – Somalia. Final Report, Phase 3.

12. Monaci, L., Downie, M. And Oduori, S. 2007. Land Cover of Selected Study Areas in Somaliland and Southern Somalia. FAO-SWALIM. Project Report No L-03. , Nairobi, Kenya.

13. Morgan, R.P.C. 1986. Soil Erosion and Conservation. Longman Scientific & Technical: Hong Kong

14. Moriasi, D. N. 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Transactions of the ASABE, 50(3): 885–900.

15. FAO-SWALIM Technical Report No W-01: Muchiri, P.W. 2007. Climate of Somalia. Nairobi, Kenya.

16. Nash, J. E. and Sutcliffe, J. V. 1970. River flow forecasting through conceptual models part I — A discussion of principles. Journal of Hydrology, 10 (3): 282–290.

17. Nichols, M.H. and Renard, K.G. 1999. Sediment yield from semi-arid watersheds, Agricultural Research Service, Southwest Watershed Research Center, Tucson, USA

18. FAO-SWALIM Technical Report No L-07: Oduori, S.M., Vargas, R.R. and Alim, M.S. 2007. Land use characterization of the Juba and Shabelle riverine areas in Southern Somalia. Nairobi, Kenya

19. Omuto, C.T. and Vargas, R.R. 2009. Combining pedometrics, remote sensing and field observations for assessing soil loss in challenging drylands: a case study of North-western Somalia. Land Degradation and Development **20**: 101-115.

20. Poesen, J., Nachtergaele, J., Verstraeten, G. and Valentin, C., 2003. Gully erosion and environmental change: Importance and research needs. Catena, 50: 91-113

21. Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K. and Yoder, D.C. 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE). USDA Agricultural Handbook 703

22. Saavedra, C. 2005. Estimating spatial patterns of soil erosion and deposition in the Andean region using geo-information techniques. A case study in Cochabamba, Bolivia. PhD Thesis, ITC, Enschede

23. Soil Conservation Service (SCS), 1972. U.S.D.A., National Engineering Handbook, Section 4: Hydrology. Washington DC.

24. Springer, G.S., Dowdy, H.S. and Eaton, L.S. 2001. Sediment budgets for two mountainous basins affected by a catastrophic storm: Blue Ridge Mountains, Virginia. Geomorphology, 37: 135-148

25. Stocking, M. and Murnaghan, N. 2001. Land degradation-Guidelines for field assessment. University of East Anglia. Norwich, UK

26. Thornes, J. B. 1985. The ecology of erosion. Geography, 70, 222–234.

27. Thornes, J.B. 1990. Vegetation and Erosion: Processes and Environments. Wiley, Chichester, London, UK

28. Torri, D., Poessen, J. and Borselli, L. 1997. Predictability and uncertainty of the soil erodibility factor using global dataset. Catena 31: 1–22.

29. FAO-SWALIM Technical Report No L-08: Vargas, R.R., Omuto, C.T. and Alim, M.S. 2007. Soil survey of the Juba and Shabelle riverine areas in Southern Somalia. Nairobi, Kenya

30. Walling, D.E. 2005. Tracing suspended sediments sources in catchments and river system. Science of the Total Environment, 344: 159-184

31. Walling, D.E. and Collins, A.L. 2000. Integrated Assessment of Catchment Sediment Budgets: A Technical Manual. University of Exeter: Exeter, UK;

32. Williams, J.R. 1975. Sediment routing for agricultural watersheds. Water Resources Bulletin 11(5): 965–974.

33. Wischmeier, W.H. and Smith, D.D. 1978. Predicting Rainfall Erosion Losses—A Guide to Conservation Planning. USDA Agriculture Handbook No. 537

34. Zhang, X., Drake, N. A., Wainwright, J. and Mulligan, M. 1999. Comparison of slope estimates from low resolution DEMs: scaling issues and a fractal method for their solution. Earth Surface Processes and Landforms, 24, 763–779

APPENDICES

Appendix 1: Input data preparation for soil erosion modelling

The input data for modelling soil erosion using the above four models were: soil texture, daily and monthly rainfall amounts, 16-day NDVI images, DEM, and land use map. The rainfall data and soil properties were extrapolated to the whole study area using regression kriging. Altitude, distance from the ocean, and landscape slope were used as predictors during the regression kriging application [19].

The above inputs were then used to estimate erosivity, erodibility, land cover, land management, and topography, which are factors for modelling soil erosion. Erosivity is the ability of rainfall or runoff to erode topsoil. It was estimated in two ways: from rainfall amounts and from overland flow. The estimates were done between January and June and between June and December for 2007 and 2008. For estimates from rainfall amounts, the following model was used [19]:

$$Erosivity = 0.029\left(3.96\left[\sum_{i=1}^{6} P_i\right] + 3122\right) - 26 \qquad (1)$$

where *P* is the monthly rainfall amounts. Erosivity estimation from overland flow was done using SCS curve number method [23]. In this method, the following steps were used: determination of runoff curve numbers, determination of potential retention, determination of runoff, determination of peak runoff rate, and determination of erosivity. Determination of runoff curve numbers (CN) was done using soil texture and land use/cover maps and the guidelines in Table A.1. The soil hydrologic groups were: A - Well-drained sand and gravel with high permeability, B -Moderate to well-drained; moderately fine to moderately coarse texture with moderate permeability, C- Poor to moderately well-drained; moderately fine to fine texture with slow permeability, and D -Poorly drained, clay soils with high swelling potential, permanent high water table, clay pan, or shallow soils over nearly impervious layer.

Table A.1: Guidelines for determining runoff curve numbers

Description of Land Use	Hydrologic Soil Group			
	A	B	C	D
Paved parking lots, roofs, driveways	98	98	98	98
Streets and Roads:				
Paved with curbs and storm sewers	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89
Cultivated (Agricultural Crop) Land*:				
Without conservation treatment (no terraces)	72	81	88	91
With conservation treatment (terraces, contours)	62	71	78	81
Pasture or Range Land:				
Poor (<50% ground cover or heavily grazed)	68	79	86	89
Good (50-75% ground cover; not heavily grazed)	39	61	74	80
Meadow (grass, no grazing, mowed for hay)	30	58	71	78
Brush (good, >75% ground cover)	30	48	65	73
Woods and Forests:				
Poor (small trees/brush destroyed by over-grazing or burning)	45	66	77	83
Fair (grazing but not burned; some brush)	36	60	73	79
Good (no grazing; brush covers ground)	30	55	70	77
Open Spaces (lawns, parks, golf courses, cemeteries, etc.):				
Fair (grass covers 50-75% of area)	49	69	79	84
Good (grass covers >75% of area)	39	61	74	80
Commercial and Business Districts (85% impervious)	89	92	94	95
Industrial Districts (72% impervious)	81	88	91	93
Residential Areas:				
1/8 Acre lots, about 65% impervious	77	85	90	92
1/4 Acre lots, about 38% impervious	61	75	83	87
1/2 Acre lots, about 25% impervious	54	70	80	85
1 Acre lots, about 20% impervious	51	68	79	84

Potential retention (S) was determined using CN as follows:

$$S = 254\left(\frac{100}{CN} - 1\right) \quad (2)$$

For example, around Marka town in the South of the study area, the land cover is less than 50% on clay soil of poor drainage (hydrologic soil group D). Hence, the CN = 89. Its potential retention using Equation (2) is 31.4.

Runoff amount was determined from the SCS equation as follows [23]:

$$Runoff_i = \begin{cases} \frac{(P - I_a)^2}{(P + 0.8S)} & P > I_a \\ 0 & P < I_a \end{cases} \quad (3)$$

where I_a = 20% of retention potential S in Equation (2) and P is the daily rainfall amount. In order to use the monthly rainfall data for the six-month duration, the runoff estimate was summed for the six-month period using an exponential relationship as shown in Equation (4), (5), (6), and (7) [34].

$$A_i = \left(n/m\right)\exp[m_i/m] \quad (4)$$

$$m_i = 0.2S + \Delta m \quad (5)$$

$$\Delta m = m_{\max} - 0.2S \quad (6)$$

$$Runoff = \sum_{i=1}^{6} runoff_i * \Delta m * A_i \quad (7)$$

where A is the rain-day frequency density, n is the number of rain days in the six-month period, m_{max} is the maximum daily rainfall amount in the six-month duration, and m_i is the mean rainfall amount per day (intensity in amount/day). Erosivity from the above runoff was then determined using Equation (8) and (9).

$$Erosivity = 11.8 * (runoff * Q_p)^{0.56} \tag{8}$$

$$Q_p = 3.97 * pixel^{0.7} * (pixel\_length)^{0.16} * \left(\frac{runoff}{25.4}\right)^{0.903 * pixel^{0.017}} \tag{9}$$

where *pixel* is the area of the pixels in km^2 and *pixel_length* is the length of the pixel along the slope (m/km).

Soil erodibility was determined from soil texture as follows:

$$Erodibility = 0.0035 + 0.00388 * \exp\left[-0.5 * \frac{(\log D_g + 1.519)^2}{0.57517}\right] \tag{10}$$

where D_g is mean soil particle diameter and which is estimated by Equation (11) [28].

$$D_g = \exp\left[\sum_i 0.01 * f_i * \ln\sqrt{d_{i1} d_{i2}}\right] \tag{11}$$

where f_i is the particle fraction in percent, d_1 is the maximum diameter (mm) of the soil fraction, and d_2 is the minimum diameter (mm) of the soil fraction. The inputs for these estimations included f_i from interpolated soil textural fractions, d_1 taken as 2 mm for sand, 0.05 mm for silt, and 0.002 mm for clay, and d_2 taken as 0.05 mm for sand, 0.002 mm for silt, and 0.0005 mm for clay [28].

The land cover was determined using Equation (12).

$$landc = \exp\left(-\alpha * \frac{NDVI}{\beta - NDVI}\right) \tag{12}$$

where *landc* is the land cover factor, *NDVI* is the mean NDVI from MODIS for the six-month duration, α and β are constants taken as 2 and 1, respectively [19].

The land management factor represents the effect of soil and water conservation practices for controlling loss of topsoil. Wischmeier and Smith [33] developed a monograph for allocating indices to different land management. In this study, land management practises were extracted from the land use map and assigned indices according to Wischmeier and Smith [33] monograph.

The topographic factor of soil erosion was determined from slope and length of slope. The length of slope was determined using Equation (13).

$$L = \frac{\left(A_{in} + pixel^2\right)^{m+1} - A_{in}^{m+1}}{pixel^{m+2} * (|\sin\alpha| + |\cos\alpha|)^m * (22.13)^m} \quad (13)$$

where A_{in} is the drainage contributing area at the inlet of a grid for which *L* is being estimated, *pixel* is the DEM grid resolution, α is the flow direction within the grid, and *m* is the exponent that addresses the ratio of rill-to-inter-rill soil loss. The value of *m* was taken as 0.4 for slope angle $St > 3^{\circ}$, 0.3 for $2^{\circ} < St \leq 3^{\circ}$, 0.2 for $1^{\circ} < St \leq 2^{\circ}$, and 0.1 for $St \leq 1^{\circ}$ [13]. The length of slope and slope were then combined to produce slope-length factor which indexes topographic factor for soil erosion as shown in Equation (14).

$$LSt = \left(\frac{L}{22.13}\right)^m \left(0.065 + 4.56 * \sin St + 65.41 * \sin^2 St\right) \quad (14)$$

where *St* is slope in degrees.

Appendix 2: Mineral glossary

Calcite: is a carbonate mineral and the most stable polymorph of calcium carbonate ($CaCO_3$). The other polymorphs are the minerals aragonite and vaterite.

Chlorites: is a group of phyllosilicate minerals. The typical general formula is: $(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2 \cdot (Mg,Fe)_3(OH)_6$. This formula emphasises the structure of the group.

Feldspar: is a huge family with very similar diffractometric properties. Chemical formula is a-$AlSi_3O_8$ with a being either K, Na or Ca (in the latter case it will be $CaAl_2Si_2O_8$) .

Illite: is a non-expanding, clay-sized, micaceous mineral. Illite is a phyllosilicate or layered alumino-silicate. The chemical formula is given as $K_yAl_4(Si_{8y},Al_y)O_{20}(OH)_4$ usually with $1 < y < 1.5$, but always with $y < 2$, but there is considerable ion substitution.

Kaolinite: is a clay mineral with the chemical composition $Al_2Si_2O_5(OH)_4$. It is a layered silicate mineral.

Quartz: is the most abundant mineral in the Earth's continental crust. It is made up of a lattice of silica (SiO_2) tetrahedral. Quartz is very hard (grade 7 on the Mohs scale) and a density of 2.65 g/cm³.SiO_2, density of 2.65 g/cm³.

Smectite: is a group of minerals including dioctahedral smectites such as montmorillonite ($(Na,Ca)_{0.33}(Al,Mg)_2Si_4O_{10}(OH)_2nH_2O$) and nontronite ($Na_{0.3}Fe_2(Si,Al)_4Si_4O_{10}(OH)_2nH_2O$) and trioctahedral smectites for example saponite ($Ca_{0.25}(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2nH_2O$).

ROCK GLOSSARY

Basalt: A dark, fine-grained, extrusive (volcanic) igneous rock with low silica content (40% to 50%), but rich in iron, magnesium and calcium. Generally occurs in lava flows, but also as dikes. Basalt makes up most of the ocean floor and is the most abundant volcanic rock in the Earth's crust.

Gneiss, Migmatite, Granulite: Gneiss is coarse-grained, foliated metamorphic rock that commonly has alternating bands of light and dark-coloured minerals (gneiss). Migmatites are metamorphic rock that are heated enough to partially melt, but not completely. The molten minerals resolidify within the metamorphic rock, producing a rock that incorporates both metamorphic and igneous features. Migmatites can also form when metamorphic rock experiences multiple injections of igneous rock that solidify to form a network of cross-cutting dikes (migmatite).

Granite: A coarse-grained intrusive igneous rock with at least 65% silica. Quartz, plagioclase feldspar and potassium feldspar make up most of the rock and give it a fairly light colour. Granite has more potassium feldspar than plagioclase feldspar. Usually with biotite, but also may have hornblende.

Gypsum (or anhydrite,): It is the commonest sulphate mineral and is frequently associated with halite and anhydrite in evaporites, forming thick, extensive beds

Limestone: A sedimentary rock made mostly of the mineral calcite (calcium carbonate). Limestone is usually formed from shells of once-living organisms or other organic processes, but may also form by inorganic precipitation.

Marbles: Marble is a metamorphic rock resulting from regional or rarely contact metamorphism of sedimentary carbonate rocks, either limestone or dolomite rock, or metamorphism of older marble. This metamorphic process causes a complete recrystallization of the original rock into an interlocking mosaic of calcite, aragonite and/or dolomite crystals. The temperatures and pressures necessary to form marble usually destroy any fossils and sedimentary textures present in the original rock.

Marl and other mixtures: Consolidated and unconsolidated earthy deposits consisting chiefly of an intimate mixture of clay and calcium carbonate, usually including shell fragments and sometimes glauconite.

Rhyolite: Extrusive rock typically porphyritic and commonly it exhibits flow texture, with phenocrystals of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. It is an extrusive equivalent of granite (rhyolite).

Sandstone: Sedimentary rock made of sand-sized grains of different nature

Schist: Metamorphic rock usually derived from fine-grained sedimentary rock such as shale. Individual minerals in schist have grown during metamorphism so that they are easily visible to the naked eye. Schists are named for their mineral constituents. For example, mica schist is conspicuously rich in mica such as biotite or muscovite.

Trachyte: is an igneous, volcanic rock with an aphanitic to porphyritic texture. The mineral assemblage consists of essential alkali feldspar; relatively minor plagioclase and quartz or a feldspathoid such as nepheline may also be present. (See the QAPF diagram). Biotite, clinopyroxene and olivine are common accessory minerals.