ENTRO

EASTERN NILE TECHNICAL REGIONAL OFFICE

NILE BASIN INITIATIVE

Initiative du Bassin du Nil

BANQUE AFRICAINE DE DEVELOPPEMENT

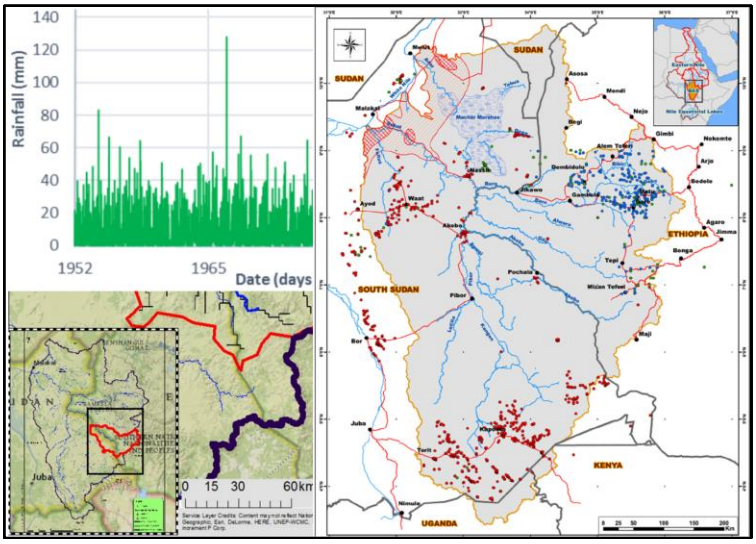
AFRICAN DEVELOPMENT BANK

BARO-AKOBO-SOBAT MULTIPURPOSE WATER RESOURCES DEVELOPMENT PROJECT STUDY

BASELINE, DEVELOPMENT POTENTIALS, KEY ISSUES AND OBJECTIVES REPORT

Annex 1: Physical environment

V.1 March 2016

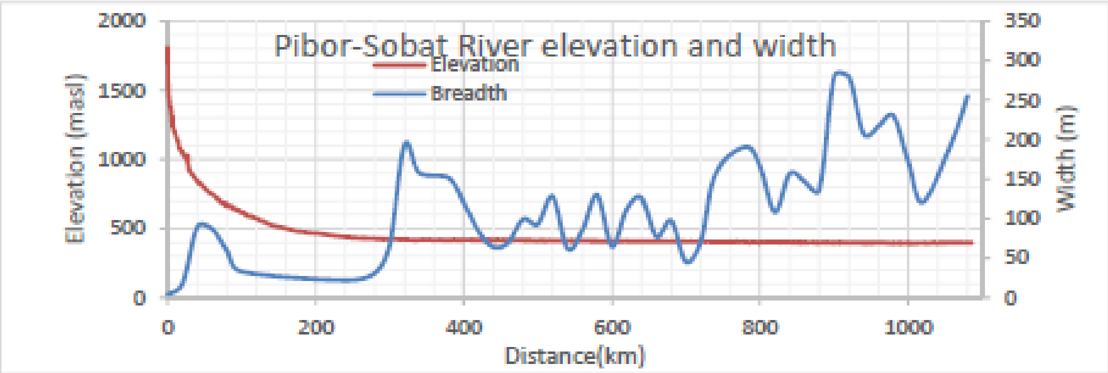


BRL Ingénierie

aurecon

CONTENT OF ANNEX 1

Annex 1-A: Longitudinal river profiles and top channel widths


Pibor-Sobat River elevation and width
Elevation
Breadth
Elevation (masl)
Width (m)
Distance(km)
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1000
500
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350
300
250
200
150
100
50
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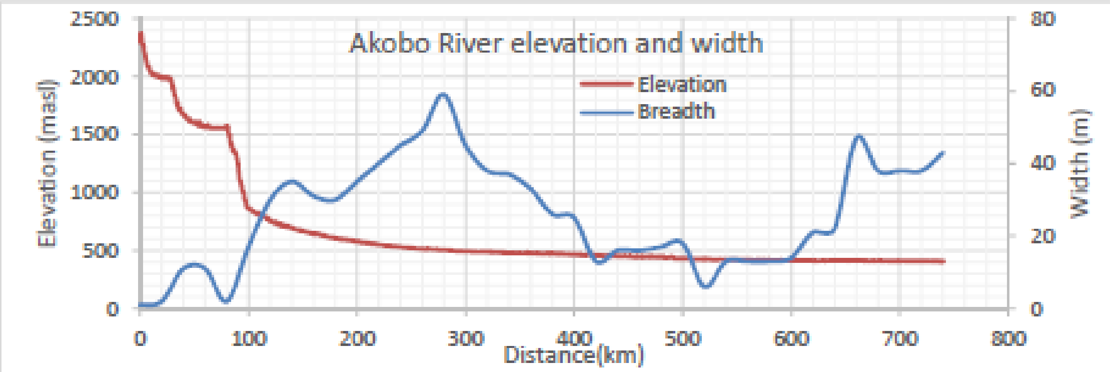
0
200
400
600
800
1000


Akobo River elevation and width
Elevation
Breadth
Elevation (masl)
Width (m)
Distance(km)
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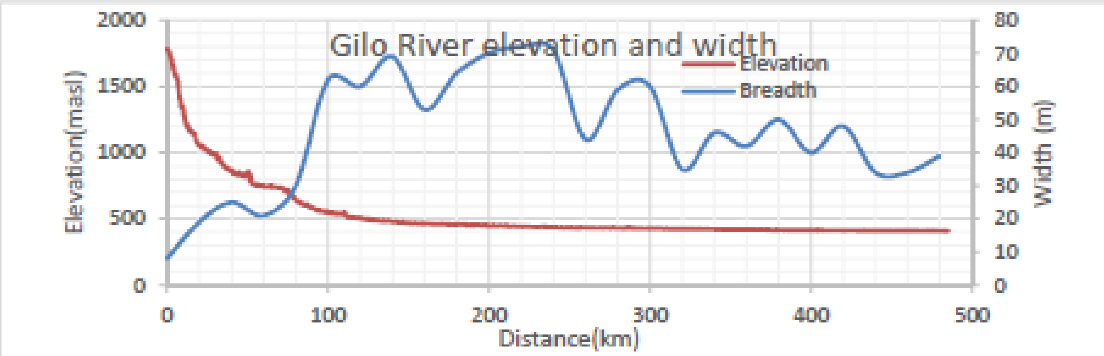
40
20
0
0
100
200
300
400
500
600
700
800


Gilo River elevation and width
Elevation
Breadth
Elevation(masl)
Width (m)
Distance(km)
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1000
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60
50
40
30
20
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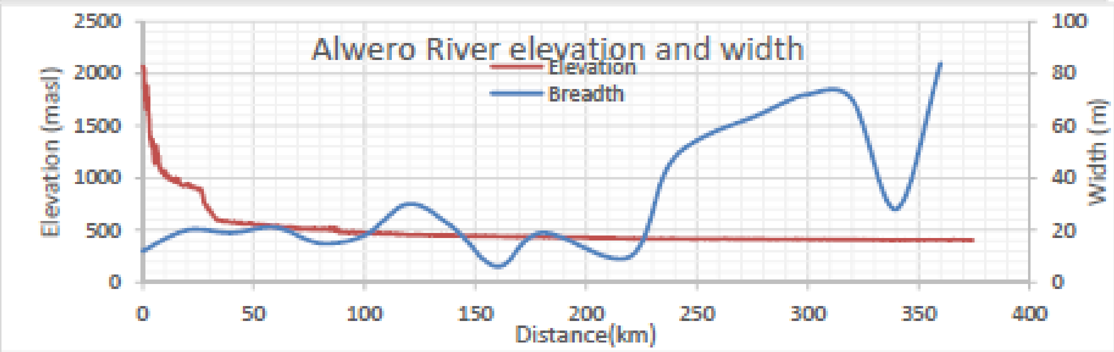
Alwero River elevation and width
Elevation
Breadth
Elevation (masl)
Width (m)
Distance(km)
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1500
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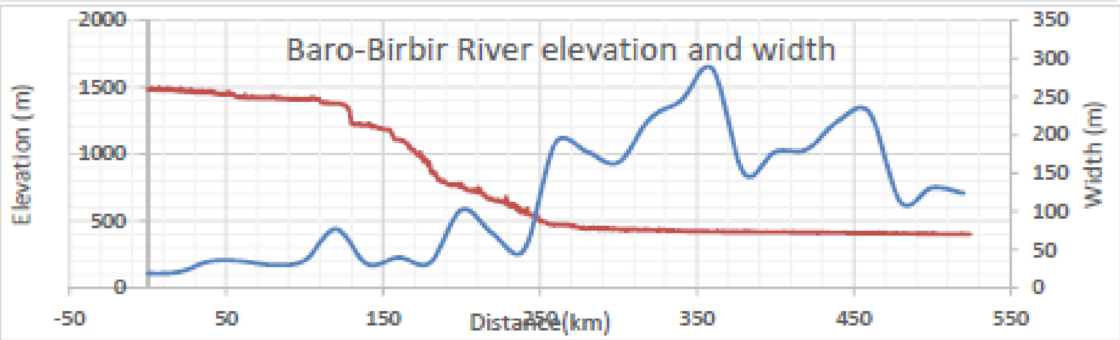
0
50
100
150
200
250
300
350
400


Baro-Birbir River elevation and width
Elevation (m)
Width (m)
Distance(km)
2000
1500
1000
500
0
350
300
250
200
150
100
50
0
-50
50
150
250
350
450
550

Annex 1-B: Potential sources of water pollution

Industrial wastewater and impacts: Concerns have been expressed about oil extraction in the Machar Marshes (ENTRO, 2007). The One System Inventory stated that exploration (cutting of seismic traces, test drilling, access road construction) and drilling and extraction (road construction, new towns, pipelines, oil wells) have already had severe environmental and social impacts. Two potential problems related to oil extraction and transport within the Machar Marshes were identified: The first was that the oil was pumped together with water and the two had to be separated. At this point the water was heavily contaminated and had to be treated before disposal. If this was not done effectively then severe pollution problems would occur. Given the importance of the marshes in terms of water supply and fishing this would have a serious impact on the livelihoods of the local inhabitants. A second potential problem was the construction of all-weather roads without effective drainage and adequate culverts. In these cases a road would acts as a dam and could cause serious flooding on the upstream side and dry conditions on the downstream side. Given the very complex drainage systems within the marshes any disruption in water flow could have very serious impacts on the distribution of the important "toich" grazing areas (ENTRO, 2007). Hydrosult Inc (2007) also concluded that “given the importance of the marshes in terms of water supplies and fishing this would have a serious impact on the livelihoods of the local inhabitants”. Seman (2011) reported that oil exploration and artisanal gold mining occurred in the basin. Both these activities disrupted the natural forest and vegetation in the mining areas, clearing land for the exploration and using wood for timber reinforcement of open pit mines and other construction activities. Artisanal gold mining can lead to severe increases in the suspended sediment loads and chemical contamination such as mercury pollution if this was used in the gold extraction process. Mercury contamination of drinking water sources is a serious concern in countries such as Zimbabwe where artisanal gold mining and mercury extraction methods are in widespread use.

Domestic wastewater: ENTRO, 2009) identified dumping of industrial waste and wastewater, and sewage in urban areas as a major concern. The report also identified dumping of domestic waste and wastewater at sub-basin household settlements as greatly affecting the quality of water and the health of populations dependent on river and groundwater for domestic supplies. Merid (2005) concluded that the lack of data about domestic solid waste and effluent volumes constrained the assessment of pollution of water supply sources and, hence, knowledge about domestic waste management was identified as a gap to be filled in the future.

Agricultural runoff: Concerns about agricultural runoff are generally associated with fertiliser washoff in the runoff, and pesticide and herbicide residues in the runoff water. Merid (2005) found that there were no data available on pesticide residues in Ethiopia and that Ethiopia had been one of the lowest fertilizers users among ASARECA member states in the region until the mid 1970s (FAO data for the period from 1991 to 2000, cited by Tsedeke, 2004). Ethiopia’s per capita fertilizer consumption for the above period (12.4 kg/ha/yr) was less than that for Kenya (27.4 kg/ha/yr). It was his opinion that the absence of water quality data for fertilizer and pesticides severely constrained an assessment of agricultural impacts and that it was important to establish baselines for such parameters. ENTRO, 2009) expressed the opinion that agricultural runoff was not yet regarded as a serious source of surface water contamination in the Baro-Akobo-Sobat sub-basin.

Deforestation and land degradation: In some parts of the basin, especially the highlands, the growing population has led to a high demand for fuel wood and charcoal for energy use resulting in over-harvesting and degradation of forests and woodlands. Conversion of degraded forests into cultivation land often has followed suite. This has resulted in a significant increase in erosion and sediment ingress into watercourses resulting in increased levels of suspended solids, turbidity and sand depositions in riverbeds and floodplains. Deforestation is identified as a major sediment source and the protection and sustainable use of forests and reforestation of degraded forests are regarded as high priority to reduce erosion and sedimentation. This is exacerbated by poor agricultural and land management practices and which leads to erosion and sedimentation.

Mining and quarrying: Runoff and leachates from mining activities can have a significant impact on surface and groundwater quality. However, Merid (2005) concluded that there were no large-scale underground and open-cast mining activities within the basin. There was evidence of quarrying which mostly involved extraction of rocks from outcrops. This extraction was done mostly by hand and the crushed stone was used for building and road construction. These activities have resulted in localised impacts on erosion and sedimentation.

Invasive aquatic plants: Water hyacinth infestations can have serious impacts on water quality (ENTRO, 2007). In about 1957 water hyacinth (Eichhornia crassipes) appeared in the White Nile in the area of the Sudd, and has since spread north and southwards into the Baro in Ethiopia in about 1976 and also into the Sobat system. The weed has a number of serious negative impacts. The presence of the weed in the river system leads to an increased loss of water via increased evapotranspiration. It also reduces the areas of open water available for fishing, which is an important livelihood strategy for the people of the Sub-basin. It also impedes river navigation along the White Nile. River navigation is an important economic activity on the Nile and sections of the Baro and Sobat rivers. Other impacts relate to low oxygen concentrations below the hyacinth mats and an increase in organic content of the water due to dead and decomposing plants. Reports indicated that the water hyacinth problem was not as serious as it was in the nineteen seventies and eighties and consequently, the water loss would be less than previous estimates. The One System Inventory (ENTRO, 2007) felt that there would still be water lost due to the presence of water hyacinth in the White Nile reaches, and hence an updated investigation was required into the ecological and climatological impacts that could be trigger by a second, even more severe, episode of infestation.

Seasonal flooding and waterborne diseases: Most of the lowland areas are susceptible to riverine and rainfall flooding. This has led to an increase in waterborne diseases as bush toilets and animal dung become flooded and mobilising pathogens into water supply systems (Muso, 2011)

Annex 1-C: Analysis of sediment yields

BARO-AKOBO-SOBAT MULTIPURPOSE WATER RESOURCES DEVELOPMENT STUDY - BASELINE STUDY

Annex 1-C Analysis of sediment yields

TABLES AND FIGURES

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ACRONYMS AND ABREVIATIONS

AfDB	African Development Bank
ACORD	Association for Cooperative Operations Research and Development
ACTED	Agency for Technical Cooperation and Development
BAS	Baro Akobo Sobat
CAMP	Comprehensive Agriculture Development Master Plan
CBA	Cost Benefit Analysis
CMA	Catchment Management Association
CRA	Cooperative Regional Assessment
DEM	Digital Elevation Model
EEPCO	Ethiopian Electric Power Corporation
EHA	Erosion Hazard Assessment
EIA	Environmental Impact Assessment
ENID	Eastern Nile Irrigation and Drainage
ENCOM	Eastern Nile Committee Of Ministers
ENPM	Eastern Nile Planning Model
ENPT	Eastern Nile Power Trade
ENSAP	Eastern Nile Subsidiary Action Plan
ENTRO	Eastern Nile Technical Regional Office (NBI)
EPA	Environmental Protection Authority
FAO	Food and Agriculture Organization
GDEM	Global Digital Elevation Model
GDP	Gross Domestic Product
GEF	Global Environment Facility
GIS	Geographic Information System
GTP	Growth and Transformation Plan
GWh/y	GigaWatt hour/year
HEP	Hydroelectric Power
IDEN	Integrated Development of Eastern Nile
ILWRM	Integrated Land and Water Resources Management
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature and Natural Resources
IWMI	International Water Management Institute
IWRDMP	Integrated Water Resources Development and Management Plan
IWRM	Integrated Water Resource Management
JMP	Joint Multipurpose Project
MAFCRD	Ministry of Agriculture, Forestry, Cooperatives and Rural Development
MASL	Meters Above Sea Level
MCA	Multi Criteria Analysis
MDG	Millennium Development Goals
MEDIWR	Ministry of Electricity, Dams, Irrigation and Water Resources
MERET	Managing Environmental Resources to Enable Transitions
MLFI	Ministry of Livestock and Fisheries
MoA	Ministry of Agriculture
MoEN	Ministry of Environment
MoWIE	Ministry of Water, Irrigation and Energy
MSIOA	Multi Sector Investment Opportunity Analysis
MTR&B	Ministry of transport, roads and bridges
MW	Mega Watt
MWC&T	Ministry of Wildlife Conservation and Tourism
NB-DSS	Nile Basin Decision Support System
NBI	Nile Basin Initiative
NCORE	Nile Cooperation for result project
NDVI	Normalized Difference Vegetation Index

NELSAP	Nile Equatorial Lakes Subsidiary Action Program
NGO	Non-Governmental Organization
Nile-COM	Nile Council of Ministers
PIM	Project Implementation Manual
PLSPP	Policies, Legislation, Strategies, Plans, and Programs
PPP	Private Public Partnership
PMU	Project Management Unit
PRSP	Poverty Reduction Strategy Program
RATP	Regional Agricultural Trade and Productivity Project
RPSC	Regional Project Steering Committee
RSS	Republic of South Sudan
RUSLE	Revised Universal Soil Loss Equation
SAP	Subsidiary Action Program
SEA	Strategic Environmental Assessments
SIS	Soil Information System
SLMP	Sustainable Land Management Program
SNNPR	Southern Nations, Nationalities and Peoples' Region
SRFE	Satellite Rainfall Estimates
SRTM	Shuttle Radar Topographic Mission
SSEA	Strategic Social and Environmental Assessment
SVP	Shared Vision Program
SWAT	Soil and Water Analysis Tool
SWOT	Strength Weakness Opportunity Threat
SWSC	Soil-Water Storage Capacity
UNDP	United Nations Development Program
UNHCR	United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
USAID	United States Agency for International Development
WaSH	Water Sanitation and Hygiene
WB	World Bank
WBISPP	Woody Biomass Inventory and Strategic Planning Project
WCYA	Women, Children and Youth Affairs
WEES	Water for Eastern Equatoria
WFP	World Food Program
WM	Watershed Management
WRMA	Water Resources Management Authority
WRMD	Water Resources Management and Development
WSS	Water Supply and Sanitation
WUA	Water Users Association

1. INTRODUCTION

1.1 STUDY AREA

The Baro-Akobo-Sobat-White Nile sub-basin is one of the four major sub-basins in the Eastern Nile Portion of the Nile basin. It is located in the southernmost portion of the Eastern Nile Basin contributing about 26 billion m^3 of water every year to the Nile system at Khartoum (ENTRO, 2007). Geographically, it extends from 15° 47' 40'' to the north down to 3° 25' 52'' in the south. Similarly, it extends from 29° 24' 43'' in the west to 36° 18' 27'' in the east, covering a total area of 468,216 km^2 (ENTRO, 2007).

The major rivers of Baro-Akobo-Sobat Basin are Baro and its tributaries (Birbir, Geba, Sor and Baro), Alwero, Gilo and Akobo. The general flow direction of the rivers is from east to west originating from the highlands and falling to the Gambela Plain (TAMS_1B, 1997). Figure 1-1 shows the major catchments and rivers in the basin which were evaluated in this study.

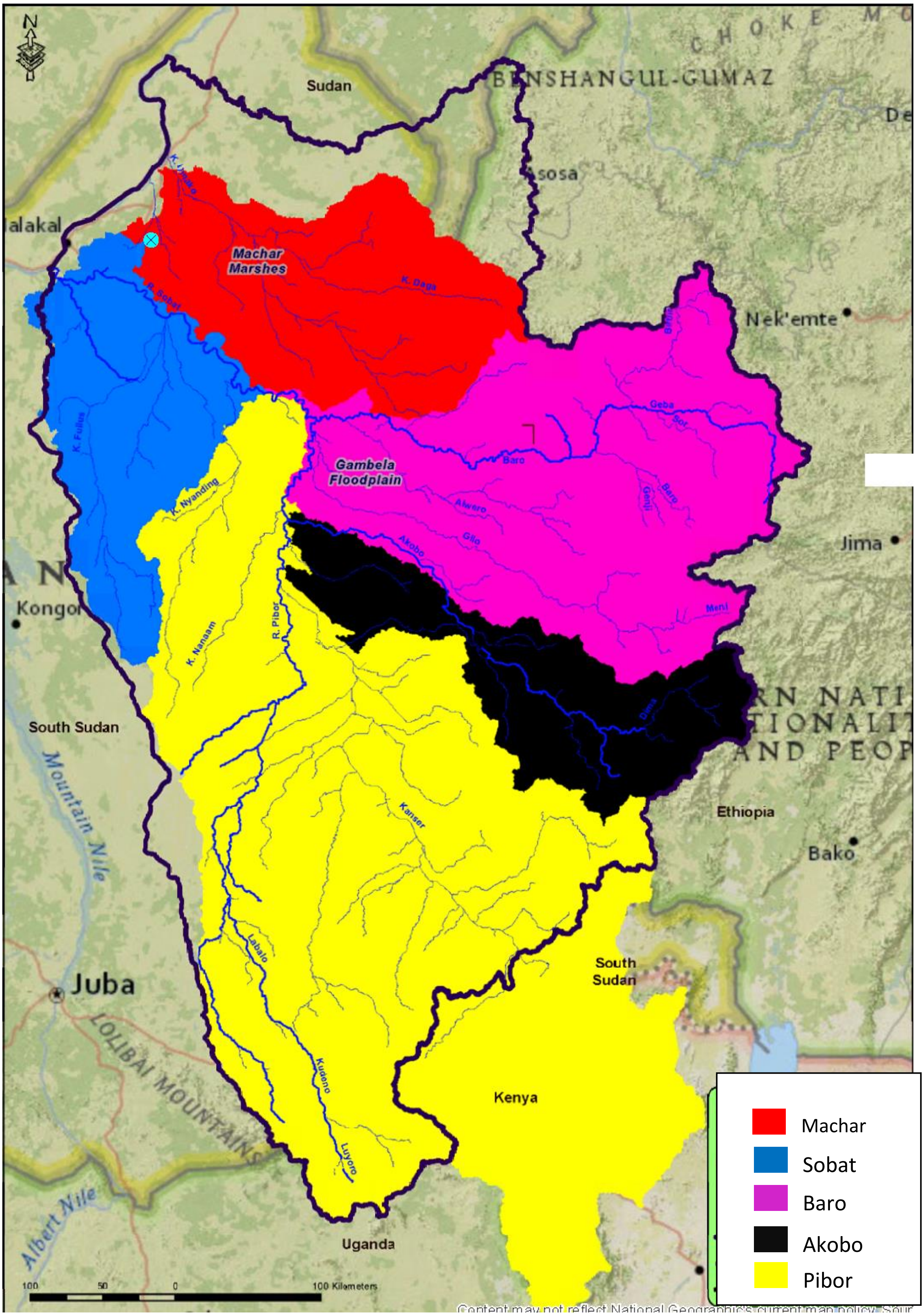

Figure 1-1: Baro-Akobo-Sobat basin major watersheds as used in this study

1.2 MAIN OBJECTIVE

The main objective of this study is to assist the Eastern Nile Technical Regional Office (ENTRO) to prepare an Integrated Water Resources Development and Management Plan (IWRDMP) based on a Strategic Social and Environmental Assessment (SSEA), and further, develop investment packages for cooperative development in the Baro-Akobo-Sobat sub-basin.

1.2.1 Specific objective of this sedimentation task

The specific objective of this study is to develop a sediment yield map for Baro-Akobo-Sobat study area.

1.3 STUDY METHODOLOGY

A physical process based model, SHETRAN, was used to simulate the sediment yields and routed sediment loads in the study area. The model was calibrated and validated against flow records and sediment transport data where data was available. The model output was used to generate a sediment yield map.

2. SHETRAN MODELLING

SHETRAN is a physically based, spatially distributed model with integrated surface/ subsurface modelling system for water flow, sediment transport and contaminant migration in river basins. The model generates the sediment yield considering rainfall-runoff-erosion processes, and routes the sediment loads along rivers by considering the sediment transport capacity.

The model can accurately describe the physical processes (hydrological cycle) in catchments of less than 2 000 km2. However, the model has successfully been used in large basins of approximately 1 808 500 km2 but it is recommended for basins of about 10 000 km2. Larger catchments are recommended to be subdivided into smaller basins for better accuracy (Shetran, 2013).

2.1 MODEL SETUP

To successfully describe the model, various inputs are required:

- Digital elevation model and catchment map.
- Time series of precipitation (mm/hr) and actual/potential evapotranspiration rates (mm/hr)
- Land cover distribution.
- Soil distributions, properties, grading and depth.
- Calibration data

These inputs are discussed further in sections **Erreur ! Source du renvoi introuvable.** to **Erreur ! Source du renvoi introuvable.**.

2.1.1 Catchment delineation

A 30 arc DEM was available for the whole catchment but due to the limitation of the SHETRAN model (200 x 200 grid squares), various catchments were delineated with the DEM altered to 1.9 km by 1.9 km spatial resolution. The catchments identified are shown in Figure 2-1 and the flow gauging stations coordinates are enclosed in **Appendix 1**.

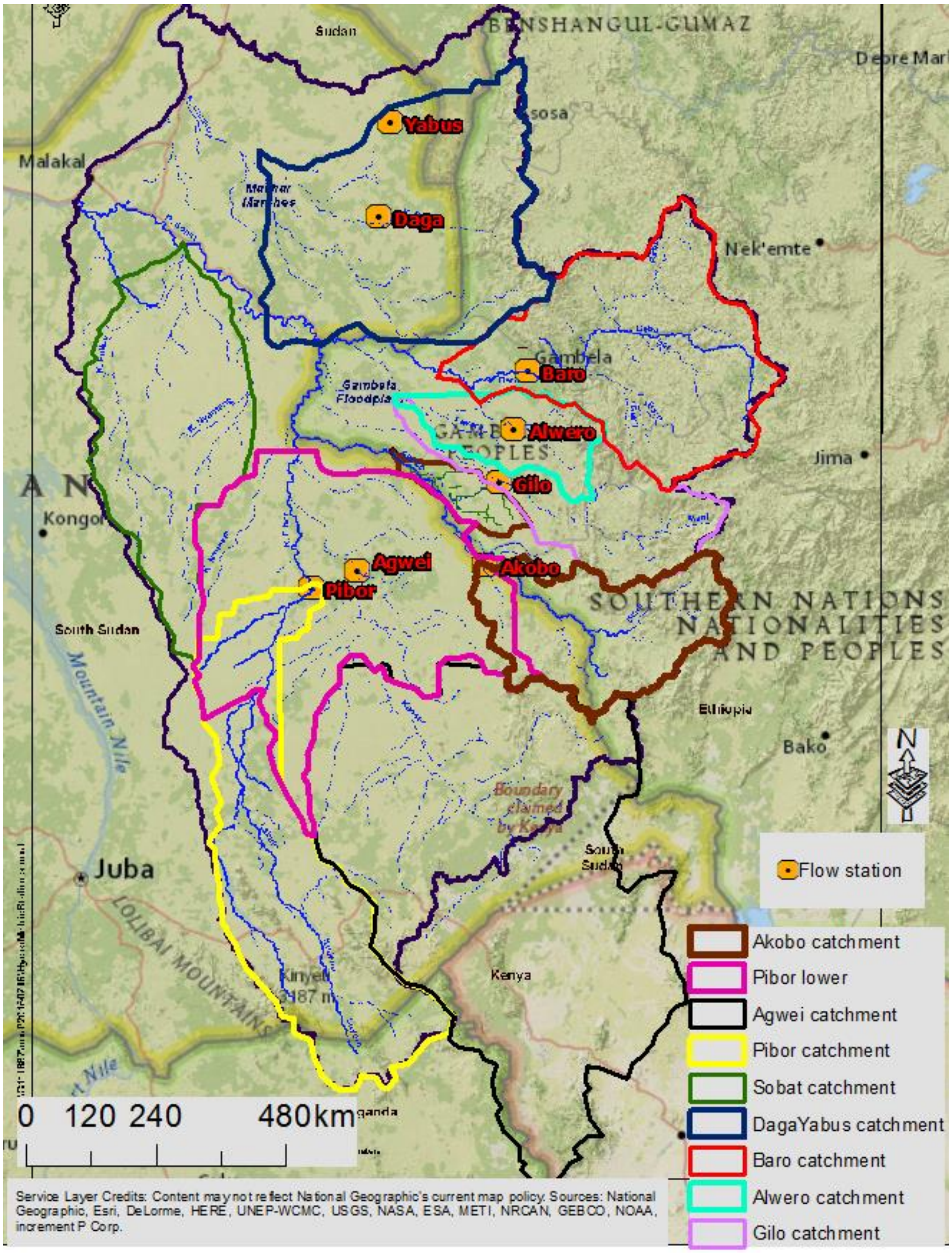

Figure 2-1: Major delineated catchments and locations of flow gauging stations as used in SHETRAN

2.1.2 Land use and soil distribution

Five main land uses were identified from the ENTRO (2007) report and are shown in Figure 2-2. They were limited to five as to conform to the SHETRAN library: shrub, grass, urban, forest and arable land. The evaporation parameters, root density function, canopy and leaf parameters such as canopy drainage, canopy storage and vegetation cover indices were based on the SHETRAN standard values (SHETRAN, 2013). These standard values are tabled in

Appendix 2 and

Appendix 3.

Two main soils types were identified, vertisols described as silty clay and nitosols described as clay loam to sandy loam. Their distribution is as shown in Figure 2-3.The two soils were set up having two layers for the whole catchment with the top layer having a thickness of 1m and lower layer varying from 5 to 15m.

The different soil parameters such as saturated water content, residual water content and vanGenuchte values were based on standard SHETRAN values. The saturated conductivity of the top 1m layer varied between 5 to 15 m/day and the lower layer between 0.1 to 1 m/day. Default soil parameters are tabled in

Appendix 4.

The channel Manning n value was calibrated with initial value selected as 0.04 and overland flow values varying between 0.07 and 0.1.

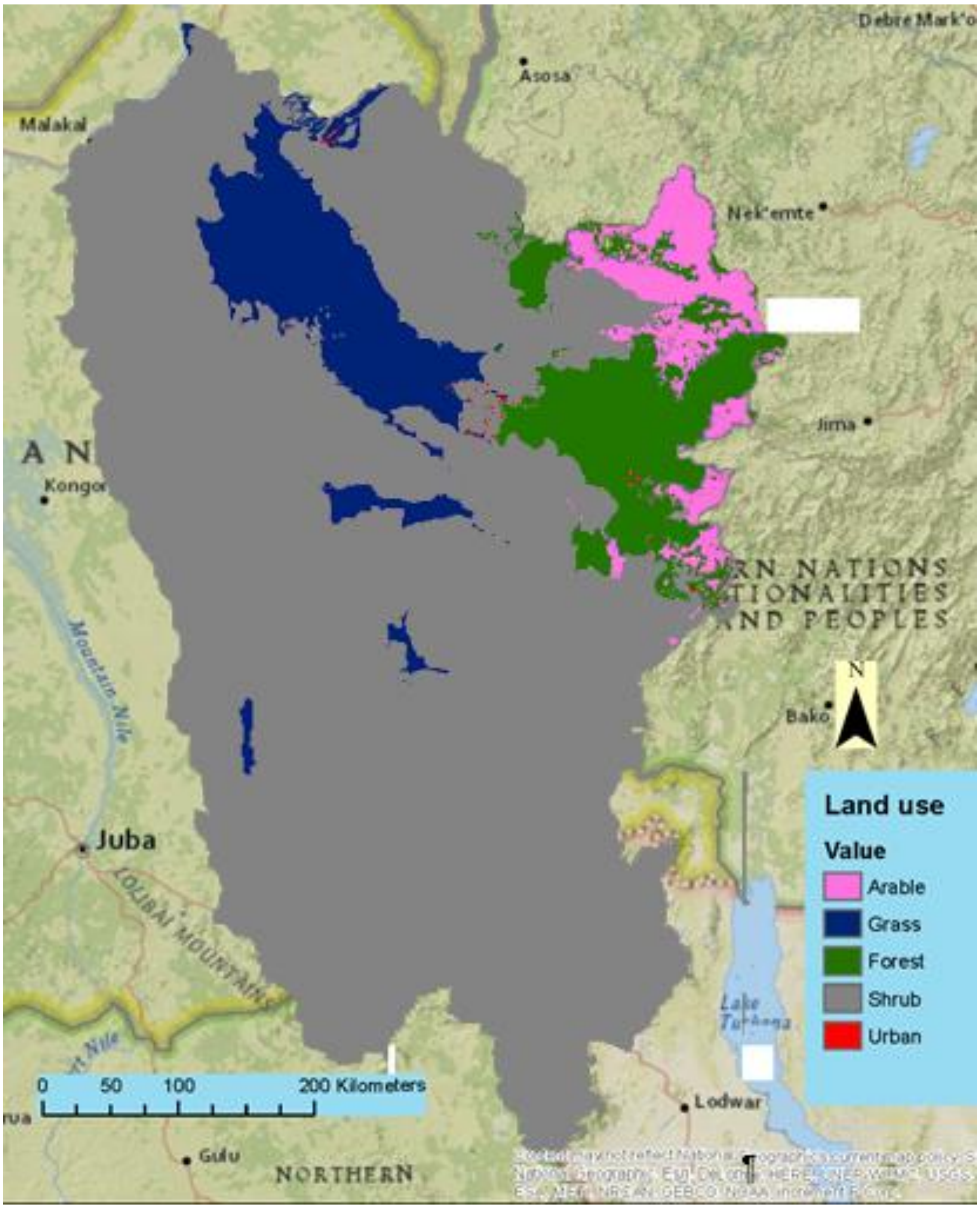

Figure 2-2: Baro-Akobo-Sobat land use distribution as used in SHETRAN

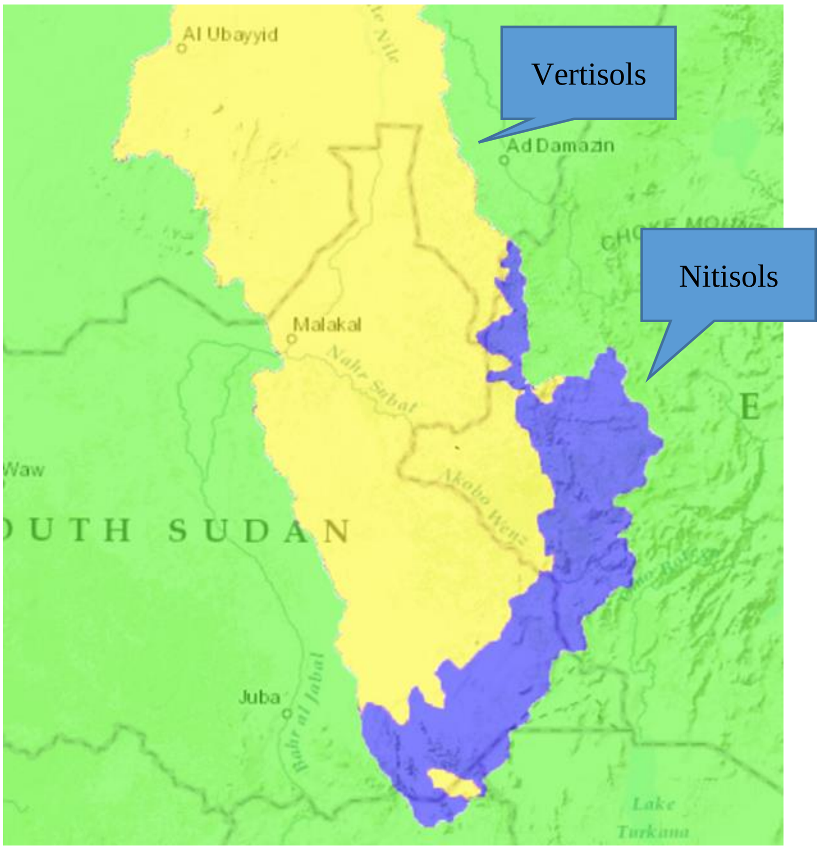

Figure 2-3: Baro-Akobo-Sobat soil distribution as used in SHETRAN

2.1.3 Rainfall, potential evaporation and flow records

The hydrological year was taken from 1st April to 31st March with all records available for periods between 1952 and 1992. Monthly and simulated flows (MIKE HYDRO Basin) at eight locations as shown in Figure 2-4 were used. The monthly flows records/sequences are shown in Figure 2-5 and Figure 2-6 with their coordinates in Appendix 1.

Time series at the flow gauging stations are shown in Appendix 5 to Appendix 9.

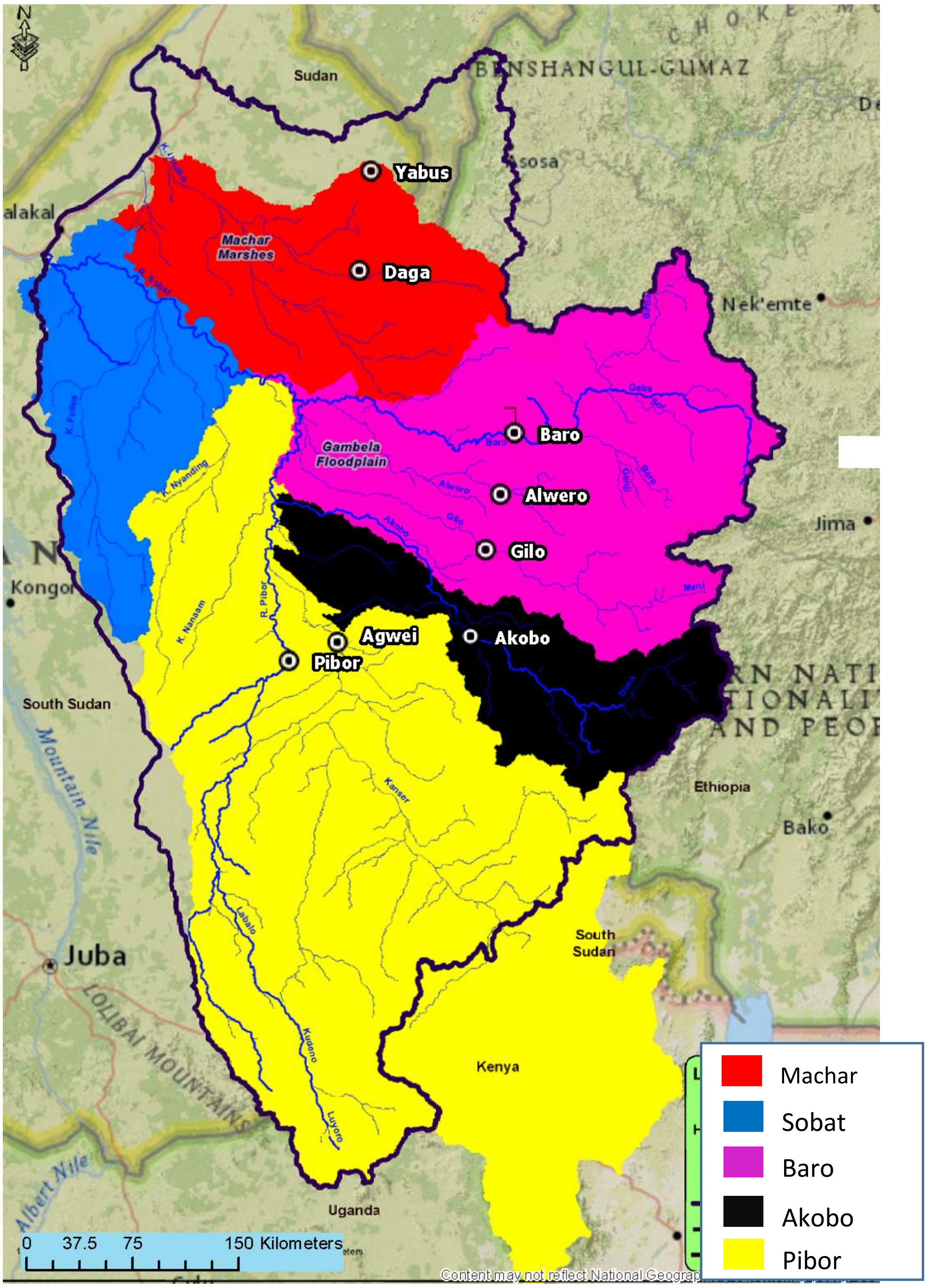

Figure 2-4: Baro-Akobo-Sobat basin watershed and gauging stations as used in SHETRAN

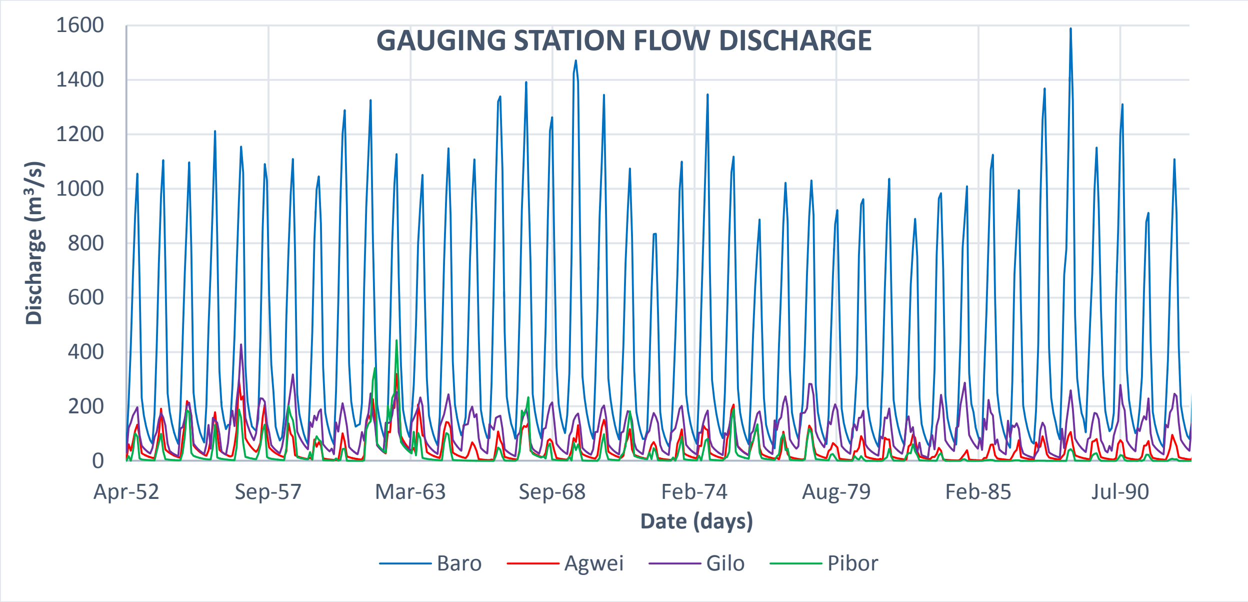

Figure 2-5: Baro-Akobo-Sobat gauging station flow records (daily data)

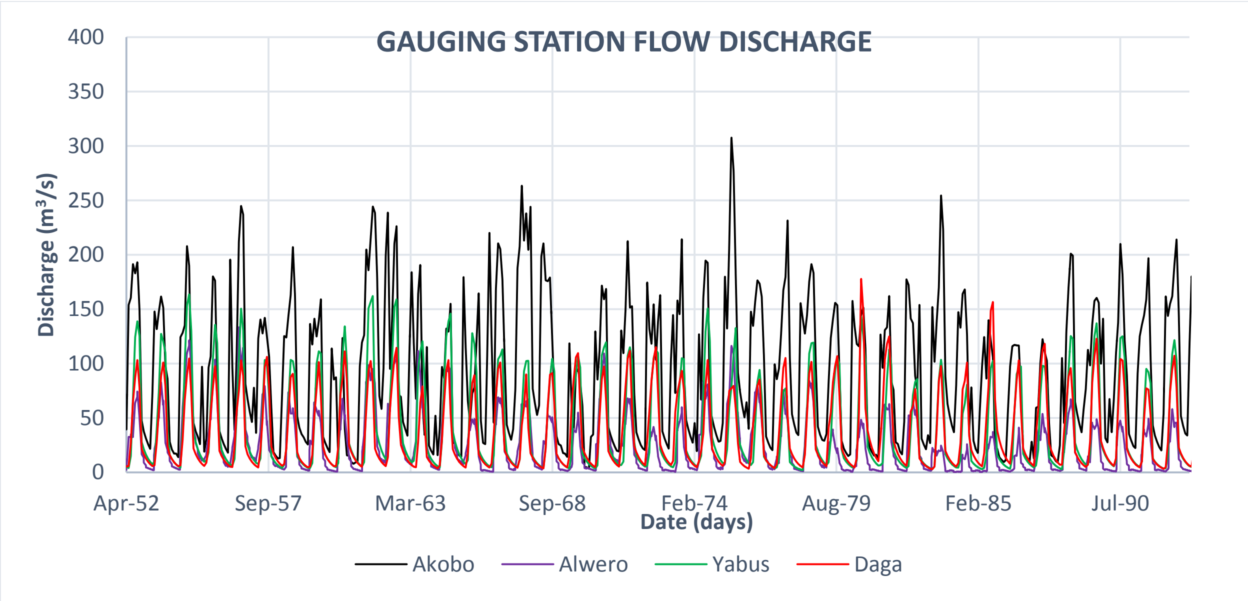

Figure 2-6: Baro-Akobo-Sobat gauging station flow records

Nineteen rainfall stations were available for the whole catchment. Their area of influence is as shown in Figure 2-7. Figure 2-8 to Figure 2-10 show a graphical representation of the daily rainfall records.

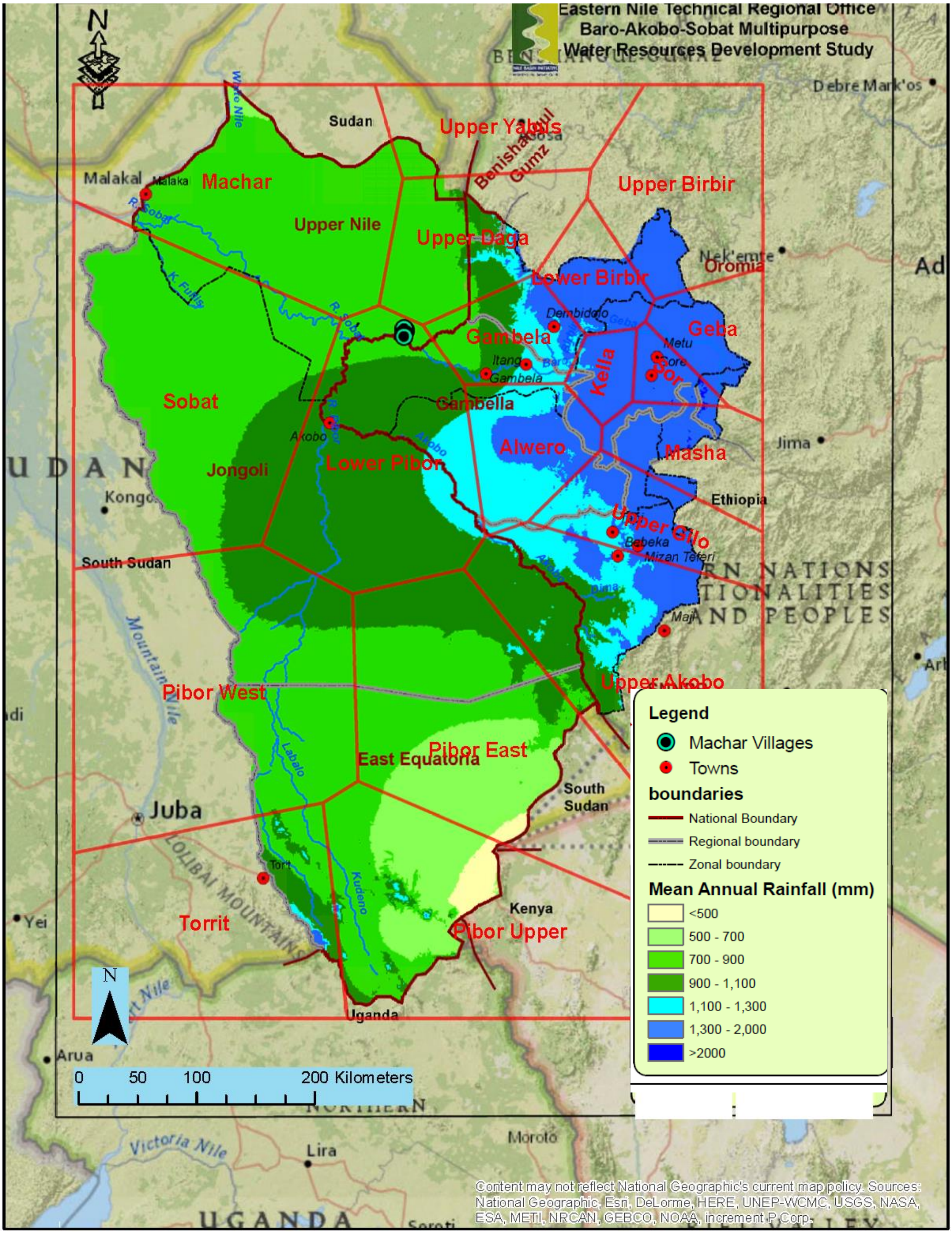

Figure 2-7: Baro-Akobo-Sobat rainfall Thiessen polygons as used in SHETRAN

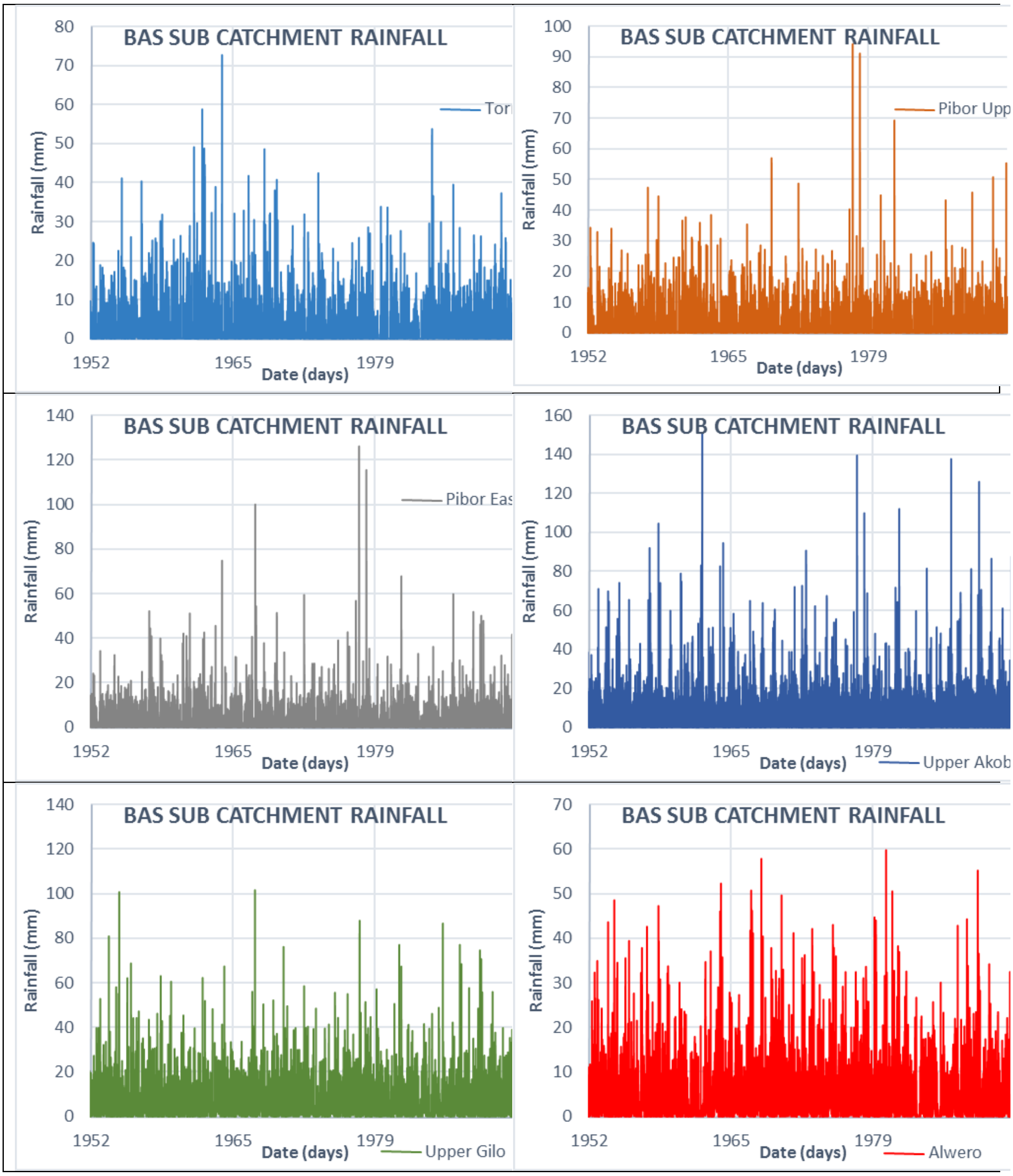

Figure 2-8: Baro-Akobo-Sobat rainfall records

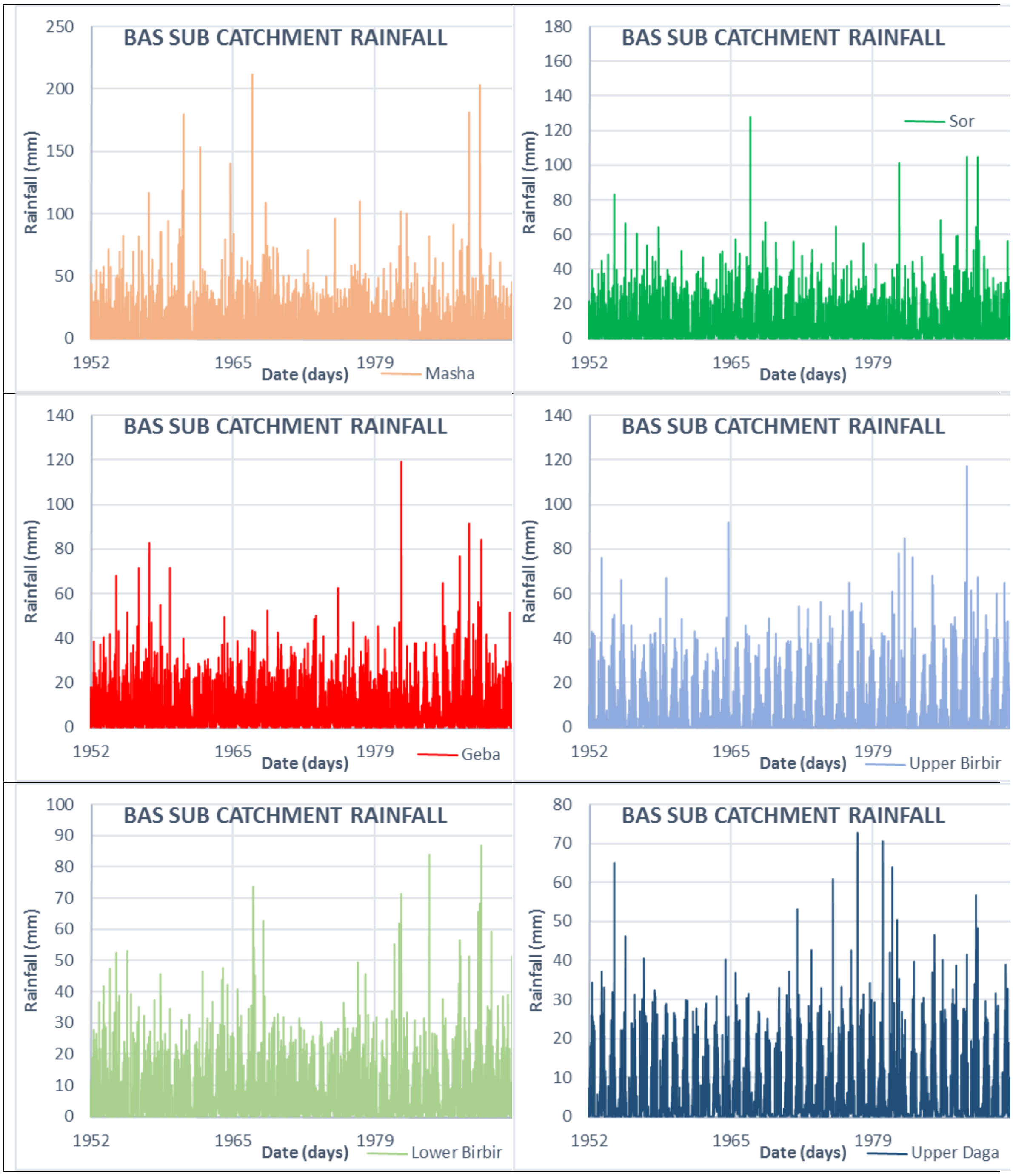

Figure 2-9: Baro-Akobo-Sobat rainfall records

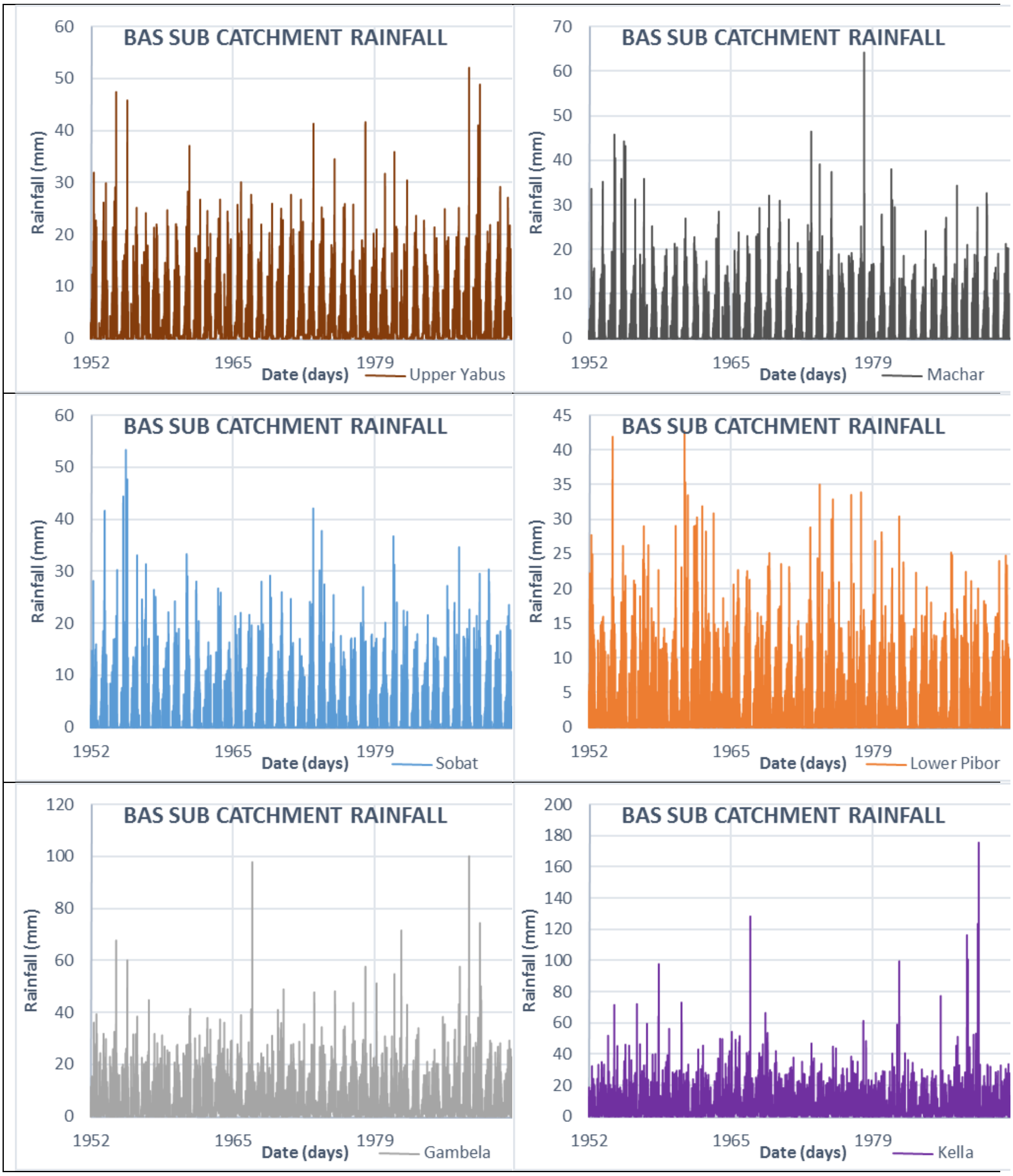

Figure 2-10: Baro-Akobo-Sobat rainfall records

Twenty-five evaporation stations are available with their distributions as shown in Figure 2-11. Their monthly evaporation records are as shown in Figure 2-12. Rainfall weather station coordinates are presented in Appendix 10.

Due to the large area of sub-catchments identified the Thiessen polygons of rainfall and evaporation were limited to a maximum of nine in each smaller sub-catchment as not to introduce instabilities in the model, although the model can handle twenty-five polygons.

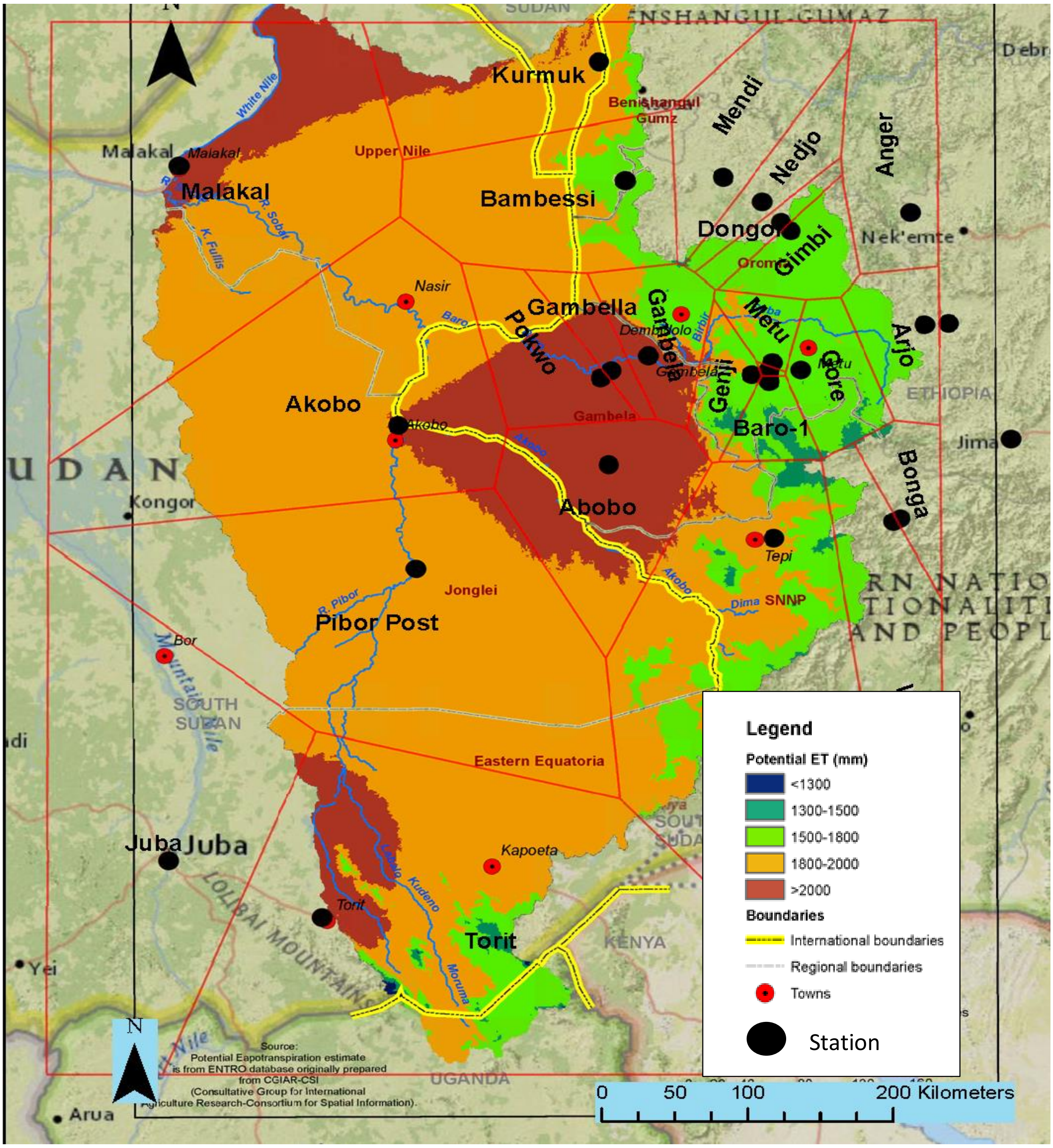

Figure 2-11: Baro-Akobo-Sabot evaporation Thiessen polygons

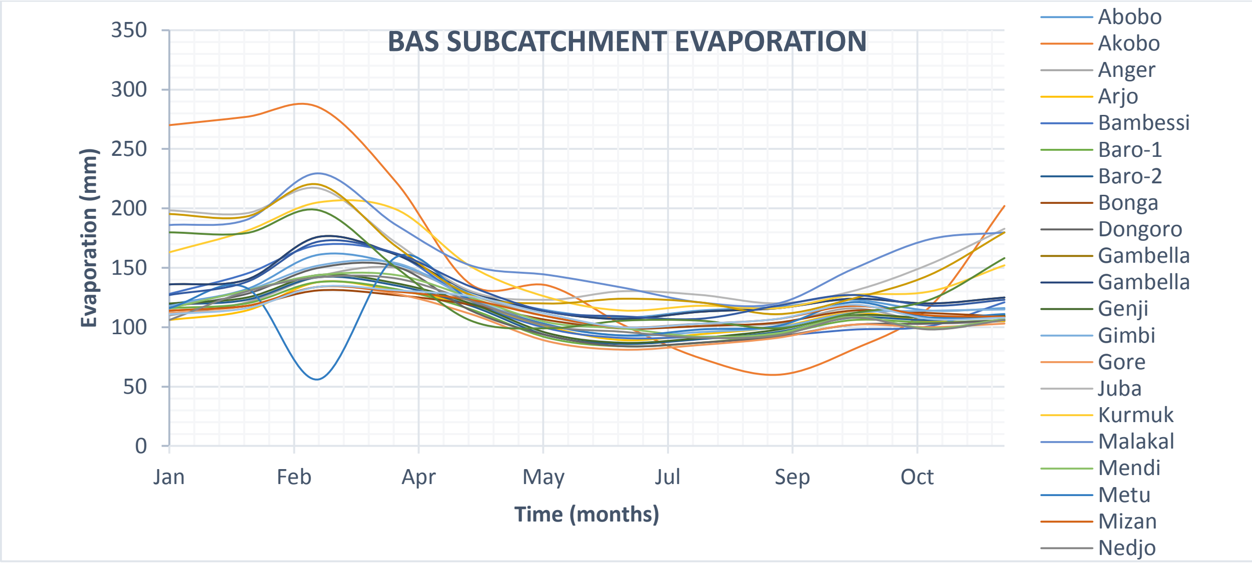

Figure 2-12: Baro-Akobo-Sobat monthly evaporation records

2.2 SEDIMENT DATA

Table 2-1 and Figure 2-14 show the available sediment yield data for the catchment. There is limited sampling data from the eleven stations in various rivers in the catchment. The data was collected from 1988 to 1990 with 101 samplings done. Based on sediment load, discharge rating curves were obtained. Note that the so-called rating curve given in Table 2-1 is not a standard rating curve from the raw suspended sediment concentrations data-discharge record, but was calculated based on a Mean Annual Flow (MAF) (TAMS_IF, 1997).

Table 2-1: Average sediment yield (TAMS_1F, 1997).

River	Catchment Area (km^2)	Mean Annual Flow (m^3/s)	Sediment Rating Curve Equation ($t/day.km^2$) and $q = \frac{\text{daily discharge}}{\text{mean annual flow}}$		Calculated annual sediment yield ($t/km^2.a$)
Keto	1006	17.6	$Qs = 0.01010\ q^{0.974}$		324
Gumero	106	2.05	$Qs = 0.00372\ q^{0.720}$		35
Ouwa	288	5.75	$Os = 0.00089\ q^{1.419}$		284
Sor	1620	52.6	$Qs = 0.00130\ q^{1.189}$		124
Gecheh	79	1.90	$Os = 0.00056\ q^{1.220}$		63
Begwaha	125	3.33	$Qs = 0.00110\ q^{1.145}$		85

From the Baro 1 and 2 feasibility study, additional studies were done and from seven additional stations the sediment yields were calculated based on discharge-sediment load rating curves, as shown in Table 2-2 (Norplan, 2006). It should be noted these values are just indicative and generally based on short records. The location of these gauging stations is represented in Appendix 11.

Table 2-2: Average Annual Sediment yield (Norplan, 2006)

River Station	#Samples	Area (km^2)	Period	Mean Annual Flow (m^3/s)	Rating curves (t/day)	Annual Sediment Load (t/km².a)
Sor nr. Metu	27	1622	1968-1996	50.1	$Q_s=4.045Q^{1.199}$ $R^2=0.942$	169
Geba at Chora	27	1582	2003	49.3	$Q_s=3.975Q^{1.239}$ $R^2=0.946$	137
Geba nr. Suppi	14	3894	1989-1990	54.8	$Q_s=5.346\ Q^{1.214}$ $R^2=0.960$	75
Uka at Uka	18	52	1988-1996	1.3	$Q_s=6.328Q^{0.781}$ $R^2=0.666$	50
Gummero nr. Gore	15	106	1988-1996	1.9	$Q_s=6.822Q^{0.728}$ $R^2=0.790$	32
Baro nr. Masha	*11+1	1400	1990-2004	56.8	$Q_s=7.459Q^{1.028}$ $R^2=0.881$	155
Genji nr. Gecha	*10	115	2004	4.6	$Q_s=11.06Q^{0.682}$ $R^2=0.638$	88

* Norplan measurements 2004

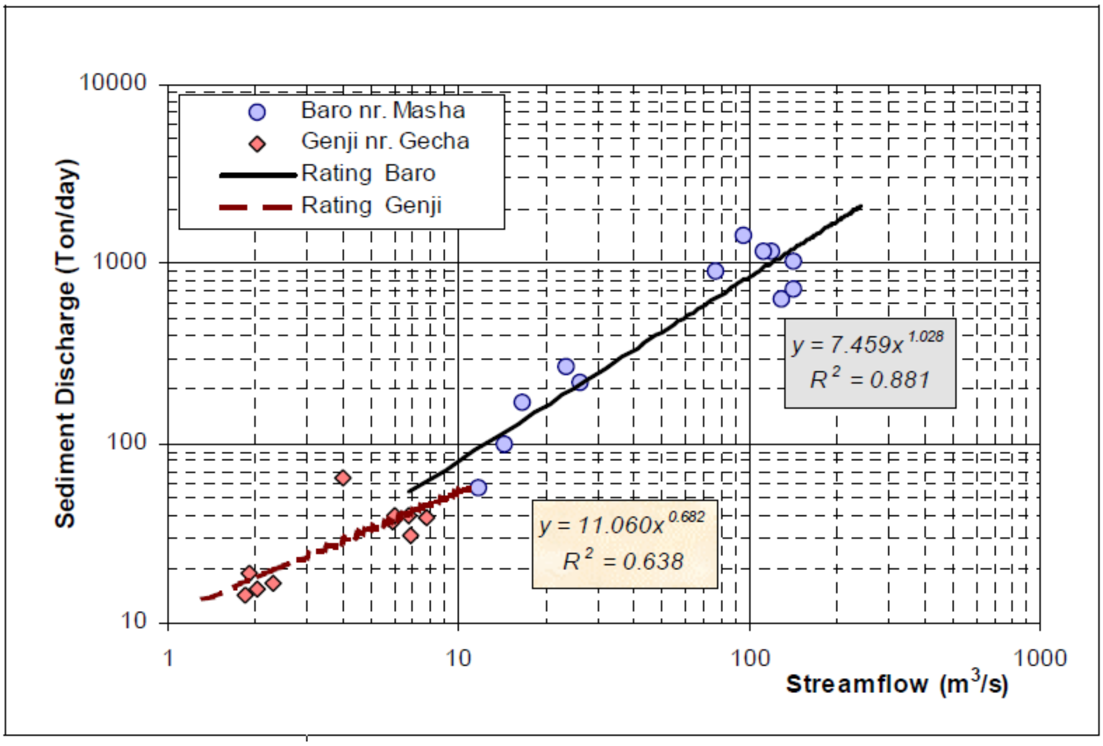

Figure 2-13: Baro and Genji Rivers sediment rating curves as calculated in Baro 1 and 2 feasibility studies (Norplan, 2006)

From the 40 years' flow records available in the catchments, it should be noted that the 100 year flood may not be included, thus the sediment yields calculated in this report should be treated with caution.

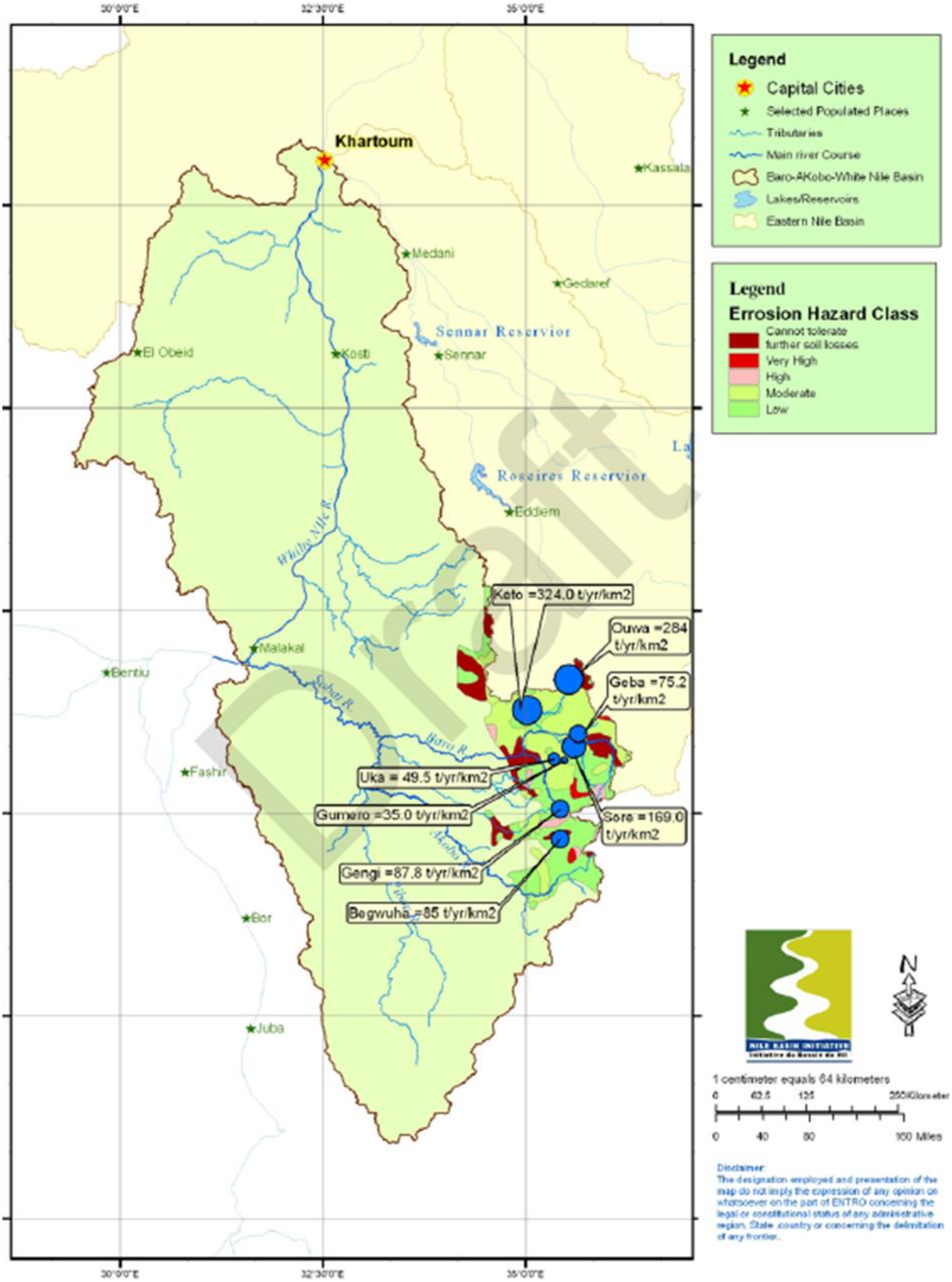

Figure 2-14: Baro-Akobo-Sobat sediment yield and land erosion potential (ENTRO, 2007)

2.3 MODEL CALIBRATION AND SIMULATION RESULTS

2.3.1 Baro catchment

Based on the SHETRAN 200 x 200 grid limitation and 1500 river channel links, a 30 arc DEM was used to delineate the watershed. 130 x 147 grids of 1970 m spatial resolution represented the watershed with a total catchment area of 22364 km^2.The watershed formed the model boundary with one gauging station at Baro near Gambela.

Figure 2-15 shows the Baro watershed extent and the river links as calculated by the SHETRAN model.

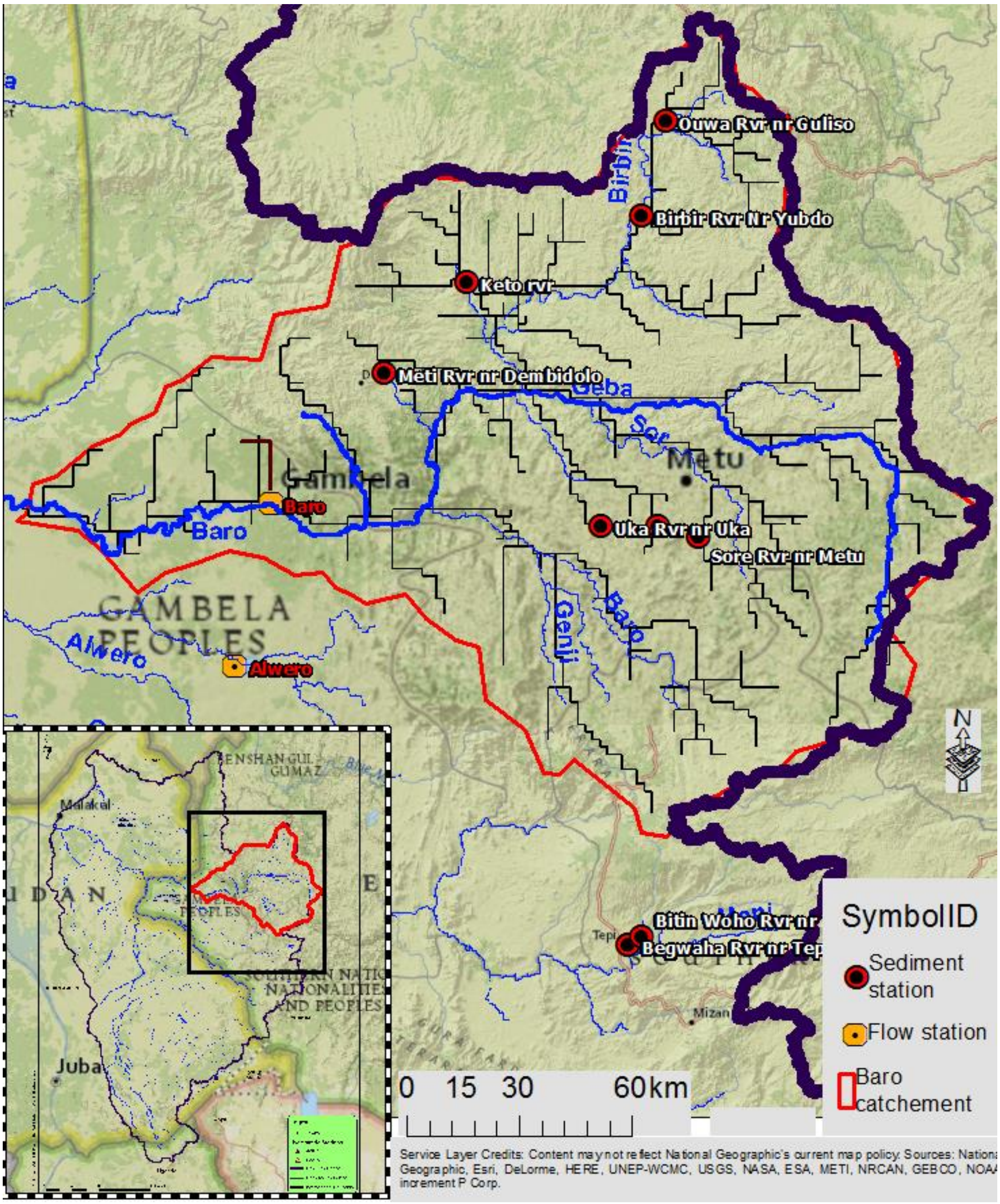

Figure 2-15: Baro River sub-catchment and SHETRAN river links (black) as used in SHETRAN model

Land use variation in the Baro model is shown in Figure 2-16 with arable, shrub and forest being dominant.

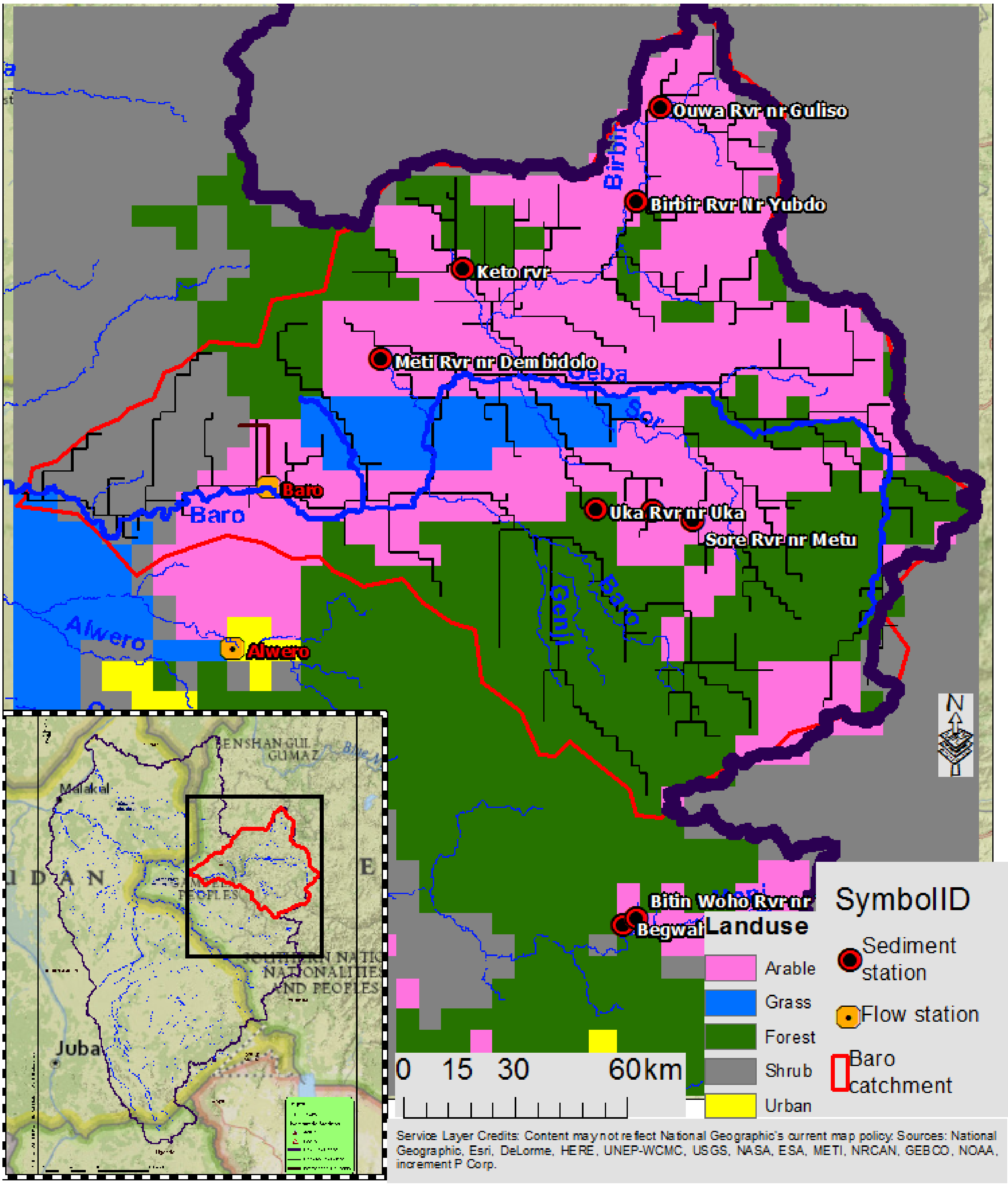

Figure 2-16: Baro River sub-catchment land use and SHETRAN river links (black) as used in the SHETRAN model

2.3.1.1 Baro flow calibration

The model was set up and calibrated against flow records for the period between 1952 to 1960 and validated for the period 1989 to 1992. Parameters that varied from the model default are shown in

Appendix 12. The main channel hydraulic roughness was calibrated with a Manning n value of 0.05 and overland value of 0.02 to 0.06, dependent on the vegetation type.

Saturated conductivity was calibrated to 30 m/day for the upper 1m horizon of soil and 5 m/day for the lower 14 m horizon. These values are high but within the acceptable limits.

Figure 2-17 shows calibration flows with the validation graph in Figure 2-18. A r-square of 0.78 was achieved at the Baro-Gambela gauging station for the whole simulation period (1952 to 1992) and the resultant simulation flow graph is shown in Figure 2-19. Note that the model output is daily simulated flows which are plotted as montly flows to compare with the montly flows.

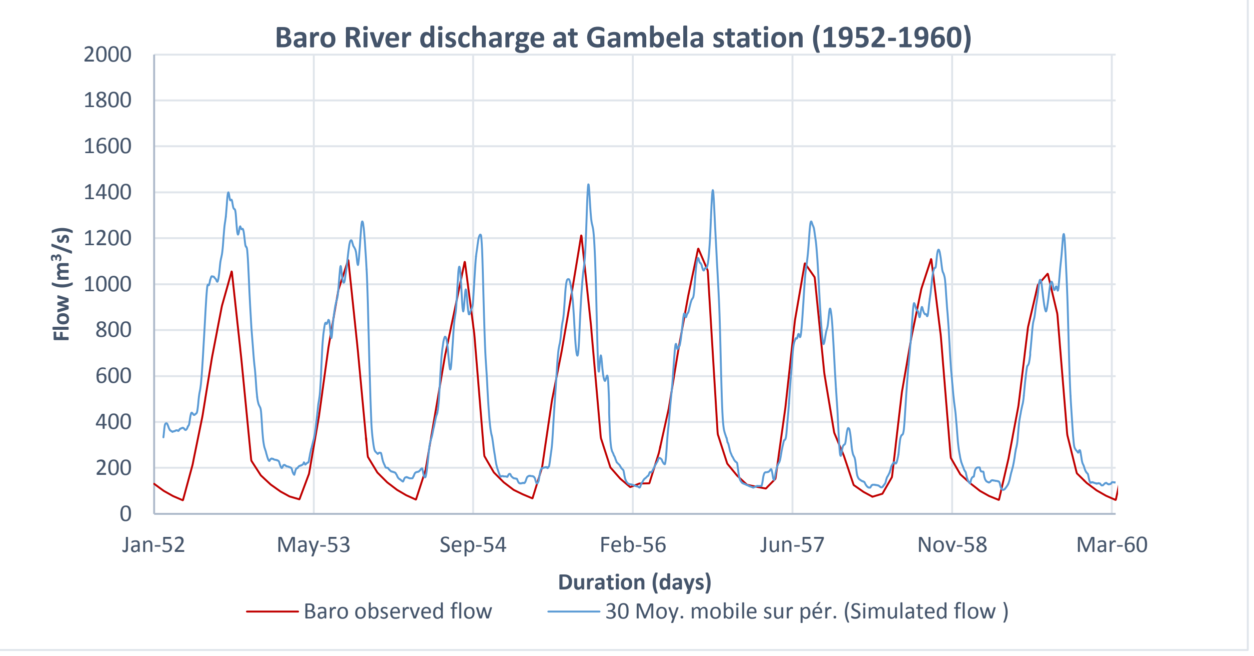

Figure 2-17: Baro River calibration at the Gambela flow gauging station (plotted as monthly flows)

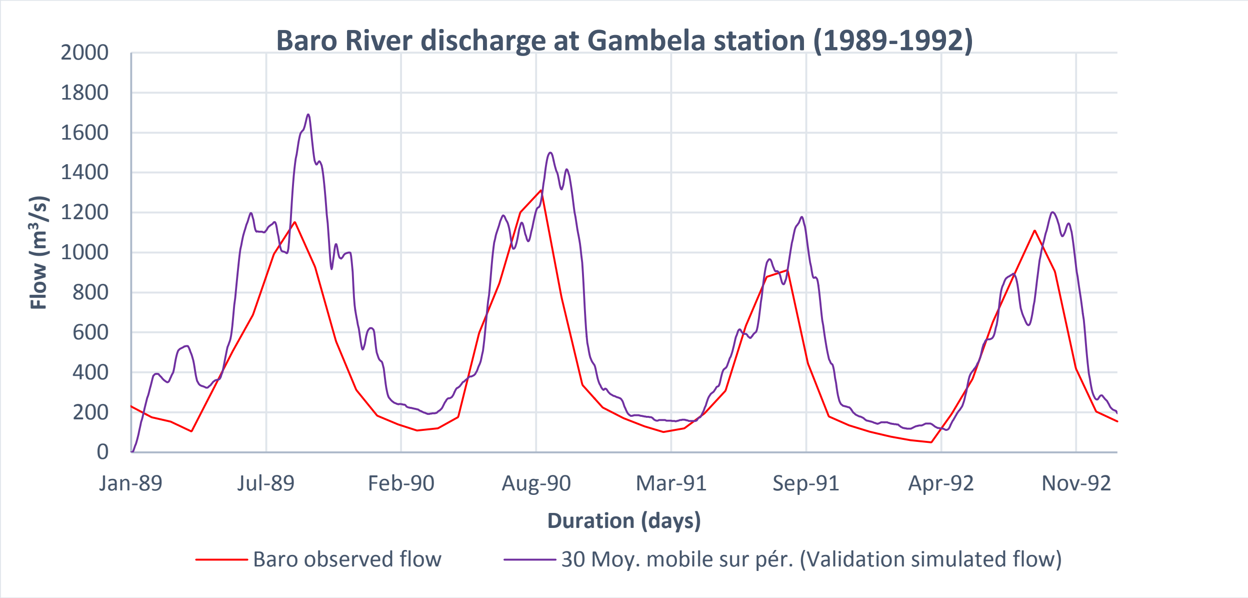

Figure 2-18: Baro River validation at the Gambela flow gauging station (plotted as monthly flows)

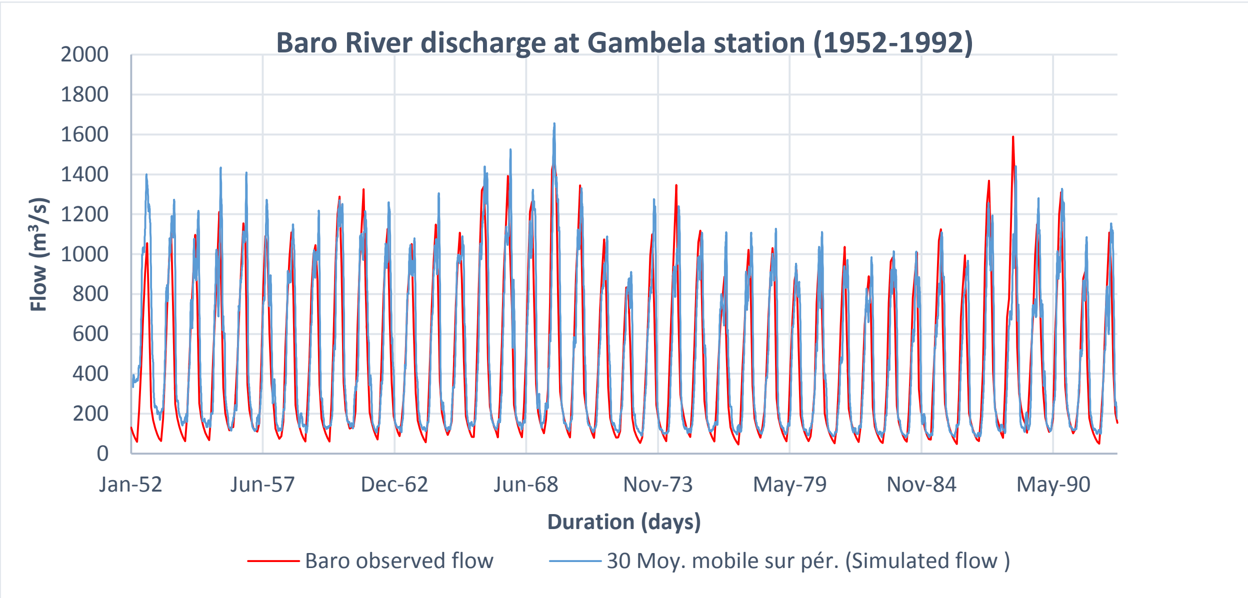

Figure 2-19: Baro River simulated long term flows at the Gambela station (plotted as monthly flows)

2.3.1.2 Sediment calibration

Seven-grain sizes were used with the initial size composition is as shown in

Table 2-3. The grain size classes were based on the SHETRAN manual while the soil composition values were adopted from the SELKHOZPROMEXPORT (1990) report to conform to clay loam type of soil.

Table 2-3 Baro River soil composition by size group

Grain size (mm)	0.1	0.37	0.89	1.5	2.2	3.2	8
Soil composition (%)	60	20	10	5	3	2	0

Sediment transport data was available at eight sampling stations in the catchment with their locations shown in Figure 2-16 and their date, flow and sediment load in Appendix 19 (SELKHOZPROMEXPORT, 1990).

Sediment rating curves were plotted for the period where corresponding measured data was available. The model was calibrated and the resulting graphs for each station are shown in Figure 2-20 to Figure 2-27.

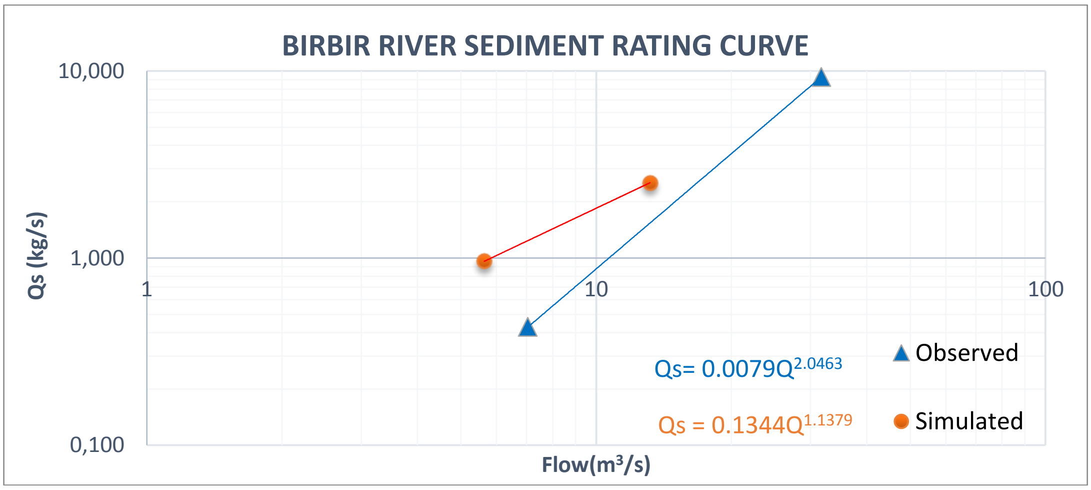

Figure 2-20: Birbir River sediment rating curve

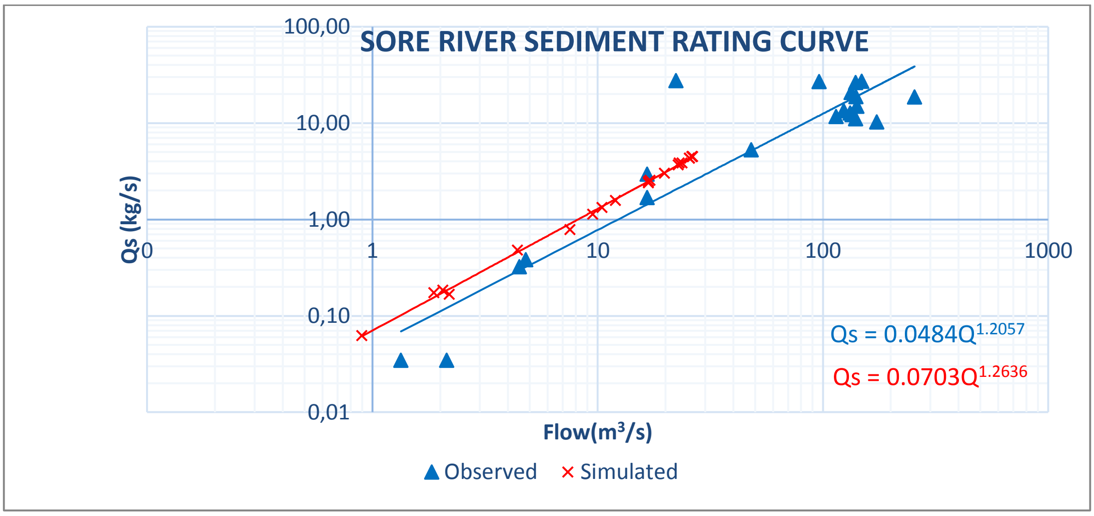

Figure 2-21: Sore River sediment rating curve

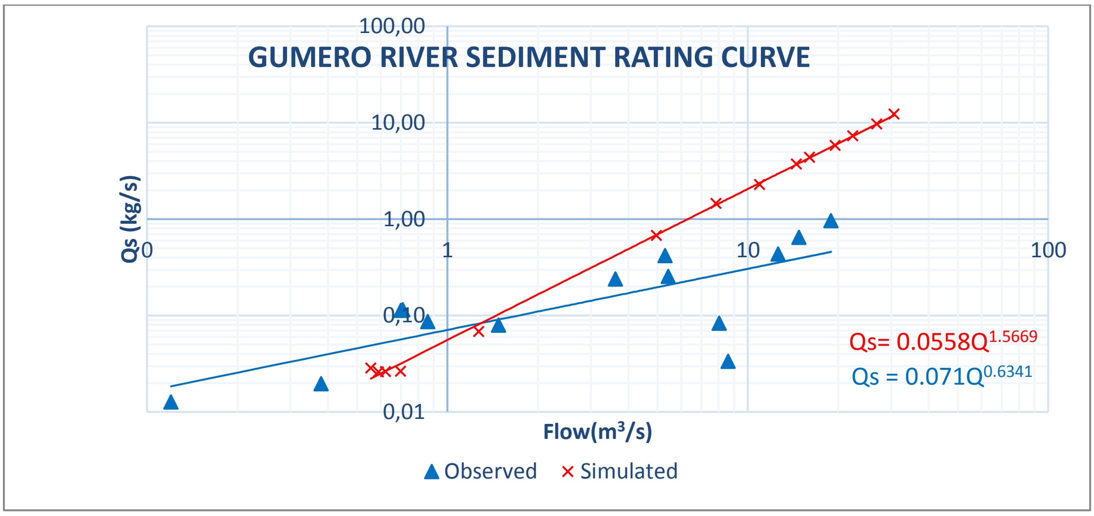

Figure 2-22: Gumero River sediment rating curve

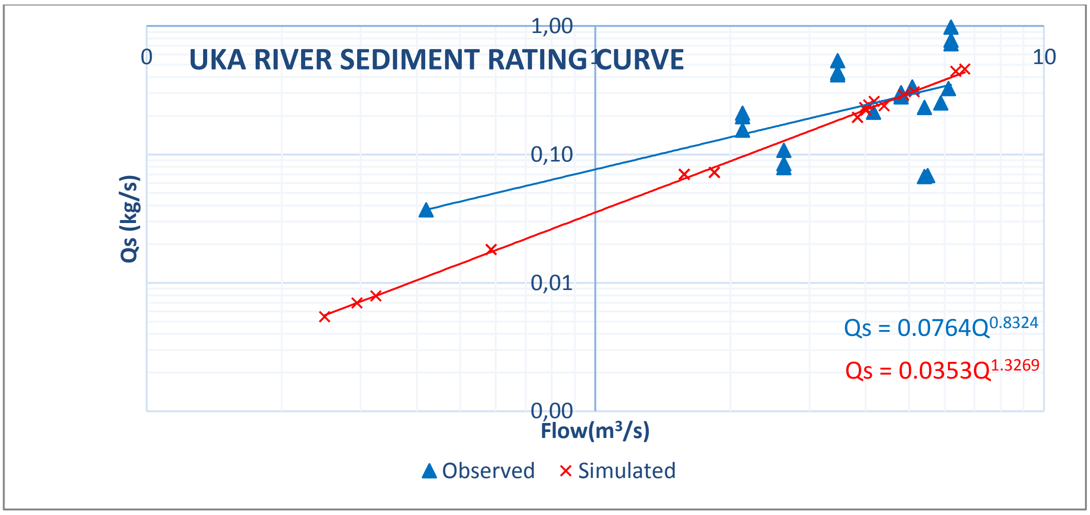

Figure 2-23: Uka River sediment rating curve

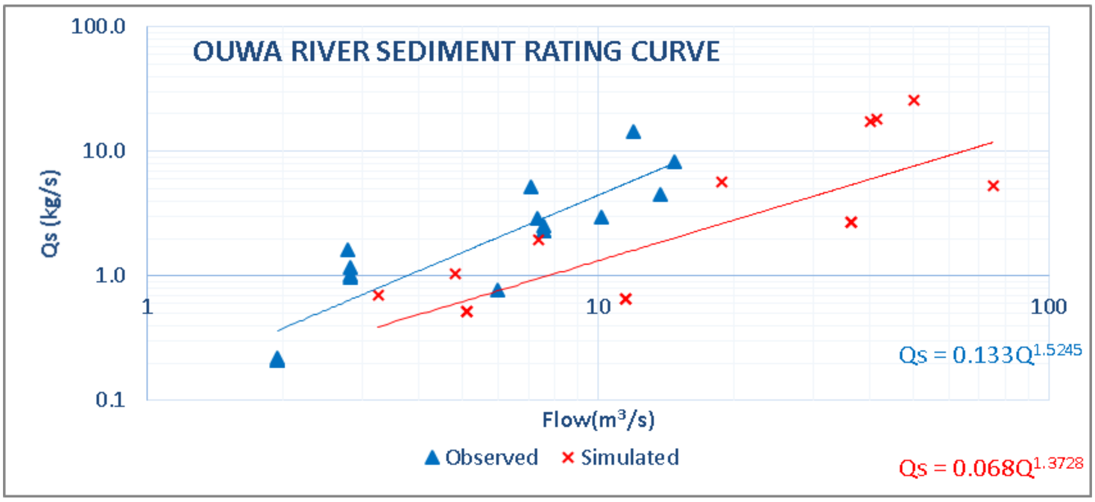

Figure 2-24: Ouwa River sediment rating curve

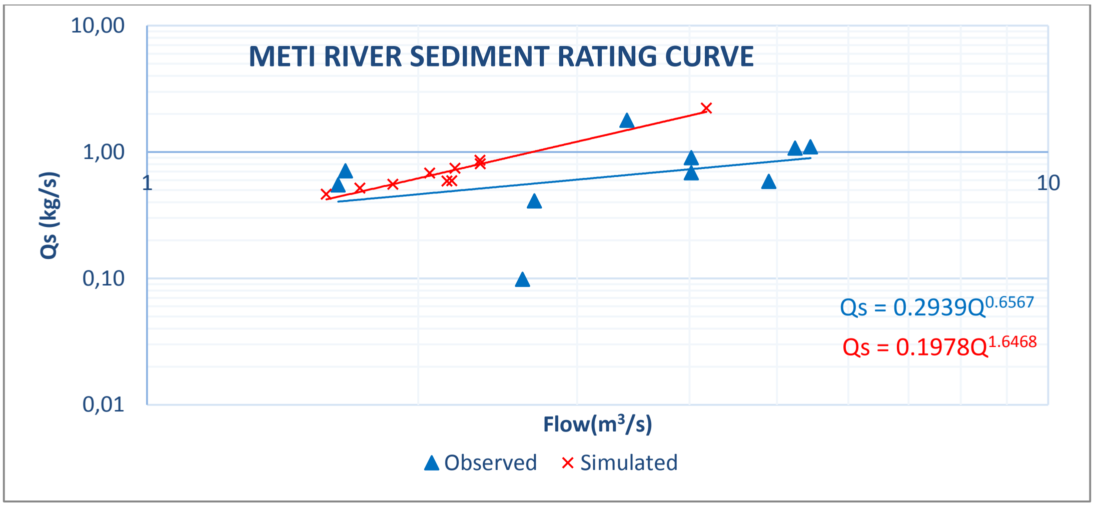

Figure 2-25: Meti River sediment rating curve

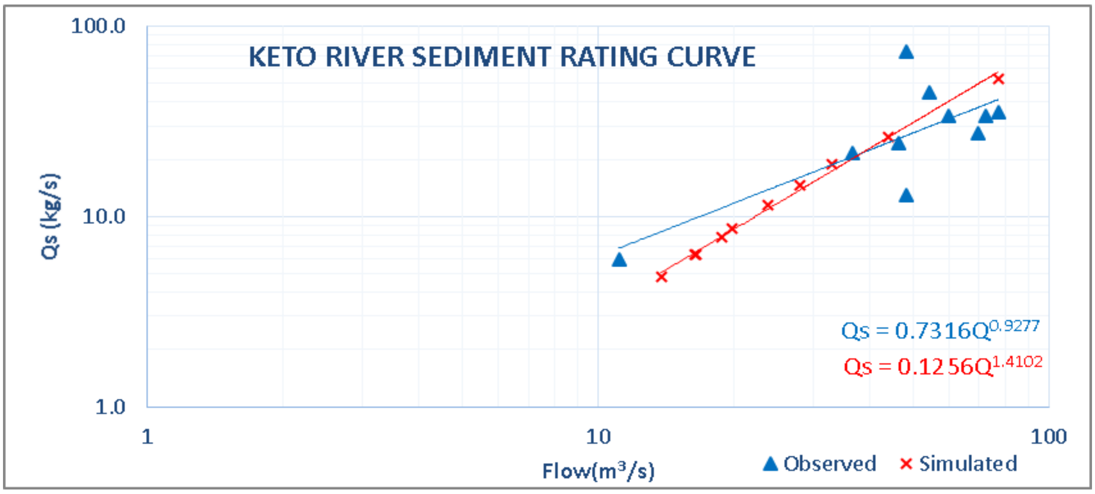

Figure 2-26: Keto River sediment rating curve

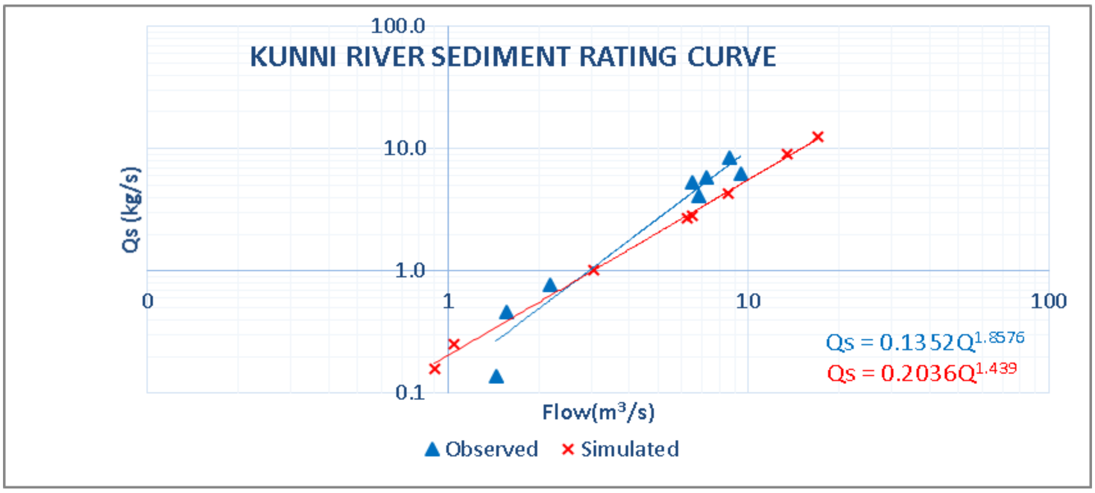

Figure 2-27: Kunni River sediment rating curve

The resulting sediment loads simulated at the Baro Gambela station is shown in Figure 2-28.

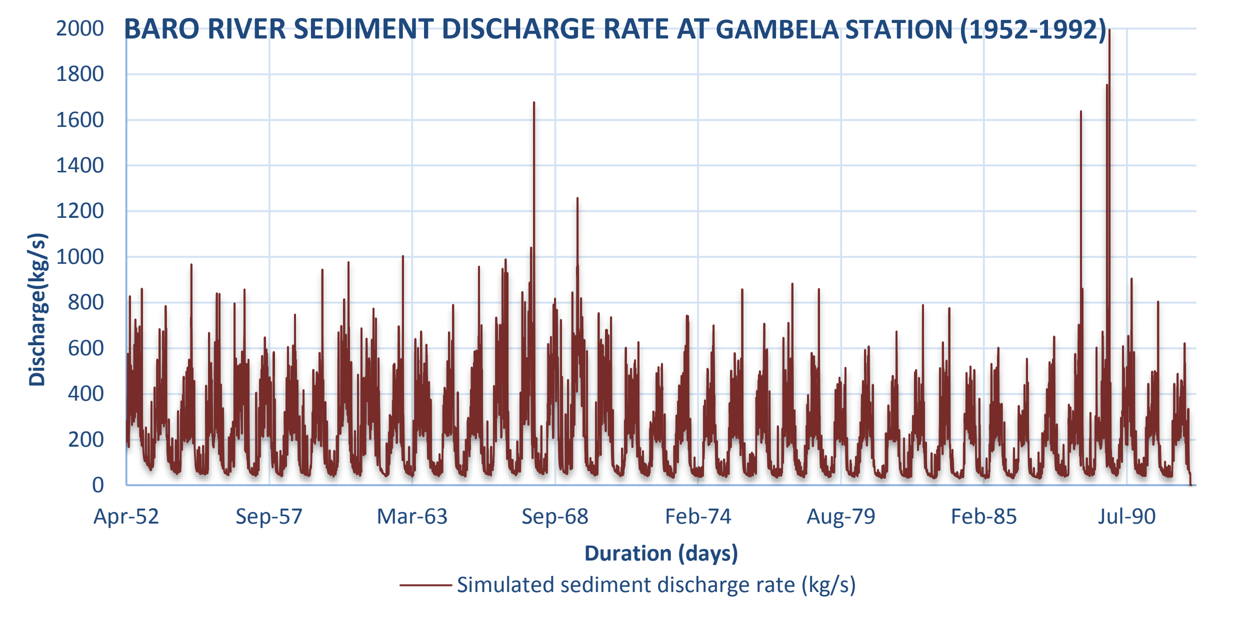

Figure 2-28: Baro River simulated sediment discharge rate at Gambela gauging station

Taking April to March as the hydrological year, the catchment sediment yield was calculated and compared to previous study results. This is shown in Table 2-4**Erreur ! Source du renvoi introuvable.**. There is a large difference in the catchment area for the first station, and the MAFs for the first two stations differ significantly. The sediment yields of this study are generally higher than the previous study values for this catchment. The sediment yields of this study were however calibrated against the limited field data and were simulated for a 40 year hydrological period. Therefore the sediment yields of this study are more reliable.

Table 2-4: Comparison of simulated sediment yields with previous studies

	Previous studies (SELKHOZPROMEXPORT, 1990)			**Simulated**		
River Station	**Area (km2)**	**Mean annual flow (m^3/s)**	**Annual Sediment Load ($t/km^2.a$)**	**Area (km2$^)$**	**Mean annual flow (m^3/s)**	**Annual Sediment Load ($t/km^2.a$)**
Sor nr. Metu	1622*	50.1	169	276	8.5	178
Geba nr. Suppi	3894	54.8	75	3894	92.7	495
Uka at Uka	52	1.3	50	70	1.4	44
Gummero nr. Gore	106	1.9	32	101	4.7	385
Baro nr. Masha	1400	56.8	155	1388	40.7	507
Genji nr. Gecha	115	4.6	88	111	0.7	449
Keto	1006	17.6	324	1038	14.4	272

Notes: * exact locations of reference not available

2.3.2 Alwero Catchment

Based on 30 arc Dem, a 125 x 95 grid of 1980 m spatial resolution Alwero watershed was delineated covering a total catchment area of 6692 km^2. Figure 2-29 shows the watershed SHETRAN boundary with the basin outlet being the downstream boundary. One gauging station at Alwero with flows record was available to calibrate the catchment. The coordinates of the gauging station are indicated in Appendix 1.

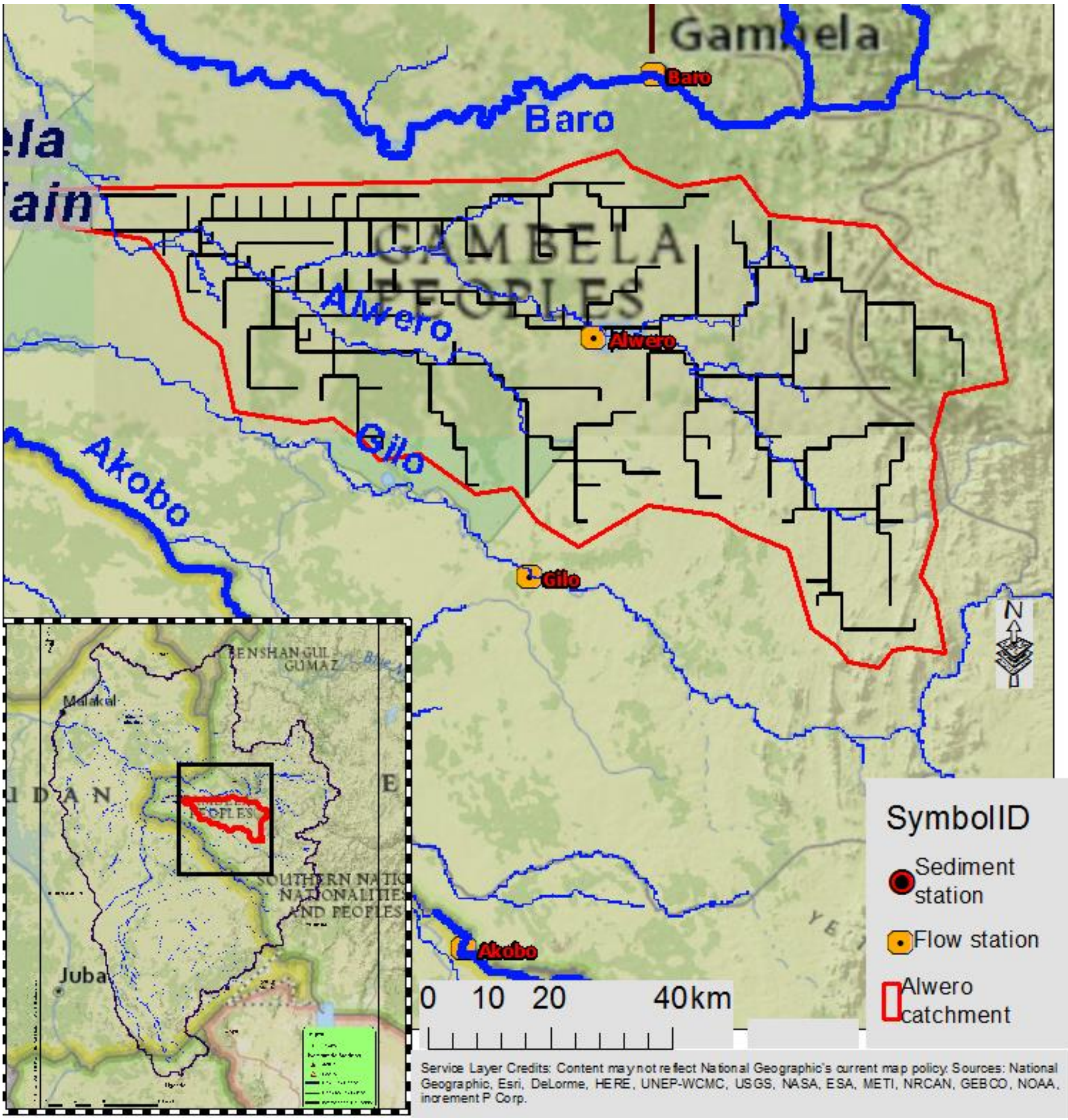

Figure 2-29: Alwero River sub-catchment and SHETRAN river links (black) as used in SHETRAN model

The main land uses in the catchment are shown in Figure 2-30 with forest, urban, grassland, and shrub being dominant.

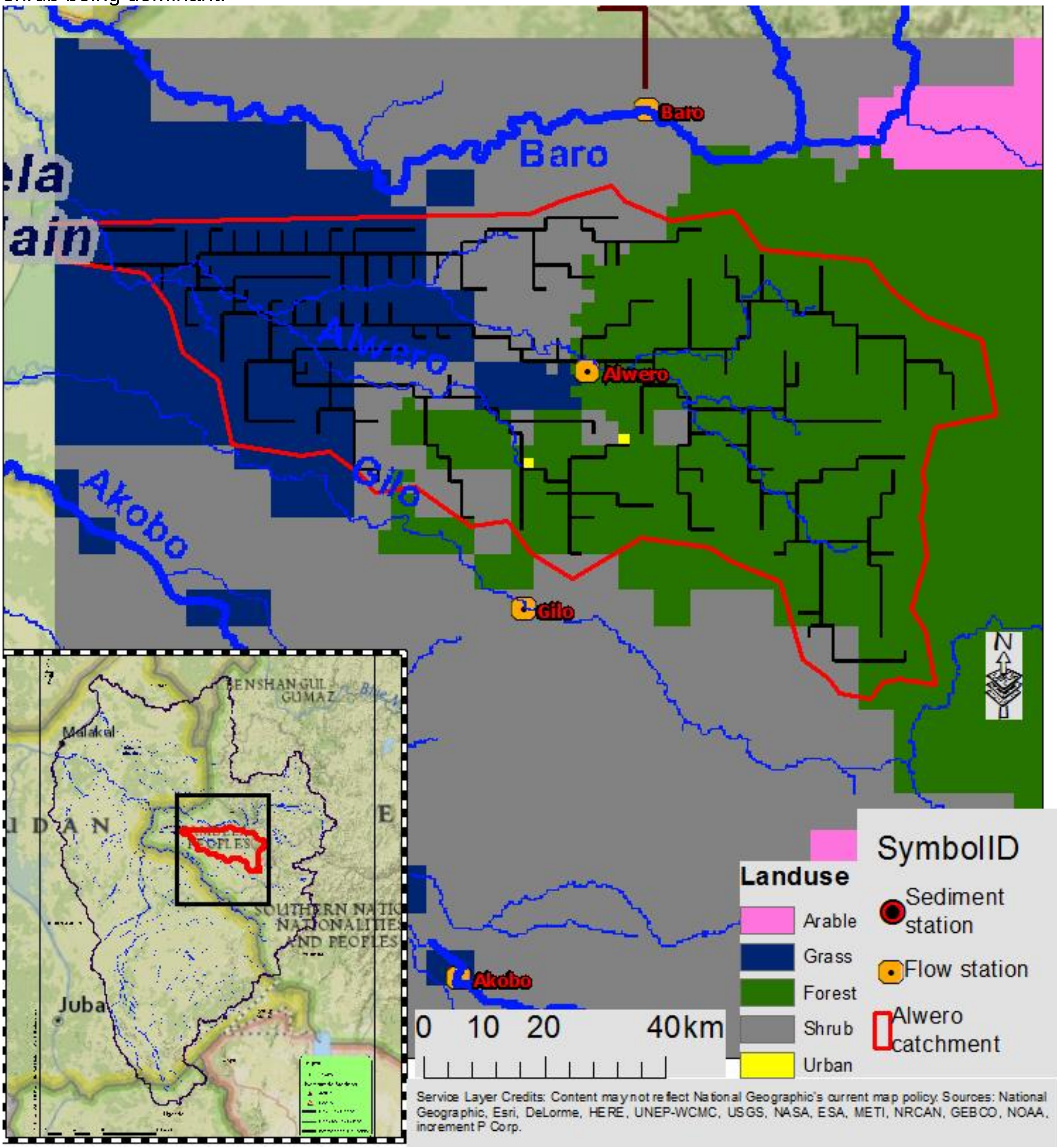

Figure 2-30: Alwero River sub-catchment land use and SHETRAN river links (black) as used in the model

2.3.2.1 Alwero catchment flow calibration

The model was set up and flow-calibrated for the period 1952 to 1960 and validated for the period 1989 to 1992. Parameters that varied from the model default are shown in Appendix 13.

The main channel was calibrated to a Manning value of 0.033 and overland range of 0.02 to 0.06, dependent on vegetation type. Saturated conductivity was calibrated to 20 m/day for the upper 1m horizon of soil and 5 m/day for 14 m lower horizon.

The calibration graph is shown in Figure 2-31 with the validation graph shown in Figure 2-32. Figure 2-33 shows the simulated long term flows.

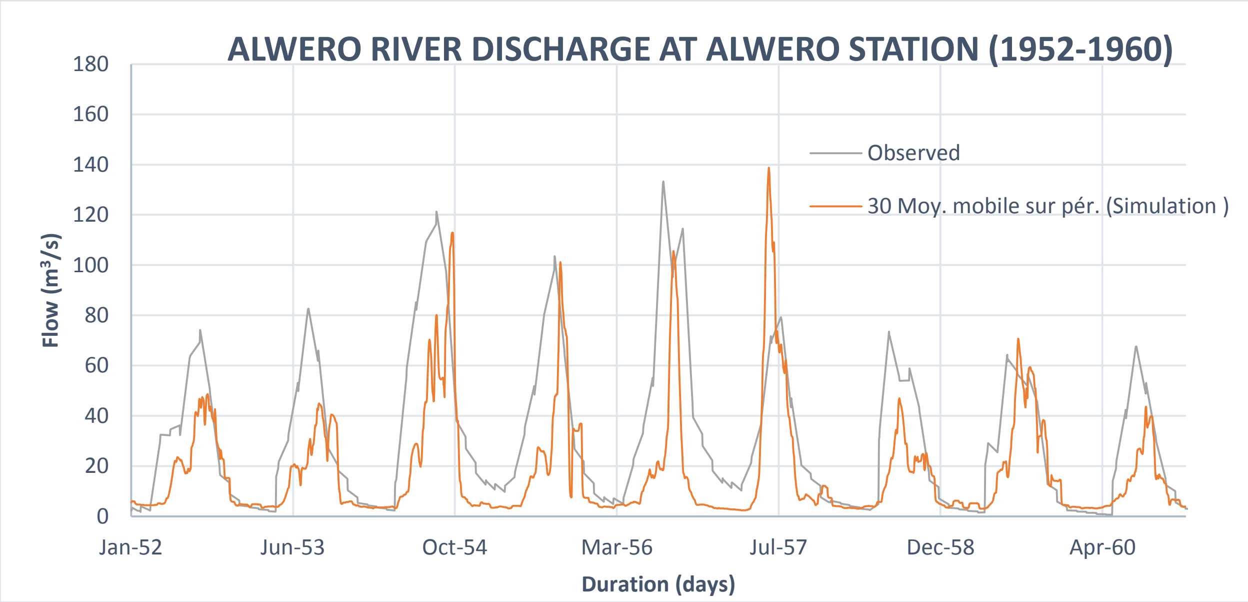

Figure 2-31: Alwero River calibration at Alwero station (Plotted as monthly flows)

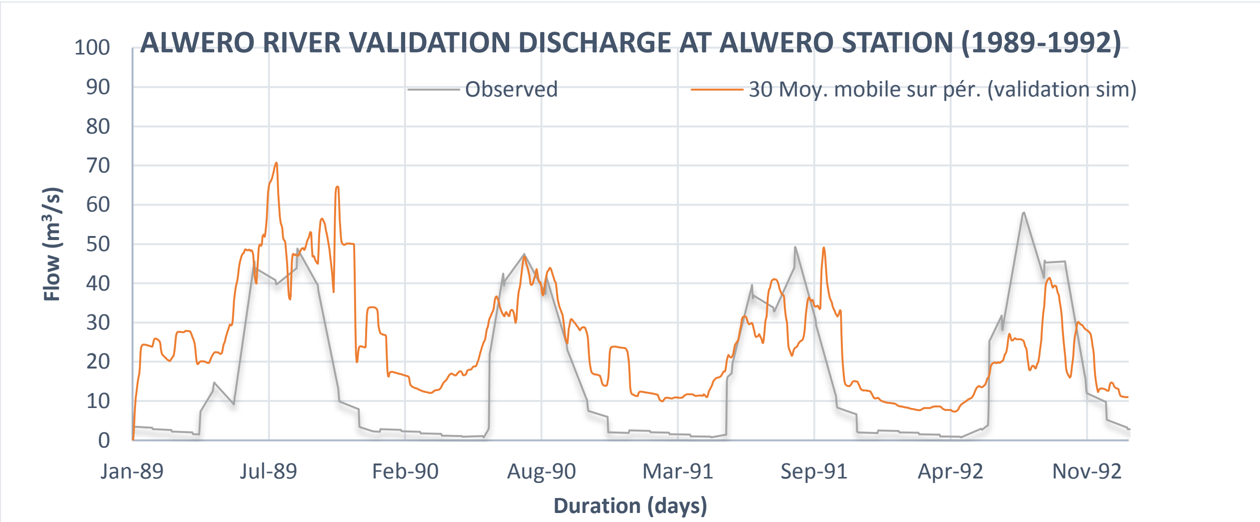

Figure 2-32: Alwero River validation at Alwero (Plotted as monthly flows)

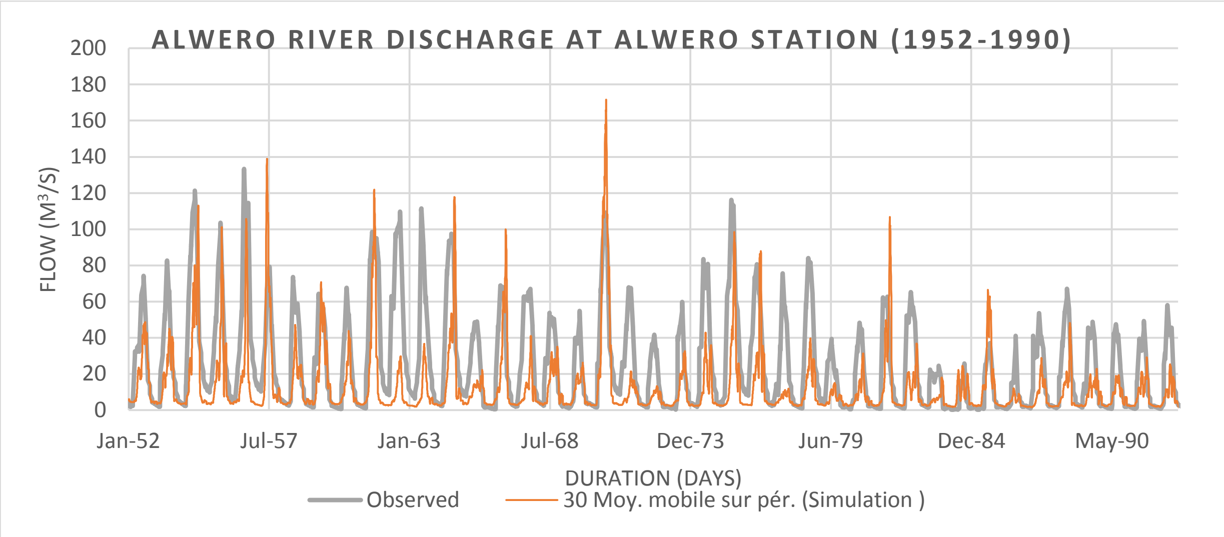

Figure 2-33: Alwero River simulated long term flows at Alwero station (plotted as monthly flows)

2.3.2.2 Alwero sediment modelling

No sediment transport data was available for this catchment and therefore the calibrated neighbouring Baro River catchment SHETRAN parameters were used. Figure 2-34 shows the simulated sediment loads at the Alwero gauging station.

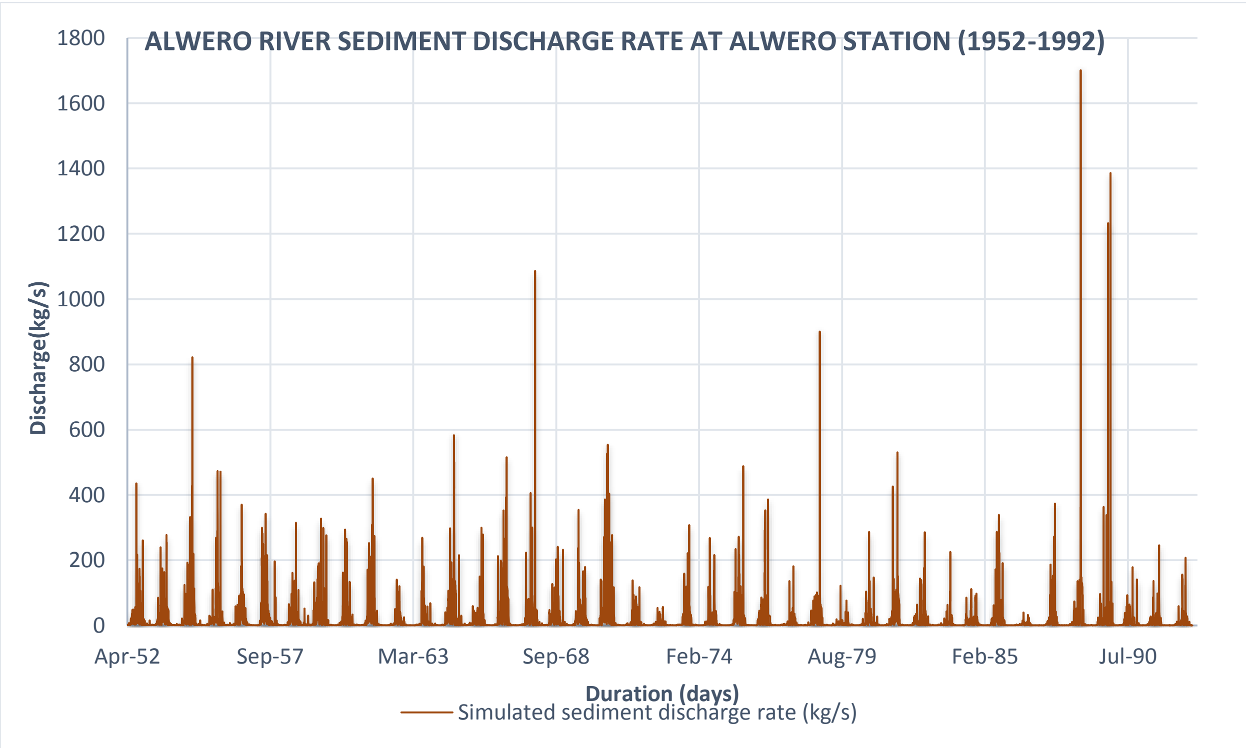

Figure 2-34: Alwero River simulated long term sediment loads at Alwero

The simulated discharge-sediment load rating curve at the Alwero station is shown in Figure 2-35.

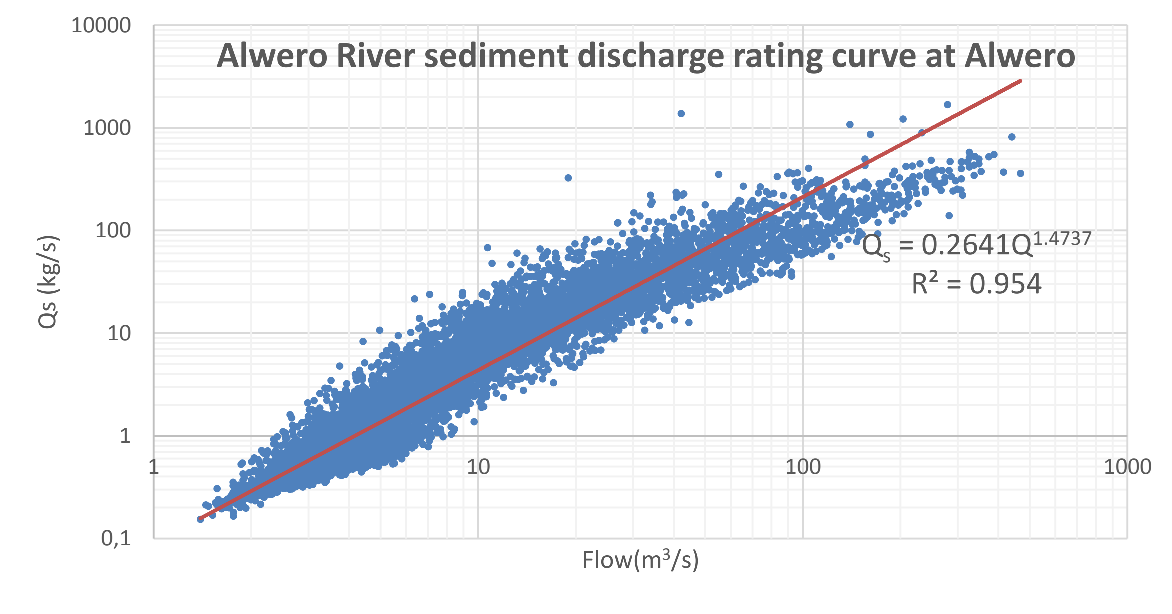

Figure 2-35: Alwero River simulated discharge-sediment load rating curve at Alwero

Taking April to March as the hydrological year, the sediment yield at Alwero station was calculated and results are indicated in Table 2-5.

Table 2-5: Alwero River simulated sediment yield at Alwero station

Catchment area (km^2)	2882
Average Qs (t/day)	1185
Sediment yield (t//km^2.a)	150

2.3.3 Gilo catchment

Based on the 30 arc Dem, a 125 x 95 grid of 1980 m spatial resolution Gilo watershed was delineated covering a total area of 10704 km^2.The watershed shown in Figure 2-36 formed the SHETRAN boundary with the basin outlet being the downstream boundary. Flow data to calibrate the catchment was available at the Gilo gauging station and sediment transport data was available at the Bitin Woho River near Tepi and Begwaha River near Tepi. Their locations relative to the whole catchment are shown in Appendix 11.

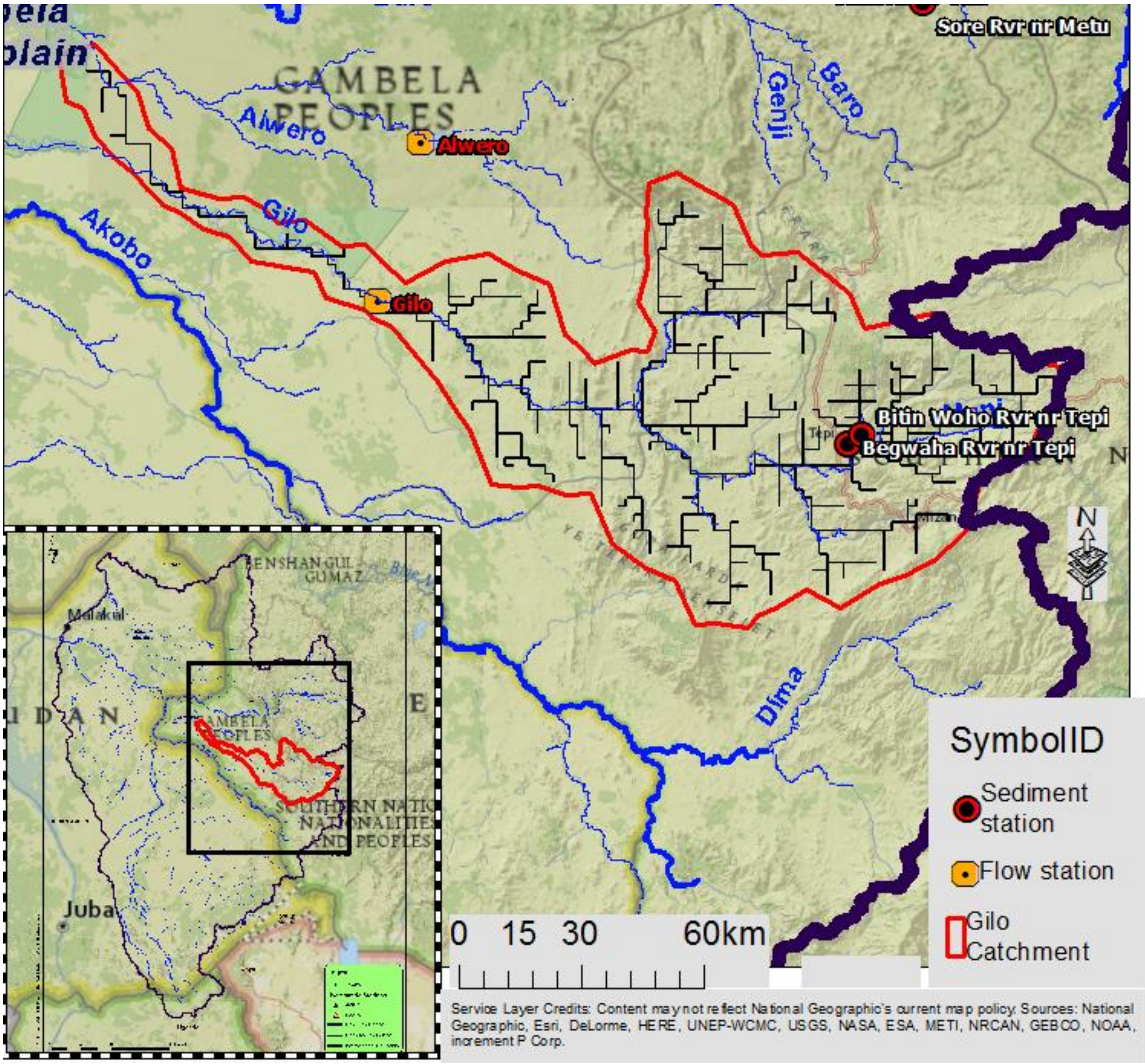

Figure 2-36: Gilo River sub-catchment and SHETRAN river links (black) as used in SHETRAN model

The main land uses in the catchment are shown in Figure 2-37 with forest, grassland, arable farming and shrub being dominant.

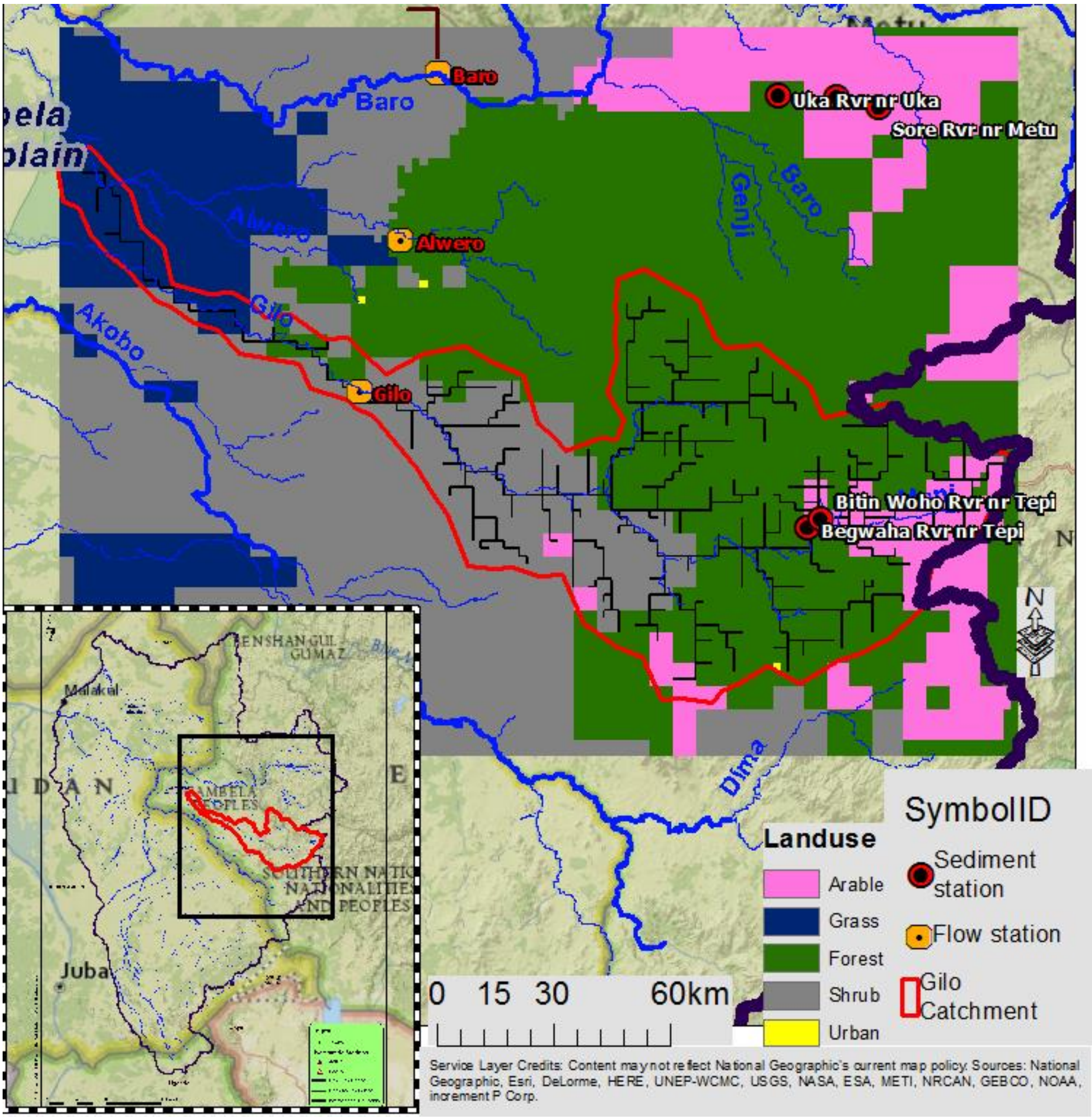

Figure 2-37: Gilo River sub-catchment land use and SHETRAN river links (black) as used in SHETRAN model

2.3.3.1 Gilo River flow calibration

The model was set up and flow-calibrated for the period 1952 to 1960 and validated for period 1987 to 1992. Model parameters that varied from the model default values are shown in Appendix 14. The main channel was calibrated to a Manning n value of 0.05 and overland values of 0.02 to 0.06 dependent on land use.

Saturated conductivity was calibrated to 15 m/day for the upper 1m horizon of soil and 5 m/day for 14 m lower horizon.

The Gilo gauging station calibration graph is shown in Figure 2-38 while the validation graph is shown in Figure 2-39.

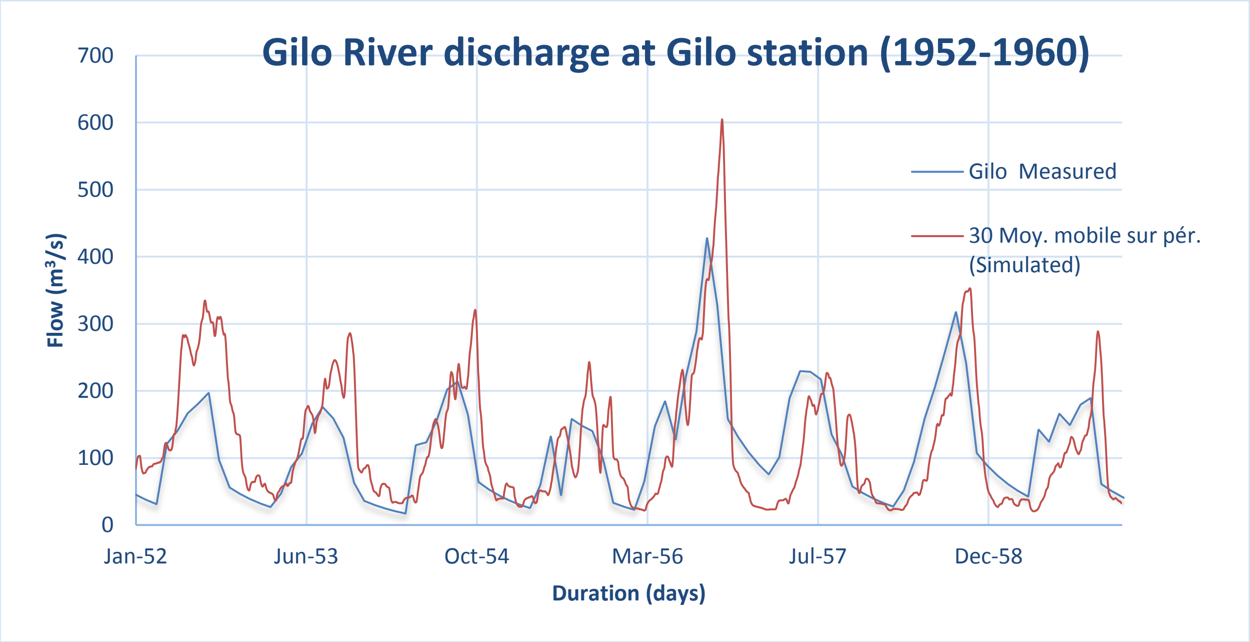

Figure 2-38: Gilo River calibration at Gilo station (plotted as monthly flows)

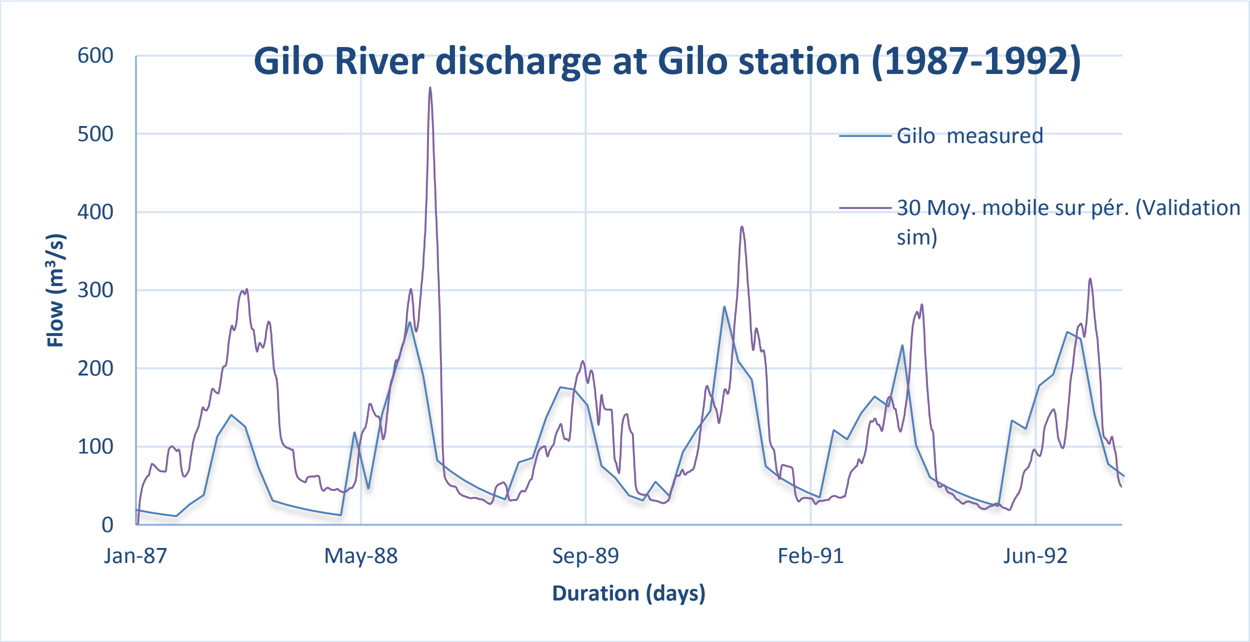

Figure 2-39: Gilo River validation at Gilo station (plotted as monthly flows)

The long term simulation flows for the whole period is shown in Figure 2-40.

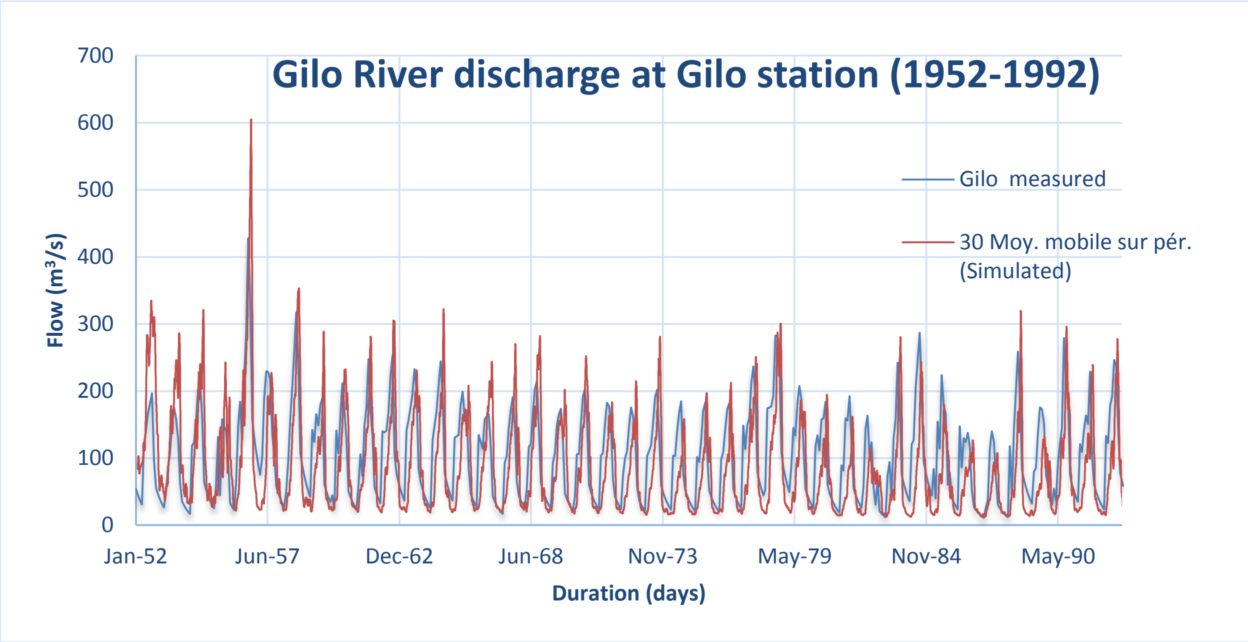

Figure 2-40: Gilo River long-term simulated flows at Gilo (plotted as monthly flows)

2.3.3.2 Sediment transport calibration

Sediment transport data at Bitin Woho River and Begwaha River near Tepi (TAMS_1F, 1997) were available. Coordinates of these sampling stations were not available, but approximate locations were used.

Seven-grain sizes were used with grains less than 0.1 mm taken as fines. The initial composition is shown in Table 2-6 which was adopted from the SELKHOZPROMEXPORT (1990) report to conform to clay loam type of soil.

Table 2-6 Gilo River soil composition by size group

Grain size (mm)	0.1	0.37	0.89	1.5	2.2	3.2	8
Soil composition (%)	60	20	10	5	3	2	0

A sediment discharge-sediment load rating curve was plotted for the data and corresponding simulated sediment discharge rate of similar period. This was used to calibrate the model and resultant graphs are shown in Figure 2-41 and Figure 2-42.

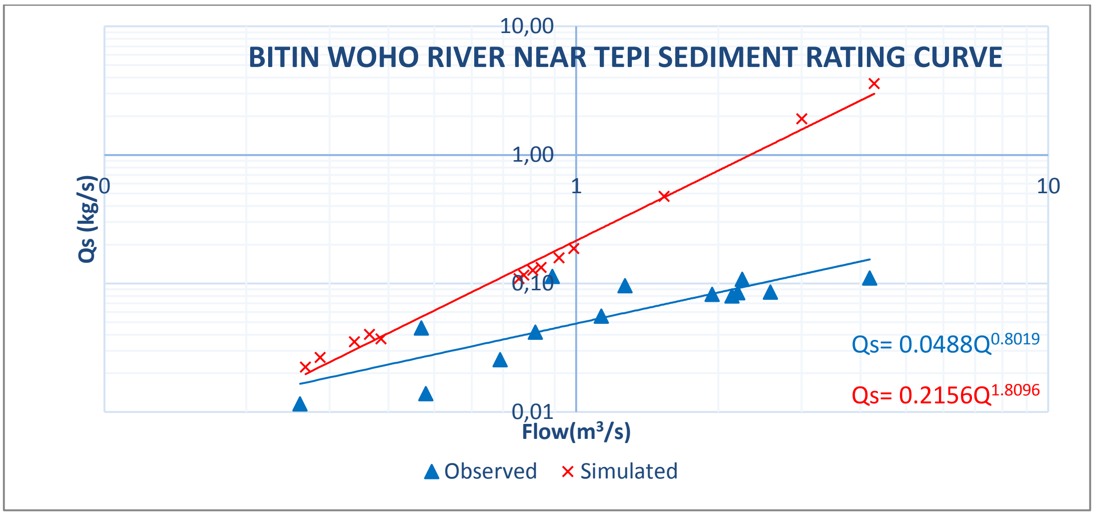

Figure 2-41: Bitin Woho River near Tepi sediment load rating curve

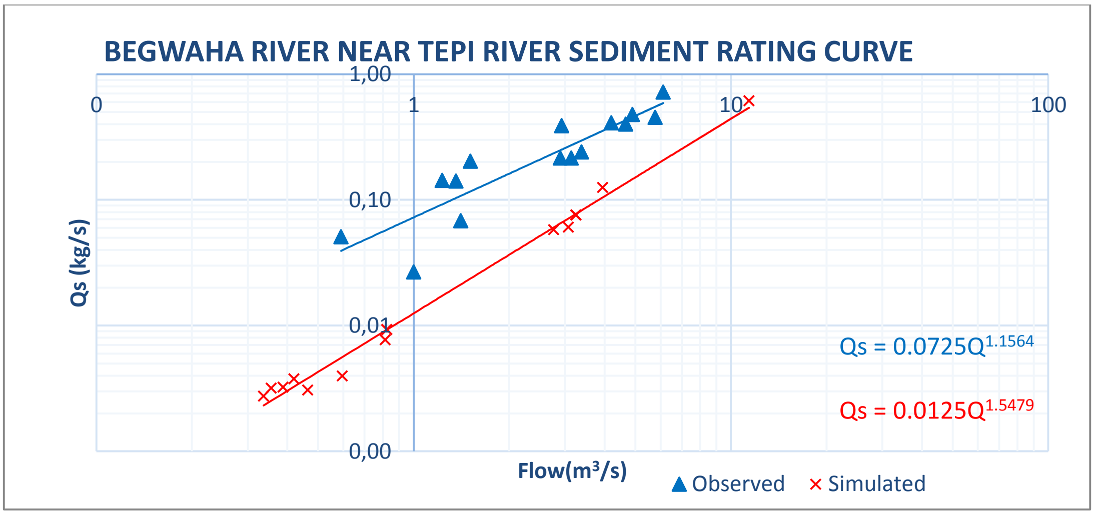

Figure 2-42: Begwaha River near Tepi sediment load rating curve

The simulated sediment loads rate at the Gilo station are shown in Figure 2-43.

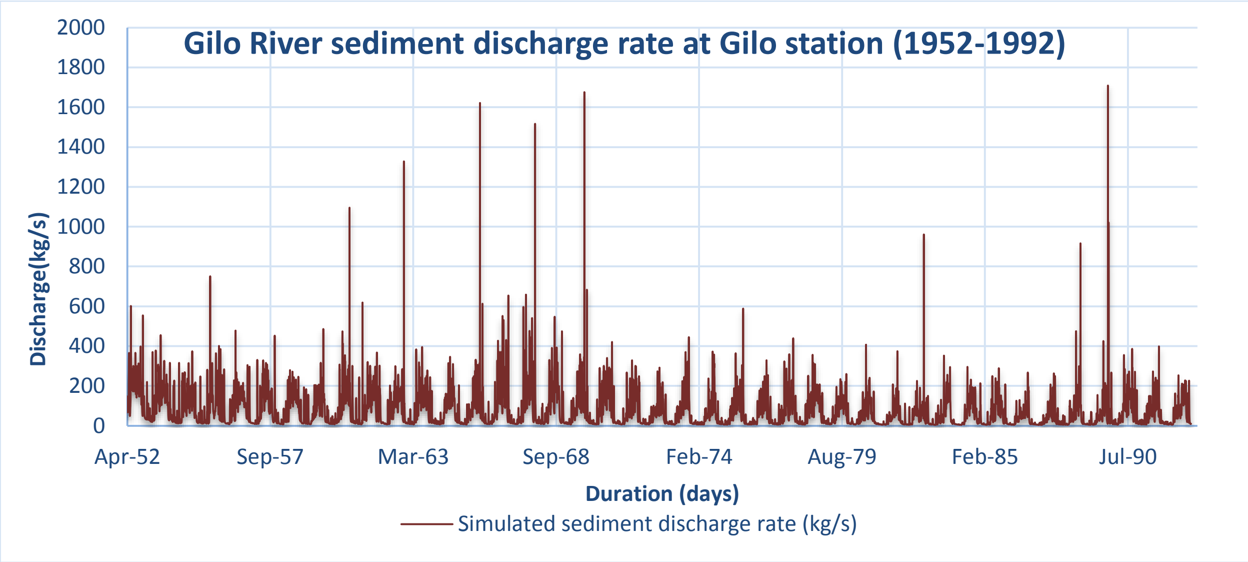

Figure 2-43: Gilo River simulated sediment loads at Gilo

The simulated discharge-sediment load rating curve for Gilo station is shown in Figure 2-44.

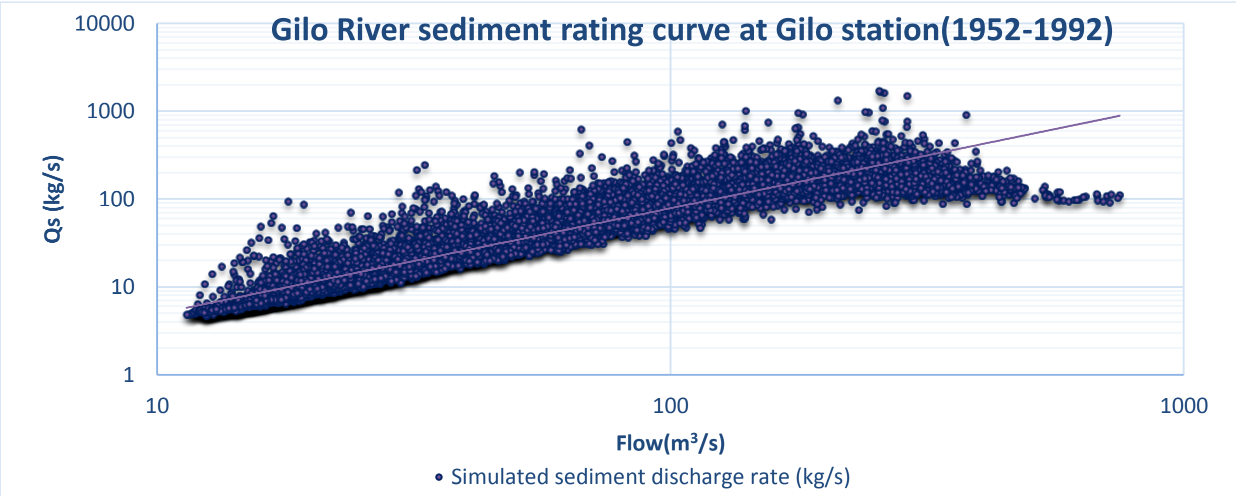

Figure 2-44: Gilo River simulated sediment rating curve at Gilo station

Taking April to March as the hydrological year, the sediment yield at the sampling location was calculated and compared to previous studies. Table 2-7 shows the resultant value. The sediment yield calculated for this study is lower than that of the previous study, but is based on a 40 year simulation. Due to the uncertainty of the sampling station location, it is difficult to compare and evaluate the results.

Table 2-7: Gilo catchment sediment yield comparison with previous studies

	Previous studies (SELKHOZPROMEXPORT, 1990)			**Simulated**		
River Station	**Area (km^2)**	**Mean annual flow (m^3/s)**	**Annual sediment load ($t//km^2/a$)**	**Area (km^2)**	**Mean annual flow (m^3/s)**	**Annual Sediment Load ($t/km^2.a$)**
Begwaha River	125	3.33	85	77	0.41	32

2.3.4 Akobo catchment

30 Arc DEM data was used to delineate the Akobo watershed based on the SHETRAN 200x200 grid limitation and 1500 river channel links. 151x95 grid of 1970 m spatial resolution represented the watershed with a total catchment area of 17809 km^2. The watershed formed the model boundary with the river outlet the downstream boundary. Forty years' flow record was available at Akobo gauging station for calibrations purposes, however with no sediment sampling data.

Figure 2-45 shows the Akobo watershed extent and river links as calculated by SHETRAN model.

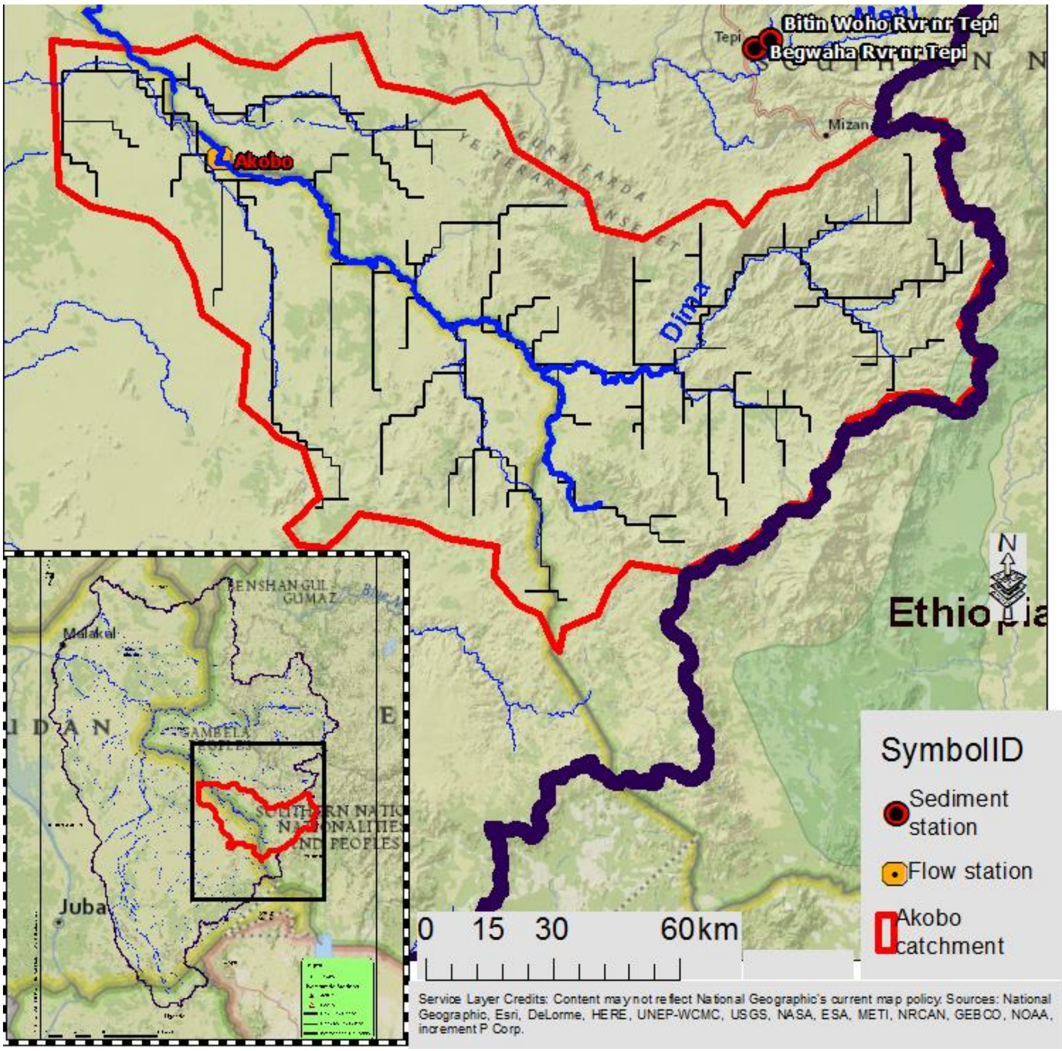

Figure 2-45: Akobo River sub-catchment and SHETRAN river links (black) as used in SHETRAN model

To conform to the SHETRAN library five main land uses were identified: arable, forest, grass, shrub and urban. Their variation in the Akobo watershed is shown in Figure 2-46.

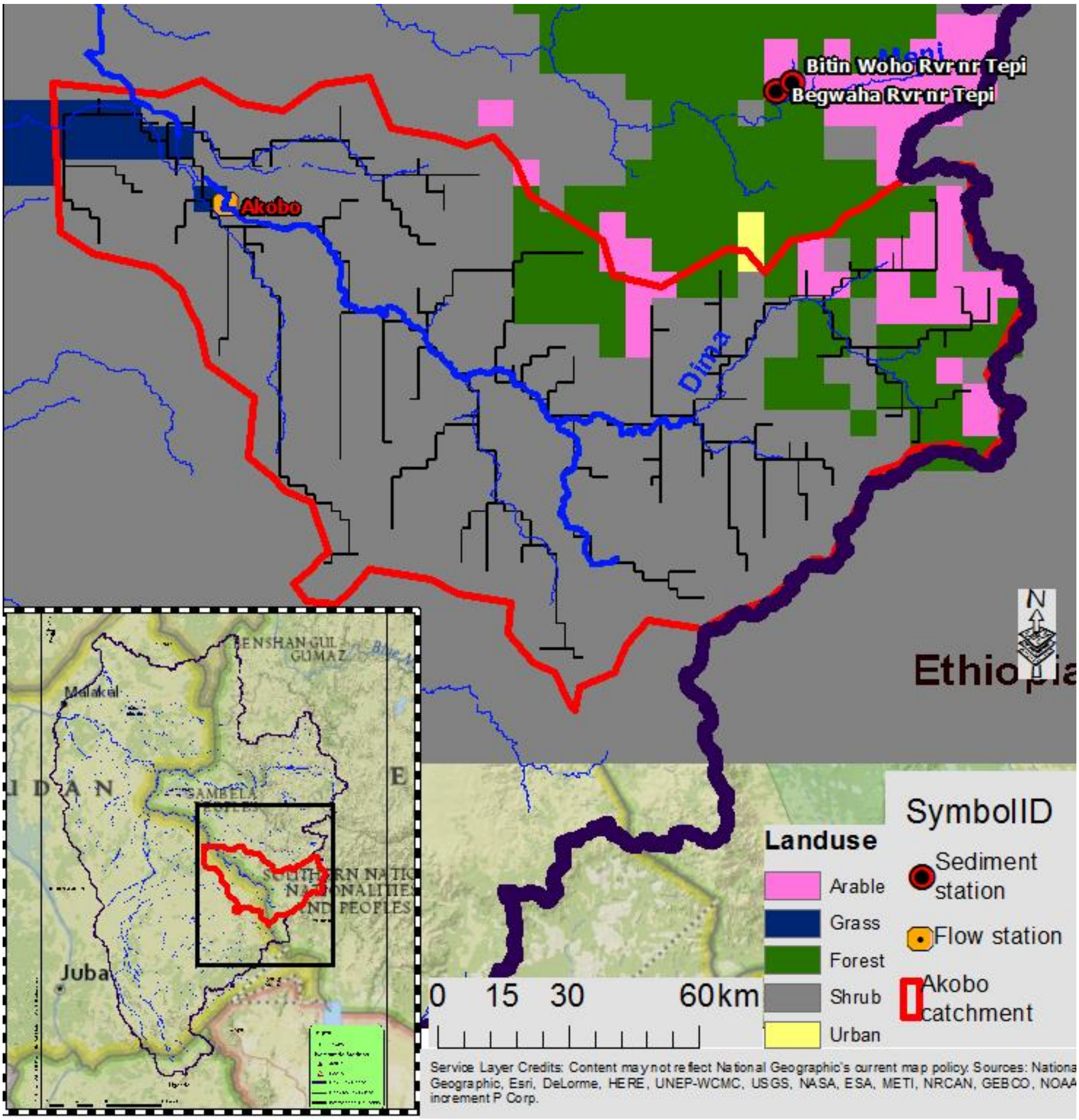

Figure 2-46: Akobo River sub-catchment (red) land use variation as used in SHETRAN model

2.3.4.1 Akobo catchment flow calibration

The model was set up and flow-calibrated for the period 1952 to 1960, and validated for the period 1987 to 1992. Parameters that varied from the model default values are shown in **Appendix 15**. The main channel was calibrated to Manning n value of 0.03 and overland values of 0.02 to 0.06 dependent on land use. Saturated conductivity was calibrated to 15 m/day for the upper 1m horizon of soil and 5 m/day for 14 m lower horizon.

The Akobo gauging station calibration graph is shown in Figure 2-47 while the validation graph is shown in Figure 2-48. The resultant simulated discharge graph is shown in Figure 2-49.

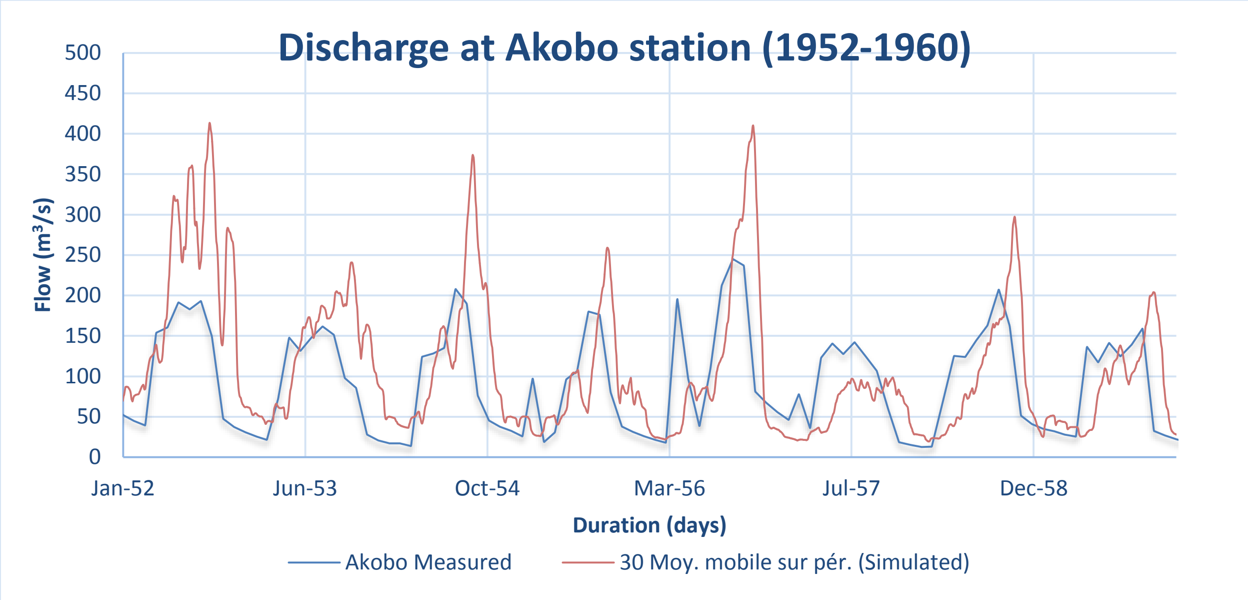

Figure 2-47: Akobo River calibration at Gilo station (plotted as monthly flows)

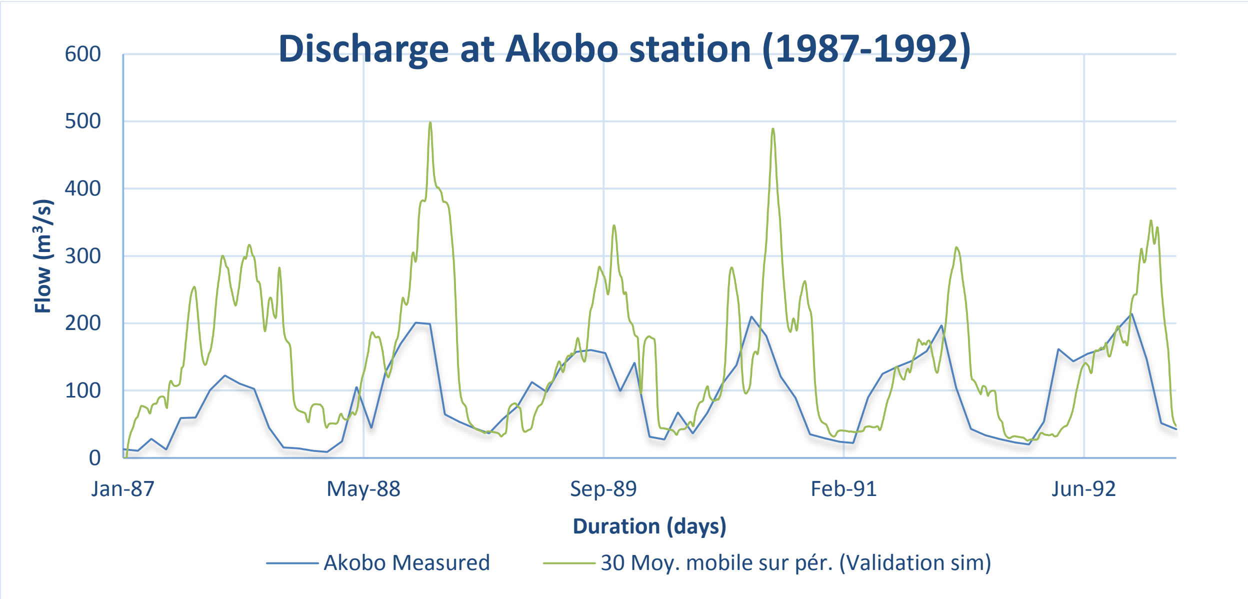

Figure 2-48: Akobo River validation at Akobo station (plotted as monthly flows)

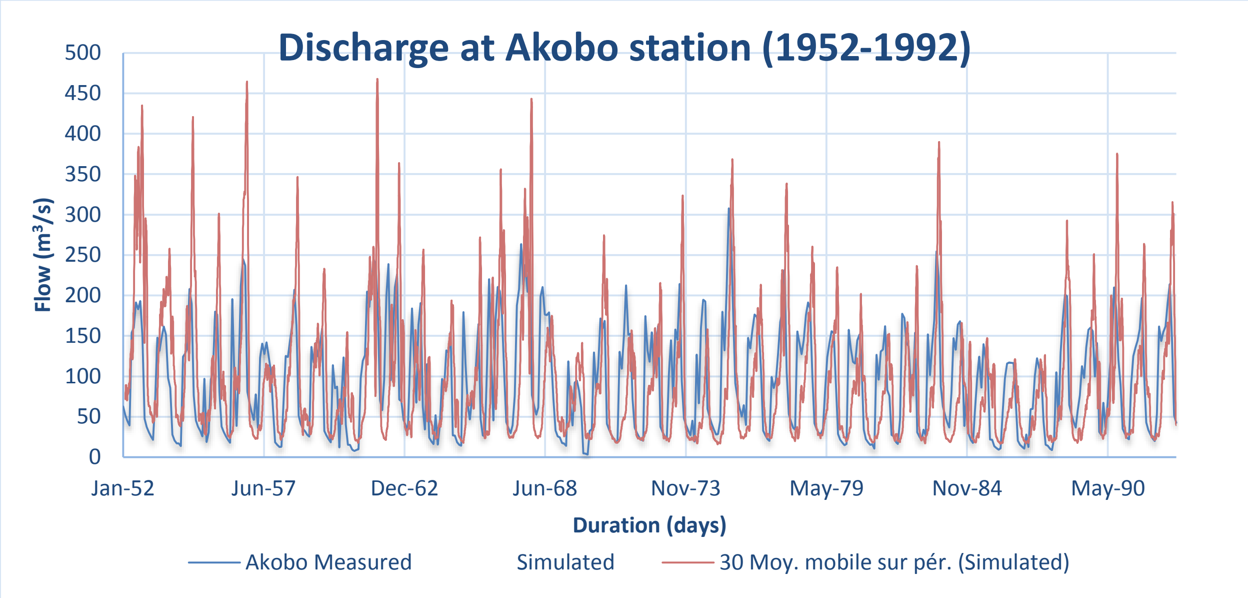

Figure 2-49: Akobo River long-term simulated flows at Akobo station (plotted as monthly flows)

2.3.4.2 Sediment calibration

There was no sediment calibration data available in this catchment thus SHETRAN parameters from the neighbouring Gilo catchment were used. Figure 2-50 shows the simulated sediment discharge rate at the Akobo gauging station.

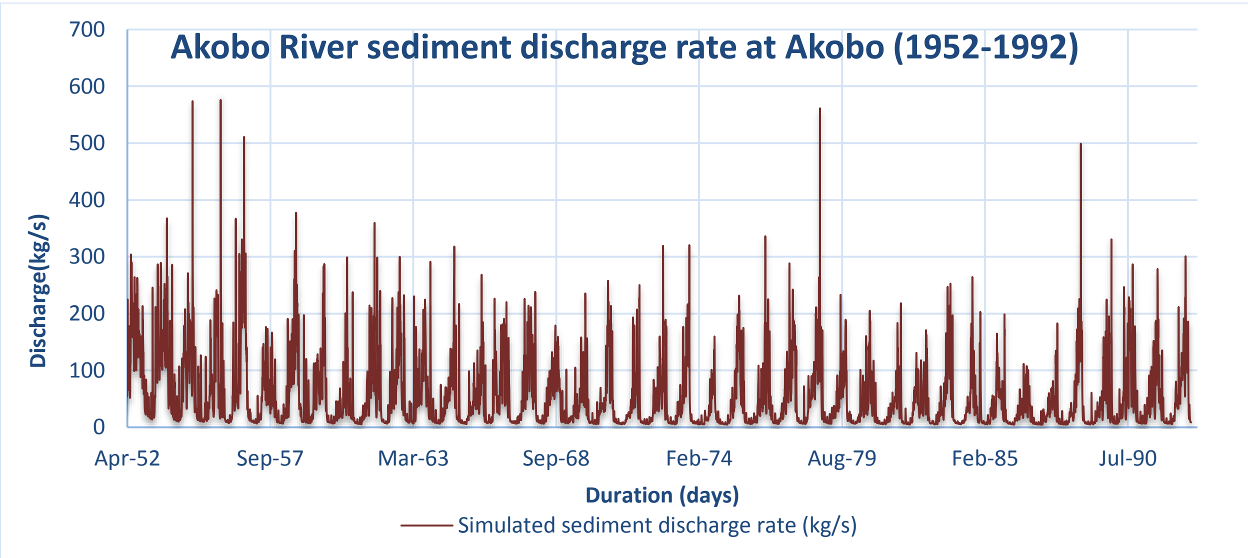

Figure 2-50: Akobo River simulated sediment loads at Akobo

The sediment discharge rating curve for the Akobo station is shown in Figure 2-51.

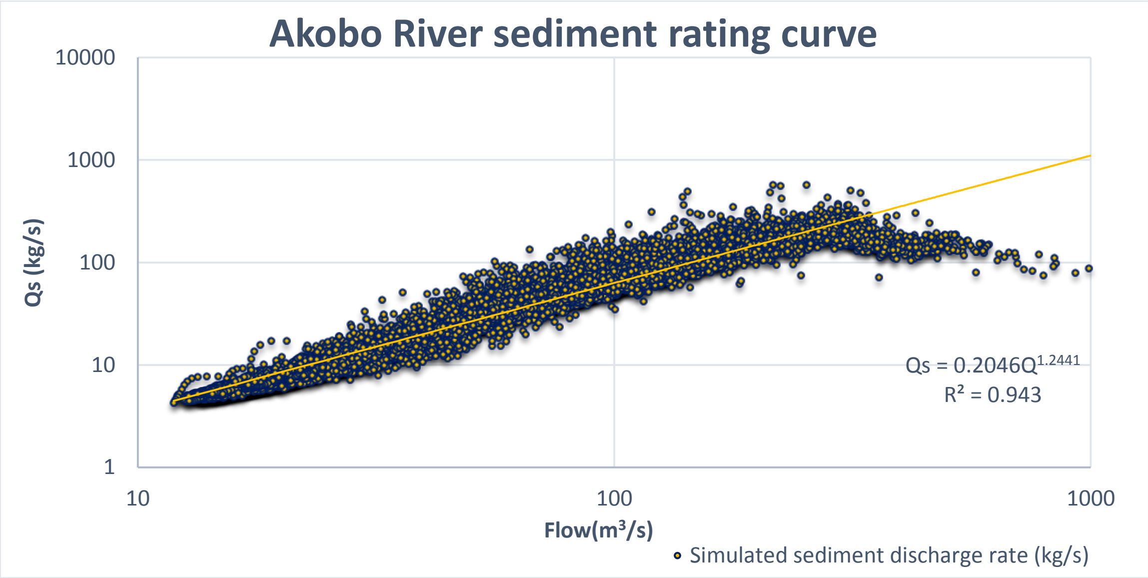

Figure 2-51: Akobo River sediment rating curve at Akobo

Taking April to March as the hydrological year, the sediment yields at the gauging station was calculated and the results are shown in Table 2-8.

Table 2-8: Akobo River sediment yield calculation at Akobo station

Catchment area (km^2)	12514
Average Qs (t/day)	4514
Sediment yield ($t/km^2.a$)	132

2.3.5 Agwei Catchment

Based on 30 arc DEM, the Agwei catchment was delineated within 200x200 SHETRAN grid limitations and 1500 river links limits. Two catchments were delineated, Agwei catchment (196x197 grids) and Lower Pibor (136x144 grids) of 1980 m spatial resolution. These are shown in Figure 2-52. The watershed formed the model outer boundary with the river outlet marking the downstream boundary.

Forty year's flow data record was available at Agwei gauging station for calibration and validation purposes. No sediment sampling data was available for this catchment.

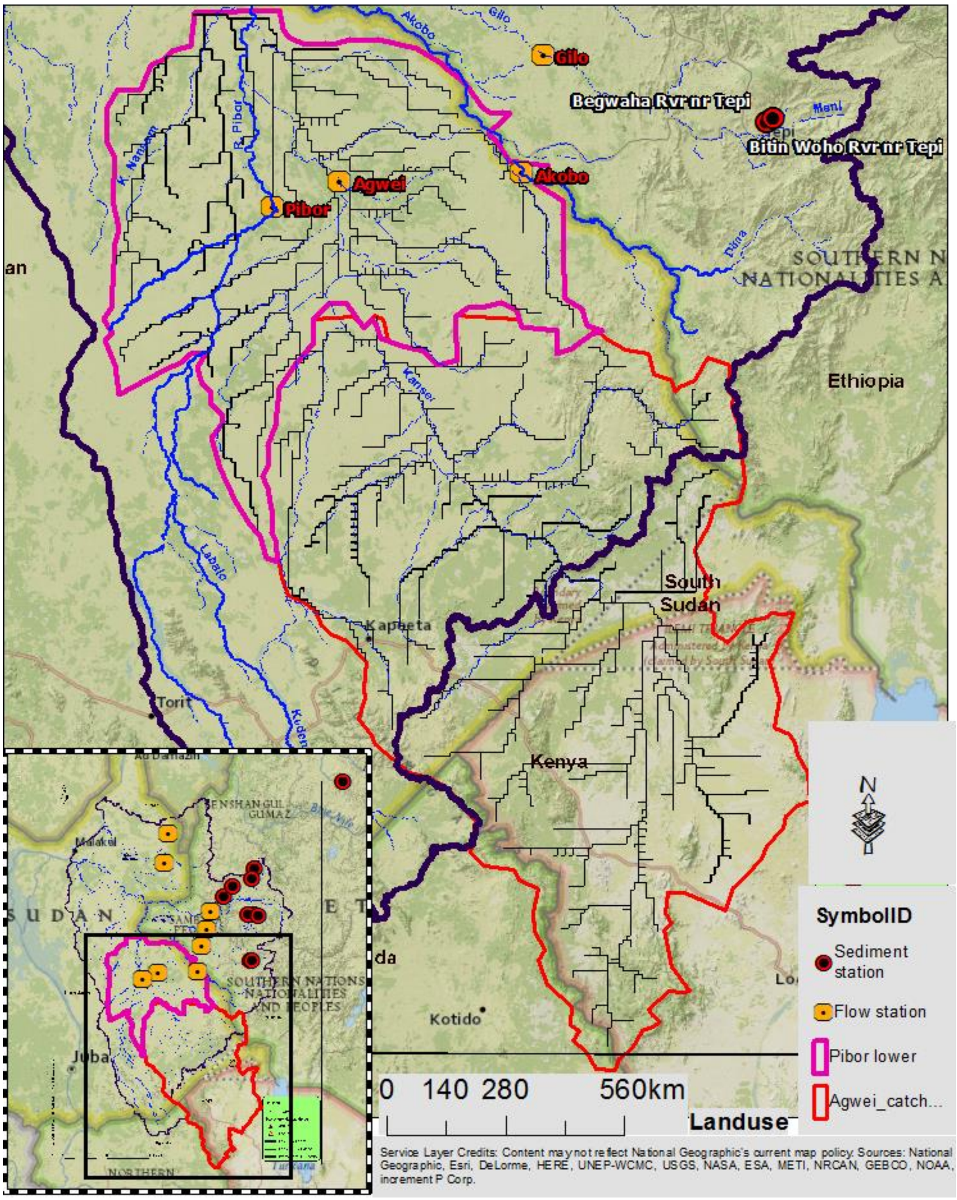

Figure 2-52: Agwei River sub catchment and SHETRAN river links (black) as used in the SHETRAN model

To conform to SHETRAN vegetation library two main land uses were identified: shrub and grass. Their variation in the catchment is shown in Figure 2-53.

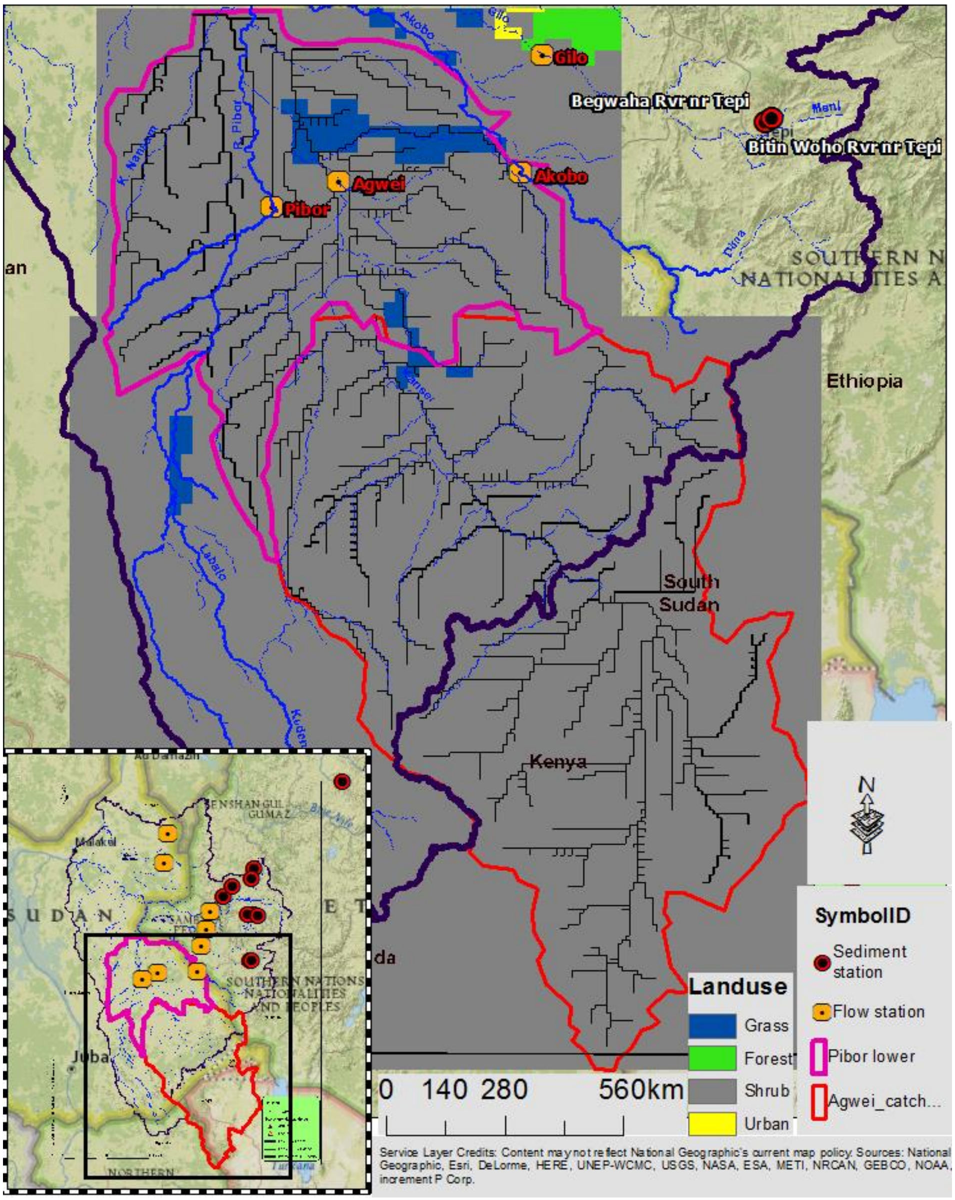

Figure 2-53: Agwei River sub-catchment land use variation as used in SHETRAN model

2.3.5.1 Agwei catchment flow calibration

The model was set up and flow-calibrated for the periods 1952 to 1960 and validated for the period 1989 to 1992. Due to the gauging station being located in the Lower Pibor catchment, SHETRAN parameters were similar with outlet flow at Agwei being the upstream boundary flows of the Lower Pibor. Vegetation parameters that varied from the model default are shown in **Appendix 17**.

The main channel was calibrated to a Manning n value of 0.04 and overland values of 0.02 to 0.06 dependent on land use. Saturated conductivity was calibrated to 15 m/day for the upper 3 m horizon and 5 m/day for the lower 12 m horizon.

The Agwei station calibration graph is shown in Figure 2-54, while the validation graph is shown in Figure 2-55. The simulated flows for 40 years (1952 to 1992) are shown in Figure 2-56).

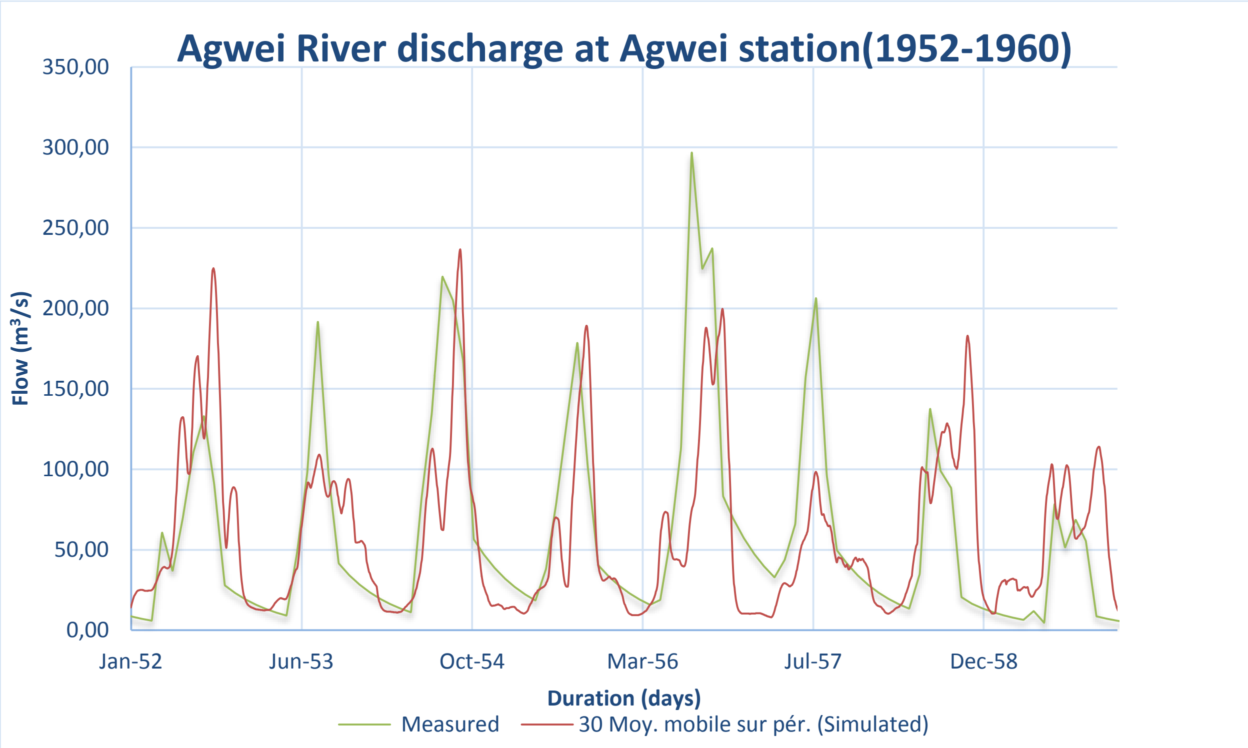

Figure 2-54: Agwei River calibration at Agwei station (plotted as monthly flows)

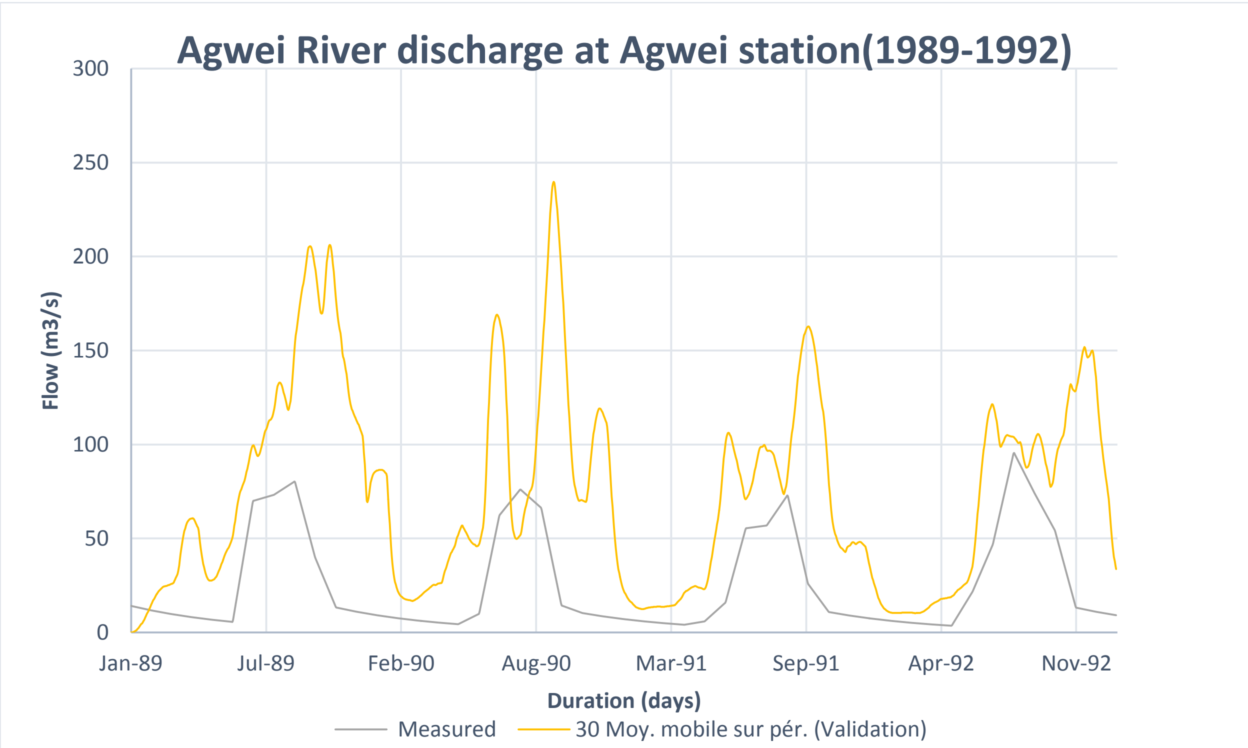

Figure 2-55: Agwei River validation at Agwei station (plotted as monthly flows)

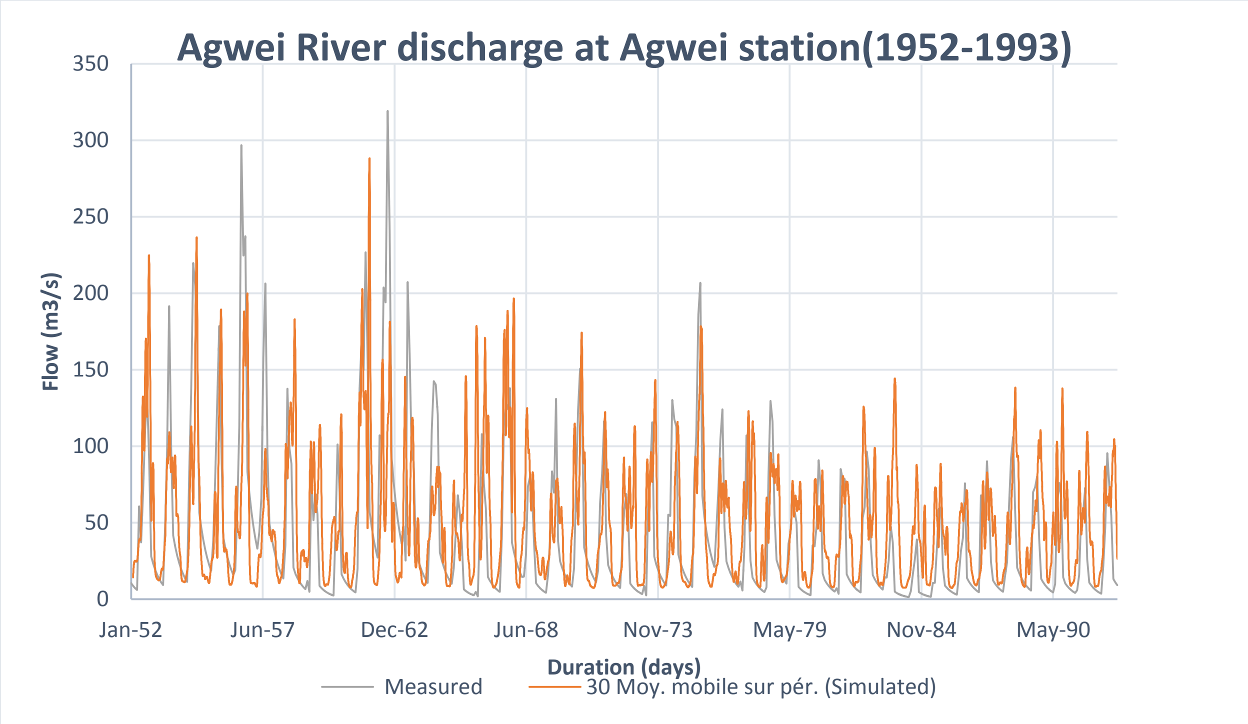

Figure 2-56: Agwei River simulated flows at Agwei station (plotted as monthly flows)

2.3.5.2 Sediment calibration

No sediment calibration data was available for this catchment thus, SHETRAN parameters from the Gilo watershed were used. The Agwei gauging station simulated sediment loads are shown in Figure 2-57 and the rating curve in Figure 2-58.

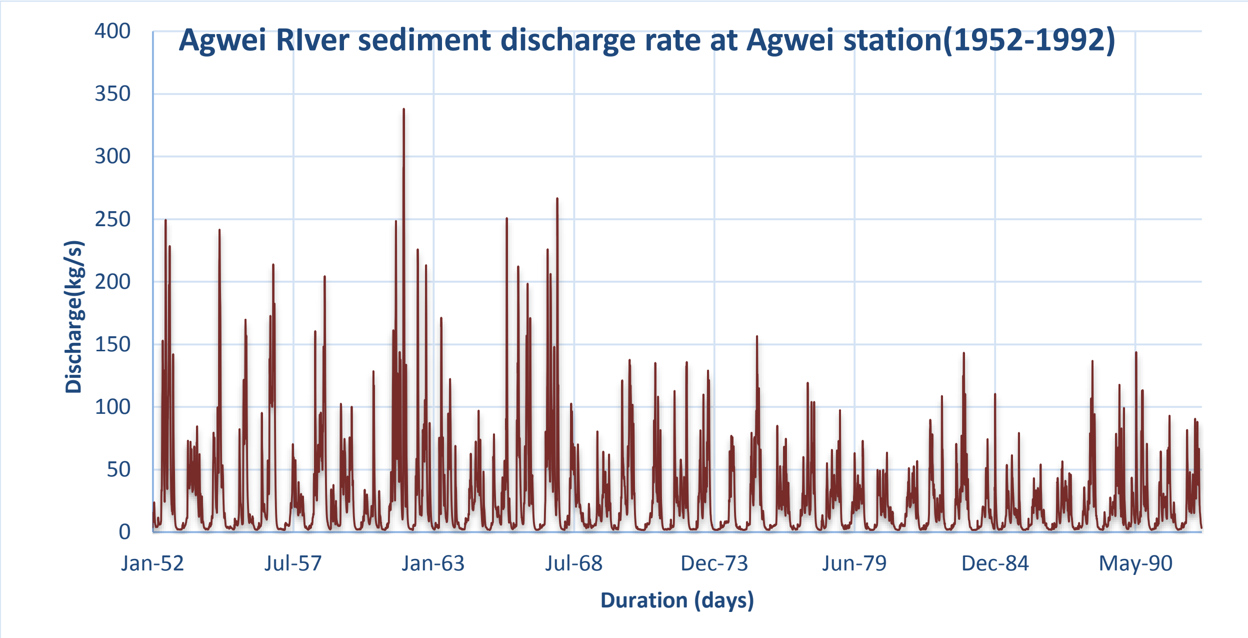

Figure 2-57: Agwei River simulated sediment loads at Agwei station

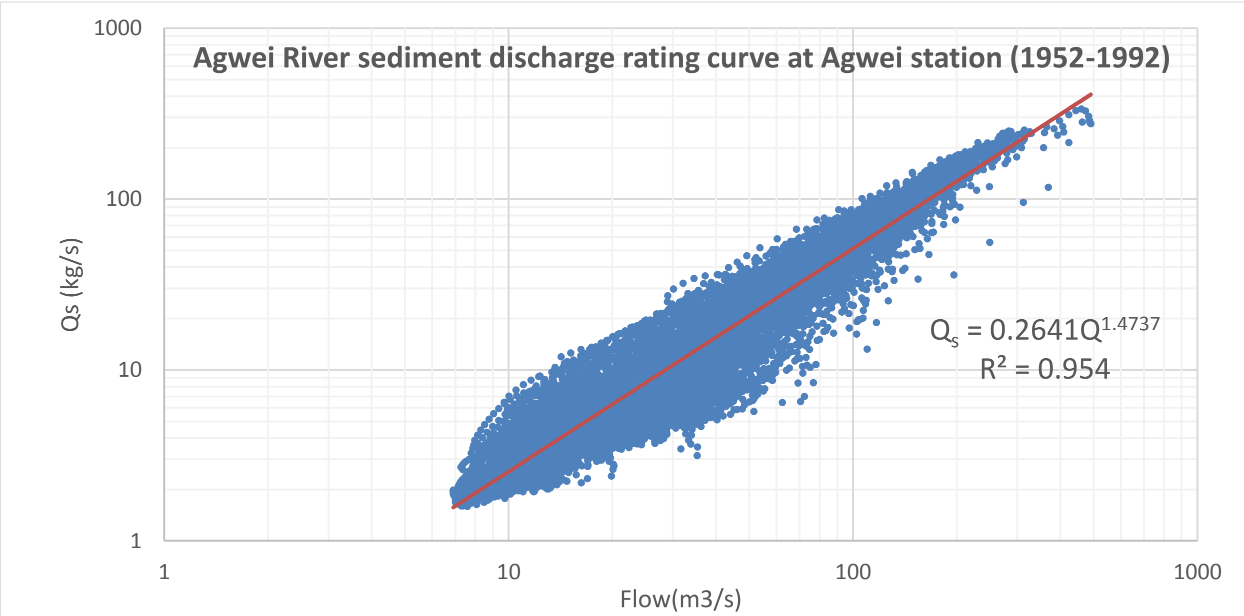

Figure 2-58: Agwei River simulated sediment rating curve at Agwei station

The sediment yield at the gauging station was calculated taking April to March as the hydrological year. Table 2-9 shows the resulting sediment yield calculation.

Table 2-9: Agwei River sediment yield calculation at Agwei station (1952-1992)

Catchment area (km^2)	81479
Average Qs (t/day)	2276

Sediment yield (t/km^2.a)	10

2.3.6 Pibor catchment

Based on 30 arc DEM, the Pibor catchment was delineated within 200x200 grids limitations and 1500 river channel links. 111x153 grid of 1980 spatial resolution represented the Pibor catchment of 28254 km^2.The catchment formed the model boundary with the outlet being the downstream boundary. Forty years' flow record data was available at the Pibor gauging station with no sediment sampling data available for this watershed.

Figure 2-59 shows Pibor River catchment extent, the location of gauging stations and river links as calculated by SHETRAN model.

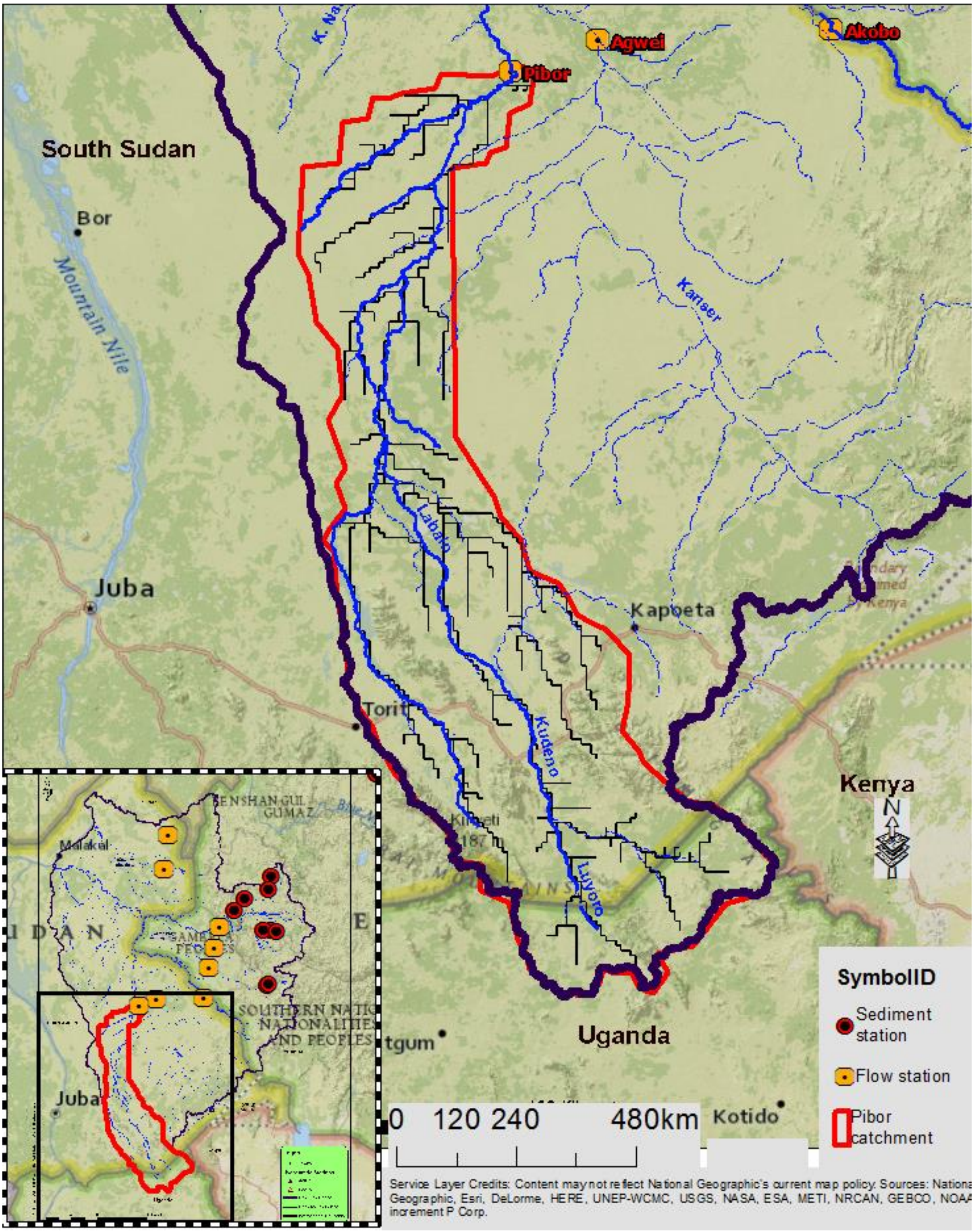

Figure 2-59: Pibor River sub-catchment and SHETRAN river links (black) as used in the SHETRAN model

To conform to the SHETRAN land use library, two main land uses were identified: grass and shrub. Their variation in the catchment is shown in Figure 2-60.

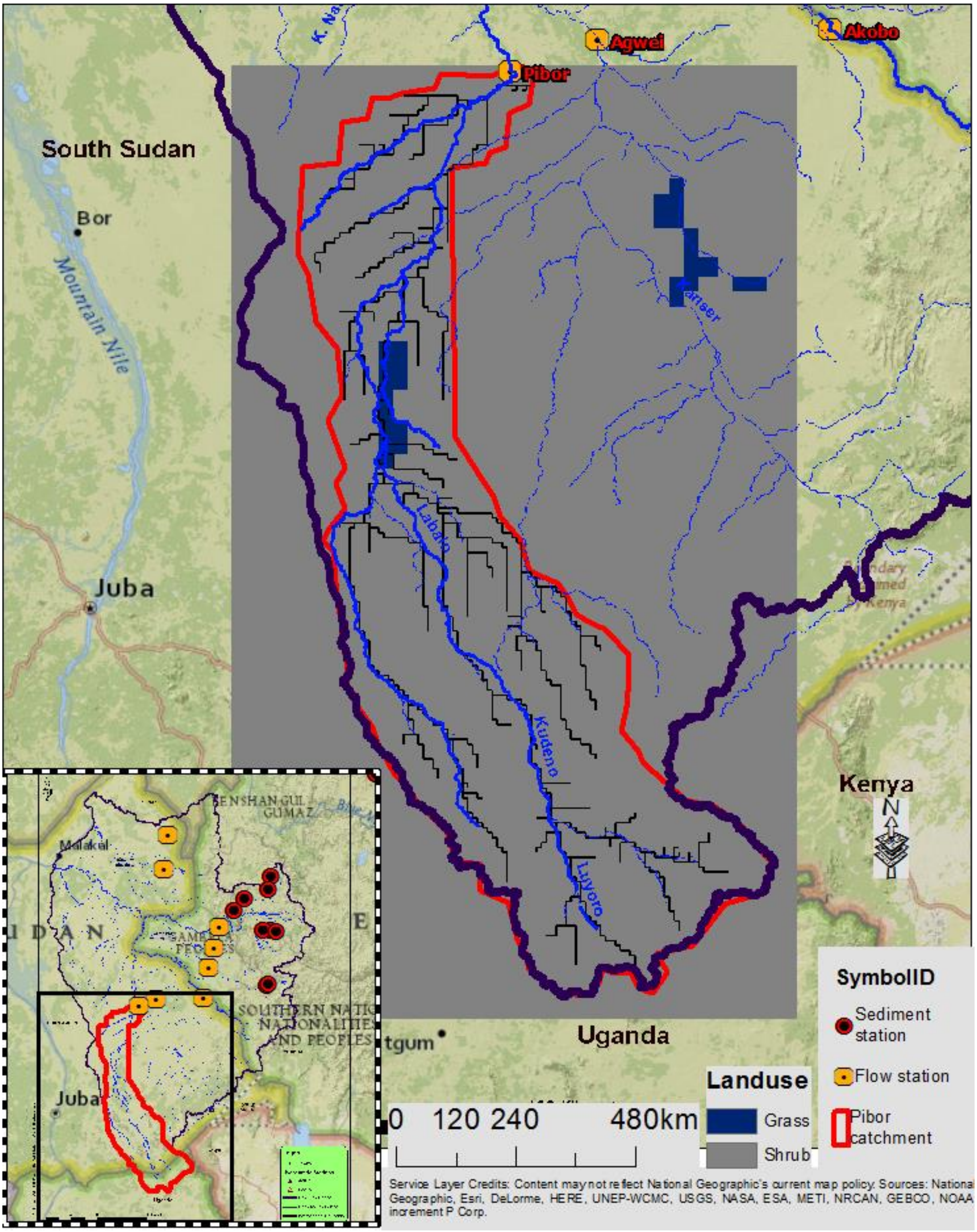

Figure 2-60: Pibor River sub-catchment land use variation as used in SHETRAN model

2.3.6.1 Pibor catchment flow calibration

The model was set up and calibrated for the period 1952 to 1990 and validated for the period 1989 to 1992. Parameters that varied from the model default values are shown in

Appendix 16. The main channel was calibrated to Manning n value of 0.04 and overland n values of 0.02 to 0.06 dependent on land use. Saturated conductivity was calibrated to 15 m/day for the upper 1 m horizon and 5 m/day in the lower 12 m lower horizon.

The Pibor station calibration graph is shown in Figure 2-61 while the validation graph is shown in Figure 2-62. The calibration seems reliable based on the flows, but during the validation period the simulated flows are overestimated. Figure 2-63 shows the simulated 40 year flow record.

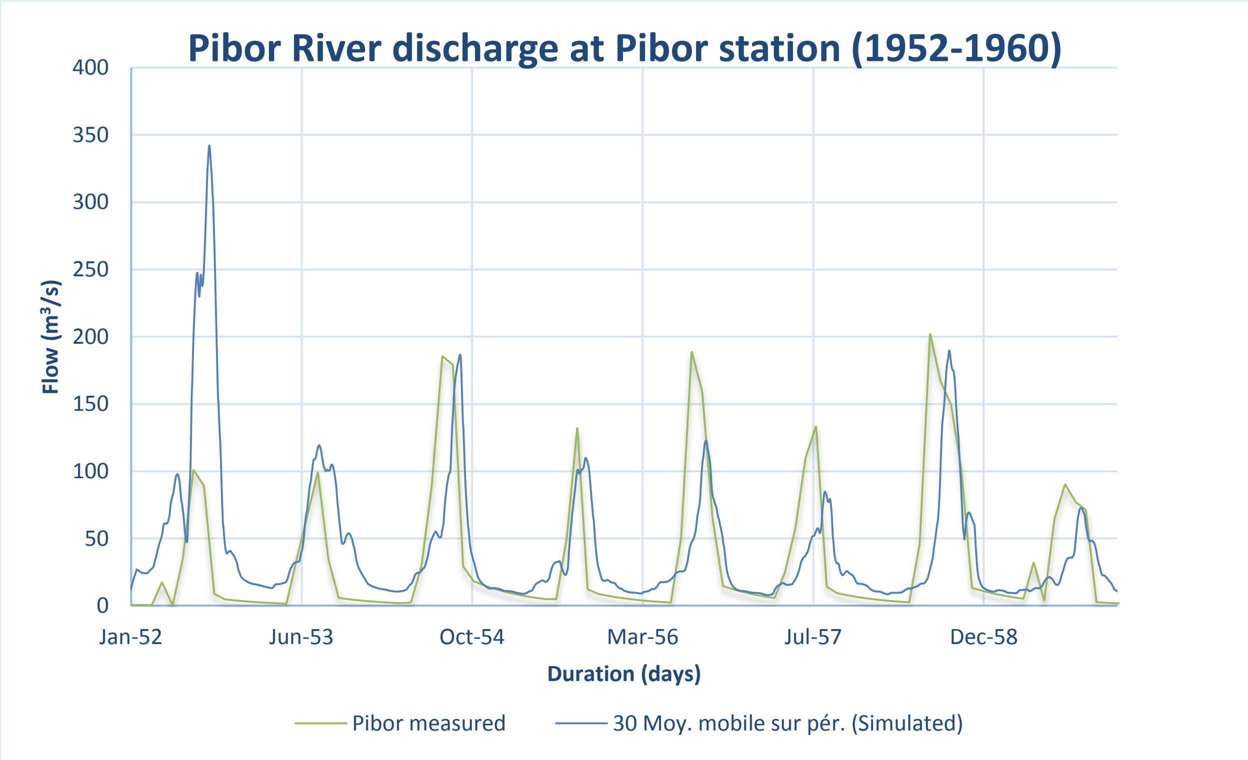

Figure 2-61: Pibor River calibration at Pibor station (plotted as monthly flows)

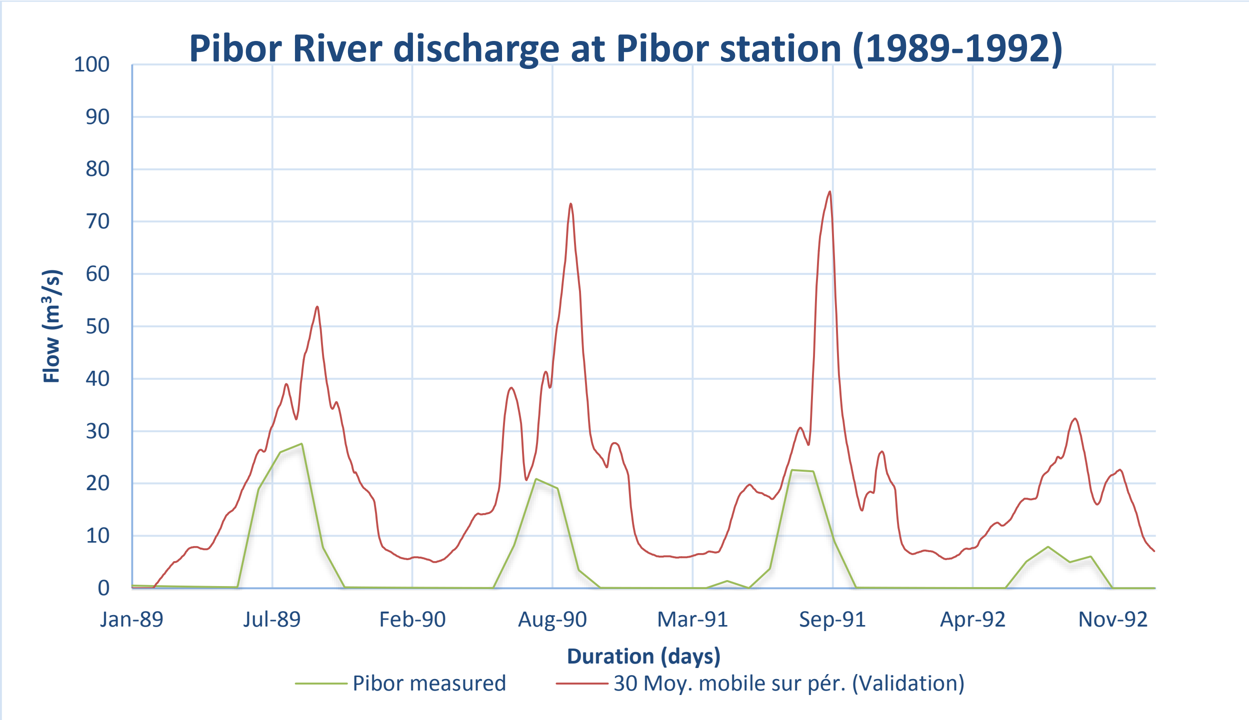

Figure 2-62: Pibor River validation at Pibor station (plotted as monthly flows)

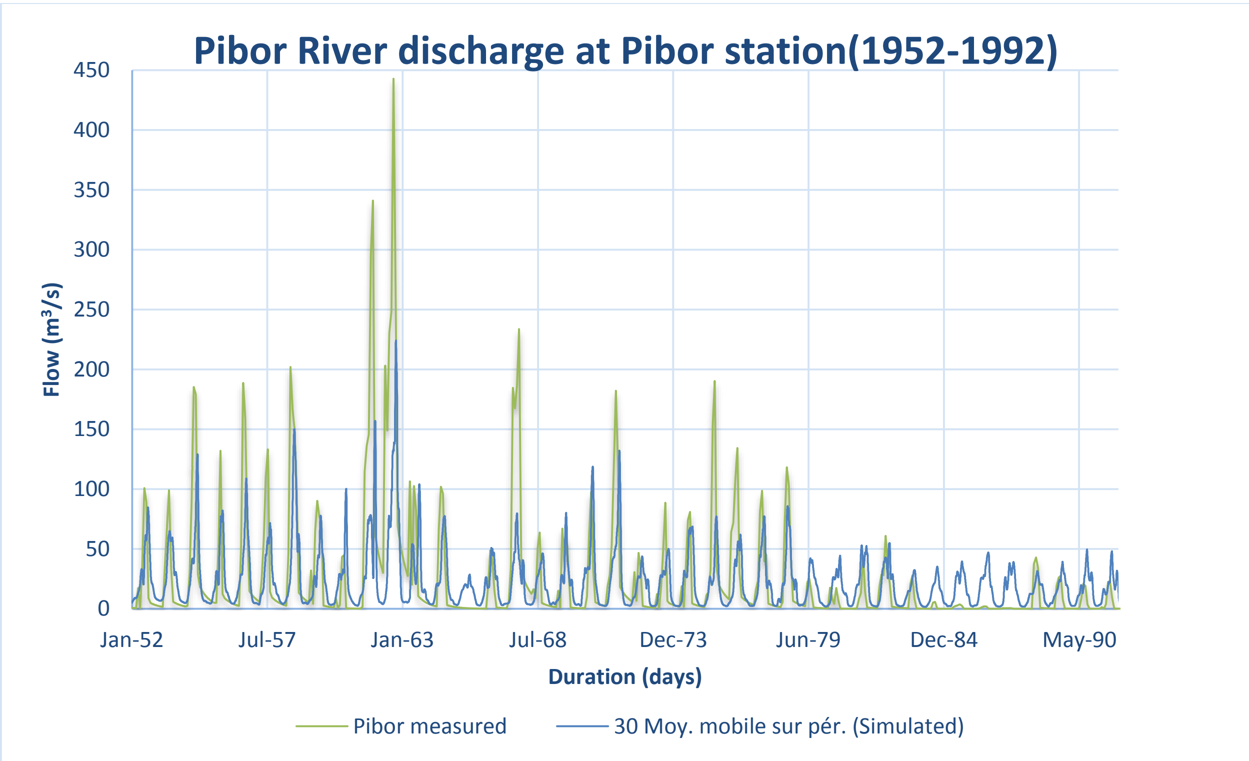

Figure 2-63: Pibor River simulated flows at Pibor station (plotted as monthly flows)

2.3.6.2 Sediment calibration

There was no calibration data available in this catchment thus the SHETRAN parameters from the Gilo catchment were used. The Pibor gauging station simulated sediment loads are shown in Figure 2-64 and the rating curve in Figure 2-65.

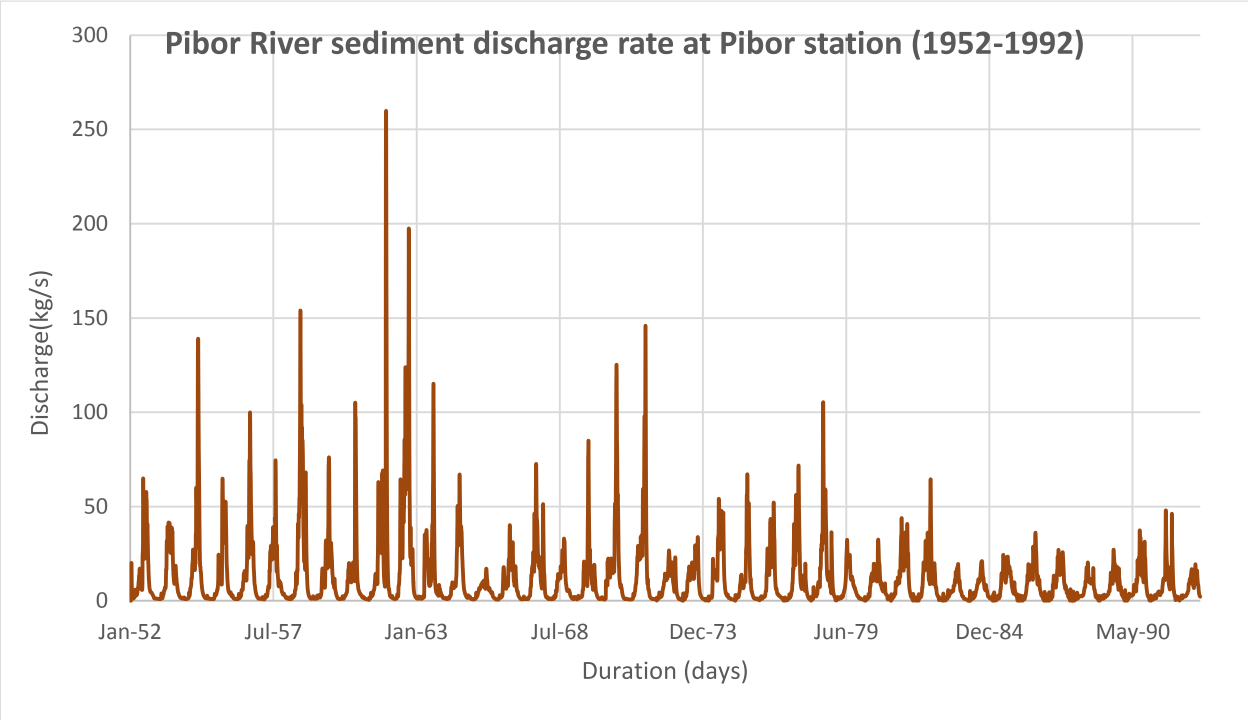

Figure 2-64: Pibor River simulated sediment loads at the Pibor station

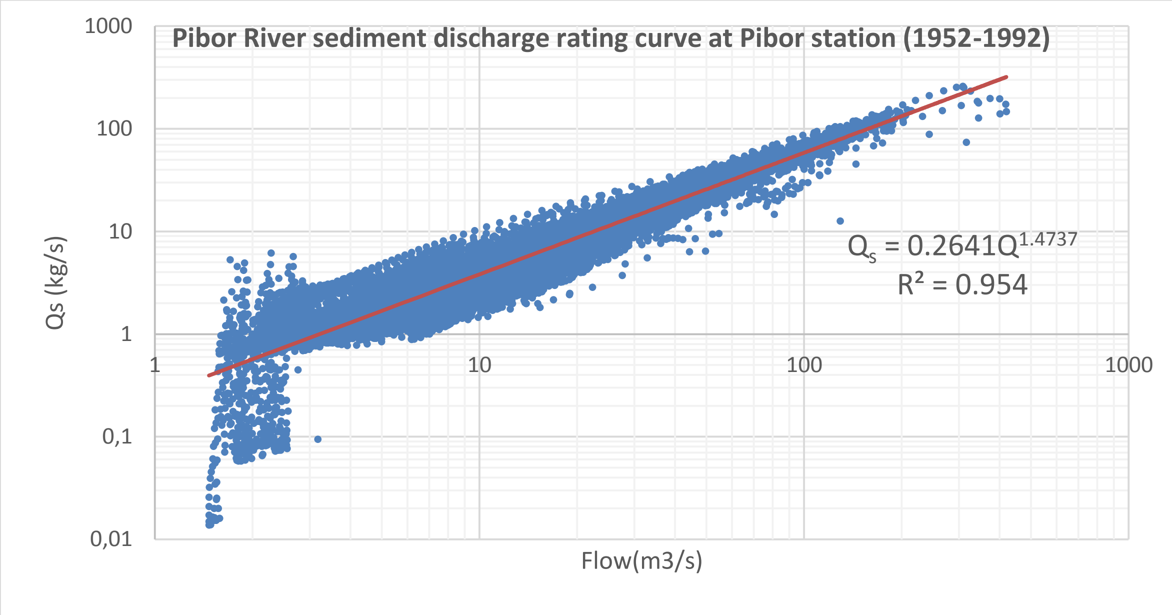

Figure 2-65: Pibor River simulated sediment load rating curve at the Pibor station

The Pibor station sediment yield was calculated taking April to March as the hydrological year. Table 2-10 shows the resulting sediment yield calculation.

Table 2-10: Pibor River sediment yield calculation at Pibor gauging station (1952-1992)

Catchment area (km^2)	28254
Average Qs (t/day)	1027
Sediment yield ($t/km^2.a$)	13

2.3.7 Daga and Yabus catchment

The Daga and Yabus catchments were delineated from a 30 arc DEM within 200x200 SHETRAN grid limitation and 1500 river links. 112 x107 grids of 1980 spatial resolution represented this watershed shown in Figure 2-66.

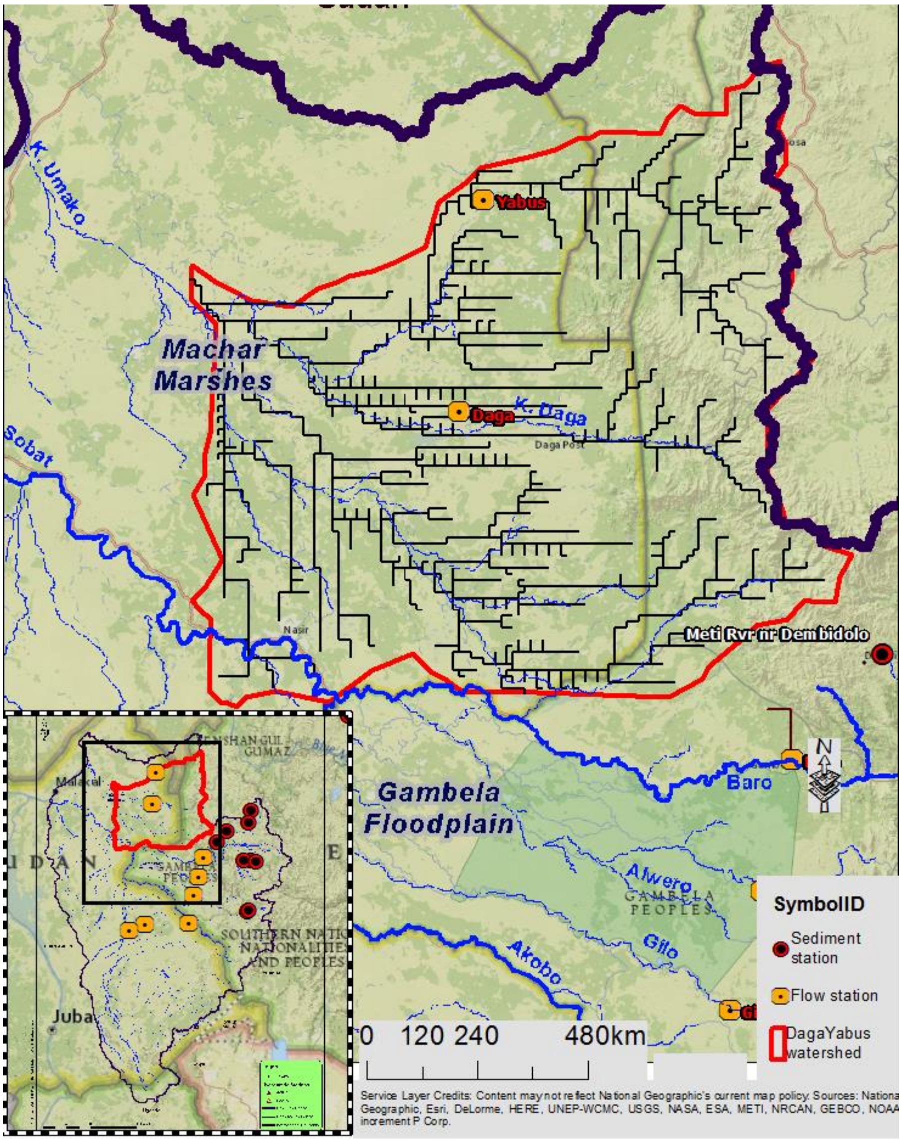

Figure 2-66: Daga and Yabus sub-catchment and SHETRAN river links (black) as used in the model

To conform to the SHETRAN land use library, four vegetation classes were identified and are shown in Figure 2-67.

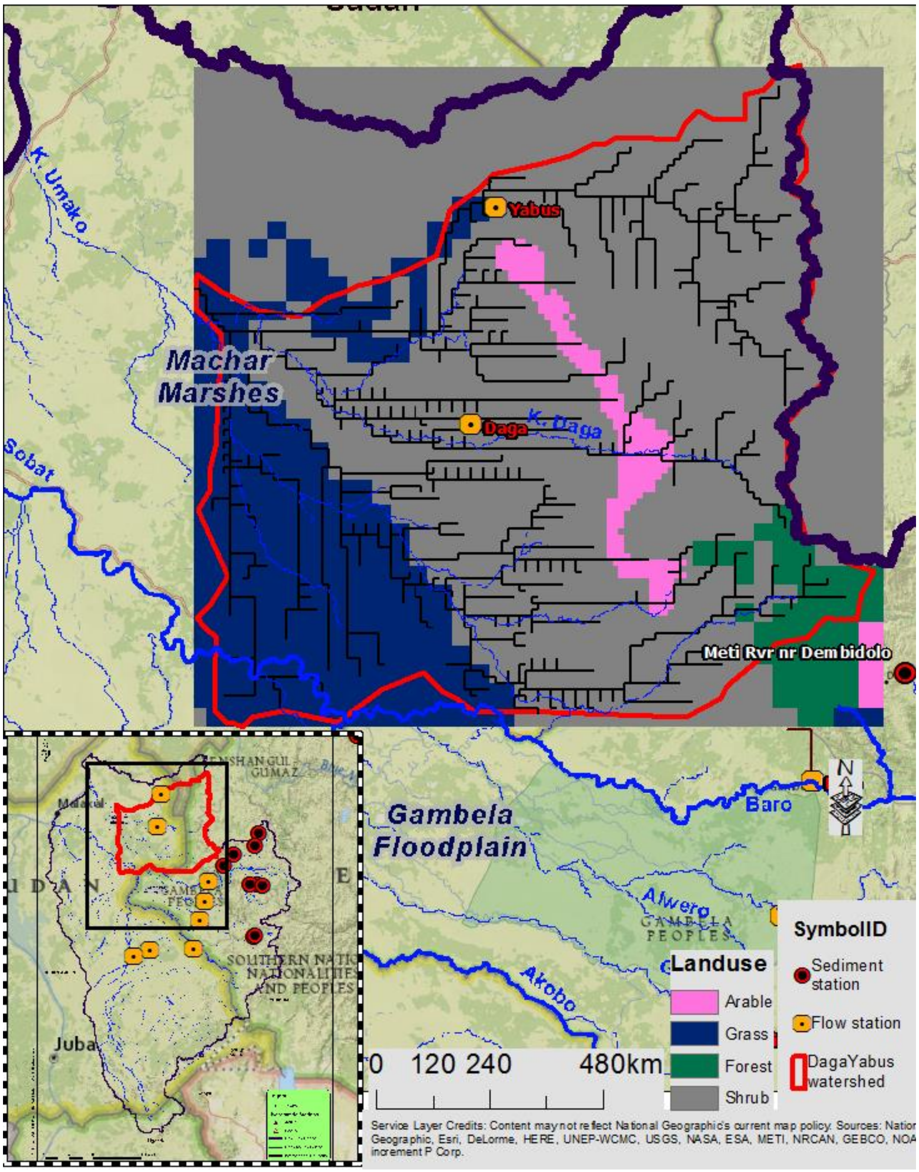

Figure 2-67: Daga and Yabus sub-catchment land used variation as used in SHETRAN model

2.3.7.1 Daga and Yabus River flow calibration

The model was set up and flow calibrated for the period 1952 to 1960, and validated for the period 1989 to 1992. Parameters that varied from the model default values are shown in Appendix 18. The main channel was calibrated to a Manning n value of 0.04 and overland range of 0.05 to 0.2 dependent on vegetation type.

The Daga River catchment calibration graph is shown in Figure 2-68, while the validation is shown in Figure 2-69. The simulation for the whole period 1952 to 1992 is shown in Figure 2-70.

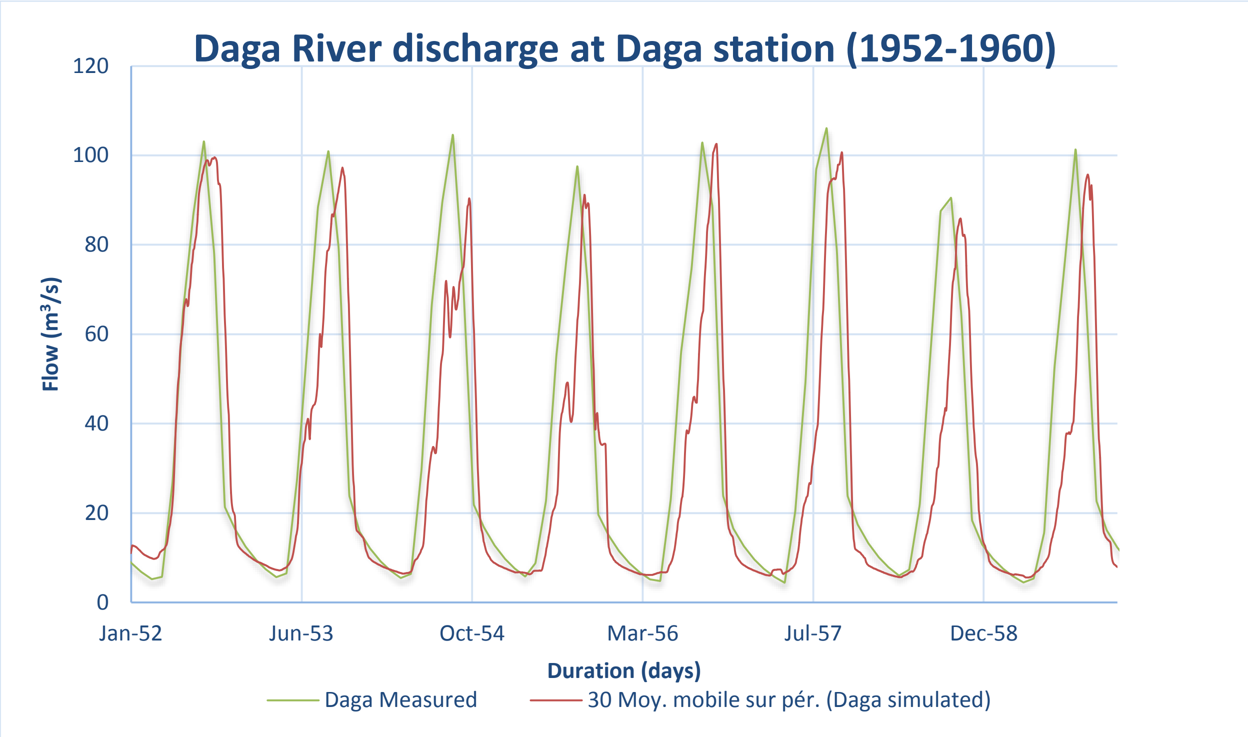

Figure 2-68: Daga River calibration at Daga gauging station (plotted as monthly flows)

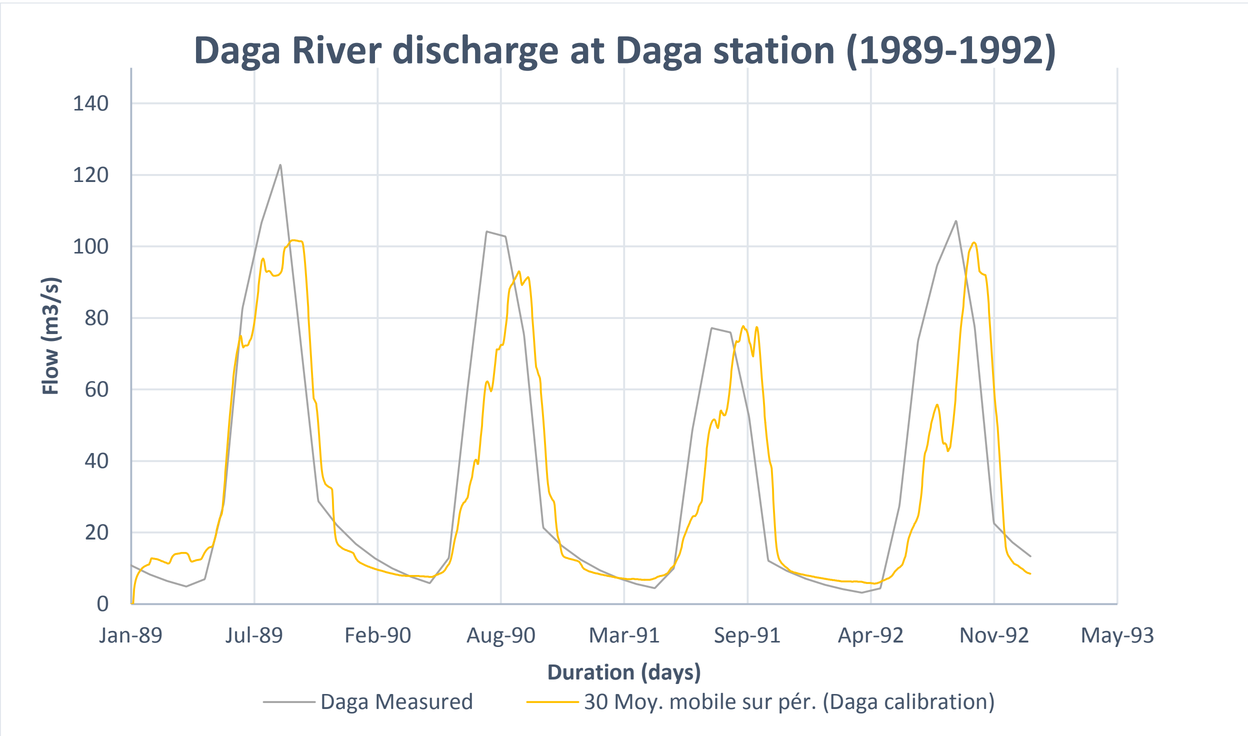

Figure 2-69: Daga River validation at the Daga station (plotted as monthly flows)

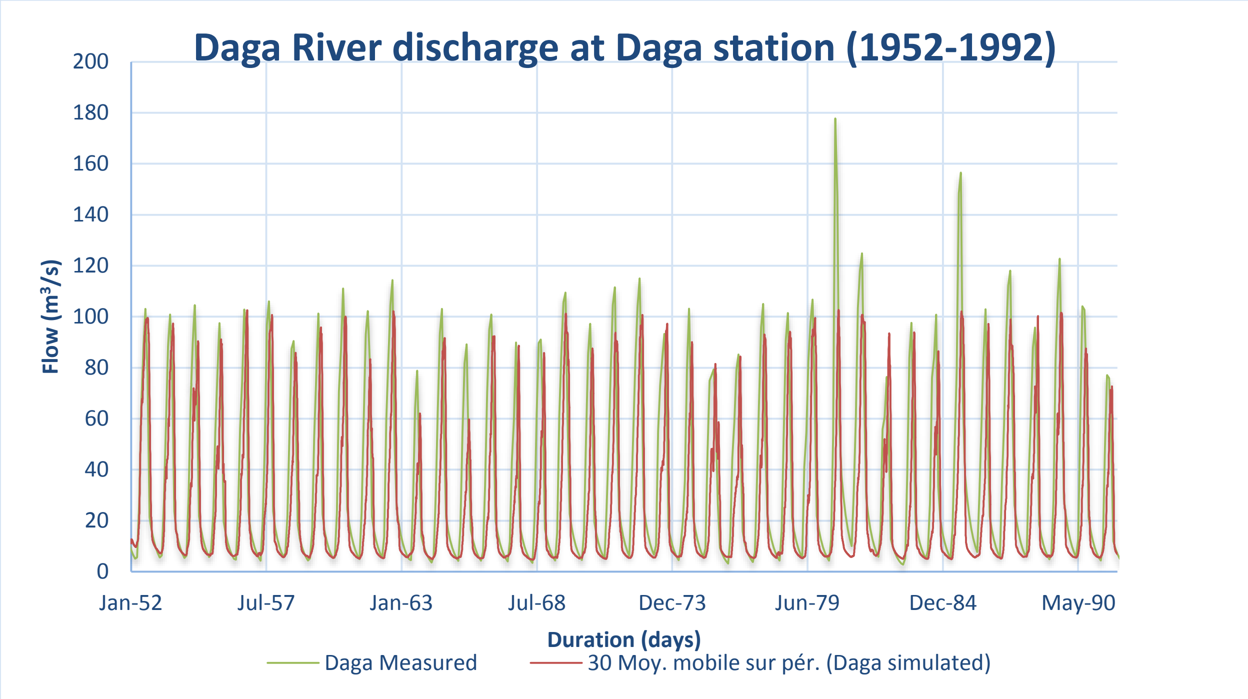

Figure 2-70: Daga River simulated flows at the Daga station (plotted as monthly flows)

The Yabus River catchment calibration graph is shown in Figure 2-71, while the validation is shown in Figure 2-72. The simulation for the whole period 1952 to 1992 is shown in Figure 2-73.

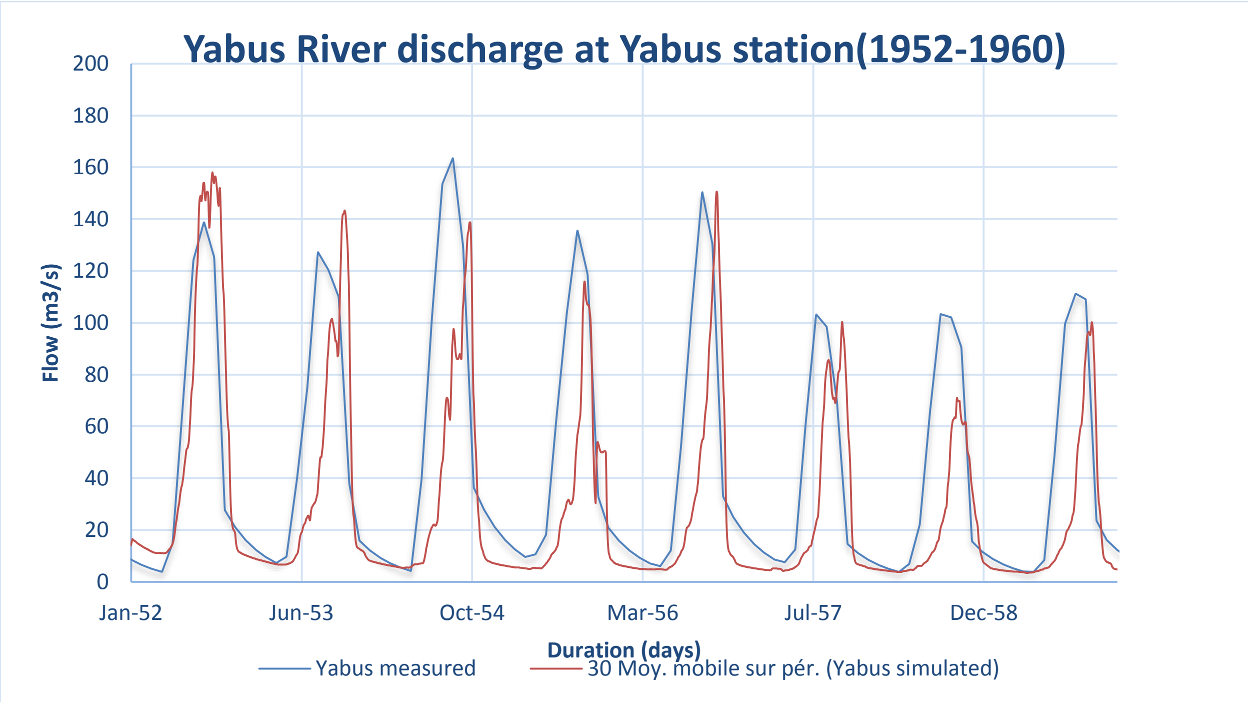

Figure 2-71: Yabus River calibration at Yabus station (plotted as monthly flows)

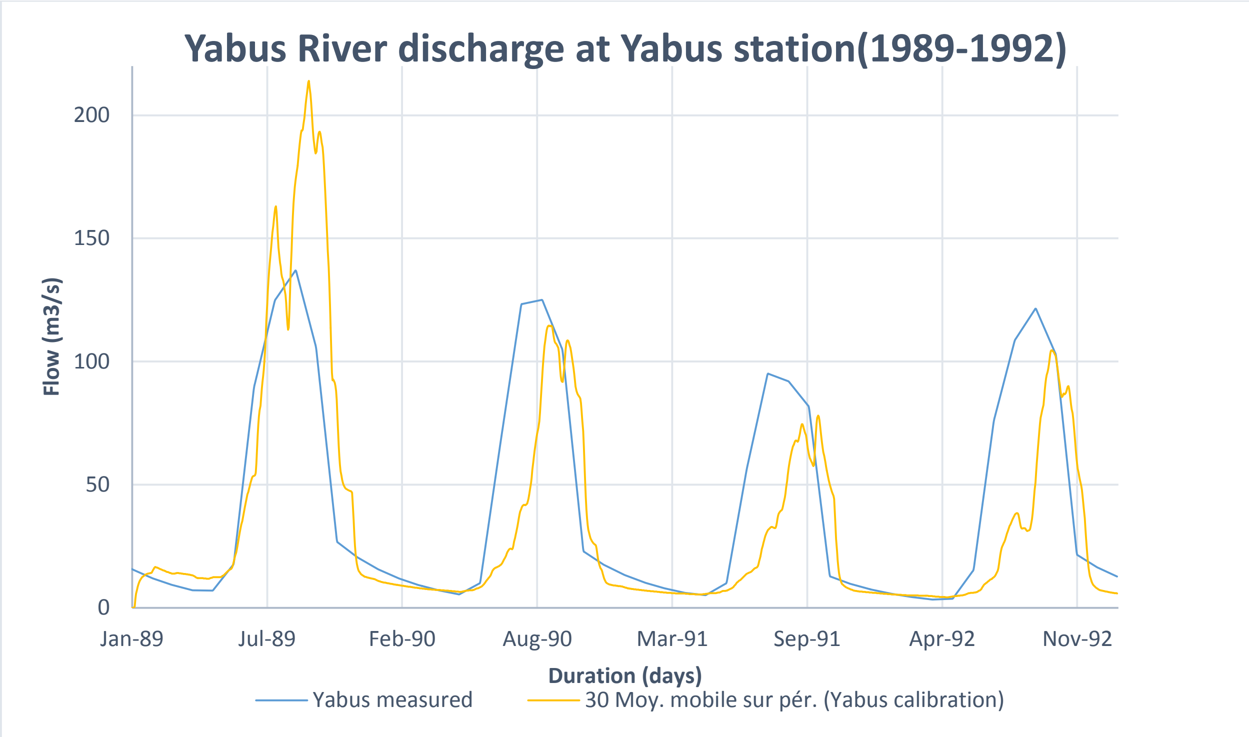

Figure 2-72: Yabus River validation at Yabus station (plotted as monthly flows)

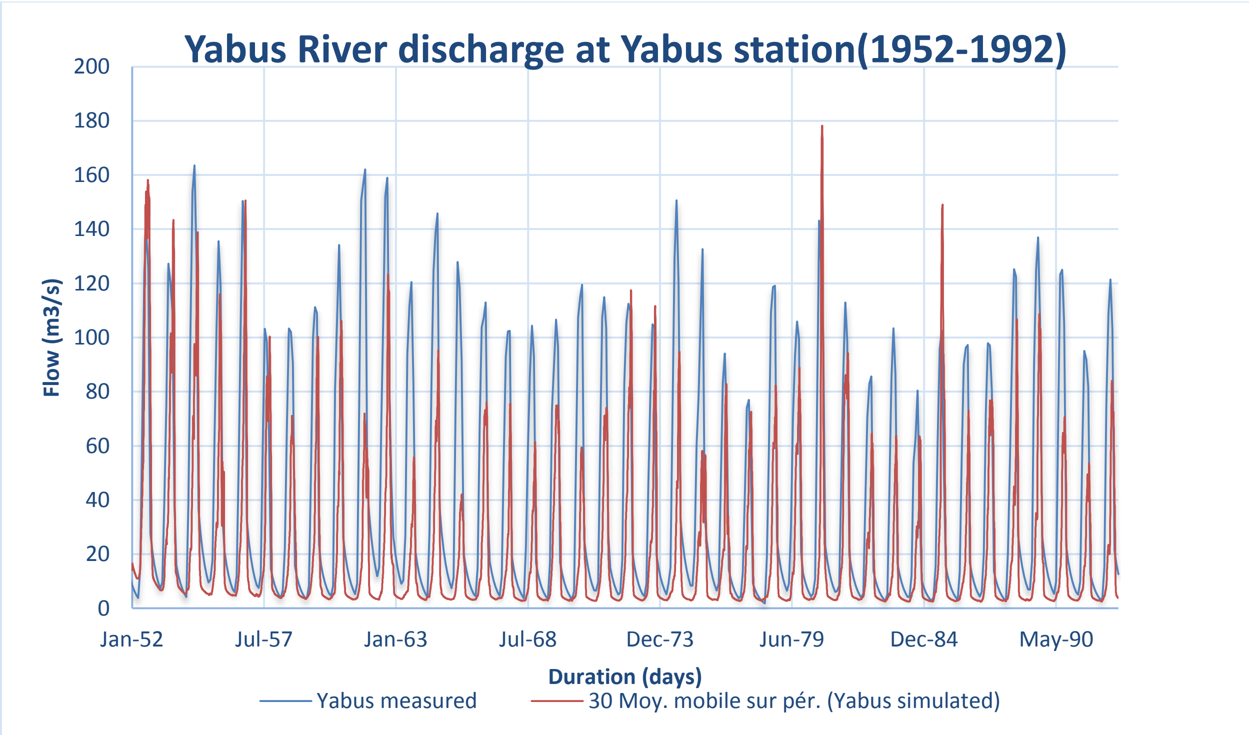

Figure 2-73: Yabus River long-term simulated flows at Yabus station (plotted as monthly flows)

2.3.7.2 Sediment calibration

No sediment calibration data was available for this catchment and therefore SHETRAN parameters from the Baro watershed were used. The Daga gauging station simulated sediment loads are shown in Figure 2-74 and the rating curve in Figure 2-75.

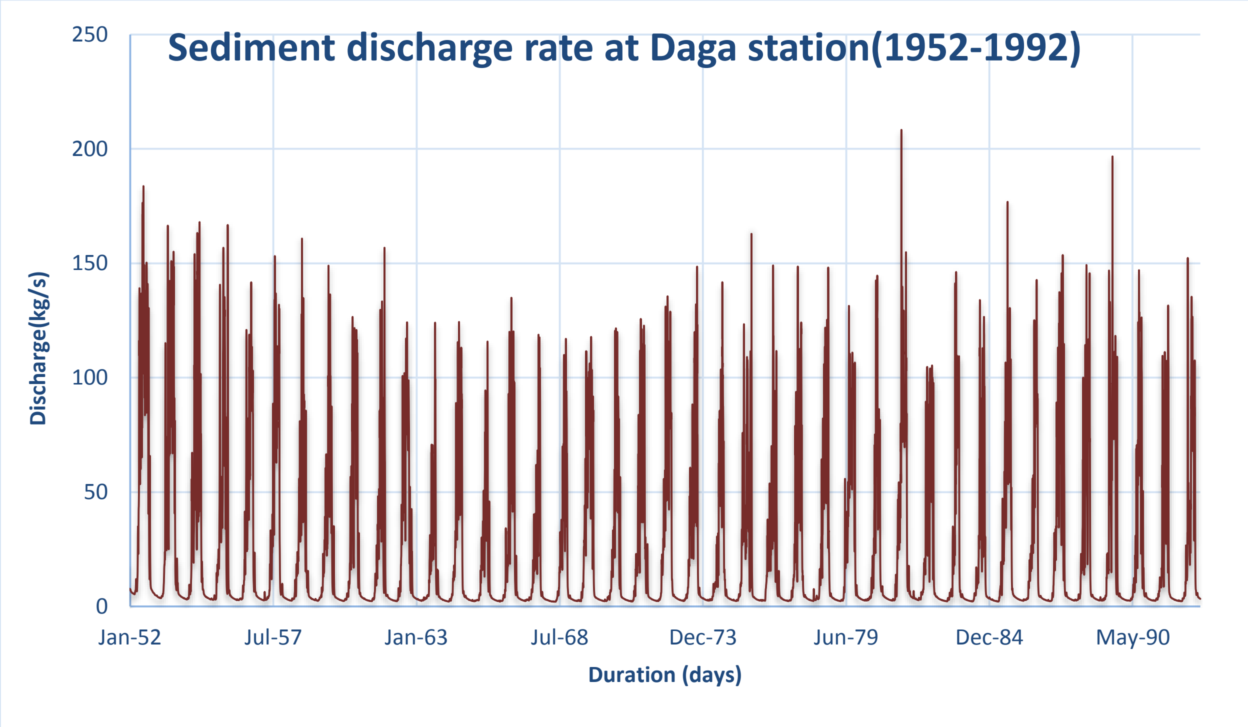

Figure 2-74: Daga River simulated sediment loads at the Daga gauging station

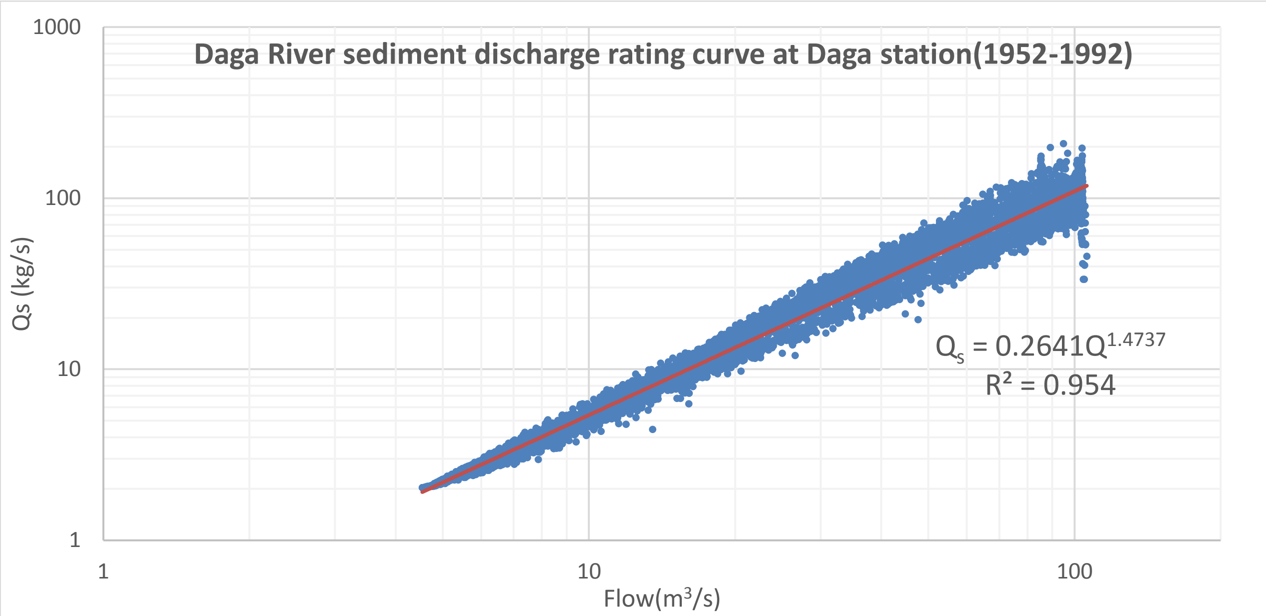

Figure 2-75: Daga River simulated sediment rating curve at the Daga station

The Yabus gauging station simulated sediment discharge rate is shown in Figure 2-76 and the rating curve in Figure 2-77.

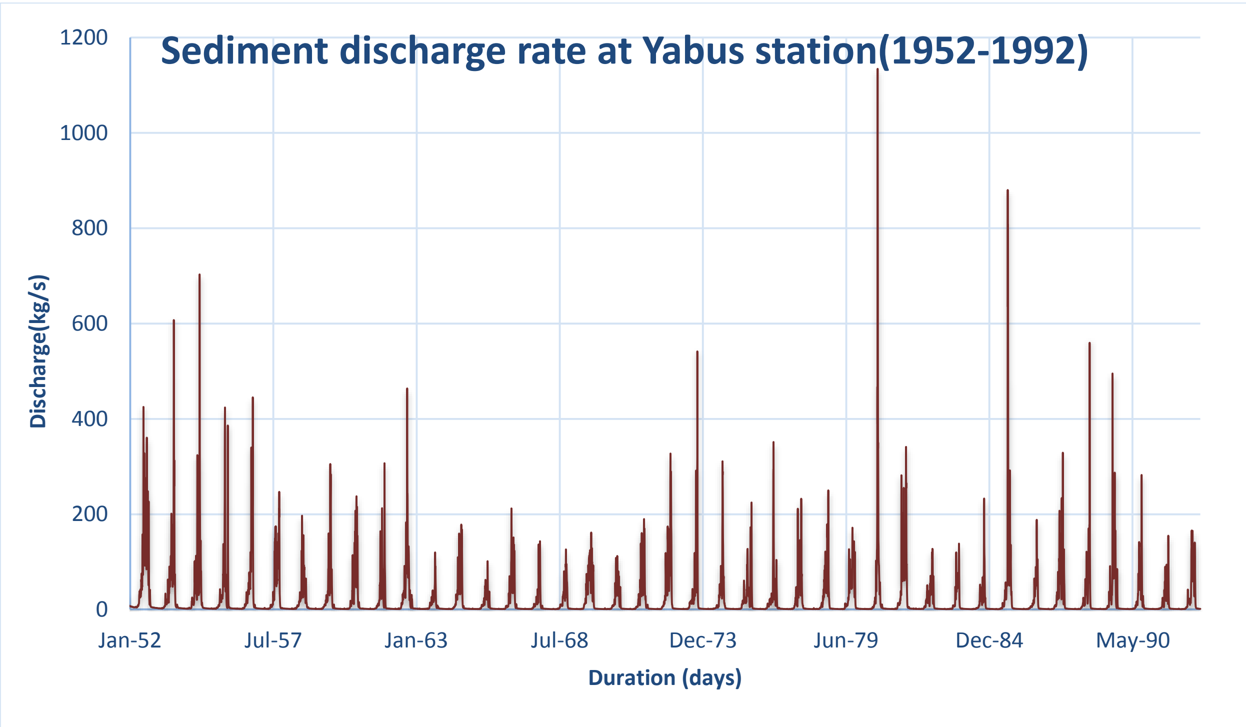

Figure 2-76: Yabus River simulated sediment loads at the Yabus station

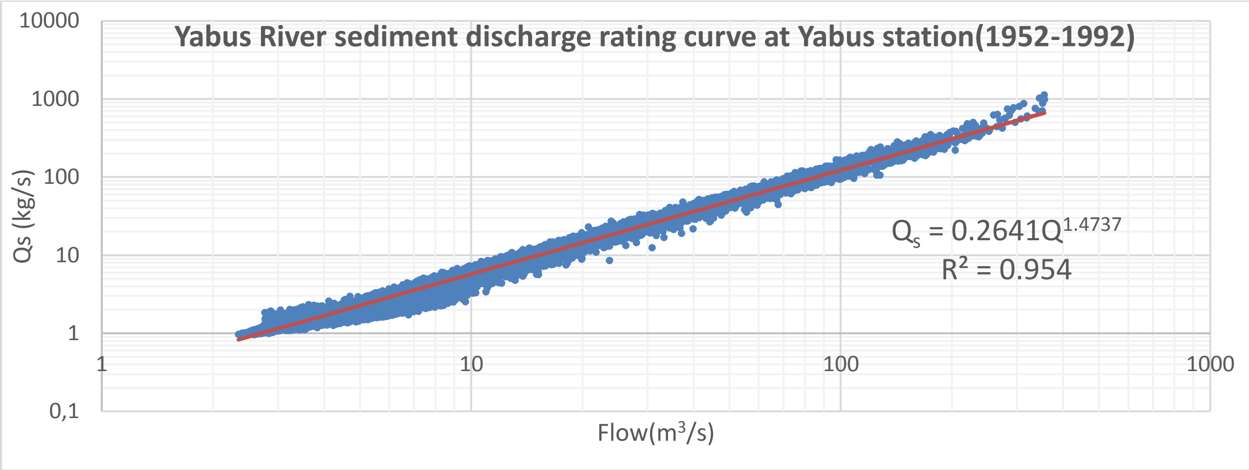

Figure 2-77: Yabus River simulated discharge-sediment load rating curve at Yabus station

The sediment yield was calculated taking April to March as the hydrological year. The Daga station simulated sediment yield calculation is shown in Table 2-11, while the Yabus station yield is shown in Table 2-12.

Table 2-11: Daga catchment simulated sediment yield at Daga station (1952-1992)

Catchment area (km²)	3356
Average Qs (t/day)	2044
Sediment yield(t/km².a)	222

Table 2-12: Yabus catchment simulated sediment yield at Yabus station (1952-1992)

Catchment area (km²)	6156
Average Qs (t/day)	1888
Sediment yield (t/km².a)	112

2.3.8 Sobat catchment

The 30 arc Dem was used to delineate Sobat catchment within the 200 x200 SHETRAN grid limitation and 1500 river links. 86x158 grids of 1980 spatial resolution represented this catchment shown in Figure 2-78. The watershed extent formed the model boundary with the river outlet as the downstream boundary. The saturated conductivity was calibrated to 20 m/day to for the upper 1 m and 5 m/day for the lower 14 m horizon.

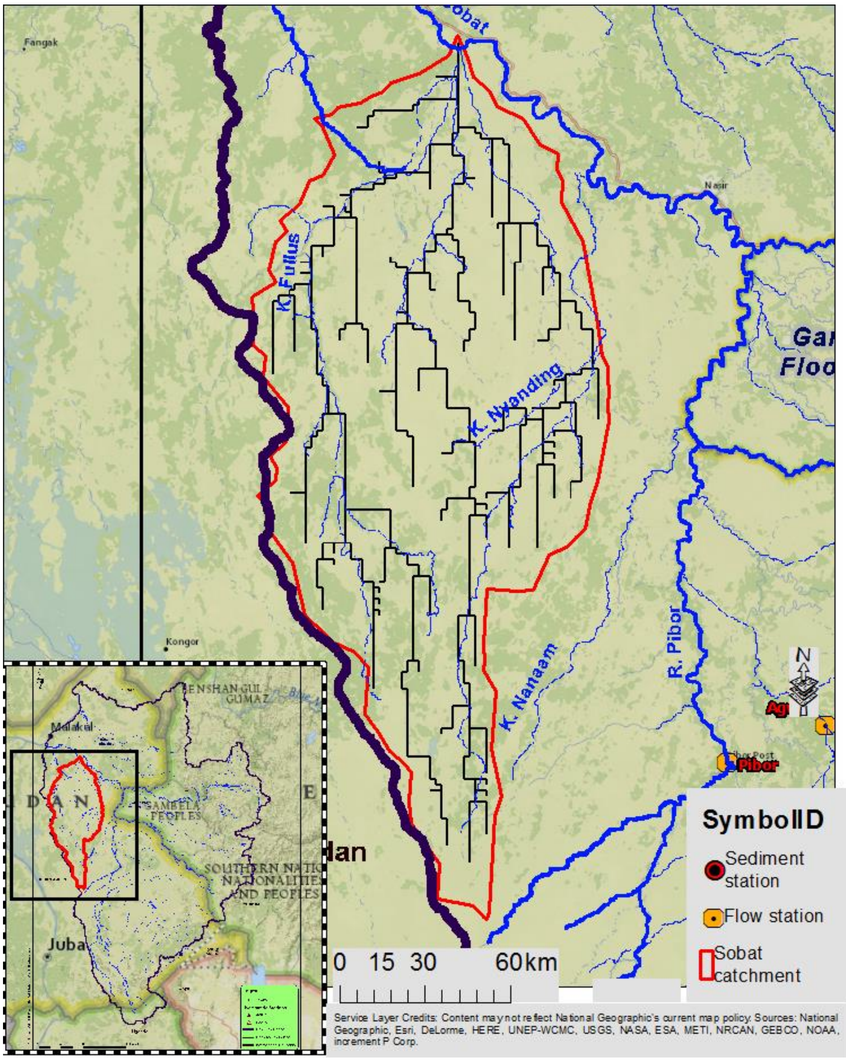

Figure 2-78: Sobat River sub catchment and SHETRAN river links (black) as used in the SHETRAN model

To conform to SHETRAN land use library, two main land uses were identified: shrub and grass. The land uses are shown in Figure 2-79.

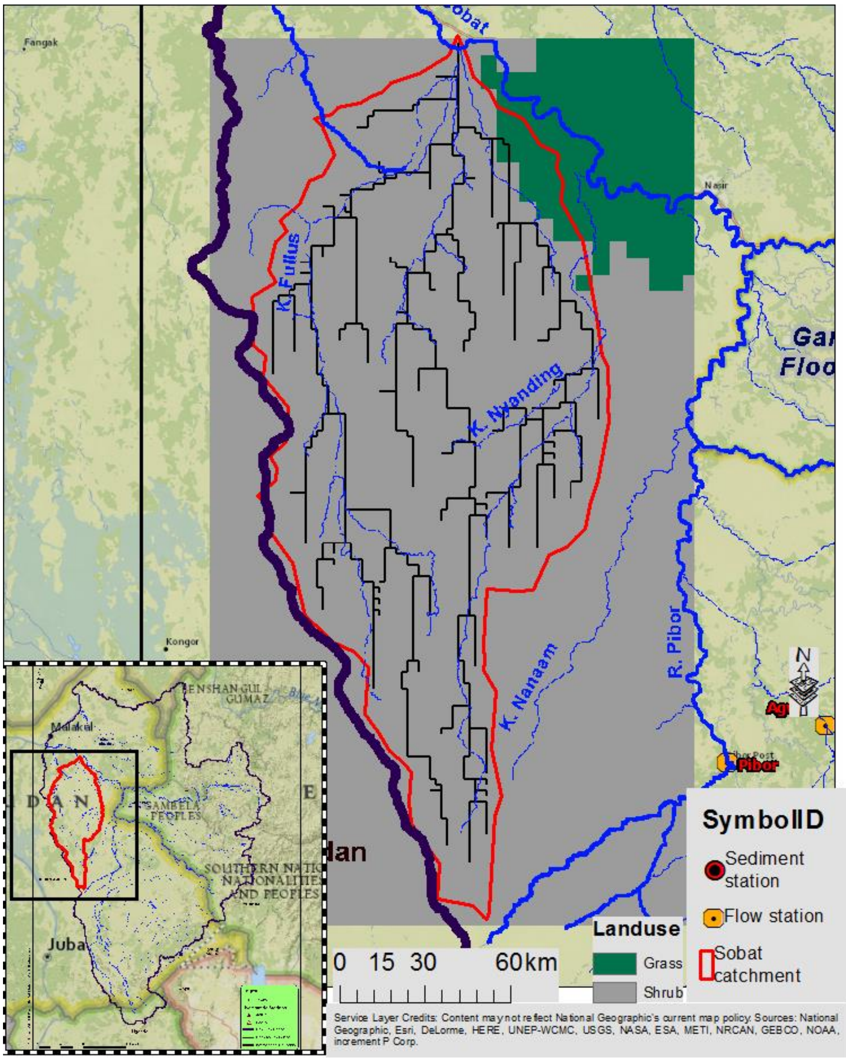

Figure 2-79: Sobat sub-catchment land use variation as used in the SHETRAN model

2.3.8.1 Sobat catchment sediment and flow calibration

No data was available for this catchment, thus SHETRAN values from the neighbouring Pibor catchment were used and simulated for the period 1952 to 1992.

Figure 2-80 shows the simulated flows with the corresponding sediment loads at the outlet of the catchment shown in Figure 2-81.The simulated discharge-sediment load rating curve at the outlet is shown in Figure 2-82 with the calculated sediment yield in Table 2-13.

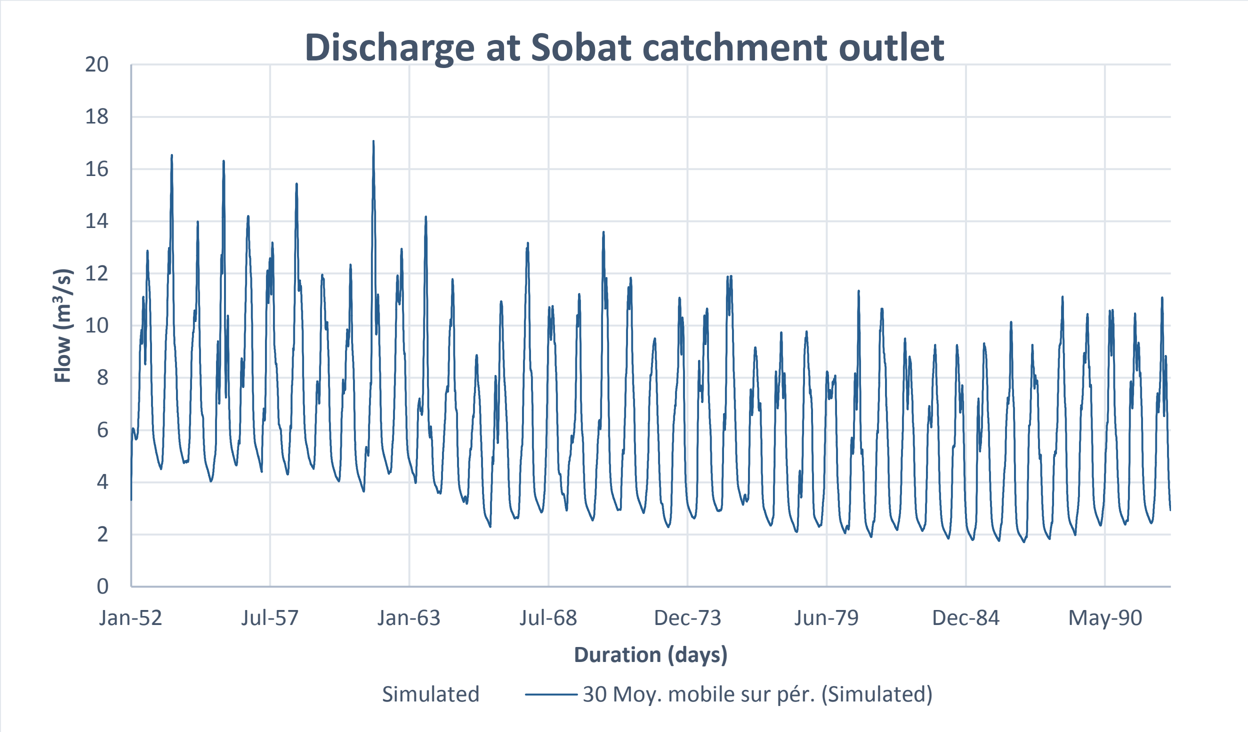

Figure 2-80: Sobat catchment simulated flows at the outlet of the catchment (plotted as monthly flows)

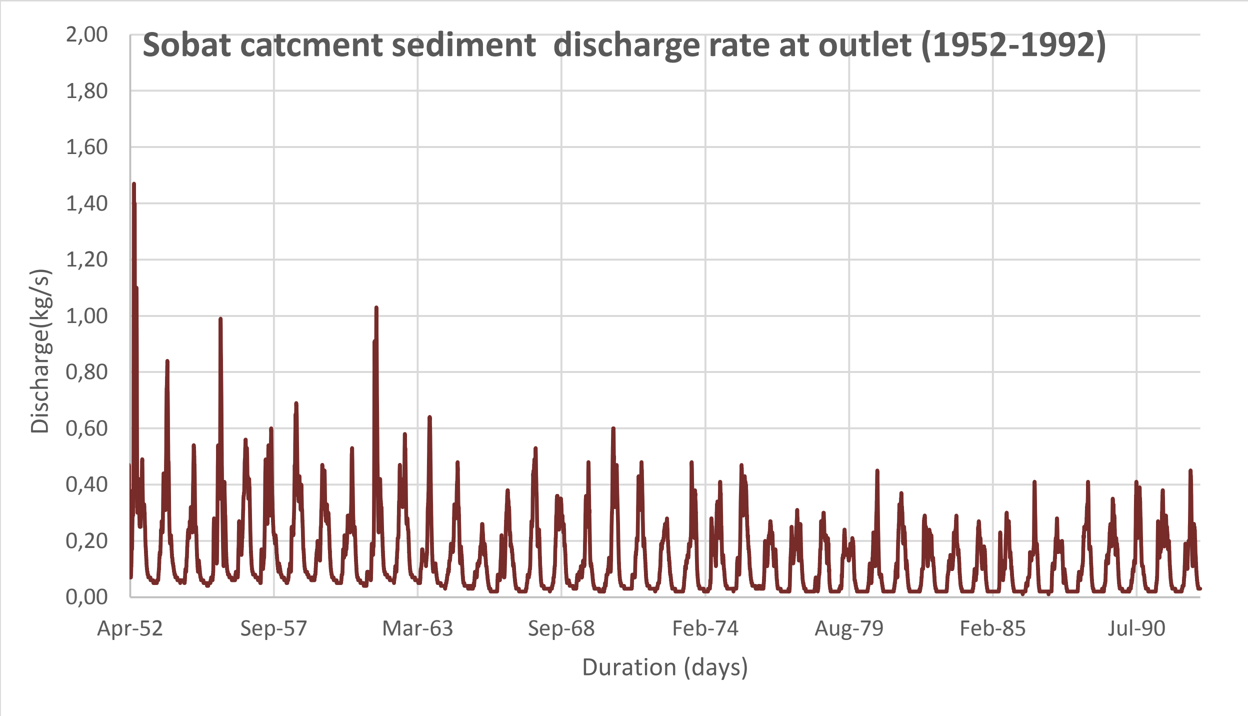

Figure 2-81: Simulated Sobat catchment sediment loads at the outlet

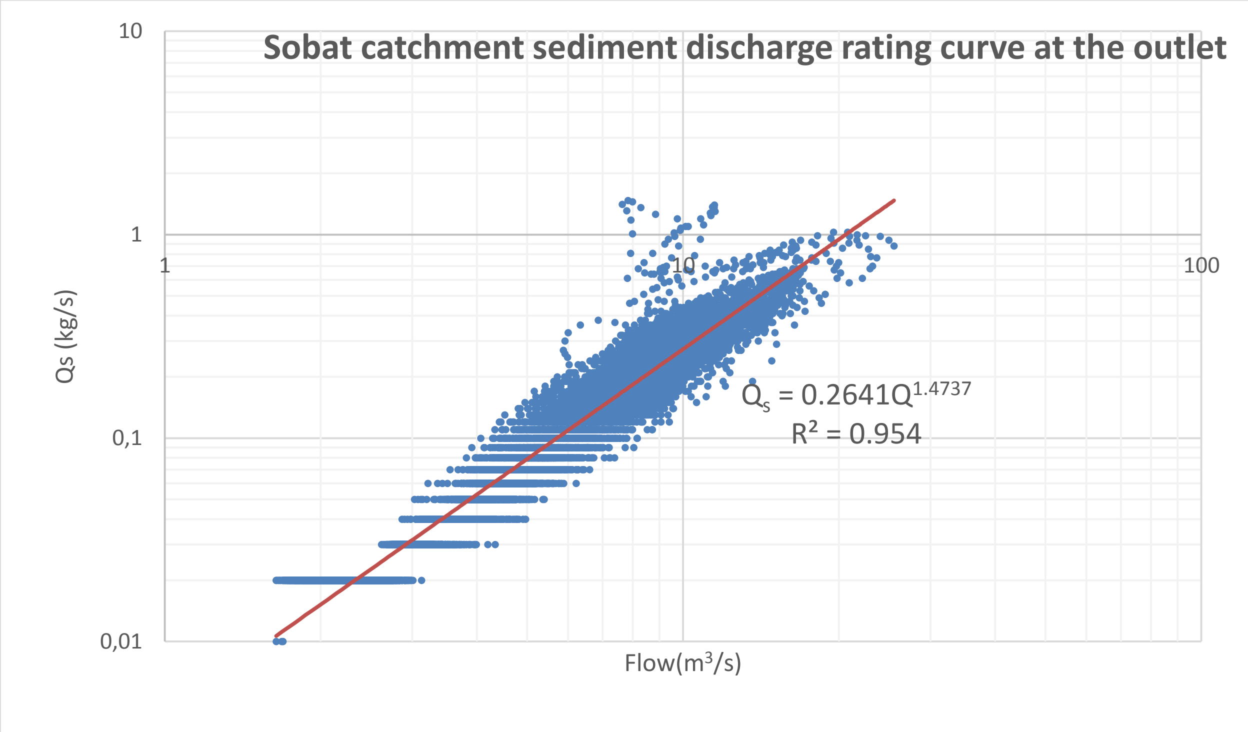

Figure 2-82: Simulated Sobat catchment discharge-sediment load rating curve at the outlet

Table 2-13: Sobat sub-catchment sediment yield at the outlet (1952-1992)

Catchment area (km^2)	22512.00
Average Qs (t/day)	24.68
Sediment yield ($t/km^2.a$)	< 10

2.3.9 Marshlands

Due to the complex flow network and SHETRAN limitation, the marshlands were not simulated. The location of the unsimulated zone is shown in Figure 2-83.

Sediment yields in this location were obtained by taking a weighted average yield from neighbouring catchments and assuming no sediment deposition.

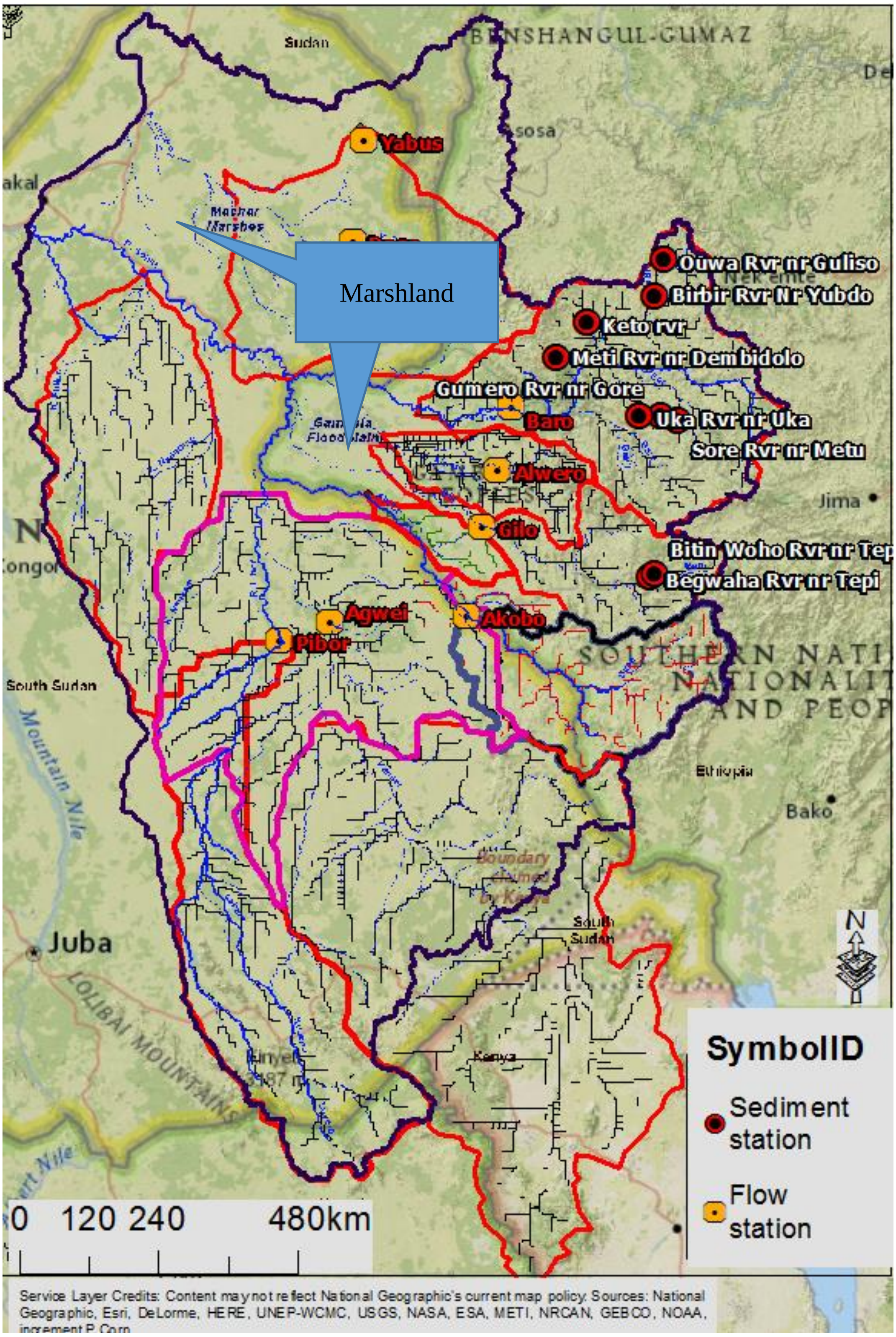

Figure 2-83: Marshland locations where SHETRAN model simulations were not carried out

3. SEDIMENT YIELD MAP

From the SHETRAN model long term simulations (40 years), smaller sub-catchments were delineated and data extracted on the river channels at the locations of interest for the whole simulated period (1952-1992). Appendix 20 shows the positions where sediment yields were calculated with the results tabled in Appendix 21. The resulting sediment yield map is shown in Figure 3-1.

Where the sediment yields were simulated to be less than 10 t/km^2.a, the yield was adjusted to 10 t/km^2.a on the map, considering the accuracy of the predictions. The sediment yield map values indicate the mean long term sediment yield of the total catchment draining to a specific location.

The highest sediment yields are in the east of the study area, with a maximum of 872 t/km^2.a. Sediment yields in catchments in the south and west of the study area are relatively low.

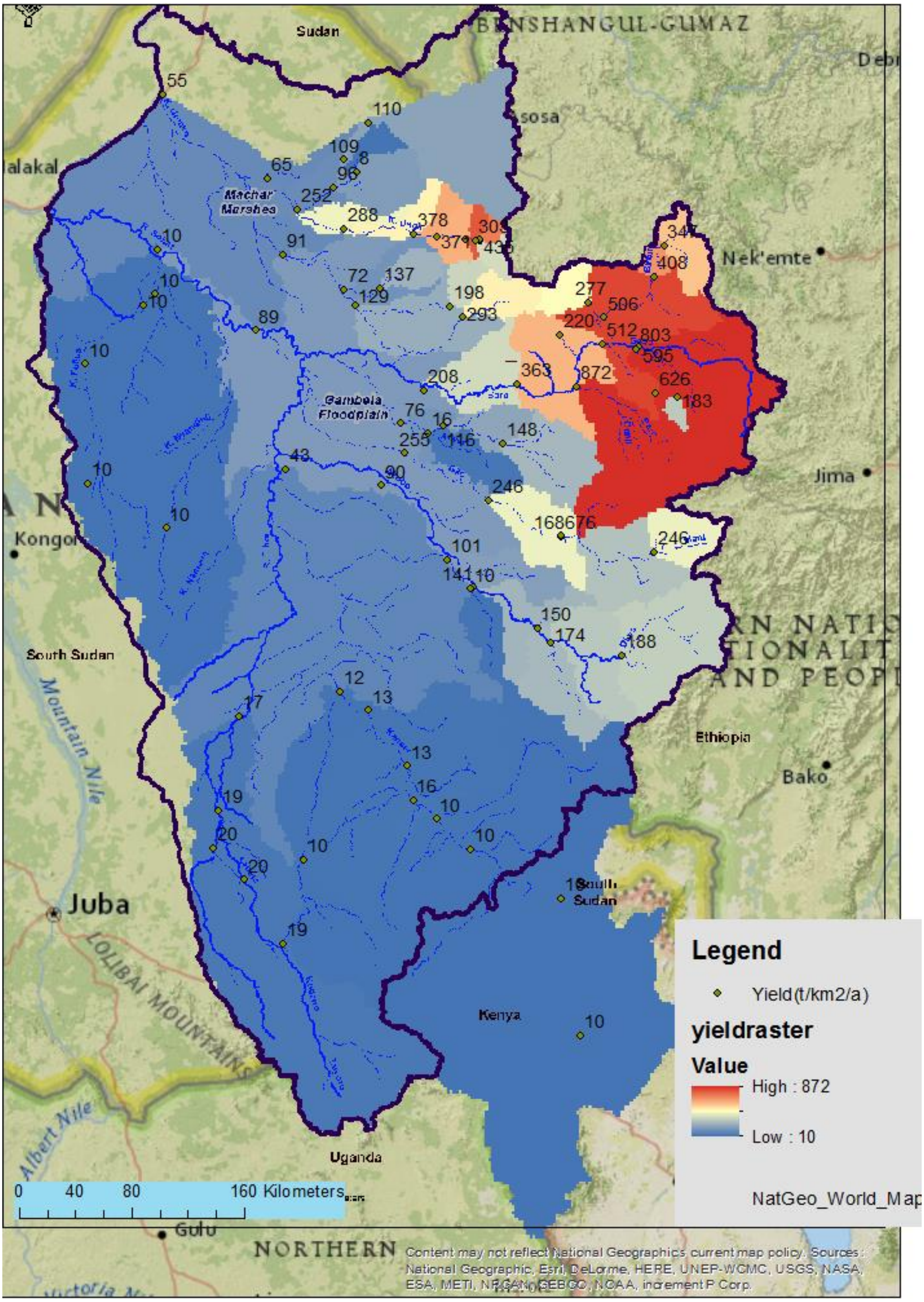
Sudan
BENSHANGUL-GUMAZ
Machar Marshes
Gambela Floodplain
Nek'emte
Jima
Kongor
South Sudan
Mountain Nile
Juba
LOLIBAI MOUNTAINS
Ethiopia
Bako
South Sudan
Kenya
Uganda
Albert Nile
Gulu
NORTHERN
0 40 80 160 Kilometers
Legend
Yield(t/km2/a)
yieldraster
Value
High : 872
Low : 10
NatGeo_World_Map
Content may not reflect National Geographic's current map policy. Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

Figure 3-1: Baro-Akobo-Sobat sediment yield map (values on map indicate sediment yields of the total catchment draining to that location)

4. CONCLUSIONS

The key objective of this report was to develop a sediment yield map for the study area. A detailed methodology was followed by using the SHETRAN model. This physically based rainfall-runoff-sediment transport model was set up on a 30 arc Dem, and sub-catchment flows were calibrated and validated where flow records are available. Simulated daily sediment loads were also calibrated against sediment loads in the rivers where records are available. A 40 year daily flow record and sediment loads were then simulated to obtain the mean long term sediment loads and yields in the study area. Due to the complex flow network and SHETRAN limitation, the marshlands in the north-west of the study area were not simulated. Sediment yields in the marshlands were obtained by taking a weighted average yield from neighbouring catchments.

Appendix 20 shows the positions where sediment yields were calculated with the results tabled in Appendix 21. The resulting sediment yield map is shown in Figure 3-1.

The highest sediment yields are in the east of the study area, with a maximum of 872 $t/km^2.a$. Sediment yields in catchments in the south and west of the study area are relatively low: (< 30 $t/km^2.a$).

5. REFERENCES

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6. APPENDICES

Appendix 1: Baro-Akobo-Sobat flow gauging stations coordinates

Station name	Longitude	Latitude
Baro	34.5812	8.25
Agwei	33.444	6.917
Akobo	34.2947	6.9542
Gilo	34.3934	7.5058
Alwero	34.4904	7.8595
Pibor	33.1308	6.7997
Yabus	33.662	9.923
Daga	33.5864	9.2889

Appendix 2: Default canopy and leaf parameters (SHETRAN, 2013).

Vegetation	Canopy Drainage1		Canopy Storage	Vegetation cover indices	
	CK (mm s-1)	Cb (mm-1)	CSTCAP(mm)	PLAI	CLAI
Arable	1.40E-05	5.1	1.5	1	6
Grass	1.40E-05	5.1	1.5	1	6
Forest	1.40E-05	5.1	5	1	6
Shrub	1.40E-05	5.1	1.5	1	3
Urban	1.40E-05	5.1	0.3	0.3	1

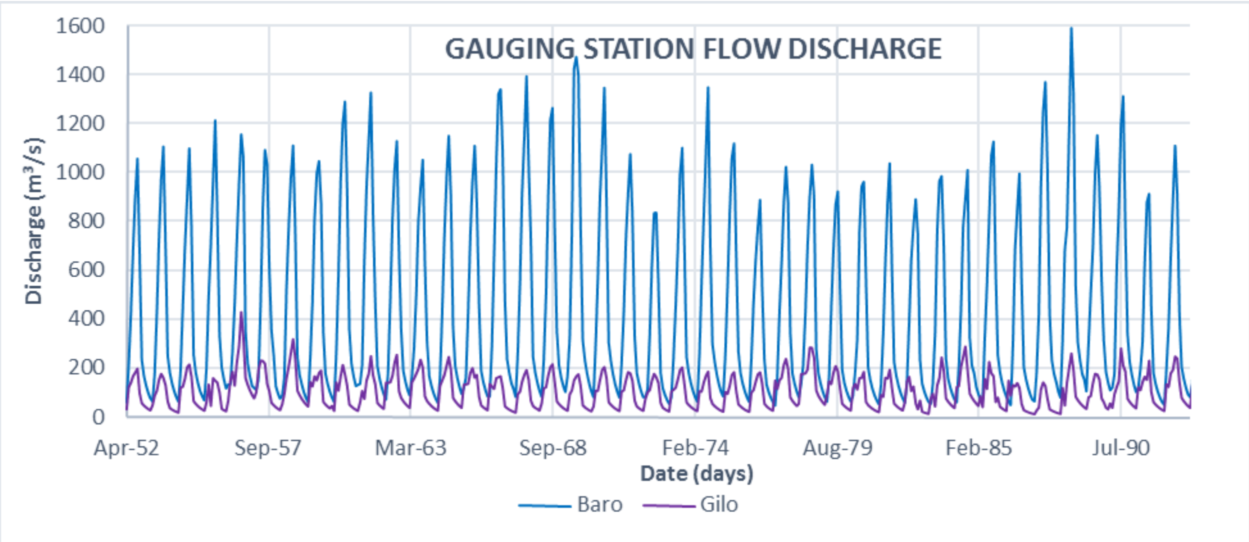
Appendix 3: Default root density function (SHETRAN, 2013)

Vegetation	Total rooting depth	Depth of cell below Ground														
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.4	1.6	1.8	2.0
Arable	0.8	0.31	0.228	0.17	0.1	0.072	0.06	0.04	0.02							
Grass	1.0	0.25	0.18	0.15	0.12	0.1	0.08	0.06	0.03	0.02	0.01					
Evergreen forest	2.0	0.13	0.12	0.11	0.1	0.09	0.08	0.07	0.06	0.05	0.03	0.06	0.04	0.03	0.02	0.01

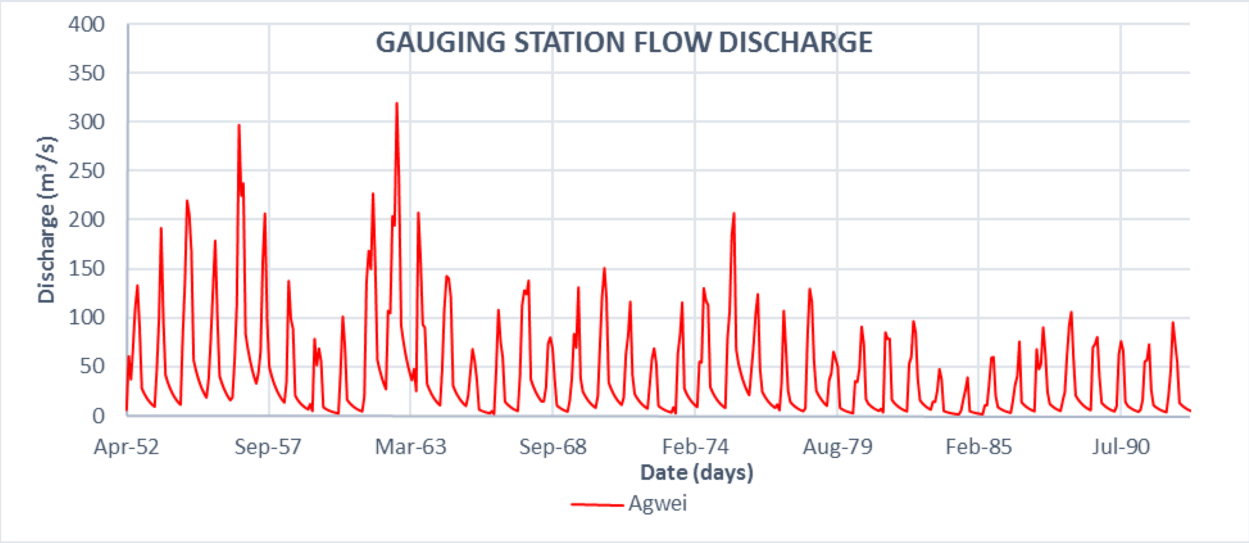
Shrub	1.0	0.25	0.18	0.15	0.12	0.1	0.08	0.06	0.03	0.02	0.01					
Urban	0.5	0.4	03	0.2	0.07	0.03										

Appendix 4: Default library of soil parameters (SHETRAN, 2013)

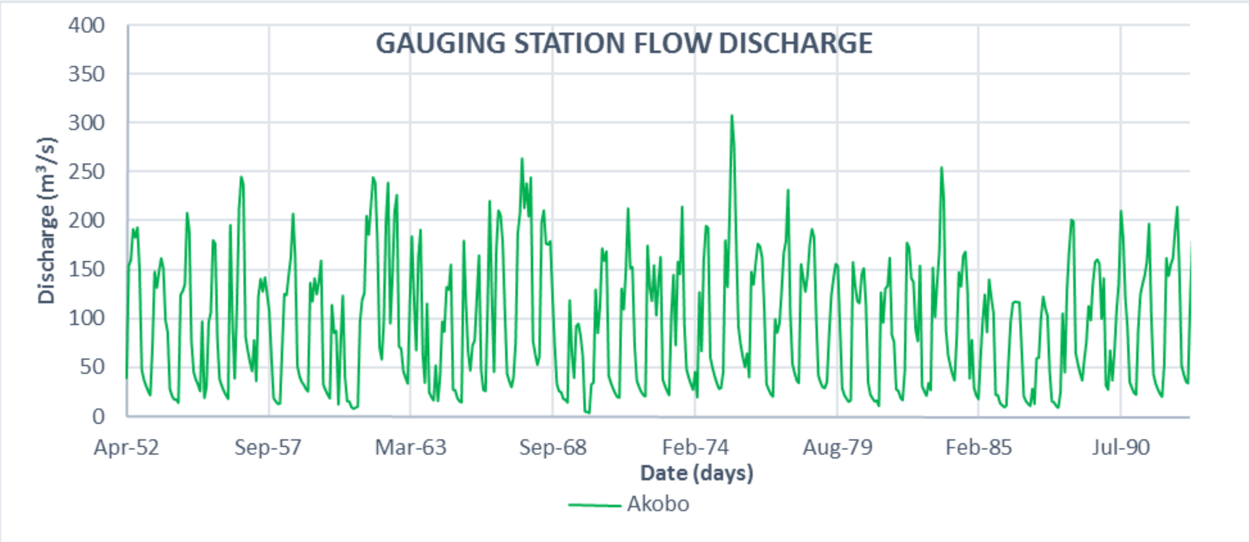
Soil Type	Saturated Water Content	Residual Water Content3	Saturated Conductivity (m/day)4	vanGenuchte n- alpha (/cm)3	vanGenuchte n-n3
Silty Clay (10% Sand, 40% Clay)	0.529	0.212	0.019	0.00654	1.531
Clay Loam (35% Sand, 27% Clay)	0.489	0.153	0.055	0.00923	1.657
Sandy Silt Loam (35% Sand, 10% Clay)	0.434	0.086	0.317	0.00838	1.587
Sandy Clay (52% Sand, 40% Clay)	0.499	0.233	0.029	0.01069	1.879
Sandy Clay Loam (65% Sand, 24% Clay)	0.461	0.167	0.103	0.01236	2.071
Sandy Loam (65% Sand, 10% Clay)	0.412	0.098	0.622	0.01441	1.736



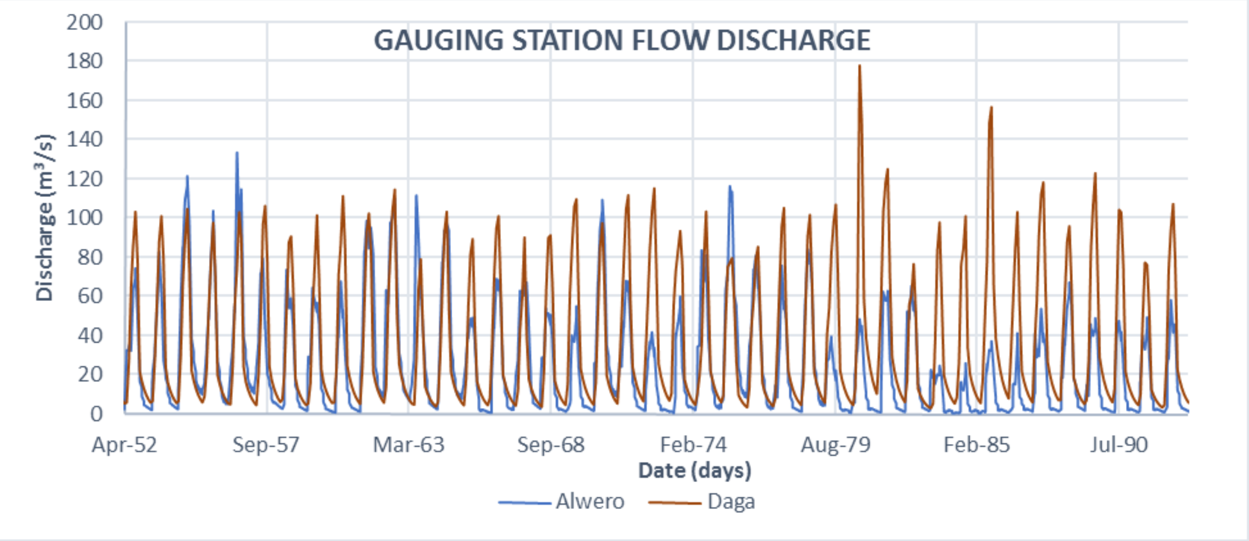
Appendix 5: monthly flows at Baro and Gilo gauging stations



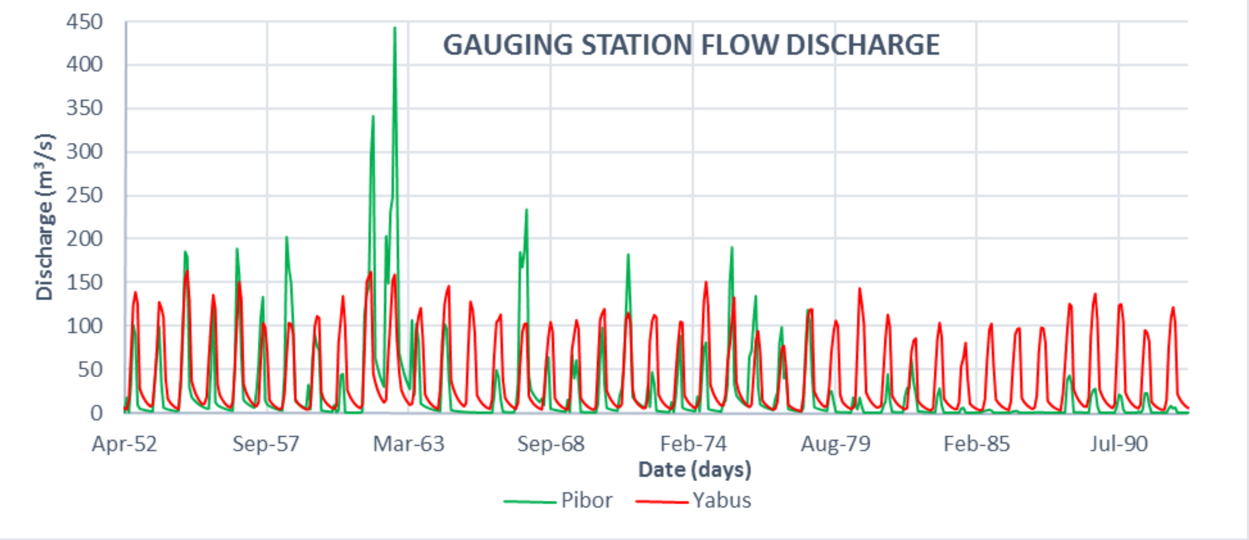
Appendix 6: monthly flows at Agwei gauging station



Appendix 7: monthly flows at Akobo gauging station



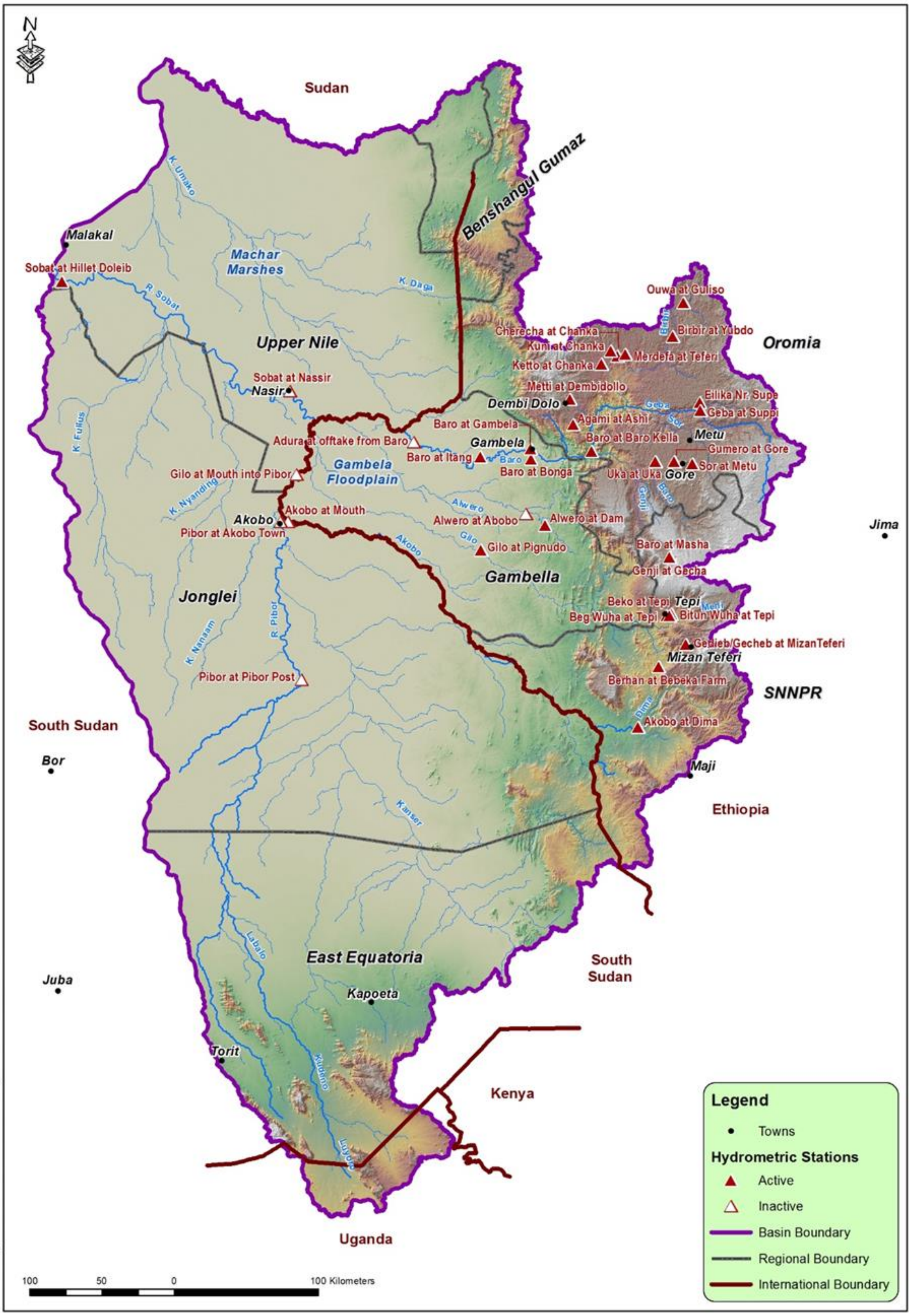
Appendix 8: monthly flows at Alwero and Daga gauging stations



Appendix 9: monthly flows at Pibor and Yabus gauging stations

Appendix 10: Baro-Akobo-Sobat rainfall weather station details

Station	Source	Type	Period	Lat	Long
Abobo	EMP	Penman	1956-1987*	7.51	34.33
Gambela	EMP	Penman	1906-1993*	8.15	34.35
Pokwo	EMP	Penman	1956-1989*	8.1	34.28
Metu	EMP	Penman	1952-1992*	8.2	35.35
Mizan	EMP	Penman	1953-1992*	7	35.35
Wush	EMP	Penman	1953-1992*	7.11	36.1
Anger	EMP	Penman	1954-1992*	9.22	36.22
Arjo	EMP	Penman	1954-1992*	8.45	36.3
Bambessi	EMP	Penman	1955-1992*	9.45	34.44
Gimbi	EMP	Penman	1952-1992*	9.1	35.47
Kurmuk	EMP	Penman	1961-1988*	10.26	34.28
Mendi	EMP	Penman	1955-1992*	9.47	35.05
Nedjo	EMP	Penman	1952-2003*	9.3	35.29
Dongoro	EMP	Penman	1952-1992*	9.16	35.41
Wama	EMP	Penman	1975-1987*	8.46	36.45
Bonga	EMP	Penman	1953-1992*	7.13	36.14
Gambela	Shahin, 1985	Open Water	1950-1957	8.25	34.58
Akobo	Shahin, 1985	Open Water	1950-1957	7.78	33.02
Gore	Norplan, 2006	Open Water	1974-2003	8.15	35.53
Baro-1	Norplan, 2006	Open Water	1974-2004	8.07	35.33
Baro-2	Norplan, 2006	Open Water	1974-2005	8.15	35.33
Genji	Norplan, 2006	Open Water	1974-2006	8.12	35.22
Jimma	FAO Calculator	Penman-Monteith		7.67	36.83
Juba	FAO Calculator	Penman-Monteith		4.8	31.6
Malakal	FAO Calculator	Penman-Monteith		9.55	31.65
Torit	FAO Calculator	Penman-Monteith		4.41667	32.55
Pibor Post	FAO Calculator	Penman-Monteith		6.8	33.133333



Appendix 11: Baro-Akobo-Sobat sediment gauging station locations

Appendix 12: Baro catchment SHETRAN vegetation parameters

	Canopy storage capacity (mm)		Leaf area index		Maximum rooting depth(m)		AE/PE at field capacity	
Parameter	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**
Arable	1.5	1	4	1	0.8	0.8	0.6	0.7
Evergreen forest	5	3	6	1	2	1	1	1
Shrub	1.5	1.5	3	1	1	1	0.4	0.7

Appendix 13: Alwero catchment SHETRAN vegetation parameters

	Canopy storage capacity (mm)		Leaf area index		Maximum rooting depth(m)		AE/PE at field capacity	
Parameter	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**
Arable	1.5	1	4	1	0.8	0.8	0.6	0.7
Evergreen forest	5	3	6	1	2	1	1	1
Shrub	1.5	1.5	3	1	1	1	0.4	0.7
Urban								

Appendix 14: Gilo catchment SHETRAN vegetation parameters

	Canopy storage capacity (mm)		Leaf area index		Maximum rooting depth(m)		AE/PE at field capacity	
Parameter	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**
Arable	1.5	1.5	4	4	0.8	0.8	0.6	1.2
Evergreen forest	5	5	6	6	2	2	1	1.5
Shrub	1.5	2	3	3	1	1	0.4	1.2
Urban	0.3	0.3	0.3	0.3	0.5	0.5	0.4	0.4

Appendix 15: Akobo catchment SHETRAN vegetation parameters

	Canopy storage capacity (mm)		Leaf area index		Maximum rooting depth(m)		AE/PE at field capacity	
Parameter	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**
Arable	1.5	1.5	4	4	0.8	0.8	0.6	1.4
Evergreen forest	5	5	6	6	2	2	1	1.7
Shrub	1.5	2	3	3	1	1	0.4	1.4
Urban	0.3	0.3	0.3	0.3	0.5	0.5	0.4	0.6

Appendix 16: Pibor catchment SHETRAN vegetation parameters

	Canopy storage capacity (mm)		Leaf area index		Maximum rooting depth(m)		AE/PE at field capacity	
Parameter	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**
Shrub	1.5	2	3	3	1	1	0.4	0.4
Grass	1.5	1.5	6	4	1	1	0.4	0.6

Appendix 17: Agwei catchment SHETRAN vegetation parameters

	Canopy storage capacity (mm)		Leaf area index		Maximum rooting depth(m)		AE/PE at field capacity	
Parameter	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**
Shrub	1.5	2	3	3	1	1	0.4	0.6
Grass	1.5	1.5	6	4	1	1	0.4	0.6

Appendix 18: Yabus and Daga catchment SHETRAN vegetation parameters

	Canopy storage capacity (mm)		Leaf area index		Maximum rooting depth(m)		AE/PE at field capacity	
Parameter	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**	**Default**	**Used**
Arable	1.5	1	4	1	0.8	0.8	0.6	0.7
Evergreen forest	5	3	6	1	2	1	1	1
Shrub	1.5	1.5	3	1	1	1	0.4	0.7
Grass	1.5	1.5	6	6	1	1	0.4	0.8

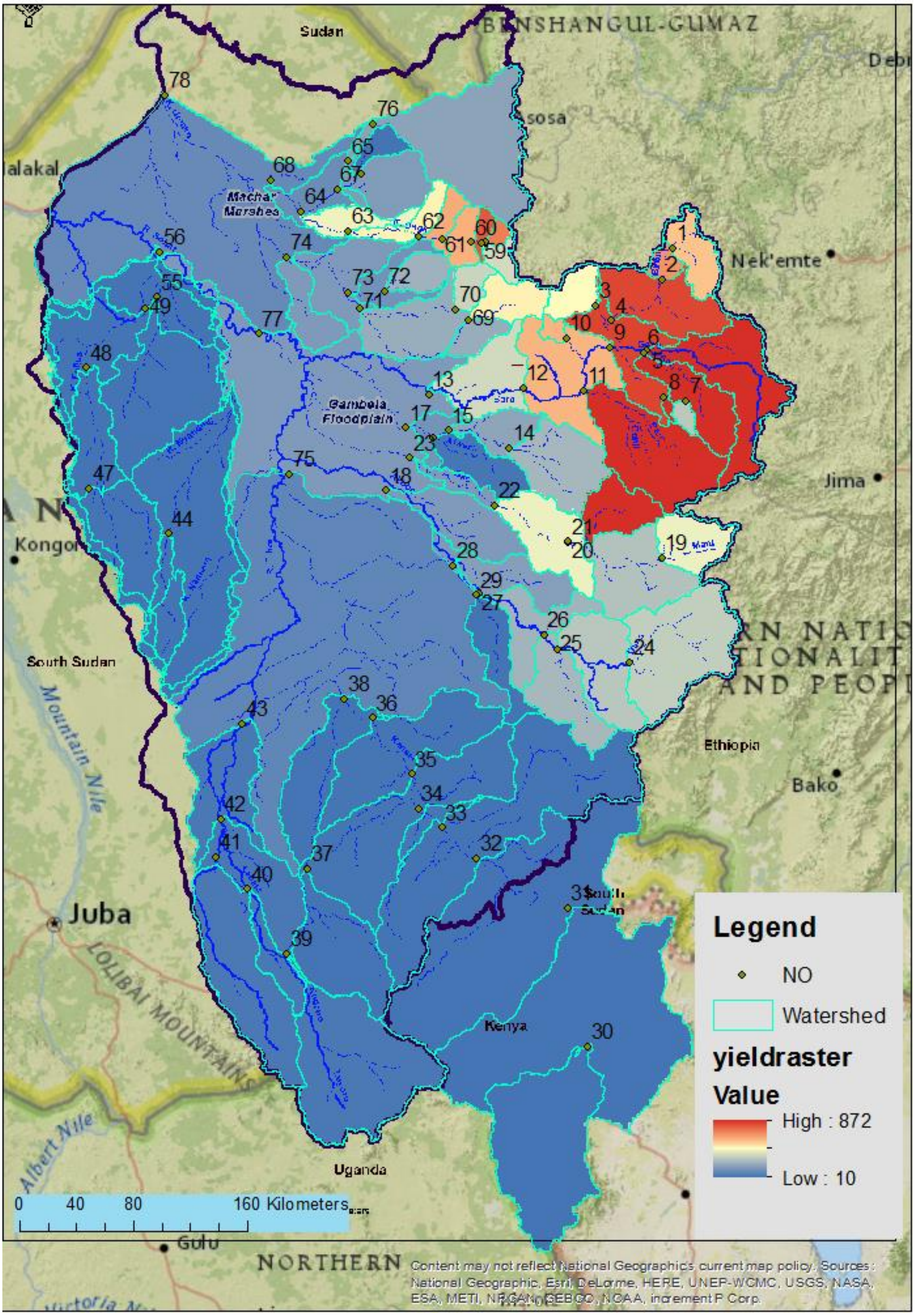
Appendix 19: Sediment concentration and load data used from previous studies (SELKHOZPROMEXPORT, 1990)

Location	Date	Flow (m^3/s)	Concentration (mg/l)	Daily sediment load (t/day)
Birbir	16-Oct-88	31.68	292.81	801
	01-Apr-90	7.05	61.25	37
Sore river near Metu	04-Sep-86	133.47	155.25	1790
	18-Mar-88	4.49	71.43	28
	05-Oct-88	173.6	59.38	891
	04-Mar-89	1.34	24.02	3
	24-Mar-89	2.14	17.84	3
	05-Jun-89	22.3	1232.53	2375
	26-Jun-89	48.03	109.6	455

	06-Nov-89	16.58	101.9	146
	16-Nov-89	16.58	178.75	256
	27-Jun-90	96.18	281.25	2337
	03-Aug-90	132.11	96.25	1099
	04-Aug-90	114.51	102.19	1011
	10-Aug-90	141.7	105.94	1297
	17-Aug-90	124	108.12	1158
	25-Aug-90	139.67	188.75	2278
	18-Aug-90	139.67	79.37	958
	18-Aug-90	255.52	82.5	1608
	26-Aug-90	140.39	134.38	1630
	27-Aug-90	134.82	90.94	1059
	27-Aug-90	148.93	183.12	2356
	24-Dec-90	4.8	78.44	33
GUMERO RIVER NEAR GORE	17-Mar-88	0.12	105.45	1.1
	22-Sep-88	5.44	46.88	22
	23-Sep-88	14.81	43.76	56
	24-Sep-88	12.63	34.38	37.5
	25-Sep-88	18.94	51.05	83.5
	16-Oct-88	8.03	10.42	7.2
	03-Oct-88	8.6	33.34	2.9
	16-Mar-89	0.7	162.35	9.8
	23-Mar-89	0.38	51.08	1.7
	06-Jun-89	1.48	53.63	6.9
	26-Jun-89	5.31	78.68	36.1
	17-Jun-89	0.71	161.66	9.9
	20-Nov-89	0.86	100.64	7.5
	01-Jul-90	3.63	66.04	20.7
UKA RIVER NEAR UKA	22-Sep-88	5.09	65.63	28.9
	23-Sep-88	5.89	42.71	21.7
	24-Sep-88	6.12	53.13	28.1
	28-Sep-88	4.17	51.05	18.4
	30-Sep-88	5.41	12.51	5.8
	02-Oct-88	5.41	42.72	20
	03-Oct-88	5.5	12.5	5.9
	06-Jun-89	0.42	88.68	3.2
	25-Sep-89	2.63	32.29	7.3
	25-Sep-89	2.63	40.71	9.3
	25-Sep-89	2.63	29.99	6.8
	20-Sep-89	3.47	154.76	46.4
	20-Oct-89	3.47	119.76	35.9

	20-Nov-89	3.47	124.99	37.5
	23-Dec-89	4.8	62.86	26.1
	23-Nov-89	4.8	61.19	25.4
	23-Nov-89	4.8	58.37	24.2
	30-Jun-90	2.13	98.44	18.1
	30-Jun-90	2.13	72.5	13.3
	30-Jun-90	2.13	92.19	17
	25-Sep-90	6.2	117.19	62.8
	25-Sep-90	6.2	124.69	66.8
	25-Sep-90	6.2	157.5	84.4
OUWA RIVER NEAR GULISO	20-Sep-84	14.71	556.37	707
	24-Sep-84	10.17	292.94	257
	14-Oct-84	5.99	130.39	67
	20-Sep-85	11.96	1206.56	1247
	19-May-88	2.77	579.42	139
	28-Jun-88	7.3	398.49	251
	16-Oct-88	13.7	329.17	390
	26-Jun-89	7.1	727.98	447
	14-Nov-89	7.55	304.38	199
	14-Nov-89	7.55	331.88	216
	14-Nov-89	7.55	307.81	201
	31-Mar-90	1.94	108.44	18
	31-Mar-90	1.94	108.13	18
	31-Mar-90	1.94	113.44	19
	24-Jun-90	2.81	421.05	102
	24-Jun-90	2.81	365.53	89
	24-Jun-90	2.81	344.74	84
METI RIVER NEAR DEMBIDOLO	20-Oct-83	5.24	204.73	92.7
	21-Oct-83	4.9	119.18	50.5
	02-Sep-84	4.02	224.2	77.9
	03-Sep-84	2.69	152.22	35.4
	04-Sep-84	2.61	98.24	8.5
	07-Sep-84	5.45	201.88	95.1
	02-Sep-85	4.02	170.53	59.2
	06-Aug-86	3.41	522.15	153.8
	19-May-88	1.66	426.24	61.1
	29-Jun-89	1.63	336.56	47.4
KETO RIVER NEAR CHANKA	16-Aug-82	36.69	587.04	1860
	17-Aug-82	46.36	522.44	2093
	18-Aug-82	48.1	271.4	1128
	19-Aug-82	72.6	467.29	2931

	20-Aug-82	69.76	395.28	2382
	21-Aug-82	60.04	561.08	2911
	07-Jul-86	48.1	1534.66	6378
	17-Oct-87	77.07	460.42	3066
	25-Aug-89	54.4	823.75	3872
	29-Jun-89	11.11	538.92	517
KUNNI RIVER NEAR CHANKA	28-Jul-89	2.18	355.39	67
	18-Aug-89	6.53	822.19	464
	19-Aug-89	6.84	607.81	359
	20-Aug-89	7.26	801.25	503
	24-Aug-89	9.4	672.19	546
	25-Aug-89	8.63	983.13	733
	04-Nov-89	1.44	98.13	12
	26-Jun-90	1.56	297.81	40



Appendix 20: Sediment yield calculation numbering

Note that sediment yields at positions 77 and 78 were calculated from neighbouring catchments.

Appendix 21: Sediment yields at various locations in the Baro-Akobo-Sobat study area (this study)

Catchment name	Sub-catchment No.	Coordinate		Accumulated catchment up to point	
				Area	Sediment Yield
		X	Y	km²	ton/km².a
Baro	1	778742.71	1010772.69	1425	347
	2	771402.10	988618.92	1865	408
	3	725249.05	970251.87	1026	277
	4	735749.42	960017.41	4781	506
	5	761183.95	938748.75	4148	595
	6	758564.57	937589.88	2330	803
	7	788524.39	903205.55	269	183
	8	773157.36	906064.82	102	626
	9	734964.33	940867.27	14738	512
	10	704494.86	947455.41	266	220
	11	716824.46	910876.69	4744	872
	12	674160.50	912280.81	23542	363
	13	607928.77	907872.69	26122	208
Alwero	14	664628.77	870372.69	2858	148
	15	621728.77	882672.69	4048	116
	16	610962.09	877881.88	1682	16
	17	592028.77	884472.69	6410	76
Gilo	19	771734.19	793276.05	1720	246
	20	705602.73	803747.80	5015	168

	21	705682.11	804365.16	1676	676
	22	654132.80	829916.88	9375	246
	23	594812.52	863480.20	9993	255
Akobo	24	748898.08	719464.52	5115	188
	25	698150.90	728777.87	8085	174
	26	688639.11	739021.67	10538	150
	27	642706.03	767762.98	12534	141
	28	625117.81	787560.47	14399	101
	18	578168.34	840322.07	17203	90
Agwei	30	719528.77	449172.69	7472	10
	31	705428.77	546672.69	21742	10
	32	641528.77	581772.69	35927	10
	33	616928.77	603072.69	46751	10
	34	600428.77	616272.69	47328	16
	35	595928.77	640872.69	58447	13
	36	568328.77	680472.69	63587	13
	37	522728.77	573972.69	3874	10
	38	548528.77	693972.69	66920	12
Pibor	39	508028.77	514272.69	7410	19
	40	480728.77	559872.69	8550	20
	41	458228.77	582672.69	5513	20
	42	461828.77	609072.69	17095	19
	43	477128.77	675972.69	20324	17
Sobat	44	424868.77	810012.69	1717	10

	47	369428.77	841692.69	3854	10
	48	367448.77	926832.69	6649	10
	49	409028.77	968412.69	8401	10
	55	416948.77	976332.69	12855	10
	56	418928.77	1008012.69	22538	10
Daga	57	647528.77	1014672.69	494	213
	58	647528.77	1014972.69	221	435
	59	644528.77	1014672.69	729	303
	60	637928.77	1014972.69	1042	486
	61	617228.77	1017072.69	1787	371
	62	601028.77	1019172.69	2372	378
	63	551228.77	1022772.69	3326	288
	64	518228.77	1036872.69	4345	252
	65	551228.77	1071972.69	6347	109
	66	559928.77	1063272.69	600	10
	67	543728.77	1052172.69	9147	96
	68	496628.77	1058472.69	14838	65
	69	635828.77	959772.69	1302	293
	70	626528.77	967572.69	683	198
	71	559028.77	968472.69	5397	129
	72	577028.77	980772.69	944	137
	73	551228.77	979872.69	2076	72
	74	508028.77	1004472.69	11358	91
	75	510114.08	851586.14	118685	43

Pibor and Agwei extension	29	641270.66	766949.38	1702	10
Yabus	76	568856.75	1098106.38	6156	110
Marshland	77	488327.38	950713.48	206107	89
Marshland exit to Nile	78	422804.07	1118223.29	43310	55

Annex 1-D: Groundwater report

BARO-AKOBO-SOBAT MULTIPURPOSE WATER RESOURCES DEVELOPMENT STUDY - BASELINE STUDY

Annex 3-D Groundwater report

TABLES AND FIGURES

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ACRONYMS AND ABREVIATIONS

AfDB	African Development Bank
ACORD	Association for Cooperative Operations Research and Development
ACTED	Agency for Technical Cooperation and Development
BAS	Baro Akobo Sobat
CAMP	Comprehensive Agriculture Development Master Plan
CBA	Cost Benefit Analysis
CMA	Catchment Management Association
CRA	Cooperative Regional Assessment
DEM	Digital Elevation Model
EEPCO	Ethiopian Electric Power Corporation
EHA	Erosion Hazard Assessment
EIA	Environmental Impact Assessment
ENID	Eastern Nile Irrigation and Drainage
ENCOM	Eastern Nile Committee Of Ministers
ENPM	Eastern Nile Planning Model
ENPT	Eastern Nile Power Trade
ENSAP	Eastern Nile Subsidiary Action Plan
ENTRO	Eastern Nile Technical Regional Office (NBI)
EPA	Environmental Protection Authority
FAO	Food and Agriculture Organization
GDEM	Global Digital Elevation Model
GDP	Gross Domestic Product
GEF	Global Environment Facility
GIS	Geographic Information System
GTP	Growth and Transformation Plan
GWh/y	GigaWatt hour/year
HEP	Hydroelectric Power
IDEN	Integrated Development of Eastern Nile
ILWRM	Integrated Land and Water Resources Management
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature and Natural Resources
IWMI	International Water Management Institute
IWRDMP	Integrated Water Resources Development and Management Plan
IWRM	Integrated Water Resource Management
JMP	Joint Multipurpose Project
MAFCRD	Ministry of Agriculture, Forestry, Cooperatives and Rural Development
MASL	Meters Above Sea Level
MCA	Multi Criteria Analysis
MDG	Millennium Development Goals
MEDIWR	Ministry of Electricity, Dams, Irrigation and Water Resources
MERET	Managing Environmental Resources to Enable Transitions
MLFI	Ministry of Livestock and Fisheries
MoA	Ministry of Agriculture
MoEN	Ministry of Environment
MoWIE	Ministry of Water, Irrigation and Energy
MSIOA	Multi Sector Investment Opportunity Analysis
MTR&B	Ministry of transport, roads and bridges
MW	Mega Watt
MWC&T	Ministry of Wildlife Conservation and Tourism
NB-DSS	Nile Basin Decision Support System
NBI	Nile Basin Initiative
NCORE	Nile Cooperation for result project
NDVI	Normalized Difference Vegetation Index

NELSAP	Nile Equatorial Lakes Subsidiary Action Program
NGO	Non-Governmental Organization
Nile-COM	Nile Council of Ministers
PIM	Project Implementation Manual
PLSPP	Policies, Legislation, Strategies, Plans, and Programs
PPP	Private Public Partnership
PMU	Project Management Unit
PRSP	Poverty Reduction Strategy Program
RATP	Regional Agricultural Trade and Productivity Project
RPSC	Regional Project Steering Committee
RSS	Republic of South Sudan
RUSLE	Revised Universal Soil Loss Equation
SAP	Subsidiary Action Program
SEA	Strategic Environmental Assessments
SIS	Soil Information System
SLMP	Sustainable Land Management Program
SNNPR	Southern Nations, Nationalities and Peoples' Region
SRFE	Satellite Rainfall Estimates
SRTM	Shuttle Radar Topographic Mission
SSEA	Strategic Social and Environmental Assessment
SVP	Shared Vision Program
SWAT	Soil and Water Analysis Tool
SWOT	Strength Weakness Opportunity Threat
SWSC	Soil-Water Storage Capacity
UNDP	United Nations Development Program
UNHCR	United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
USAID	United States Agency for International Development
WaSH	Water Sanitation and Hygiene
WB	World Bank
WBISPP	Woody Biomass Inventory and Strategic Planning Project
WCYA	Women, Children and Youth Affairs
WEES	Water for Eastern Equatoria
WFP	World Food Program
WM	Watershed Management
WRMA	Water Resources Management Authority
WRMD	Water Resources Management and Development
WSS	Water Supply and Sanitation
WUA	Water Users Association

1. INTRODUCTION

The aim of this report is to present the groundwater development potential in a format that is accessible and useable for development planning purposes. In relation the Terms of Reference (with respect to groundwater), it states the following: "Based on secondary data and studies, the Consultant will map and characterize groundwater resources potential and utilization for development uses".

The Inception and Scoping Phases included assessing the availability and quality of data and a start was made in compiling data for the Baseline Study. During the Baseline Study data was compiled in the final formats and this involved extrapolating from the incomplete data sets obtained in the Scoping Phase or developing new data sets from scratch. Because most original data sets are sparse and because the mapping scale is small (to cover the vast study area), some of the results presented cannot carry a high degree of confidence, although on a qualitative basis, the results are likely to reasonably reflect the groundwater conditions of the area.

The main deliverable, where a considerable portion the team's time was spent, are the maps on the 'Extractable rate of groundwater recharge' (Chapter 3). Given the sparse available data sets, new data sets were generated in most cases, and a methodology to quantify the groundwater resource potential was developed. The results are satisfactory and compare favourably to similar regional studies on other areas in Africa. It is recomemnded that Option 2 of the 'Extractable rate of groundwater recharge' (Figure 3-3) be adopted as the current best estimate of the groundwater potential for the BAS sub-basin.

The hydrogeologists responsible for this report are:

- Mr Abebe Ketema, Consultant Hydrogeologist, Ethiopia.
- Mr Gedion Tsegaye Sahle, GTS Services Plc., Ethiopia.
- Dr Ricky Murray, Groundwater Africa. South Africa.

2. GROUPING AREAS WITH SIMILAR GROUNDWATER SUPPLY POTENTIAL

The process of grouping areas with similar groundwater supply potential and then quantifying the potential yields of these areas was as follows:

Step 1. Define the groundwater yield-related criteria

i. Regional permeability (termed BAS Lithologic Permeability). Assumption: Yield potential increases with higher regional permeability. Regional permeability may be primary permeability (like pore spaces in unconsolidated and consolidated formations), or it may be the regional permeability that is associated with average jointing and fracturing in hard-rocks.

ii. Secondary permeability (termed BAS Geologic Structures). Assumption: Yield potential increases with higher lineament, joint and fault densities.

iii. Topographic location (termed BAS Topography: Slope). Assumption: Yield potential increases in areas with gentle slopes and in valley bottoms.

iv. Groundwater recharge (termed BAS Regional Groundwater Recharge). Assumption: Yield potential increases with increasing recharge.

Step 2. Quantify the above criteria

i. BAS Lithologic Permeability: Group geological formations with similar regional permeabilities. The source information was compiled from numerous studies and text books (identified during the Scoping Study – see the following section).

ii. BAS Geologic Structures: Group areas with similar lineament densities. The lineament data set used was from this study (see the following section) and areas were selected based on geological formations and geographical areas.

iii. BAS Topography: Slope: The DEM used in this study (see the following section) was used to compile a slopes layer (in degrees) and areas with similar slopes were grouped together.

iv. BAS Regional Groundwater Recharge: Using recharge estimates from various sources identified in the Scoping Study a formula to estimate recharge was developed using a percentage of Mean Annual Precipitation (MAP). The MAP data used was generated in this project (see the hydrology section). The recharge values were checked with previous studies and correlated sufficiently well to use for the entire study area.

Step 3. Develop a weighting system

i. The four criteria above were each divided into groups: For Regional Permeability, 5 groups were created, and for the other 3 criteria, 3 groups were created. Each group has a score with the most favourable groundwater areas having high scores, and the least favourable having low scores. I.e. the groups reflect how favourable an area is for groundwater development.

ii. Each criteria was applied a weighting factor based on the value of each criteria to groundwater development. The weighting factors applied were: Regional permeability (25%); Secondary permeability (20%); Topographic location (30%); Recharge (25%).

Step 4. Group areas of similar weights

i. Applying the above approach to the study area produced areas ranging from low values representing poor groundwater development areas to high values representing good groundwater development areas.

ii. The areas were then grouped into 5 classes: High, Medium to High, Medium, Low to Medium, Low.

Step 5. Quantify the 5 class areas

i. This was done by assigning extractable percentages of groundwater recharge to the groundwater availability layer.

2.1 BAS LITHOLOGIC PERMEABILITY

The main geological spatial data produced are lithological units and geologic structures (structural linearments), mainly mapped or derived from remotely-sensed data and existing geological maps. The remote-sensing analysis was carried out in 2015 by TTI Production (a sub-contractor used on the project).

Some 31 mapping units (30 lithologic and 1 water) were identified at 1: 100,000 (100K) scale. The attribute table of the geology GIS shapefile includes relevant information like lithological descriptions, stratigraphy and mapping codes. The surficial lithological units were first grouped according to main permeability types. Each mapping unit within these groups was assigned relative permeability classes by referring to available maps and reports as well as incorporating personal experiences of the study team (see Table 2-1, Table 2-2, Table 2-3 and Figure 2-1, Figure 2-2). These classes take into consideration primary permeability and regional secondary permeability due to degrees of large-scale fracturing and weathering. A description of the lithological codes is give in Appendix 1.

Table 2-1 Sediments, mainly intergranular permeability type

Stratigraphy	Litho-Unit Code	Permeability Class
Holocene to Recent	Q_undif Q_fan Qal Qc	Medium Medium - High Medium High
Pleistocene to Holocene	Qal2	Medium
Cenozoic, Plio-Pleistocene	CzUR	Medium

Table 2-2: Volcanic, mainly fracture permeability type

Stratigraphy	Litho-Unit Code	Permeability Class
Quaternary?	VL	Low
Cenozoic	CzVa	Low
	CzVb	Medium
Paleogene to Neogene	Pga	Medium

Table 2-3: Basement, mainly fracture/weathering permeability type

Stratigraphy	Litho-Unit Code	Permeability Class
Precambrian	PE_Gabbro	Low
	PEGr	Low
Upper Proterozoic	Gt1	Low
	Gt2	Low
	PE3a	Low
	PE3lb	Low
	UB	Low
Middle Proterozoic	PEs	Low
	PEsa	Low
	PEsm	Low - Medium
	PEsq	Low
	PEsy	Low
	PEum	Low
Lower to Middle Proterozoic	PE1	Low-Medium
	PE1_hard	Low
Lower Proterozoic	PEp	Low-Medium
	PEpgns	Low
	PEps	Low
Archean?	PE1b	Low
Archean	PEx	Low

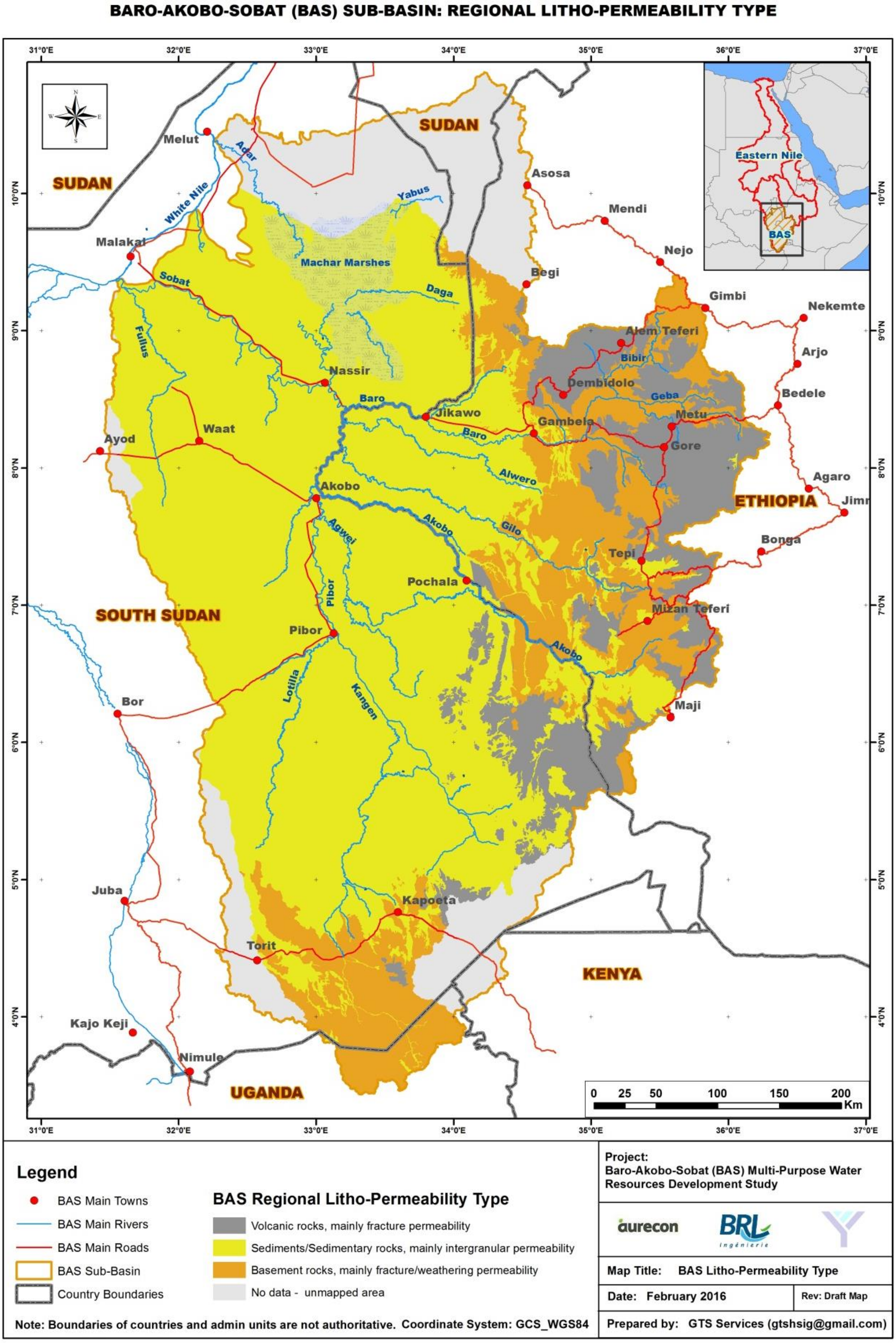

Figure 2-1: BAS Regional Litho-Permeability Type

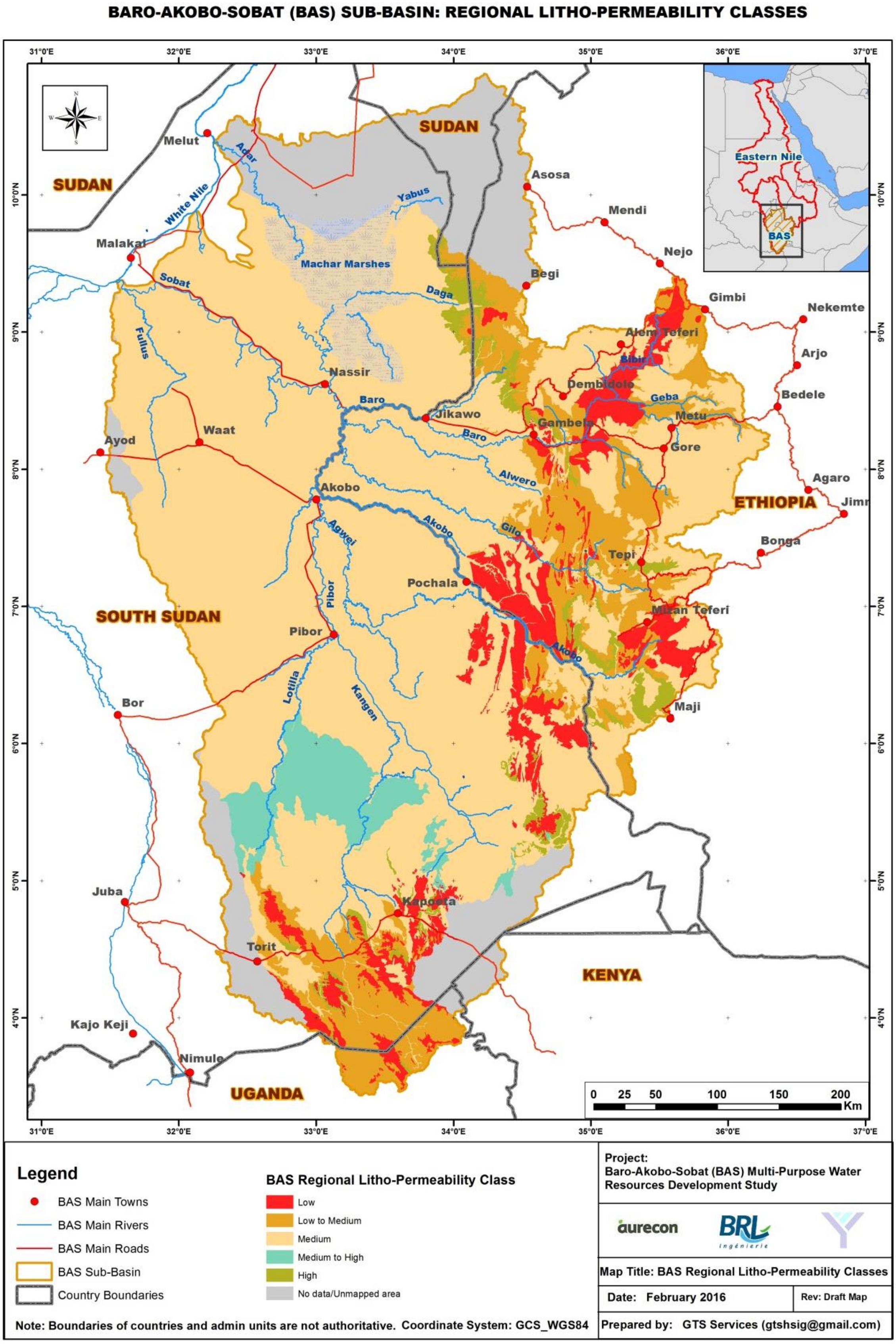

Figure 2-2: BAS Regional Litho-Permeability Class

2.2 BAS GEOLOGIC STRUCTURES

Some geological structures play an important role in enhancing the permeability of the host rocks by creating secondary porosity and permeability. While this statement holds in most places, it does not necessarily hold in all places, as fractures may have been cemented up, for example, during geothermal processes. Detailed analysis and field mapping would be necessary to identify only those structures that enhance permeability, but this was outside the scope of this exercise. Regional geological structures were mapped as part of this project at 1:100,000 scale using mainly remote sensing techniques. Areas of high fault/lineament densities were considered favourable for groundwater occurrence.

The main geo-structures identified and mapped, include faults (certain & inferred), photo-lineaments and tecto-lineaments. Their densities were assessed and grouped into different classes (Table 2-1) and mapped accordingly (Figure 2-3). The high land parts of Baro Akobo (Ethiopia) and parts of Eastern equatorial state of South Sudan are characterised by high structural densities owing to their underlying hard rock formations, while the flat low lands of the project area are characterised by poor structural densities as these area are covered by alluvial deposits of primary porosity and permeability.

Table 2-4: Regional Geologic Structures Density

Geo-structures Density (per Km^2)	**Class**
< 0.025	High
0.02 – 0.05	Medium
0.05 – 0.1	Low-Medium
0.1 – 0.2	Low
> 0.2	Very Low

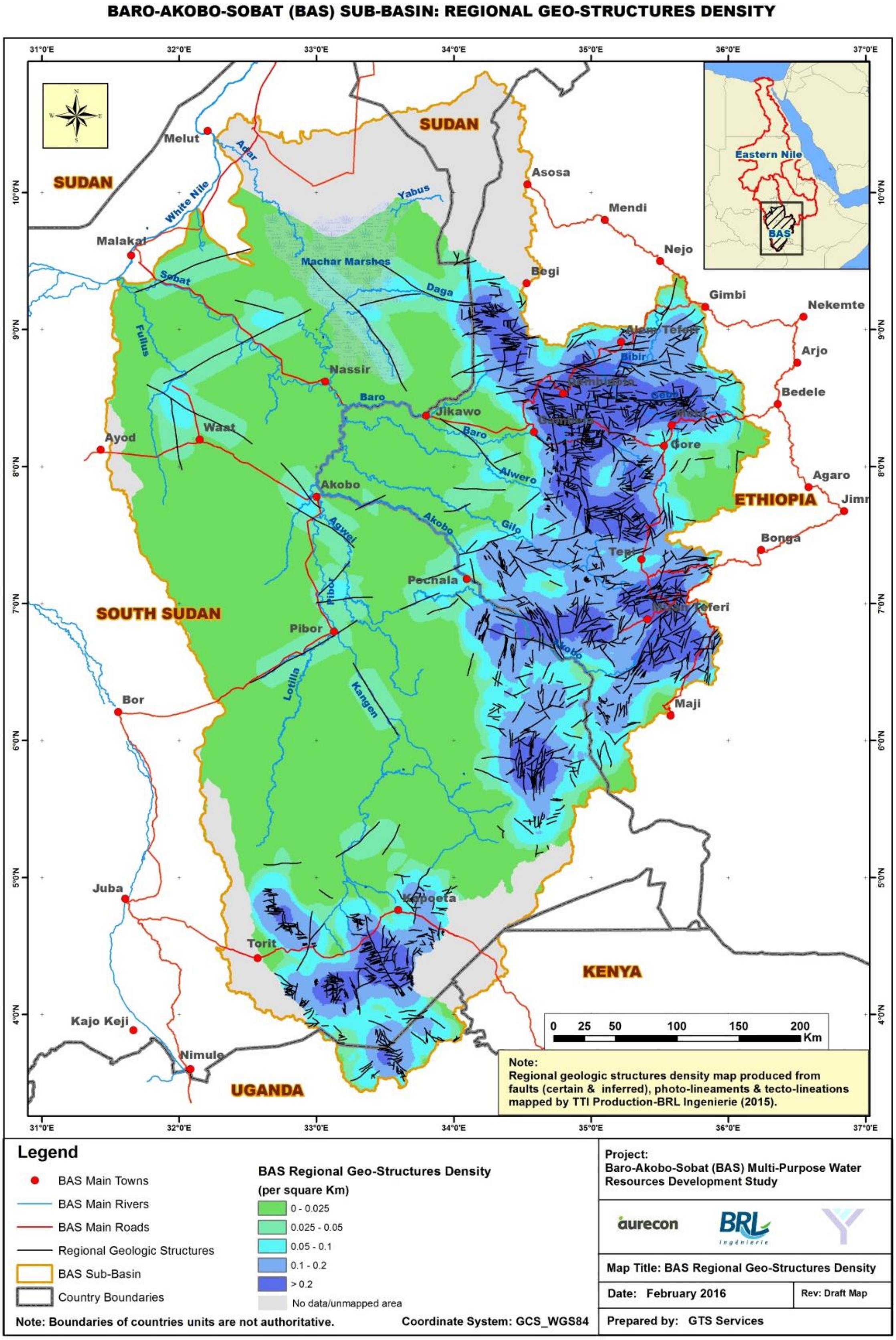

Figure 2-3: BAS Geo-StructuresDensity

2.3 BAS Topography: Slope

Mountains and areas with steep slopes are generally not favourable for groundwater development. While they may form areas of high recharge and throughflow, it is generally the flatter areas that are targeted for groundwater supply. A slope map (the BAS Slope map) was produced from the SRTM Digital Elevation Model (DEM) at a 30m spatial resolution. The slopes were in degrees were then grouped into flat/plain area, gentle, moderate, and steep slope groups (Figure 2-4).

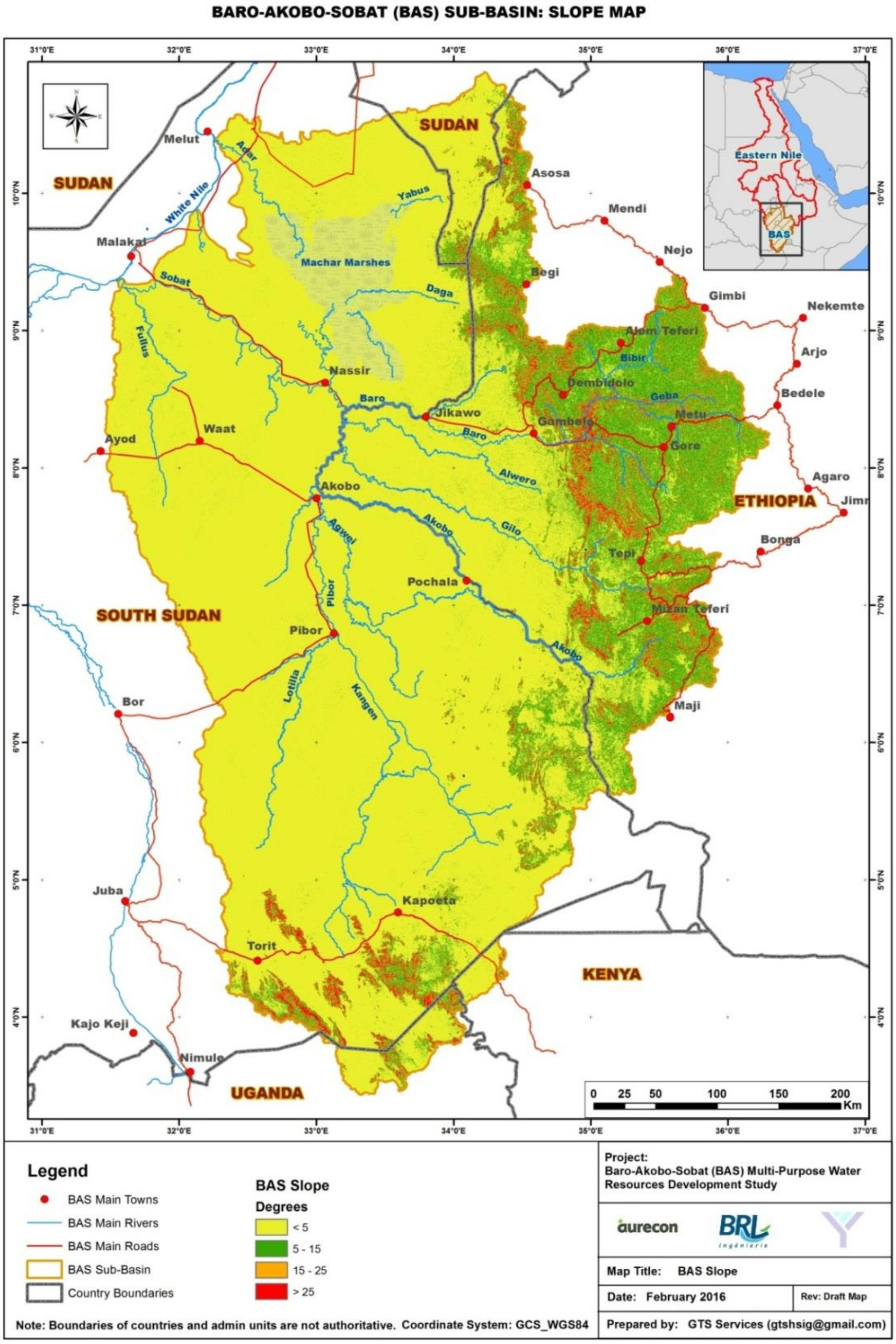

Figure 2-4: BAS Slopes

2.4 BAS REGIONAL GROUNDWATER RECHARGE

2.4.1 Introduction

Groundwater recharge rates are difficult to establish without good field data. In the absence of this, indirect means are needed to provide reasonable estimates. The approach adopted was to use the two main determining factors: Rainfall and infiltration capacity.

2.4.2 BAS Mean Annual Rainfall

Groundwater recharge generally occurs after a certain rainfall threshold has been surpassed within a specific time period. Without local time-series data on rainfall-infiltration relationships, a reasonable approach is to use mean annual rainfall as the baseline data.

The rainfall map (Figure 2-5) prepared during this project shows that the mean annual rainfall over the study region ranges from < 800mm for the areas of Upper Nile in the North of the project area and Eastern Equatoria state in the South of the study area, to over 1500mm over the Ethiopian highlands of the Baro Akobo basin in the East. The rest of the rainfall values are zoned in a decreasing pattern from East to West of the BAS study area.

BARO-AKOBO-SOBAT (BAS) SUB-BASIN: MEAN ANNUAL RAINFALL

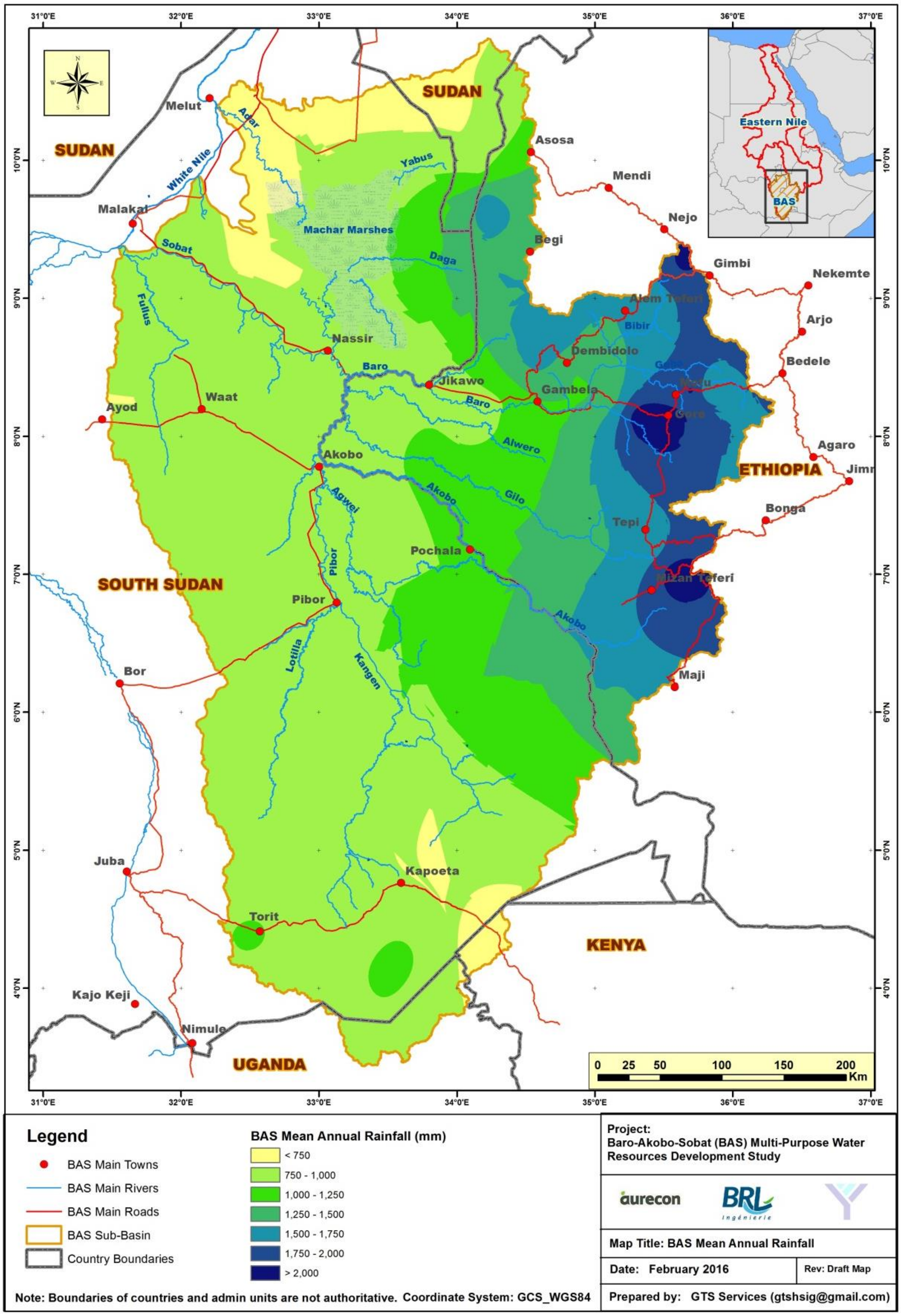

Figure 2-5: BAS Mean Annual Rainfall

2.4.3 BAS Regional Infiltration Coefficients

Direct infiltration into the weatherd zone overlying the hard rock and into exposed fissures and fractures varies depending on the permeability and infiltration capacity of the rock units over the study area. In areas where the permeability of the surface formation is low, the infiltration capacity is limited and much of the potential recharge is rejected and enters drainage channels and rivers as surface runoff. The relationship between recharge and rainfall varies significantly, even at a local scale, and can be established by taking the nature of precipitation into account, the nature and thickness of the topsoil and the weathered zone, the rock types and fracture systems, topographical factors, etc. In this study, a generalised approach was followed and the BAS regional litho-infiltration coefficient map was produced by giving infiltration coefficients to the various geologic lithologic units depending on their permeability class (Table 2-5and Figure 2-6).

The high infiltration rates correlate with geological units inferred to posses relatively high permeability. From the table, it is evident that that the sediments with intergranual permeability of the type (Qc) are characterized by relatively high infiltration rates (0.175%), while other sediments covering large portion of the study area are given medium values (0.1%). Volcanic rocks are characterized by variable permeability properties and hence the infiltration coefficient of these volcanic units ranges from low (0.05%,CzVa) to medium (0.10%, CzVb, Pga). The infiltration coefficient assigned to the basement rocks is in general low (0.05 %).

In general, the capability of an aquifer system to integrate the effects of the precipitation over a number of years depends on the deep infiltration properties of the rocks and the drainage area. Infiltration rates vary widely, depending on geology, land use, the character and moisture content of the soil, and the intensity and duration of precipitation, from possibly as much as 0.175% over permeable grounds to about 0.05 % over basement environments of the study area.

Table 2-5: BAS Regional Infiltration Coefficients

Litho-Unit Code	Permeability Class	Infiltration Coefficient
Q_undif	Medium	0.1
Q_fan	Medium - High	0.15
Qal	Medium	0.1
Qc	High	0.175
Qal2	Medium	0.1
CzUR	Medium	0.1
VL	Low	0.05
CzVa	Low	0.05
CzVb	Medium	0.1
Pga	Medium	0.1
PE_Gabbro	Low	0.05
PEGr	Low	0.05
Gt1	Low	0.05
Gt2	Low	0.05
PE3a	Low	0.05
PE3lb	Low	0.05
UB	Low	0.05
PEs	Low	0.05
PEsa	Low	0.05
PEsm	Low - Medium	0.08
PEsq	Low	0.05
PEsy	Low	0.05
PEum	Low	0.05
PE1	Low - Medium	0.08
PE1_hard	Low	0.05
PEp	Low - Medium	0.08
PEpgns	Low	0.05
PEps	Low	0.05
PE1b	Low	0.05
PEx	Low	0.05

BARO-AKOBO-SOBAT (BAS) SUB-BASIN: REGIONAL LITHO-INFILTRATION COEFFICIENTS

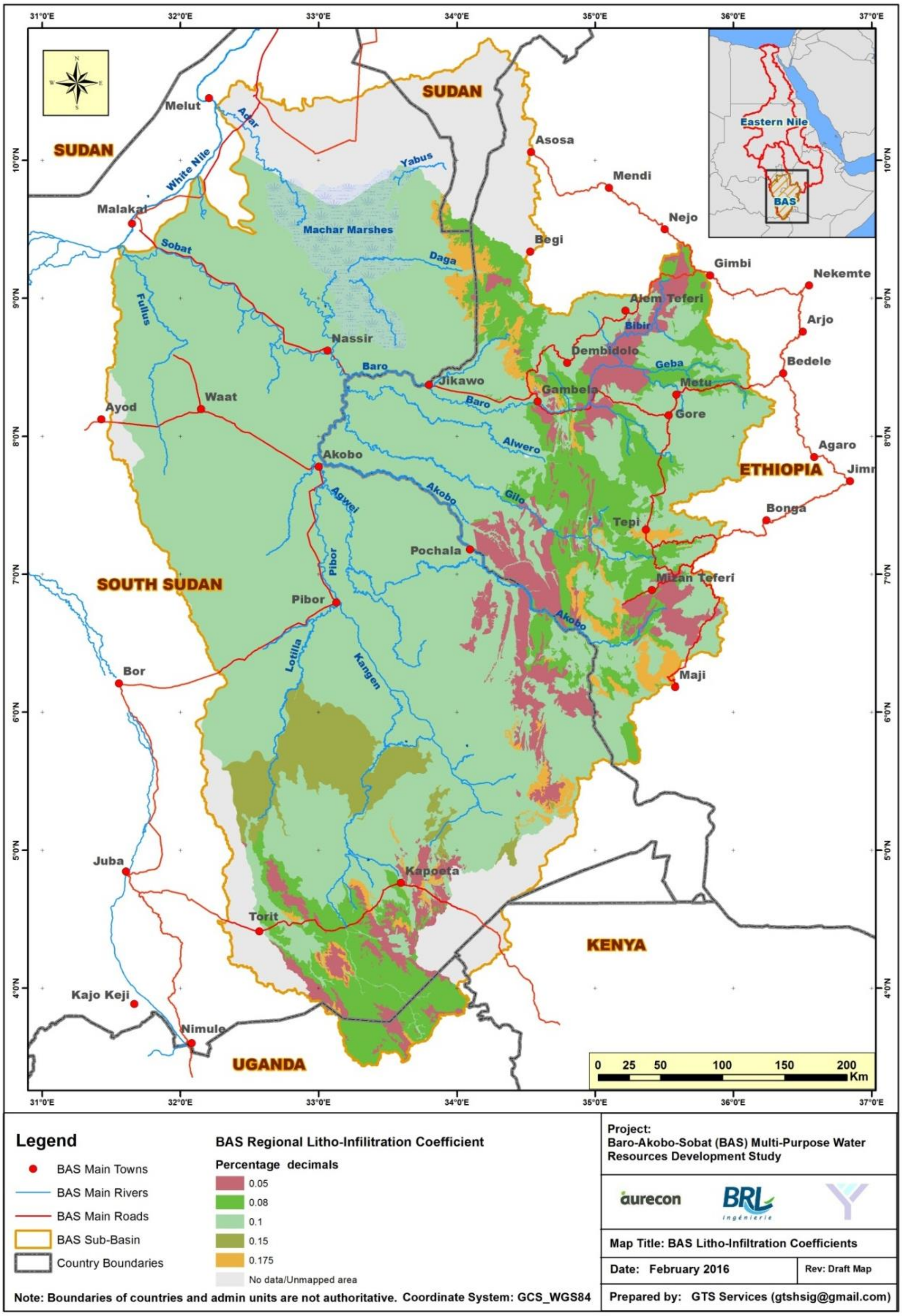

Figure 2-6: BAS Regional Litho-infiltration Coefficient

2.4.4 BAS Regional Groundwater Recharge

While acknowledging the complexity of groundwater recharge and the various local hydrogeologic processes that govern its effectiveness, rainfall data together with infiltration estimates were combined to present a regional map of groundwater recharge (Figure 2-7).

The annual recharge rates determined for the study area fall in the range of < 50mm/yr to about 300mm/yr. The relatively higher recharge rates correspond to the highland areas with permeable grounds especially the Ethiopian highland parts of the Baro Akobo basin. The vast plain areas covering the South Sudan as well as the low lands of Gambela plain gets relatively lower recharge rates (<100mm/yr) mainly due to the lower rate of precipitation over these areas. However, it should be noted that the aquifers, especially the deep aquifers underlying these areas, such as the regional aquifers within the Alwero Formation underlying the Gamela Plain which are inferred to extend towards South Sudan, could receive additional recharge from the lateral influx of water as a result of deeper percolation processes from the adjacent high lying areas in the east of the study region (the Ethiopian highlands). The details of this and its quantifications, however, would require a specialist study.

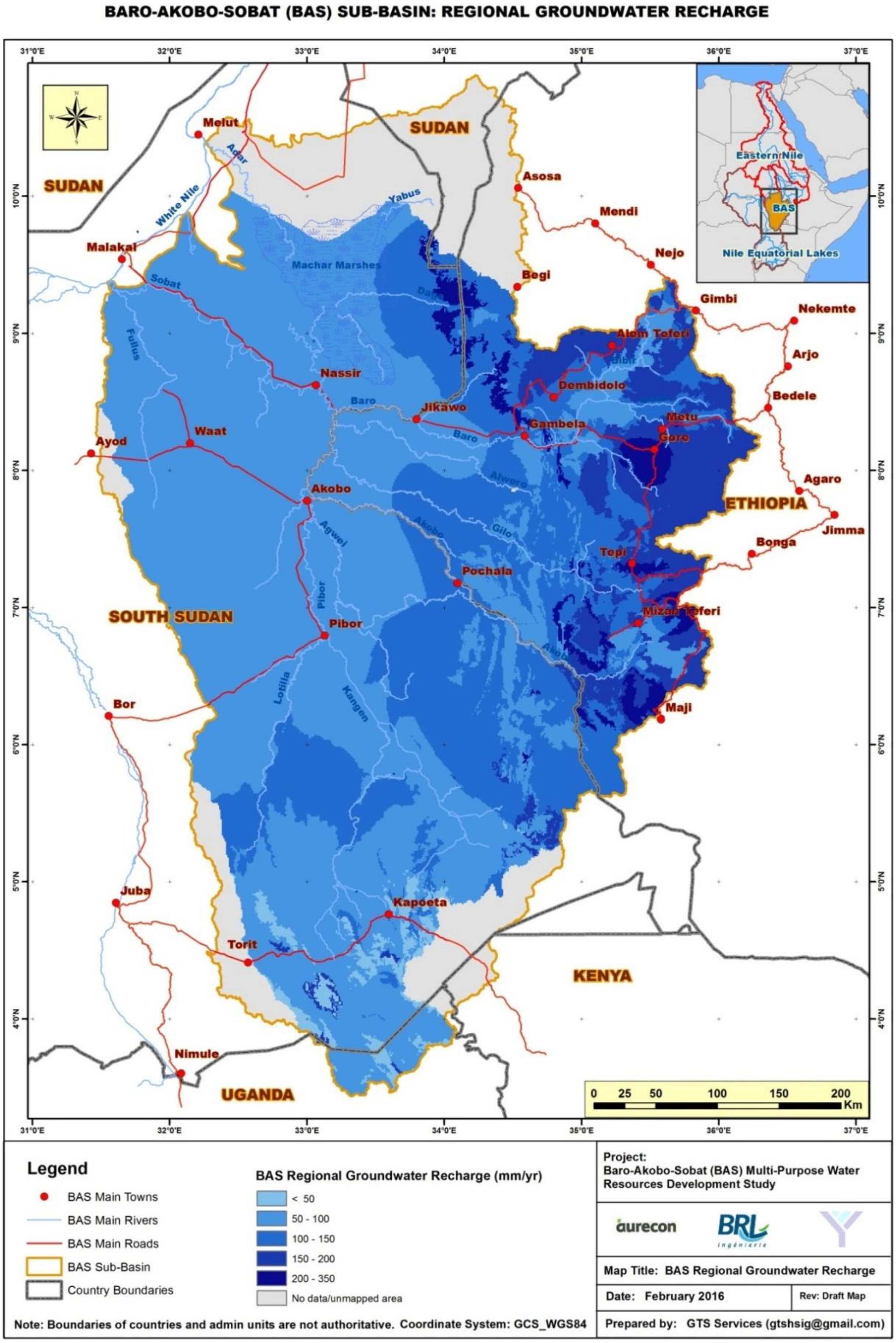

Figure 2-7: BAS Regional Groundwater Recharge

3. BAS GROUNDWATER POTENTIAL

3.1 INTRODUCTION

The process used to quantify the groundwater potential followed two steps:

i. Define groundwater availability by develop a weighting system that takes the four criteria above into account.

ii. Quantify the areas by assigning extractable percentages of groundwater recharge to the groundwater availability layer.

3.1.1 BAS Groundwater Availability

In order to obtain a regional groundwater availability map, an overlay analysis was performed using the above layers. ArcGIS 10.3 spatial analyst was used to assist in weighting and combining the multiple input layers and to produce the groundwater availability map (Figure 3-1). The main input layers used for the overlay analysis together with the layer and class weights are shown in Table 3-1 to Table 3-4.

Table 3-1: BAS Regional Litho-Permeability

Permeability Class	Weight	Layer Weight
Low	5	0.25
Low to Medium	10	
Medium	20	
Medium to High	30	
High	35	

Table 3-2: BAS Regional Geo-Structures Density

Geo-Structures Density (square Km)	Class	Weight	Layer Weight
0 - 0.025	Very Low	5	0.2
0.025 - 0.05	Low	10	
0.05- 0.1	Low to Medium	20	
0.1 - 0.2	Medium	30	
> 0.2	High	35	

Table 3-3: BAS Topography: Slope

Slope (degrees)	Type	Weight	Layer Weight
0 - 5	Flat / Plain Areas	50	0.3
5 - 15	Gentle Slopes	30	
15 - 25	Moderate Slopes	15	
> 25	Steep Slopes	5	

Table 3-4: BAS Regional Groundwater Recharge

Recharge (mm/yr)	Class	Weight	Layer Weight
< 50	Low	5	0.25
50 - 100	Low to Medium	10	
100 - 150	Medium	20	
150 - 200	Medium to High	30	
200 - 335	High	35	

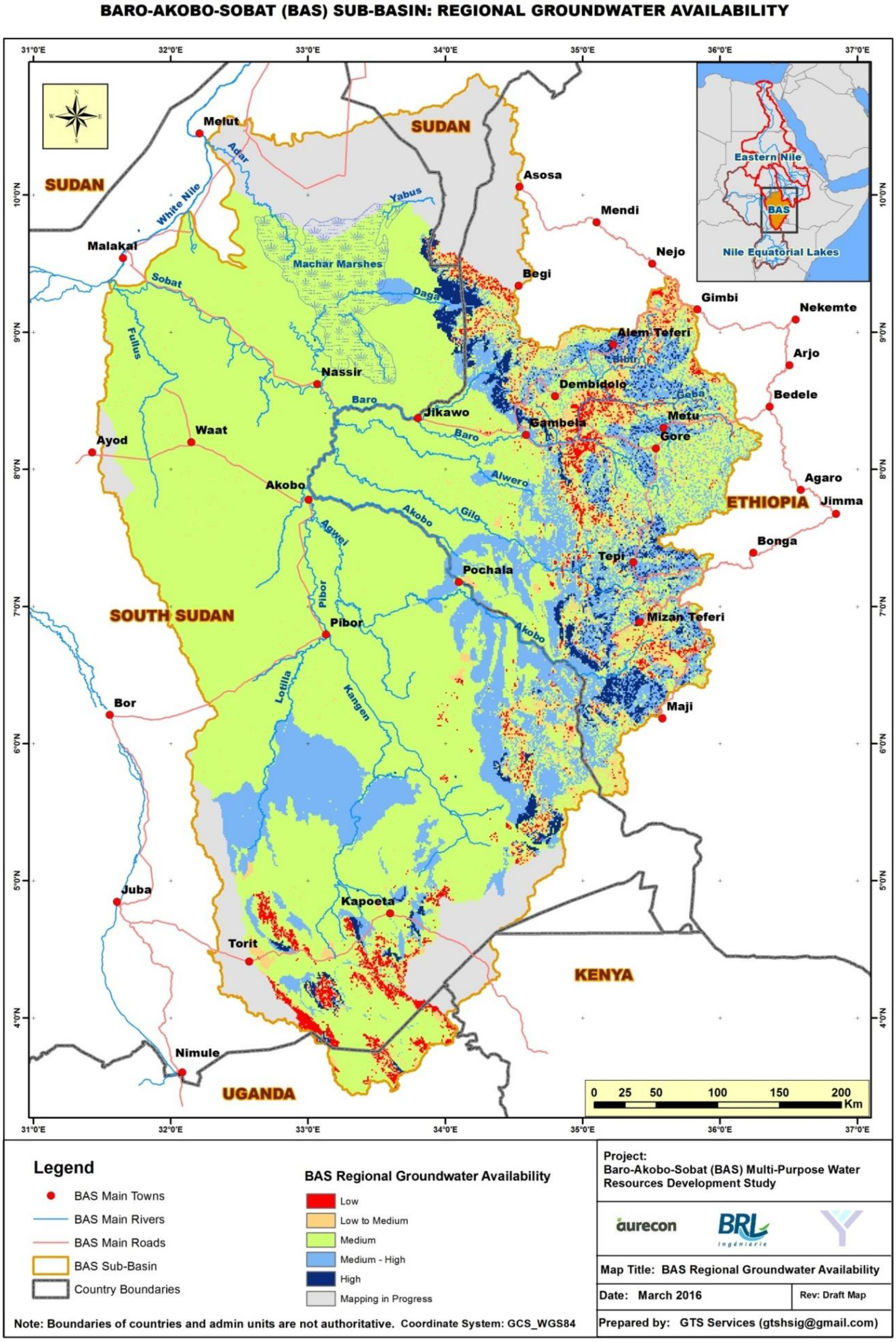

Figure 3-1: BAS Regional Groundwater Availability

3.2 BAS GROUNDWATER POTENTIAL

The final step in presenting the groundwater yield potential was to quantify the Groundwater Availability groups. This was done by assigning extractable percentages of groundwater recharge to the groundwater availability layer (Table 3-5). While the concept and quantification of extractable groundwater potential, safe yields, sustainable yields, etc, remain a contentious debate amoungst hydrogeologists, the approach taken (using % recharge) was considered a reasonable option given the available data. Previous studies have shown that in using this approach, the abstractable proportion of recharge has a wide range of values, from ~10 % to ~70 % (Miles and Chambet, 1995; Hahn et al., 1997), depending on variations in local geological conditions; and Ponce (2007) found average values to be ~40%.

Table 3-5: BAS Extractable Percentage (%) of Regional Groundwater Recharge

Groundwater Availability	Extractable % of Recharge (Option 1)	Extractable % of Recharge (Option 2)	Extractable % of Recharge (Option 3)
Low	5	5	7
Low - Medium	10	15	17
Medium	20	25	27
Medium - High	30	30	35
High	40	50	50

The values from these options were used to determine the extractable rate of recharge in mm/yr as well as prepare the groundwater potential maps in $10^3m^3/km^2/yr$ (Table 3-6, Table 3-7, Table 3-8 and Figure 3-2, Figure 3-3, Figure 3-4).

It must be noted that the above approach take surface geology into account, and not aquifers that may exist at depth that are not evident at the surface. An example of this is in the lowers plains where the Alwero Formation exists in the sub-surface. This formation is considered to have high groundwater potential, but is not exposed at the surface, and receives lateral recharge from the highlands. It is discussed later in the report.

Table 3-6: BAS Abstractable Volume of Groundwater, Option 1

GW Availability Zones	Extractable % of Recharge	Area (Km^2)	% of Total BAS Area	Yield (Mm^3/yr)	Yield ($m^3/day/km^2$)
Low	5	6 077	2.3	24	11
Low - Medium	10	13 274	5.1	138	29
Medium	20	163 246	62.7	3 063	51
Medium - High	30	37 520	14.4	1 583	116
High	40	6 689	2.6	552	226
Area to be processed		33 608	12.9		
Total		260 414	100.0	5360	56

Table 3-7: BAS Extractable Volume of Groundwater, Option 2

GW Availability Zones	Extractable % of Recharge	Area (Km^2)	% of Total BAS Area	Yield (Mm^3/yr)	Yield ($m^3/day/km^2$)
Low	5	6 077	2.3	24	11
Low - Medium	15	13 274	5.1	208	43
Medium	25	163 246	62.7	3 828	64
Medium - High	30	37 520	14.4	1 583	116
High	50	6 689	2.6	690	283
Area to be processed		33 608	12.9		
Total		260 414	100.0	6333	67

Table 3-8: BAS Extractable Volume of Groundwater, Option 3

GW Availability Zones	Extractable % of Recharge	Area (Km^2)	% of Total BAS Area	Yield (Mm^3/yr)	Yield ($m^3/day/km^2$)
Low	7	6 077	2.3	34	15
Low - Medium	17	13 274	5.1	235	49
Medium	27	163 246	62.7	4 133	69
Medium - High	35	37 520	14.4	1 847	135
High	50	6 689	2.6	690	283
Area to be processed		33 608	12.9		
Total		260 414	100.0	6940	73

All options appear reasonable when compared to similar regional studies that used different approaches, for example in the Awoja Catchment in Uganda (Murray, 2013) where yields between 21 – 129 $m^3/day/km^2$ were obtained, and in the Karoo, South Africa where yields ranging up to 182 $m^3/day/km^2$ were obtained (Murray, et al, 2012).

Since the results are not hugely different, it is recomemnded at this stage, that Option 2 be adopted as the current best estimate of the groundwater potential of the BAS sub-basin.

While the figures presented above are based on regional generalisations, a few specific points need to be made:

- A considerable part of the Ethiopian highland volcanics shown as medium to high in terms of groundwater availability are also regarded in previous studies as relatively high productive volcanic aquifers belonging to Mekonnen and Tepi basalts.
- The north-trending geologic structures associated with intrusive plugs and dykes may act as groundwater barriers but it is mentioned in the ARDCO-GEOSERV study (1995) that areas in contact with these features could be highly fractured and favorable for groundwater abstraction, indicating the validity of the geologic structures density map.
- Considerable parts of the BAS sub-basin have been mapped as alluvial/colluvial deposits (including lacustrine-alluvials, screes and talus) which have been generally regarded as unconsolidated sediments of intergranular porosity with relatively medium to high permeability. Underlying these deposits in the Gambela plain is the Alwero Formation which comprises sandstones, aleurolites and argilites (Selkhozpromexport, 1990). Reported is an artesian borehole in this formation showing the confined nature of the relatively deeper sandstone aquifer. In the transition zone between the Ethiopian highland and the Gambela plain, there are also the Paleogene Gilo formations (aleurolite, argillites, sandstones and limited conglomerates) and the relatively productive Miocene Gog basalts underlying the alluvio-colluvial deposits (Selkhozpromexport, 1990).
- Despite the fact that the basement rocks on the highlands are considered as having relatively low and low-medium primary permeability, fractured and weathered parts of some of these rocks in areas receiving considerable rainfall can give rise to better productivity. This has also been noted also in the ARDCO-GEOSERV (1995).
- The lateritic deposits which commonly form from weathering of underlying rocks are common sources of shallow groundwater as evidenced from the hand-dug wells data compiled by ARDCO-GEOSERV, 1995.

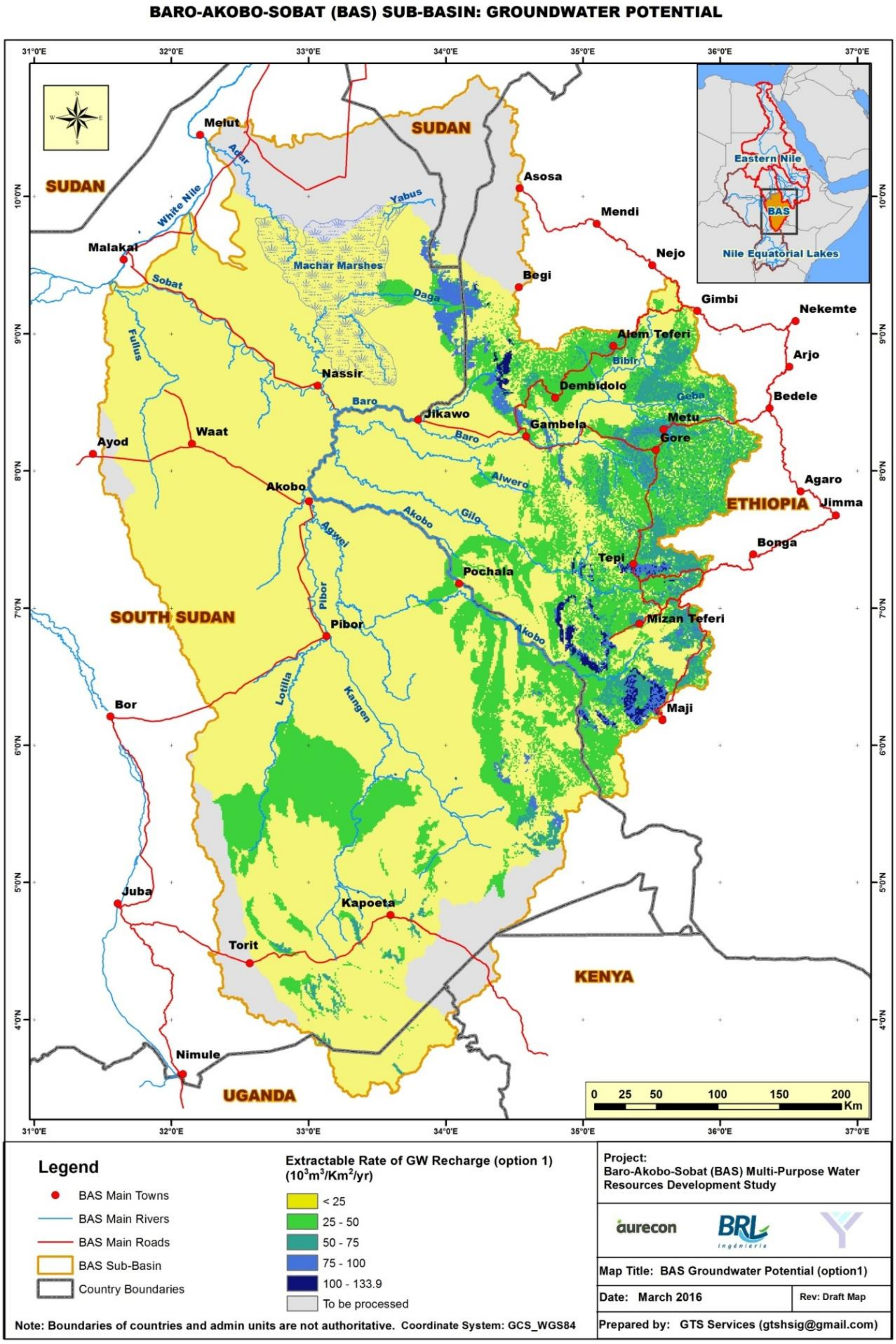

Figure 3-2: Extractable rate of groundwater recharge – Option 1

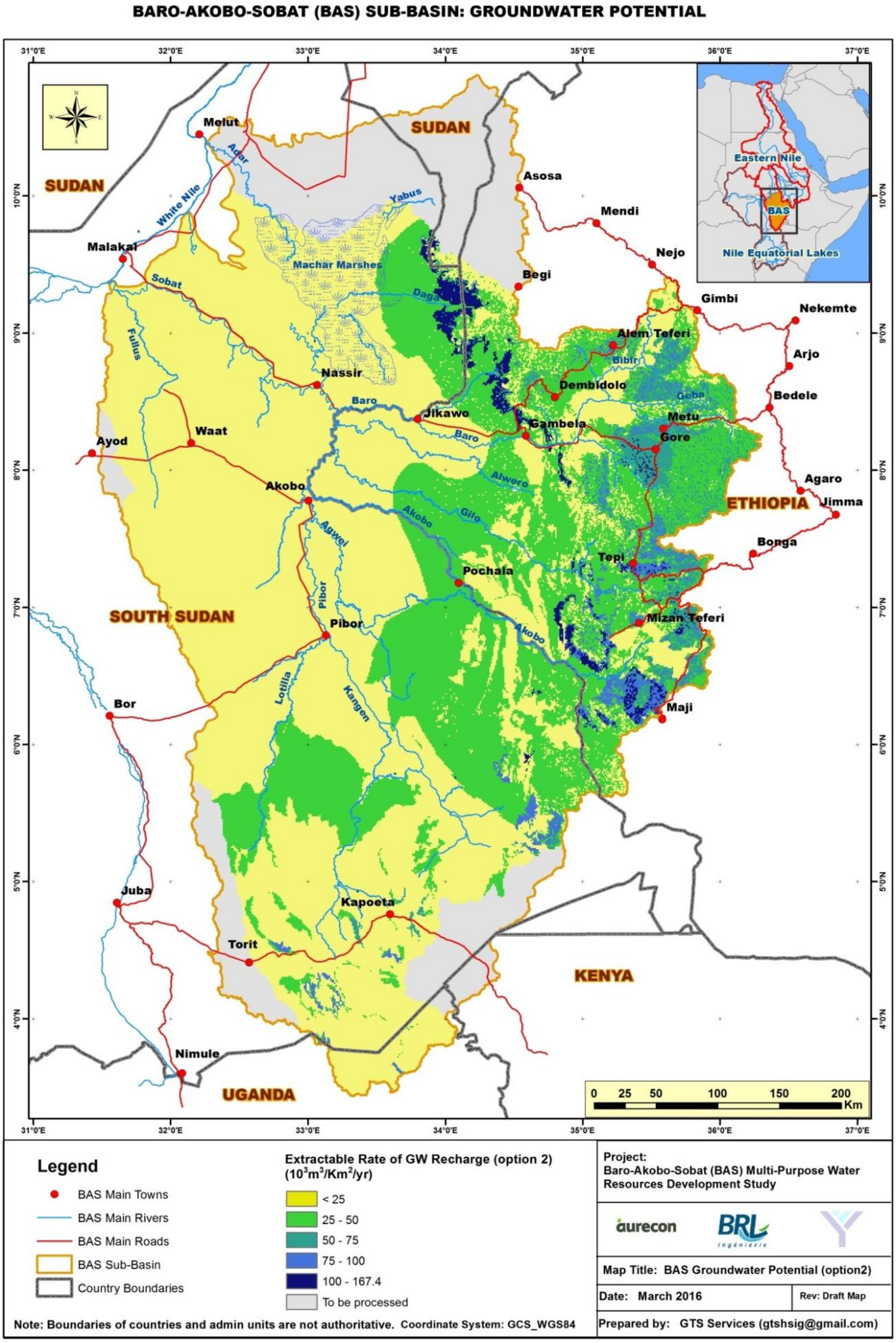

Figure 3-3: Extractable rate of groundwater recharge – Option 2

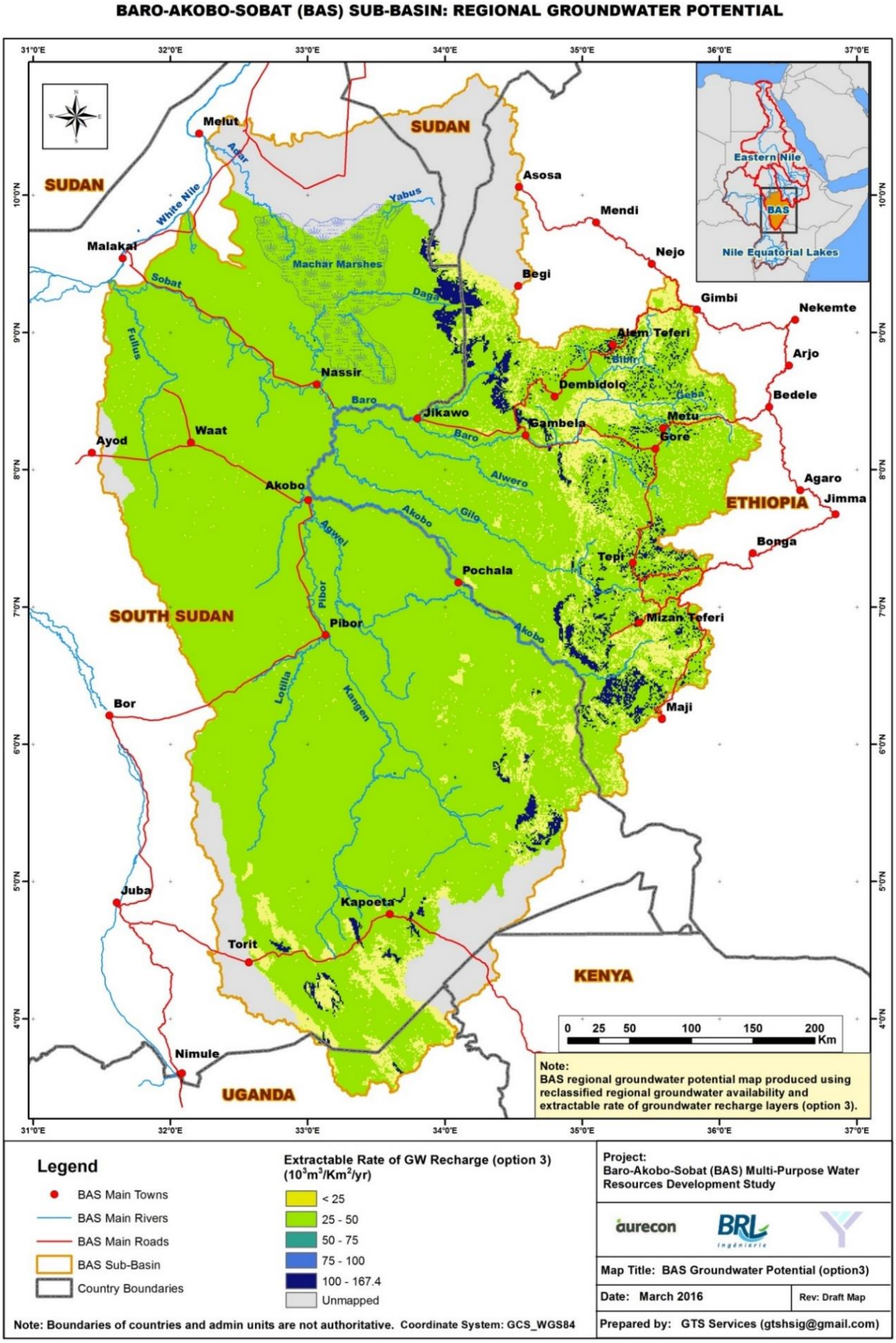

Figure 3-4: Extractable rate of groundwater recharge – Option 3

4. GROUNDWATER QUALITY

4.1 INTRODUCTION

Water quality variations over the project area are complex as a result different physical and geochemical processes that take place due primarily to the diversity in the geology. The spatial coverage of data is also limited and usually dependent on localised surveys of individual projects.

The available literature indicate that generally groundwater quality is good throughout the Blue Nile Basin part of the study area. The water is generally “fresh” (low salinity) and suitable for most uses. There are, however, localized exceptions such as high salinity due to mineralization arising from more reactive rock types, and from contamination due to urbanization. Contamination is greatest in areas with highly permeable unconsolidated sediments, and where water is drawn from hand-dug wells and unprotected springs (Demlie and Wohnlich, 2006) as quoted by Charlotte MacAlister (2010).

Works of Charlotte MacAlister (2010), showed that salinity of the Umm Ruwaba sedimentary formation in South Sudan (an aquifer which is considered to be the second-most important groundwater resource in the region after the Nubian Sandstones aquifer), is generally good, but may rise over 5000 mg/l along its margins (Ahmed *et al.,* 2000). The study also indicated the need for establishing groundwater quality monitoring systems. The same work also indicated that in the adjacent Ugandan part of the region, groundwater quality in most areas meets the guideline requirements for drinking water with the exception of iron and manganese in highly corrosive low pH groundwater, and nitrates in densely populated areas associated with poor sanitation. Generally, however, the groundwater is fresh.

The TDS (total dissolved solids) of the springs on BAS Ethiopian highlands were plotted with graduated symbols (Figure 4-1). Except for few highly mineralized samples, most of the springs have TDS less than 500 mg/l. Data is still being collected to present TDS for the whole BAS sub-basin I.e it will include the well-known saline and brackish waters in the Upper Nile part of South Sudan).

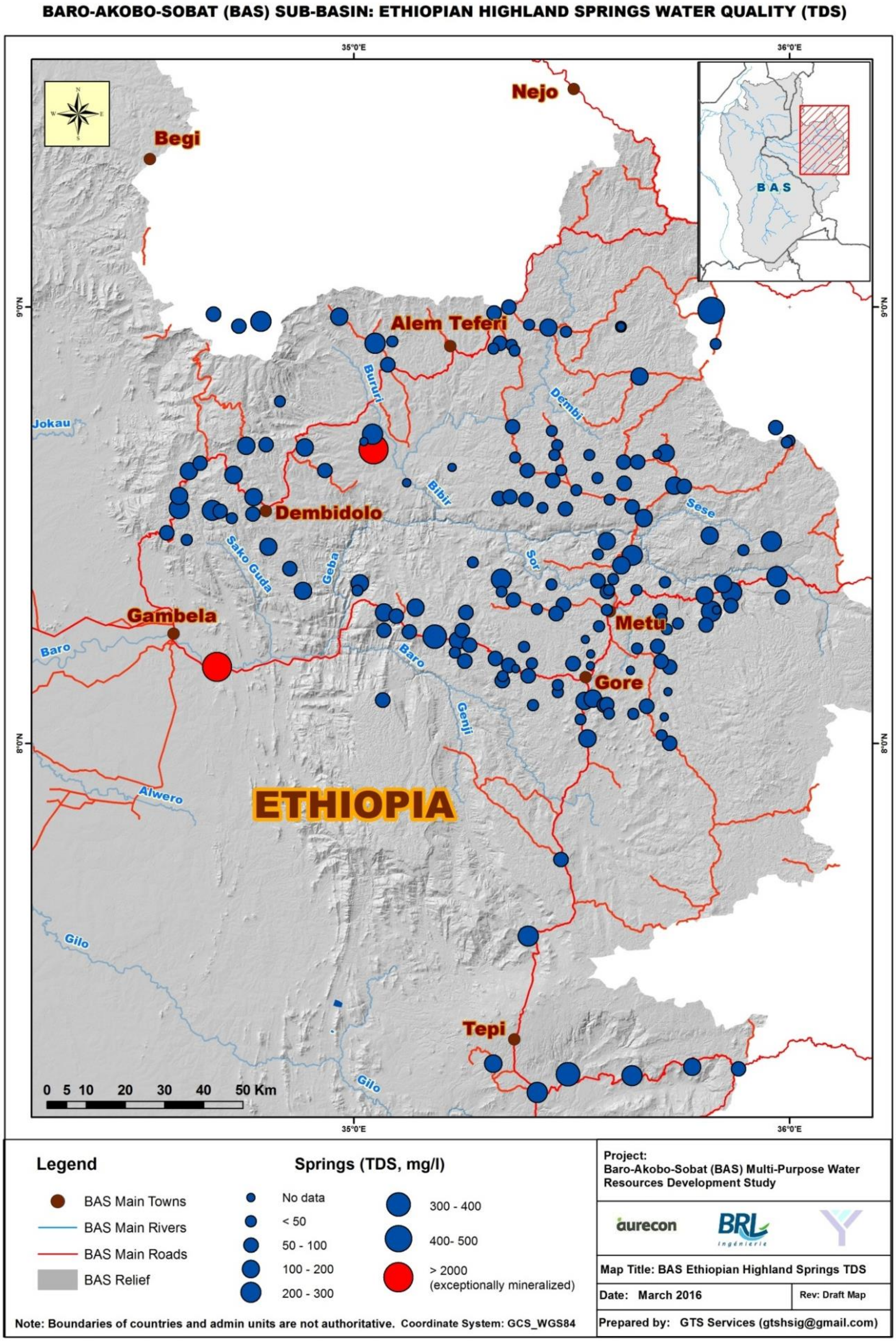

Figure 4-1: Spring TDS values on the Ethiopian side of the study area.

4.2 UPPER BARO AKOBO

During the study of ARDCO-GESERV (1995) for the upper part of the Baro Akobo Basin, about 237 groundwater samples were collected and analyzed from different sources (springs, hand dug wells and boreholes), most of which were from springs. The results from these samples indicate that the area has fresh groundwater and the dominant water type is calcium bicarbonate.

Except very few fault controlled springs which are reported to show high mineralization (TDS 2230mg/l), all samples indicate fresh groundwater with TDS less than 600mg/l. This is due to the favorable hydrogeological setting of the region in that it gets rapid flushing by the prevailing high rainfall and short distance from the recharge areas. In the Upper Baro Akobo Basin, four thermal springs have been located in the Bako and Godere River valleys bounding the Tepi Shield in the north and south.

4.3 GAMBELA PLAIN

The Russian Master Plan study (Selkhozpromexport, 1990 ; commonly referred to as the 'Russian Study') on water and land resources of Gambela Plain included fairly detailed studies on water quality. According to this study, the groundwater is slightly saline to fresh i.e its (TDS) is not higher than 1000 mg/l and in most cases it is 200 to 600 mg/l, and pH values varie from 6.5 to 8.4. The total hardness is mostly 1.5 to 4.0 meq and in a few cases reaches to 7.5 meq.

The study showed that in the Jikawo–Baro inter fluvial area, the groundwater is primarily of hydrocarbonate of sodium and sodium-magnesium type while in the Baro-Alwero and Alwero-Gilo inierfluvlal areas, it belongs to bicarbonate of calcium magnesium or sodium types. Towards the east, near the Abobo-Chiru the groundwater is reported to be characterized by hydrocarbonate –chloride and sodium magnesium type of mineralization, and at Gog, the water type is calcium-magnesium.

In terms its suitability for irrigation, the groundwater is classified as a low salinity hazard with SAR values from 0.1 to 6.13.

The study also indicated that there are strips of areas where the iron content is high - up to 89 mg/l, and its use for potable water supply is not possible without treatment. Areas indicated are: In the Jikawo-Baro interfluves, nearly right on the watershed along the Baro River there is an aquifer strip with an iron concentration of more than 10 mg/l, the maximum being 23.9 mg/l. A similar strip trending east of the Gambela Plain was distinguished in the Baro-Alwero interfluvial area. There the iron concentration was found to be 29.0 mg/l, and at Gog, which is in the Alwero-Gilo interfluves, it was 61 .5 mg/l. The maximum limit for potable water supply is considered to be 1mg/l. Similarly, the contents of manganese and copper are also higher than usual: up to 14.8 and 1.6 mg/1, respectively. Their permissible values for potable water supply are 0.5 mg/l and 1 mg/l respectively for manganese and copper.

The study showed that quality of artesian water from the Alwero Formation is fresh with TDS values of 300 mg/l, the pH i.s ~7.0, and the total hardness 3.8 meq. Because of the confined nature of the aquifer, contamination is virtiually impossible.

The other source of data/information regarding water quality is from the works of Seifu Kebede (2013) in his Groundwater in Ethiopia Book. In this work, the water quality conditions of the aquifers within the Gambela plain are characterized as follows:

Recent alluvial deposits: The alluvial deposits although of limited aerial extent are considered an important water source for villages. They have generally good water quality, high permeability, are unconfined, have a shallow water table of <10 meters and recharge each wet season. Except for few cases of mineralized water samples, the water quality of the area is good for water supply and irrigation uses. Total dissolved solids in the Gambella Plain range from 72 to 955 mg/l making the groundwater suitable for irrigation use.

Quaternary alluvio lacustrine sediments: Groundwater in the quaternary alluvio lacustrine sediments is slightly saline with TDS slightly less than 1000 mg/l. In most cases it varies between 200 and 600 mg/l.

Alwero formations: The Alwero formation underlies the quaternary alluvio lacustrine sediments, buts dips to the west and would be found in the sub-surface in the adjacent South Sudan, is considered to be a high groundwater potential, confined aquifer with fresh groundwater (TDS of 300 gm/l). The groundwaters are dominated by the Ca cation, and HCO_3, SO_4 and Cl anions.

4.4 SOUTH SUDAN

The water quality characteristics of groundwaters of the South Sudan side of the project area have been abstracted from the information obtained from the hydrogeological map of the South Sudan and from the water supply study reports of Bor and Torit towns which are the capitals of the Jonglei and Eastern equatoria regions respectively. Two dominant aquifer systems are described:

Umm Ruwaba Formation: The bulk of South Sudan groundwater resources are found within this formation which is characterized by unconsolidated sands, clays and gravels with low to high permeability. The Umm Ruwaba Formation is considered part of a regionally extensive confined aquifer, and is found to occur as semi-continuous, sub-continuous and continuous aquifers of local to sub regional extent. In South Sudan, it is the principal source of drinking water, but very little work has been undertaken to determine its distribution and extraction levels.

Around the Bor area, located on the Eastern bank of the Bahr el-Jebel river in the centre of South Sudan, within the southern end of the Sudd Basin, the Umm Ruwaba Formation is described as consisting of both vertically and horizontally variable permeability aquifers. The aquifers usually consist of confined sand and gravel layers (alluvial sediments). The thickness of the unconsolidated sediments is reported to be at least 1000 metres. The depth to water is around 10 meters and water salinity varies from 100 to over 5000 mg/l (fresh to brakish, rarely saline). Generally, groundwater quality is considered suitable for raw water supply. However there is variable hardness, iron and manganese that may pose a risk of scale formation and pipeline blockage in some areas such as Bor locality (SMEC, 2013).

The study indicated that although there are many boreholes in the Bor town area, some have been abandoned due to water quality problems. The groundwater is described as low salinity, variable pH and moderate hardness with elevated nitrate. Elevated nitrite and total coliforms are encountered especially in the shallow aquifer. All metals analyzed are reported to be below laboratory detection limits. It was recommended that if well water in Bor is considered as a source for town water supply, it should be chlorinated and mixed with at least an equal volume of treated surface water. The suggested measures to be taken are softening or mixing with river water to reduce the total hardness to less than 200 mg/L.

A water quality baseline assessment study was carried out by the Nile Basin Transboundary Environmental Action Plan in 2005. In this report, a monitoring station at Malakal was established to assess the concentration levels of different contaminants. Some of the elevated constituents considered were total dissolved solids (TDS), electrical conductivity (EC), chloride, nitrate, nitrite and ammonia. A comparison with WHO guidelines was also made. Since Bor is located on the Bahr el-Jebel which ultimately flows to Malakal, the data at Malakal station was considered indicative only. The EC results based on monthly data showed a variation with time which was related to the agricultural activity in the upstream catchment of Bahr-el-Jebel. The Bar el-Jebel river water is already used as a source of supply for Bor, but the intake location is not ideal as it is too close to the built-up area and vulnerable to pollution from commercial and residential activities (SMEC 2013).

The basement complex: The Basement Complex rocks form an extensive hydrogeological unit in South Sudan covering one third of the country. Groundwater occurs in fractures and fault zones and may be recharged directly from rainfall. Water quality is generally considered good with low salinity.

This unit prevails in parts of the Eastern Equatoria region in the southern part of the project area and includes the Torit area. In general, it is characterized as a poor water bearing formation. However, fractures and weathered zones provide water of good quality and quantity. The existing sources of water for Torit are both surface water and groundwater. Torit town is situated on Basement Complex rocks beside the Keneti River. Currently Torit obtains some water from the Keneti River and also from groundwater for its urban water supply.

Not all wells are operating in Torit due to reported salinity problems and other factors. The groundwater is said to be of variable quality, being fresh to brackish, however there is no analytical information on water quality or bacteriological contamination (SMEC 2013). Since the groundwater quality around Torit urban area is not considered suitable for long term raw water supply due to high salinity, very hard water, elevated cations and high levels of contamination, the study recommended the softening or mixing of groundwater with surface water to reduce the total hardness to less than 200 mg/L

4.5 SALINE GROUNDWATER ZONES

Previous studies indicate that salinity levels exceeding allowable limits have been observed in Jonglei and Unity States of South Sudan making groundwater unsafe in some areas of these areas. While higher concentrations of fluoride, sulphate and nitrates have been observed in a few states, overgrazing and deforestation has also affected water resources quality by increasing the turbidity and siltation in water structures.

From the hydrogeological map prepared for South Sudan (SMEC, 2013) and DVA-GIS : African Development Bank, hydrogeological map of Sudan and South Sudan, it can be noticed that in the Northern part of the study area, within the Gonglei State, an area with brackish groundwater TDS 1500 – 5000 mg/l is mapped.

Areas of elevated salinity may coincide with oil exploration sites in Unity State. It is recommended that groundwater be monitored and that the impact of effluent from waste stabilization and oxidation ponds around Juba, west of the present project boundary, be assessed.

5. EXISTING GROUNDWATER USE

The Baro-Akobo-Sobat (BAS) sub-basin water points collected for the project include springs, hand dug wells, boreholes and limited water harvesting, hafir and spring catchment points. The water point records were evaluated as indicators of groundwater use from different source types.

Figure 5-1 and Figure 5-2 show the BAS water points collated/database used for the project thus far. The springs spatial database for the Ethiopian highland part has been properly organized but the hand dug wells and boreholes database for Ethiopia and South Sudan have been plotted just to produce the required map but requires some quality checking and cleaning. Additional borehole data will also be included.

The Ethiopian highland springs were plotted on the BAS groundwater availability map and coincide with the areas delineated as relatively high and medium-high, indicating partly the validity of the GW availability results.

Except where there are limitations of the resource base in terms of its availability or water quality, groundwater is the preferred source of water supply for rural as well as urban centres within the project area. In general, the current use of groundwater is at its lower rate and limited to the shallow aquifer systems largely for domestic water supply, while there is also a possibility for utilization from the potentials of deeper aquifer systems.

There are no known large scale development works in the basin using groundwater such as for irrigation purposes. Recent inventory records have not been obtained for existing groundwater use supported by abstraction rate and monitoring data. From the records during the ARDCO-GEOSERV (1995) inventory, 22 boreholes, 68 hand dug wells (HDW) and 42 springs were recorded, which are reported as sources of domestic water supply in the Baro Akobo highland part of the project area.

Depths of boreholes were in the range of 44 to 108 m with yield records in the range of 1.5 l/s to 8 l/s. However, studies have also indicated a potential yield of 20 l/s (Selkhozpromexport, 1990). The hand dug wells have depths of 4 to 24m.

Similarly, the boreholes data retrieved from South Sudan for the Jonglei, Eastern Equatoria and upper Nile states provide regional information on the status of groundwater development and drilling practices. Though the information contained is not complete, registrations of a total of 1642, 305 and 73 boreholes data records have been obtained for the Eastern Equatoria, Jonglei and Upper Nile states respectively out of which 1343 of them fall within the present study area. From the data with records and at a regional scale, it is evident that the wells drilled are shallow mostly in the range of 30 – 100m depth and their yields are low in the range of less that 0.01 to 5 l/s.

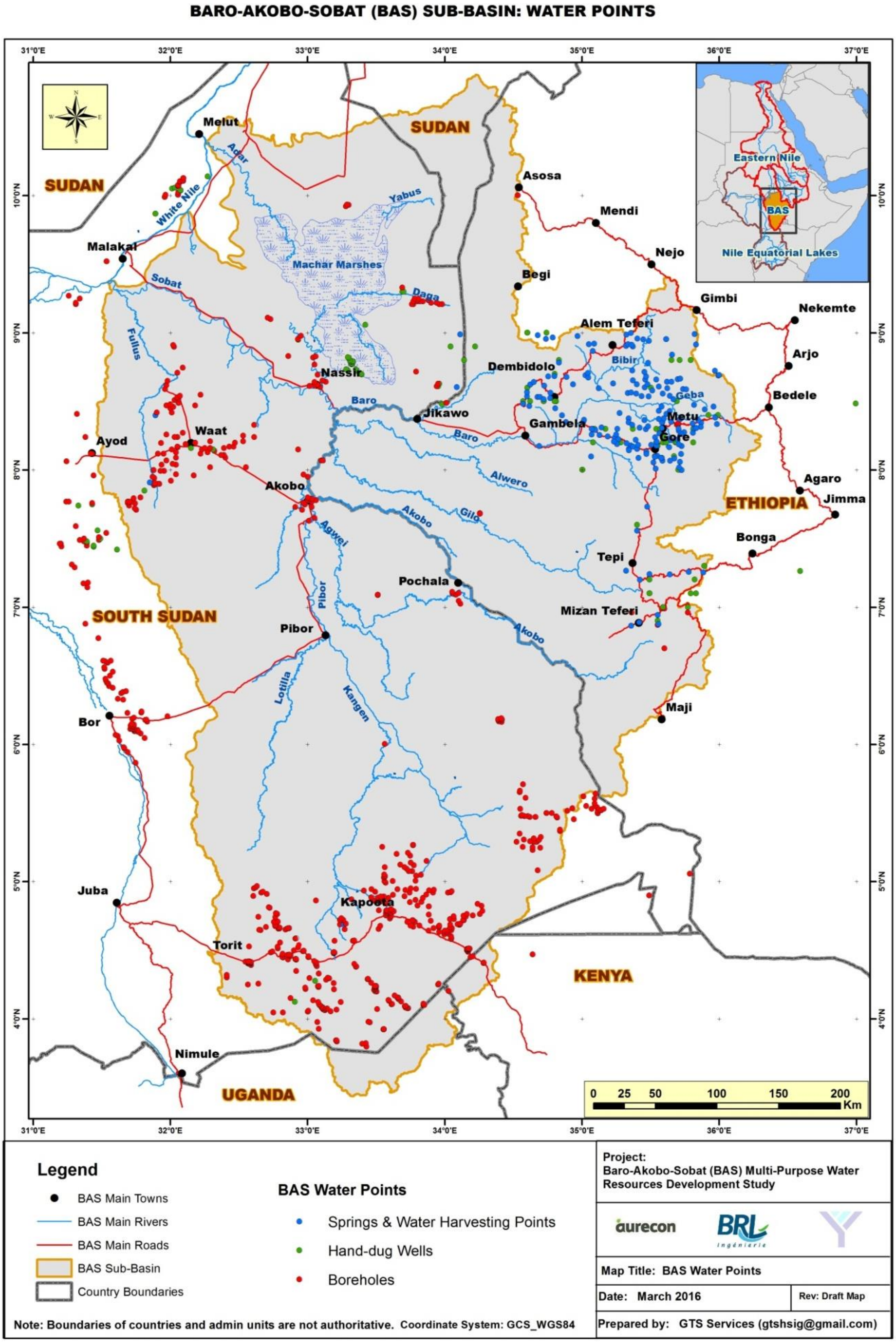

Figure 5-1: Water points distribution

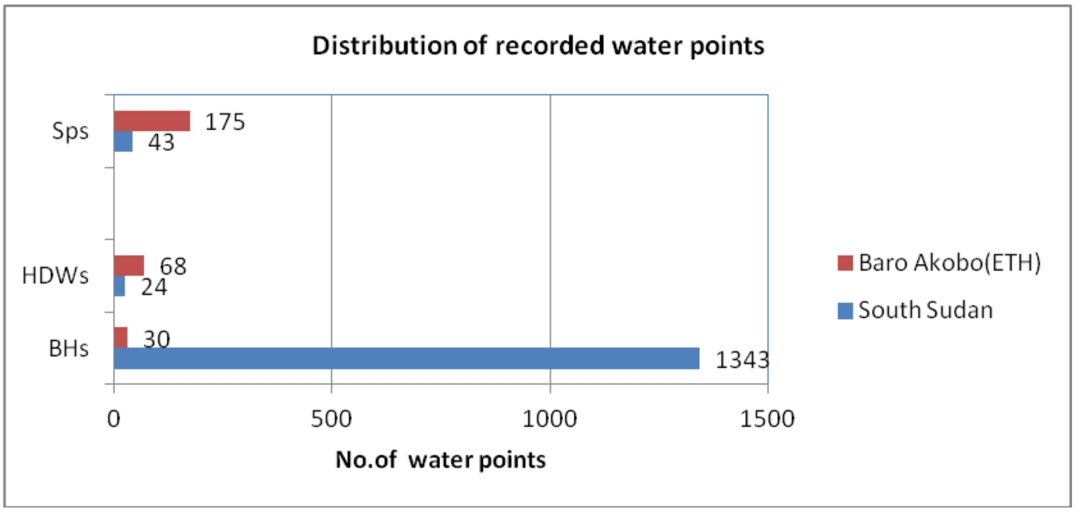

Figure 5-2: Distribution of recorded water points within the study area

Records show that relatively large number of boreholes have been drilled within the Southern Sudan part of the study area while concentrations of springs exist in the highland part of the Baro Akobo Basin of Ethiopia (although some of the springs have not been protected). The density of hand dug wells may indicate the potential of shallow groundwater which is expected in the recent alluvial deposits close to river channels.

Groundwater data is hugely dependent on having good drilling, test pumping and water use records. Typical information includes: depth and method of drilling, whether the targeted aquifers were penetrated, borehole construction and evaluation (testing), water quality analyses, water levels, water temperatures, etc. In general, there is limited data, and this constrains the proper evaluation and characterization of aquifer systems, estimations of groundwater potential and use. In many parts of Africa, and it is uncertain to what extent this applies to the study area, groundwater use is frequently restricted by the lack of robust conveyance infrastructure, or poor maintenance thereof, rather than the resource itself.

Figure 5-3 and Figure 5-4 indicate that 89 % of the boreholes drilled in the areas fall within the shallow groundwater systems zones. Only few boreholes appear to have been drilled into relatively deeper aquifers; the notable case being the boreholes drilled during the Russian Study (Selkhozpromexport, 1990) of Gambela Plain. Boreholes exceeding 100m gave potential yields of up to 20 l/s within the deeper aquifer system of the Alwero Formation. The maximum borehole depth recorded was 176m. This hole penetrated the Gilo formation on the Gambela Plain.

All in all the data shows that currently groundwater use is limited to waters found at shallow and medium depths. As demand increases, for example for irrigation use, the option of drilling into deeper aquifers that could provide large yields should be explored.

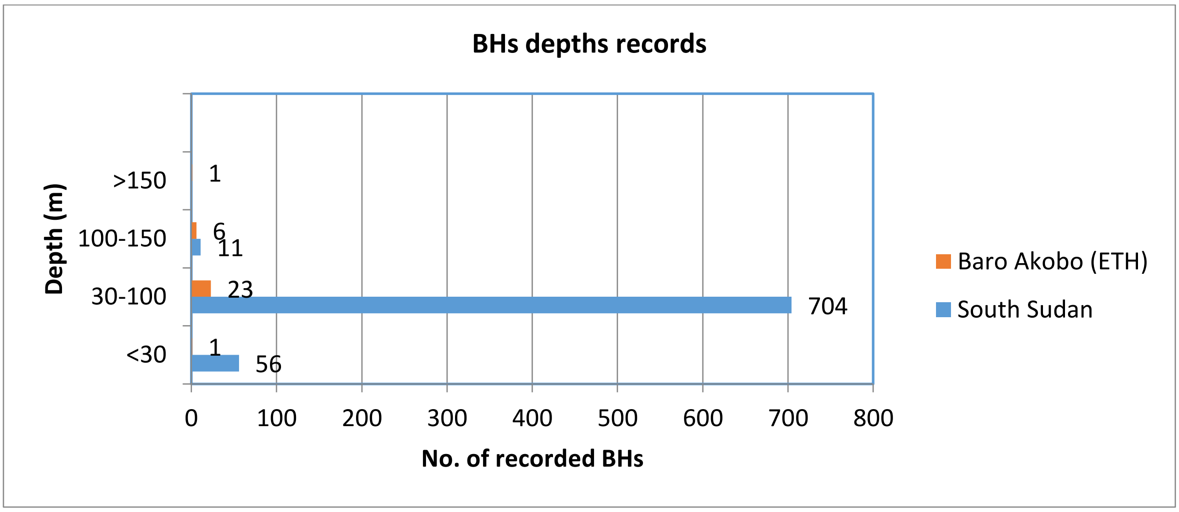

Figure 5-3: Recorded ranges of Boreholes depths

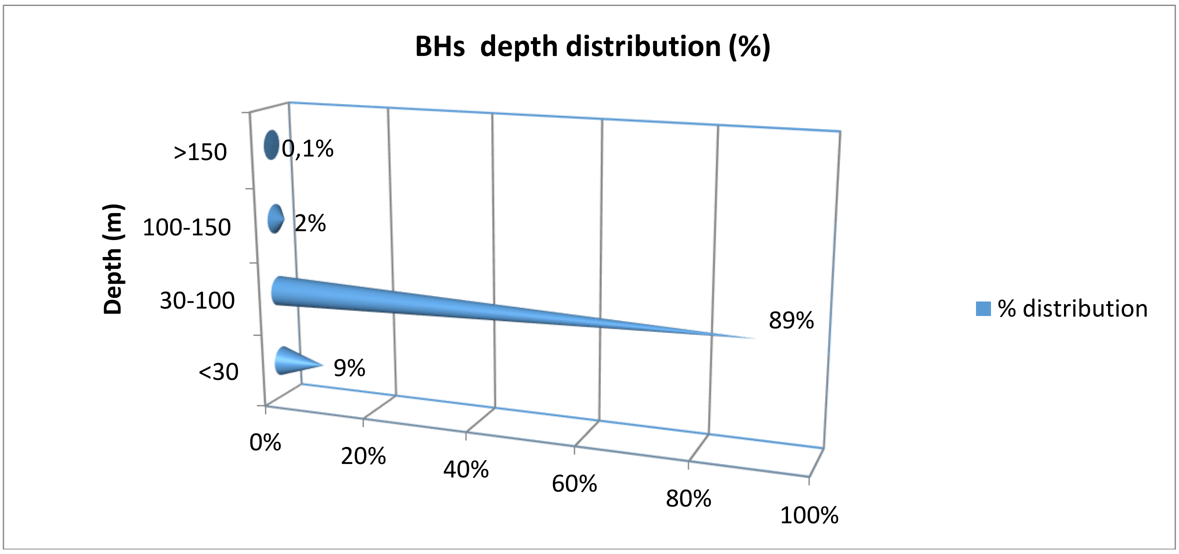

Figure 5-4: Percentage distribution of boreholes depths

Borehole yields are controlled by many factors among which geological factors, particularly permeability, and drilling methods are major determinants. Borehole yields in the study area are reportedly generally low. Only 4 % of the wells show yields falling in the range of 2 to 5 l/s and only 0.3 % fall within the 5 to 10 l/s range. The majority of the wells (67 %) are reported to have very low yield below 0.5 l/s (Figure 5-5).

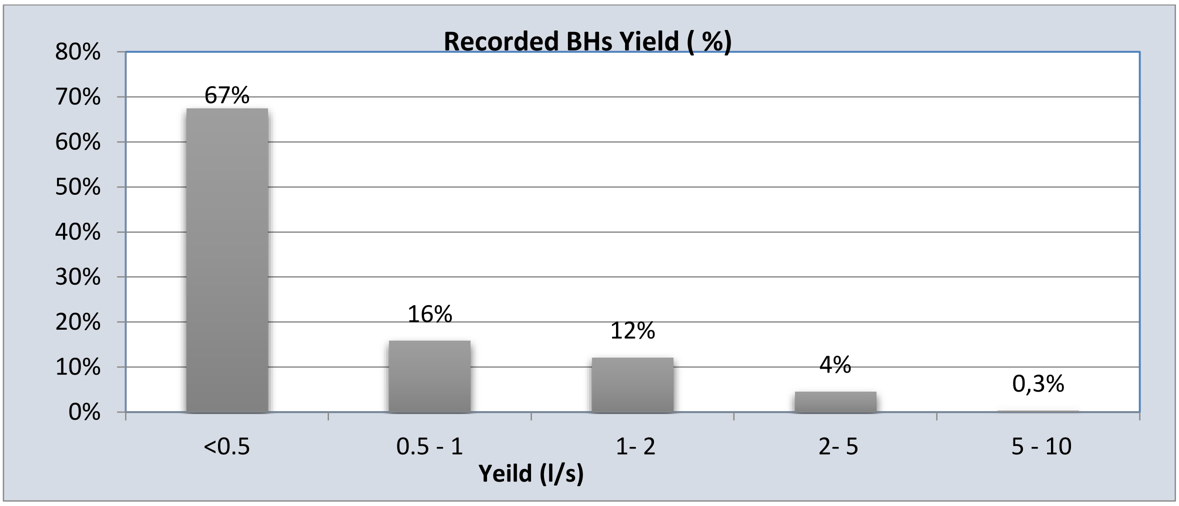

Figure 5-5: Graph showing recorded boreholes yields

For the Sobat part of the study area, it is evident that groundwater significantly supports water supplies for the towns of Bor and Torit, together with other centres. However, this practice is confronted with problems such as wells becoming dry, saline or polluted and this has resulted in abandoning many of them and shifting to surface water. Since relatively sophisticated treatment is required for surface water, this option is expensive and poses a number of management challenges. It must be noted that in many parts of Africa, boreholes and wells have been reported as “dry” when actually the pumps or conveyance infrastructure is faulty. It is not known whether the reportedly dry wells in the study area are indeed dry or whether this is the term commonly used when people cannot draw water from a well, irrespective of the reason.

Bor town, located on the banks of the Bahr el Jebel River (Nile), uses treated surface water. There are about 55 domestic water supply boreholes in the town, some of which are apparently abandoned due to being dry, saline or contaminated. Drilling records suggests that prior to 2008 most boreholes were drilled to a depth of less than 40m. Since 2008 borehole depths increased to around 80m. This may suggest over-use of the resource, but there could be numerous other reasons why boreholes were drilled deeper (e.g. better equipment may have made it easier to drill). Yields are said to be ‘moderate’ to ‘good’ although no quantitative data is available. Water is generally intersected from 30 to 60 metres depth, but the best quality is found from around 80 to 90 m below ground. The geology is thought to be alluvial sands and gravels of the Umm Ruwaba Formation which are considered part of a regionally extensive confined aquifer. Records indicate a well drilled to a depth of 150m has a potential yield of 12 l/s.

Torit is located on the northern bank of the Keneti River, and like Bore, uses treated surface water. Studies indicate that 98 boreholes have been located in the town. Some 19 bores were abandoned or were disused due to being dry, saline or equipment (pump) failures, which needs further evaluations. Borehole yields are low, and most are relatively shallow (<40 m prior to 2007/8), tapping into groundwater at the weathered rock - fresh rock interface. Recent drilling completion reports indicate the average borehole is now 70 m deep and screened in fresh fractured rock.

In conclusion, and from the review of previous works and present evaluations, it can be concluded that there is very little utilization of groundwater resources within the project area compared to the available resource. Although data from recent surveys has not been obtained, as indicative information, the study of ARDCO-GEOSEV (1995) shows that groundwater abstraction rates from all ground water sources is only in the range of 3.4 Mm^3/year for the upper Baro Akobo part of the study area. This is comprised of springs (2.0 Mm^3/year), hand dug wells (0.675Mm^3/year) and drilled wells (0.66 Mm^3/year). In total, this yield is equivalent to an abstraction of groundwater from about 10 boreholes at a rate of about 10.5 l/s from the entire mapped study area. The assessment was made based on the surveys conducted over 34 woredas.

6. BOREHOLE WATER SUPPLY POTENTIAL

6.1 NUMBER OF PEOPLE THAT CAN BE SUPPLIED WITH DIFFERENT PUMPS

The number of people that can be served at various abstraction rates and the number of boreholes required is shown in Figure 6-1 and Figure 6-2. Figure 6-1 shows that a borehole that is equipped with a hand pump can serve about 200 people if operated for 12 hours a day (this equates to each person having ~3 minutes to fill a 20 L container, or continuous abstraction at 0.1 L/s). The higher-yielding solar pumps can yield ~80 m^3/day (although this varies with pumping head and pump type), and this can supply ~4 000 people/day (e.g. average of 2 L/s x 12 hours/day). A diesel or electric powered pump supplying 5 L/s can supply ~10 000 people/day using a 12-hour pumping cycle.

Figure 6-2 shows, for example, that 5 boreholes equipped with hand pumps can supply ~1000 people, but if the borehole yields were sufficient to support solar, diesel or electric pumps, then up to ~30 000 people could be supplied with solar pumps and >50 000 people could be supplied with diesel or electric pumps.

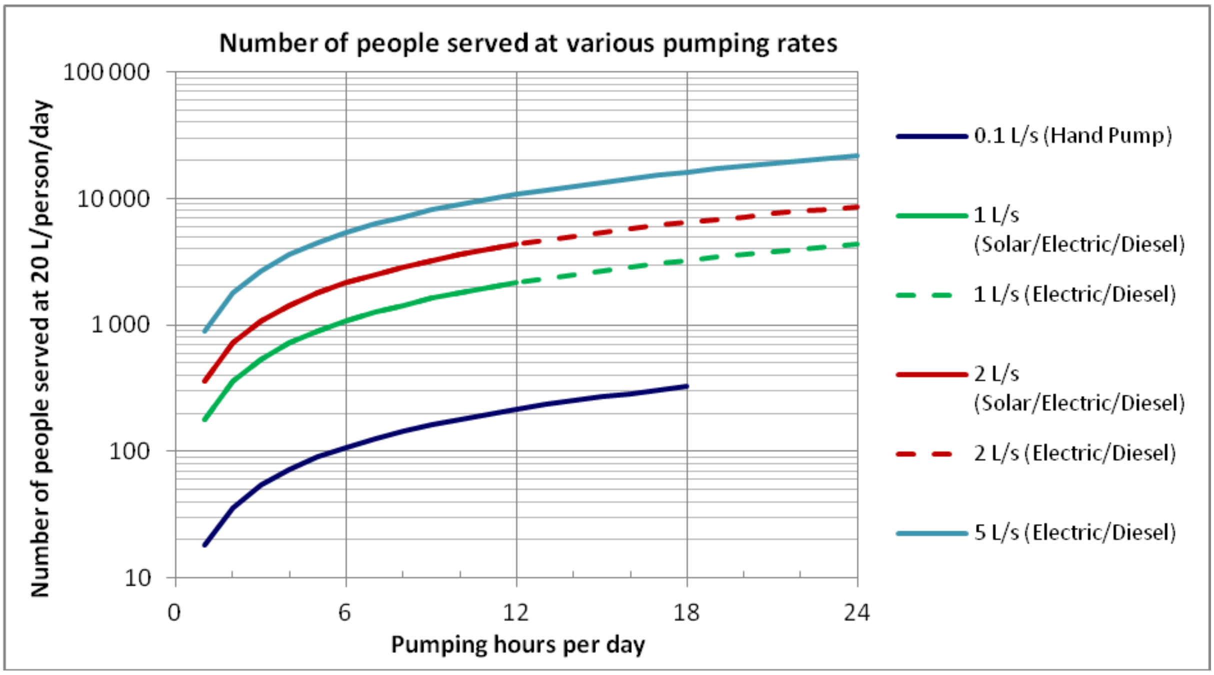

Figure 6-1: The number of people that can be served by one borehole at various pumping rates

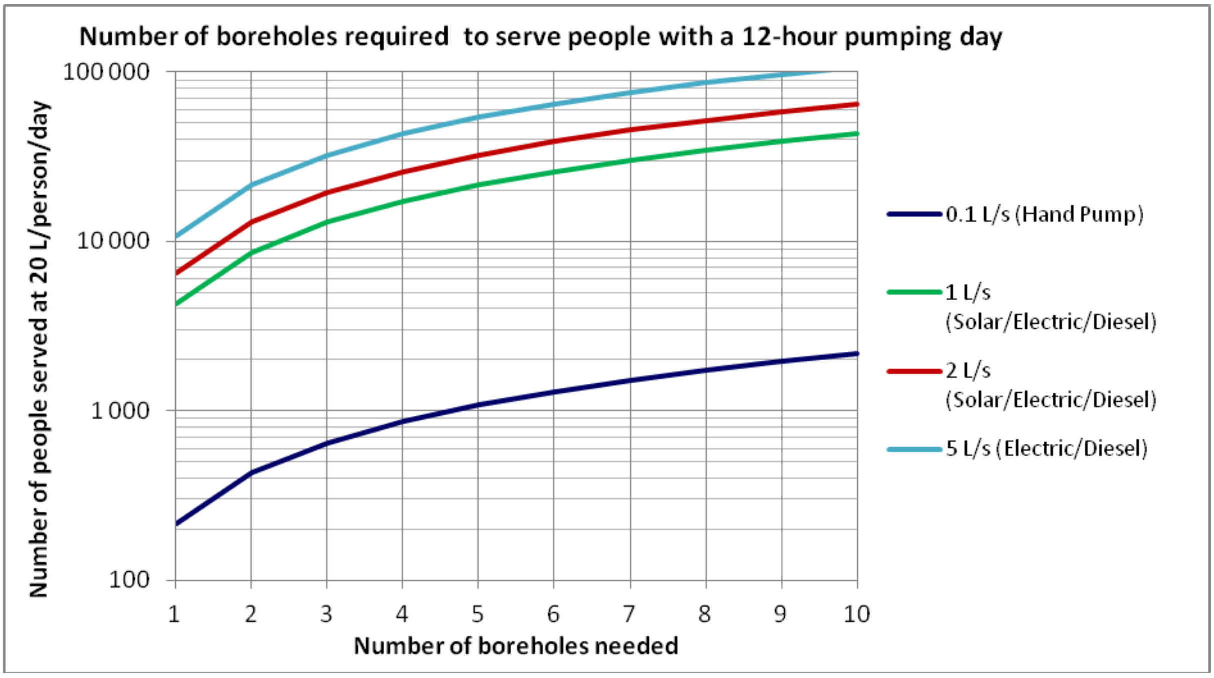

Figure 6-2: The number of boreholes required to serve various population sizes

6.2 GROUNDWATER DEVELOPMENT POTENTIAL

6.2.1 Summary

The statement from the TAMS-LGL (1997) report "*There is some groundwater development potential in effectively all areas of the Baro-Akobo Basin*" could equally apply to the entire study area (the BAS Basin), as all areas have enough groundwater resources to meet small-scale rural domestic and livestock requirements. However there are 4 main aquifer types that can potentially provide more water than merely the basic requirements for scattered rural settlements; these are:

i. Fractured Basement Complex rocks

ii. Porous and permeable unconsolidated sediments

iii. Fractured basalts, and in particular the Gog Formation basalts.

iv. Permeable sandstone of the Alwero Formation.

All four aquifer types appear to be underutilised (and the Alwero Fm sandstones are not used at all), and all can possibly be developed to meet domestic, livestock and irrigation requirements, although for irrigation purposes, prime areas in these aquifers would need to be located.

In essence, groundwater can meet the needs of all rural villages (including pastoralists), small towns and most medium-sized towns. In some areas it can also meet the requirements of main cities. The populations associated with these terms are those used by TAMS-ULG (1997), and are shown in Table 6-1 (just the upper population values are given). Table 6-1 also shows the pumping supply options that could be used to meet these demands.

Table 6-1: Number of boreholes and pumps required to meet domestic water demands (at 20 L/p/day)

Settlement	Population	Hand Pump	Solar Pump	Diesel/Electric Pump
Villages	1 000	5	2	1
Small towns	4 000	-	6	1
Medium towns	10 000	-	-	1
Main cities	>10 000	-	-	>1

6.2.2 The high-potential but poorly understood Alwero Formation

There is one major area of uncertainty in the study area and additional knowledge on this could open up development opportunities for people in both western Ethiopia and southern South Sudan. This is the Alwero Formation sand/sandstone aquifer. During the Russian Study (Selkhozpromexport, 1990) 6 boreholes were drilled into this confined aquifer in the Gambela Plains, and after testing them, the recommended combined production yield was 50 L/s (or ~8 L/s on average; see Table 6-2). These boreholes did not fully penetrate the aquifer, and it is expected that with properly designed production boreholes, the yields could be higher.

Table 6-2: Summary of drilling results from the Russian Study (Selkhozpromexport, 1990)

Bh. No.	Depth (m)	Recommended Production Rate (L/s)
200	62	10
100	79	5
104	130	20
A84	35	3
4	63	5
38	26	7
	Av. 66 m	Total 50 L/s

Besides the high yields, the water quality was also found to be very good. Borehole 104 had a TDS of 313 mg/L (~50 mS/m) and a pH of 7.0, and low in all constituents including rare elements (TAMS-ULG, 1997). By all accounts, the water should be suitable for domestic and irrigation use. Being a confined aquifer, the water is unlikely to be contaminated with micro-organisms, and therefore for bulk domestic supplies would possibly require no treatment, although chlorination is recommended due to possible contamination in the conveyance infrastructure.

The aquifer has not been mapped and thus its geographic extent in the sub-surface is not known, but it is expected to stretch from the eastern parts of the Gambela Plains in Ethiopia to the west, into South Sudan; and it’s northern and southern boundaries are likewise, not known. The aquifer is considered to be recharged in the east via seepage through basalts and the granites/gneisses of the Basement Complex. It is also thought to dip gently to the west (i.e. deepen) and that it may become increasingly artesian in that direction – i.e. the further west one drills into it, the greater the pressure in the aquifer (to an extent that it may flow freely at the surface).

The aquifer thickens westwards where it was found to reach a thickness of 200 - 300 m in the central part of the Gambela Plain. It consists of two bands with the thicker, upper band (~120 m thick) consisting of sands, sandstones and clays, and the lower, thinner band (~80 m thick) consisting of clays. The groundwater targets are the sands/sandstones in the upper band. Where these are fairly coarse grained and thick, high-yielding boreholes can be expected. They can be located with reasonable accuracy by conducting geophysical surveys.

The transmissivity values obtained from the Russian Study (Selkhozpromexport, 1990) varied from 7 – 190 m^2/day, and it was concluded that the "prevailing" transmissivity value was in the order of 100 – 120 m^2/day.

In order to establish the potential yield from this aquifer, a hypothetical wellfield was modelled using the aquifer parameters obtained during the Russian Study (Selkhozpromexport, 1990). The model used was designed by Murray, et al (2012) called the C-J Wellfield Model and is based on the Cooper-Jacob approximation of the Theis equation (which is suitable for the Alwero Fm confined aquifer). The model was developed to assist in well field designs – i.e. positioning the spacing of boreholes in a well field. It is a relatively simple model in comparison to groundwater flow models that require large time-series data sets to calibrate. This model uses aquifer parameter values to calculate the effect (drawdown) that boreholes have on each other; it does not take aquifer recharge, storage or discharge into account (a sophisticated finite difference or finite element numerical model is required for this). In using the C-J Wellfield Model, it is assumed that after each year of abstraction, the groundwater levels return to their starting levels due to natural recharge. So long as the abstraction rates are not too high, this assumption is reasonable, as it has been noted by various authors (eg TAMS-ULG, 1997) that potential groundwater recharge vastly exceeds natural discharge and abstraction.

The boreholes were placed in 4 rows, all 1 km apart. An arbitrary place for the wellfield was given merely to show the lay-out (Figure 6-3), but this could be anywhere in Ethiopia or Southern Sudan, where the Alwero Fm lies below the surface. The location of the area shown in Figure 6-3 is about 50 km west of Gambela, near Itang (which was an area recommended for groundwater development by TAMS-ULG, 1997).

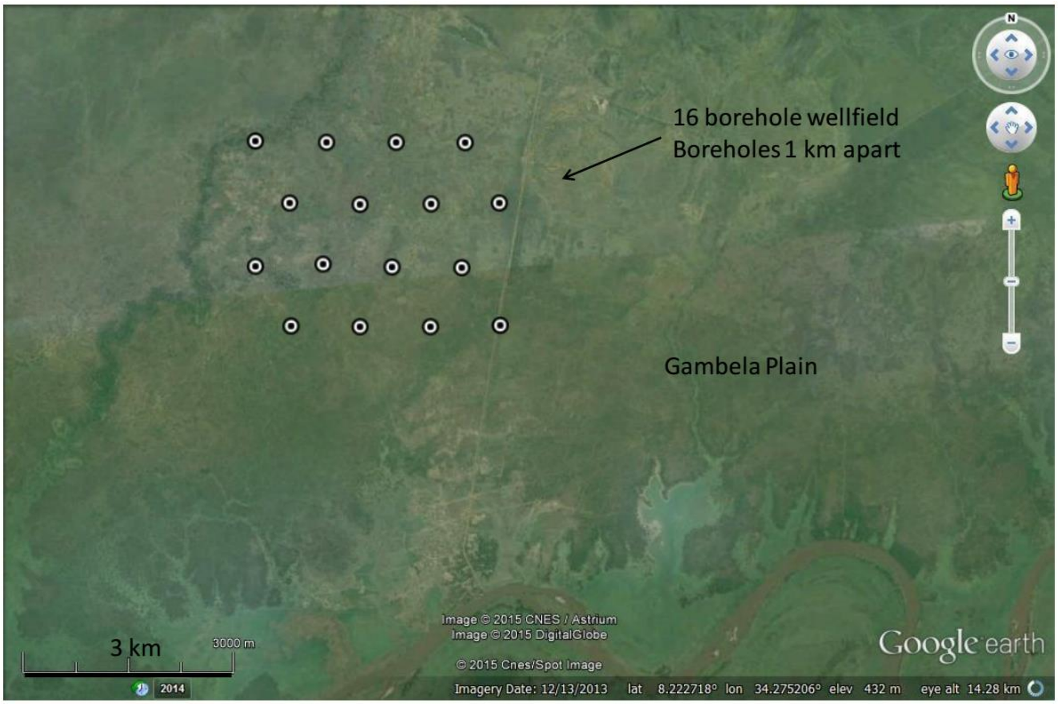

Figure 6-3: Layout of boreholes in theoretical wellfield (this borehole configuration could be anywhere in Ethiopia or Southern Sudan where the Alwero Fm lies below the surface)

The transmissivity value given to all boreholes was 100 m^2/day, and the storage coefficient (S-value) was 0.001, which represents a confined aquifer (the Russian Study, Selkhozpromexport, 1990, did not provide S-values). Four scenarios were run and after each the drawdown (water level decline) in all boreholes was noted after one year of non-stop pumping. In each scenario, all boreholes were pumped at the same rates for the year. The pumping rates were 2.5 L/s; 5 L/s; 7.5 L/s and 10 L/s, giving combined yields of 40 – 160 L/s. Figure 6-4 shows the results of a model run, and Figure 6-5 presents the results from all scenarios.

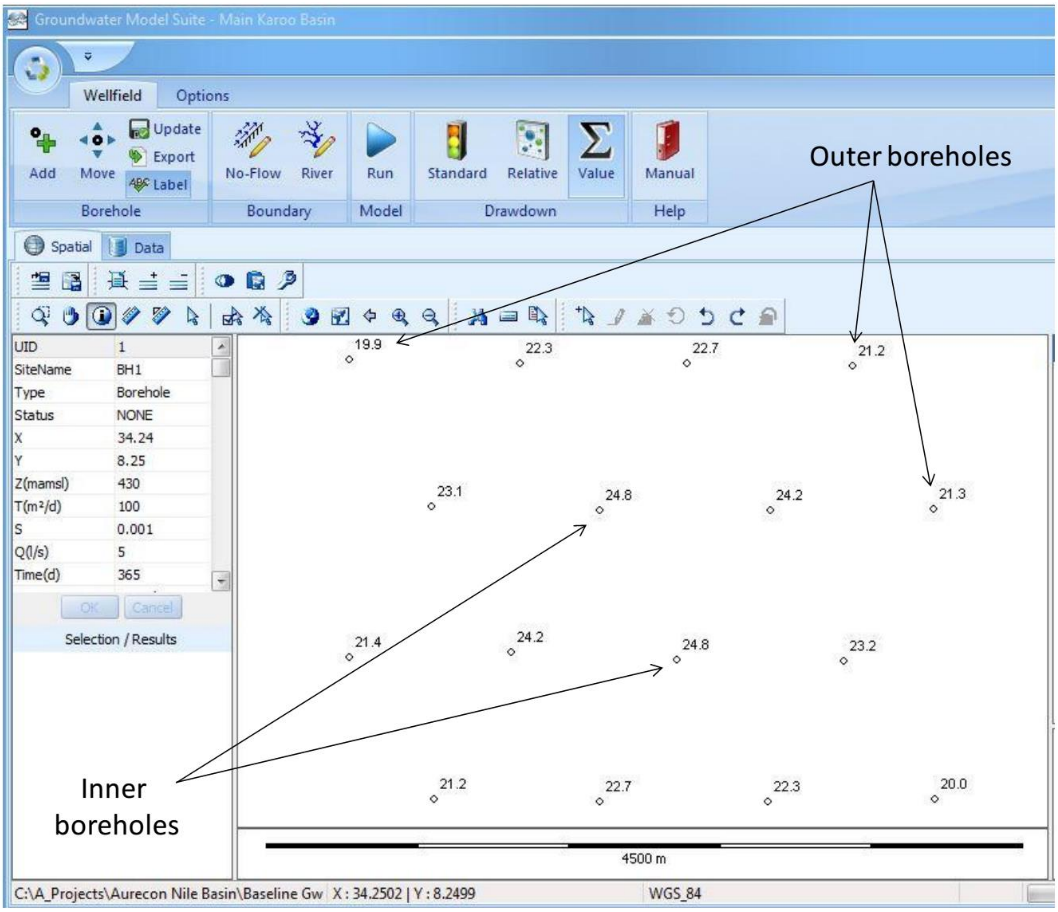

Figure 6-4: The C-J Wellfield Model - an example of a model run showing drawdown after a year of pumping all 16 boreholes

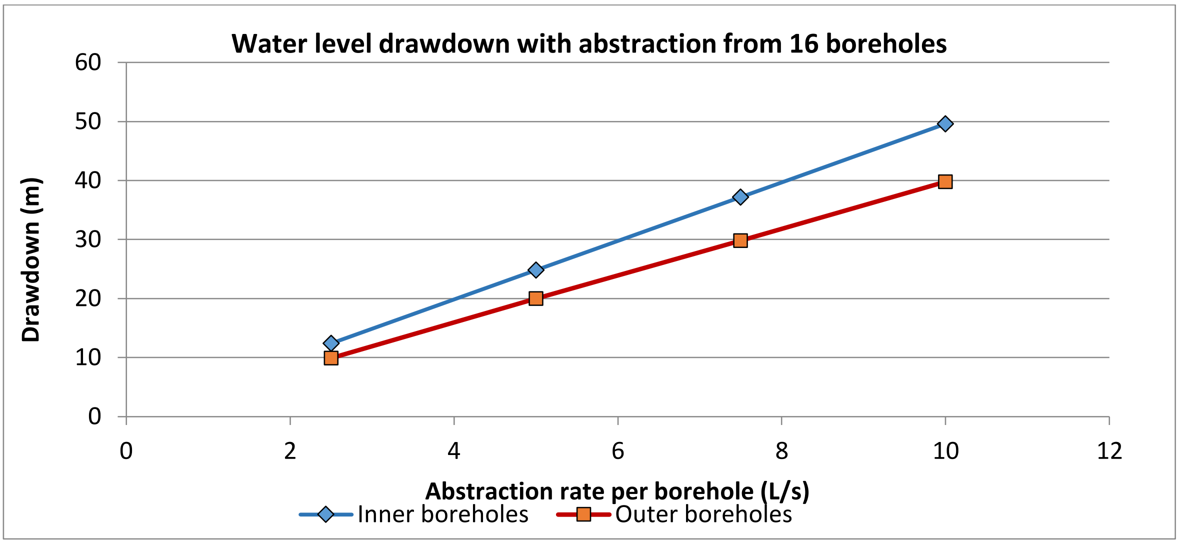

Figure 6-5: Results from the C-J Wellfield Model showing the water level drawdown after 1 year of abstraction (the boreholes in the centre of the wellfield are called the inner boreholes and those at the edge of the wellfield called the outer boreholes)

The results from the model show, for example, that if all 16 boreholes are pumped at 5 L/s (i.e 6 912 m^3/day in total), then after 1 year of pumping, the water levels in the centre of the wellfield will decline ~25 m, and at the outskirts of the wellfield, the will decline ~20 m. These are the drawdown levels in the pumping boreholes. If the boreholes were pumped at 10 L/s (13 824 m^3/day), the water levels would drop by ~50 m in the centre of the wellfield and by ~40 m at the outskirts.

From this wellfield layout, it is evident that the pumping rates should not be higher than about 5 L/s as it is not good management practice to draw water levels down too deeply. The scenario with abstraction at this rate was repeated using an S-value of 0.0005 to cater for a conservative storage coefficient, and it was found that the maximum drawdown in the inner boreholes was 29 m and the outer boreholes 24 m. I.e. 5 L/s appears to be about the maximum abstraction rate with a 1 km borehole spacing.

A last scenario was run, this time every alternative borehole was switched off, i.e. the spacing between pumping boreholes was ~1.7 – 2 km, and it was found that if the 8 remaining boreholes were pumped at 8 L/s continuously for a year, the drawdowns were similar to those obtained by pumping all boreholes at 5 L/s (the drawdown values obtained were 25 m and 21 m for the inner and outer boreholes respectively). In this scenario, 5530 m^3/day was abstracted for 8 boreholes as opposed to the 6 912 m^3/day from the 16 boreholes. The conclusion from this is that a more economically favourable borehole layout would be place them ~2 km apart and pump them at ~8 L/s. In reality, actual drilling results would dictate production yields, but this nevertheless suggests that with the aquifer parameters obtained from the Russian Study (Selkhozpromexport, 1990), a borehole spacing of ~2km should be planned.

The modelling exercise shows that if the Alwero Fm does have a regional transmissivity value of about 100 m^2/day, and if the storage coefficient is in the order of 10^{-4} – 10^{-3}, and if natural recharge can replenish the aquifer during the rainfall season, then it is possible to abstract ~ 5 500 m^3/day from a 8-borehole wellfield, and ~7 000 m^3/day from a 16-borehole wellfield that occupies a ~4 km by ~4 km space on the ground.

7. GROUNDWATER MANAGEMENT

7.1 INTRODUCTION

Managing groundwater for water supply purposes should have three main functions. The *first* should be to ensure that the aquifer is used optimally. This means that it should not be over-pumped as that would negatively impact on its long-term sustainable yield or on the environment. It also means that if the aquifer is being under-utilised, this will become known. The *second* main reason is to ensure that the water quality in the aquifer is not negatively affected. This may be as a result of high abstraction from the aquifer, or from poor groundwater protection (from latrines, animal enclosures, etc). The *third* main reason is to optimise borehole pumping rates so that the pumping equipment operates efficiently. Pumping rates are frequently set too high, and this cause unnecessarily high pumping heads, a waste of energy, and at times, pump failure. An additional function, which is usually captured in the first two points, is to ensure that environmental integrity is maintained. This may mean abstracting groundwater at a rate lower that the aquifer's sustainable yield in order to maintain spring flows.

The management system needs to include the following main tasks: data collection; data capture; data analysis; and operational changes (Figure 7-1).

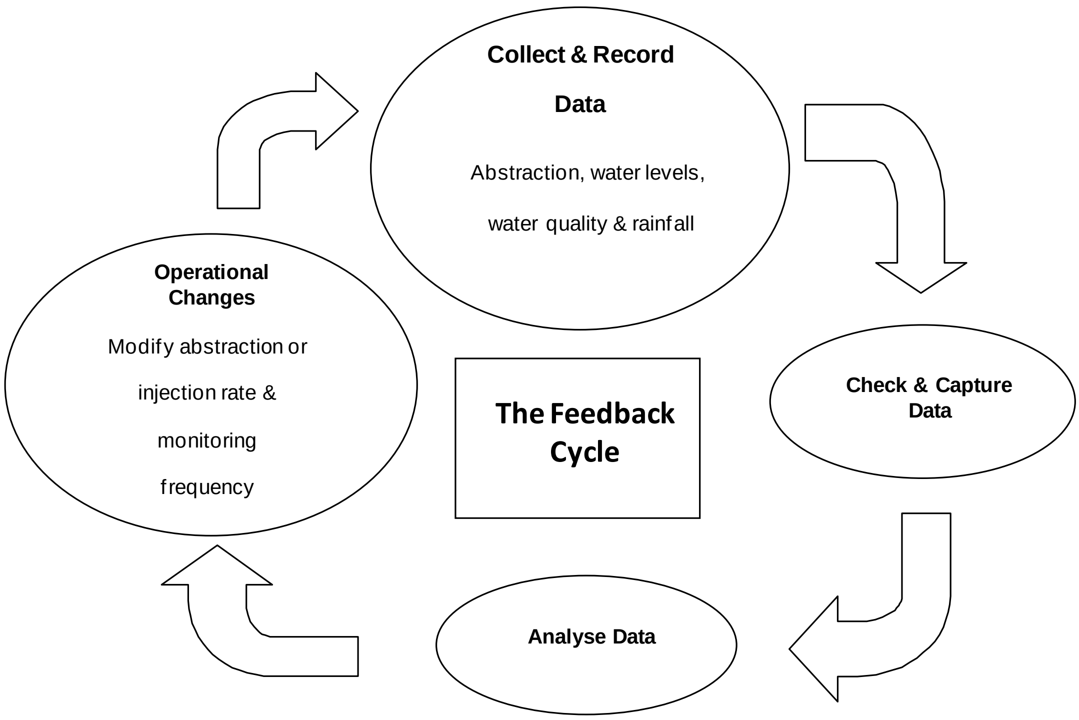

Figure 7-1: Groundwater Management Tasks

Data collection is simple and inexpensive, and should form part of all pump operators' operation and maintenance (O&M) tasks. Inexpensive data logging equipment is also recommended to ensure good quality data is obtained. Information needed includes borehole water levels and abstraction data on a monthly basis (although with data loggers this can be recorded on a daily basis or even more frequently), and water samples for water quality assessments on a seasonal or yearly basis. In certain areas more frequent water quality monitoring may be advisable. *Data analysis* needs to be done by a hydrogeologist who then must recommend *operational changes* if needs be. A management system can only be effective if all four components in the management cycle are attended to. Integrating groundwater management into O&M procedures is thus critical for overall resource and infrastructure management.

7.2 CURRENT MANAGEMENT STATUS

At this stage it is assumed that very little groundwater management (as described above), if any, takes place in the study area. All proposed projects will need to incorporate the necessary monitoring and management tasks mentioned above. In addition to this, and in order to obtain more information on the aquifers recommended for demonstration projects, additional monitoring boreholes should be installed. These boreholes will enable the hydrogeologist who analyses the data to establish if there is any regional effect of large-scale groundwater abstraction, and this will help in managing the wellfields and it will help in designing future wellfields and groundwater development projects.

The concept of groundwater management goes with the process of proper understanding of the resource base and balancing the demands with the available potential without causing adverse impacts. These include issues such as availability of comprehensive and complete studies (mapping of the resource at larger scales), groundwater database, water abstraction and monitoring records, proper operation and maintenance practices, etc. These are dependent on the availability of skilled manpower and institutional capacity as well the required budgets.

The contention that the current practice of groundwater management within the study area is in a poor state is borne out by the observation from previous studied that many of the boreholes are not properly functional. An example are the boreholes drilled in thick alluvial sediments around Bor town in South Sudan. Here the borehole yields are limited by screen lengths, small diameters and limited pump capacities. Similar limitations are also recorded in the Ethiopian side of the study area.

To improve the current groundwater management status, following measures should be undertaken:

- Capacitate the sector institutions for proper monitoring, management, development and utilization of groundwater resources.
- License and control groundwater development and use practices.
- Prepare detailed and exhaustive studies to map and determine the available resource in a reliable and more accurate way.
- Develop groundwater management plans at local and regional levels.
- Establish proper metering and monitoring systems for sustainable use of the resource including applications of modern technologies.
- Give appropriate emphasis on groundwater development technological issues and operation and maintenance requirements.
- Establish applicable environmental protection regulation in relation to groundwater resources protection.

8. POSSIBLE DEVELOPMENT PROJECTS

Groundwater can probably meet the demand for **domestic** water in most areas. The limiting factor from a groundwater perspective is the number of boreholes or wells that would be required to meet a specific demand and not the reliability of the resource itself. In low-permeability areas a number of boreholes may be required, but in the areas with high permeability, a few boreholes should meet the requirements for most domestic use. There are, however, specific areas where the water quality may be the limiting factor. In such areas, additional treatment, besides chlorination, would be required.

Urban centers should be supplied from deep boreholes or large diametre wells sunk into properly protected aquifers. Rural settings can be supplied from shallow wells, protected springs or hand dug wells depending on their respective demands. In most case, well yields of 0.2 to 1 l/s could meet the demand for rural villages if good construction and sanitary protections are provided.

In this project, priority areas of the Akobo and Jore woredas, and the Kapoeta area, were identified as possible sites for groundwater development projects that would target the needs of both human and livestock requirements. Projects in these areas should reduce conflict and improve health.

Livestock water supplies can be integrated with domestic supplies or developed independently depending on the local conditions and requirements. Like domestic supplies, it is quite likely that all areas can be supplied with groundwater.

At this stage it appears as if no groundwater-based **irrigation** projects exist in the study area. The ARDCO GEOSERV (1995) study mentioned that “the potential for high rate of groundwater production for irrigation is not considered feasible throughout most of the project area”. While this certainly holds for the low-permeability areas where hand dug wells are prevalent, it probably does not hold for the prime aquifers that are yet to be exploited such as the Alwero Formation aquifer described above.

The following areas were identified as prospective groundwater development areas with production capacities in the range of 1.5 l/s to 20 l/s (TAMS,1996):

- Itang vicinity (50 km west of Gambela)
- Vicinities of Jikaro-Baro
- Vicinities of Baro-Alwero
- Vicinities of Alwero-Gilo
- Vicinities of Gilo-Akobo

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[1] **The list of references is not exhaustive and is currently being completed.**

10. APPENDIX 1. LITHOLOGICAL DESCRIPTIONS

Tertiary-Quaternary Sediments

Stratigraphy	Litho-Unit Code	Lithologic Description
Holocene to Recent	Q_undif	Undifferentiated alluviums and unconsolidated recent deposits
	Q_fan	Fan deltas type deposits with rapid lateral facies changes
	Qal	Recent alluvium in active river beds and wadi undifferentiated deposits
	Qc	Colluvium - unconsolidated screes and slope deposits - undifferentiated talus materials
Pleistocene to Holocene	Qal2	Older alluviums deposits - raised or incised terraces and large levees - abandoned distributary channels
Cenozoic, Plio-Pleistocene	CzUR	Unconsolidated sands with some gravels, silts and clays

Tertiary-Quaternary Volcanic Rocks

Stratigraphy	Litho-Unit Code	Lithologic Description
Quaternary ?	VL	Small volcanoes or plugs and ring complex
Cenozoic	CzVa	Rhyolitic volcanic rocks
	CzVb	Basaltic volcanic rocks
Paleogene to Neogene	Pga	Trap basaltic series - Alkali olivine basalt and tuffs with some trachytes and rare rhyolites

Precambrian Basement Rocks

Stratigraphy	Litho-Unit Code	Lithologic Description
Precambrian	PE_Gabbro	Gabbroic rocks
	PEGr	Granitic rocks
Upper Proterozoic	Gt1	Syntectonic granitoid rocks
	Gt2	Post-tectonic intrusive granites
	PE3a	Amphibolite, chlorite, talc schists, greenstones and quartzites
	PE3lb	Chlorite schists, quartzites and intermediate metavolcanics
	UB	Ultrabasic rocks
Middle Proterozoic	PEs	Undifferentiated metasediments (amphibolite facies of metamorphism)
	PEsa	Amphibolites
	PEsm	Marbles - amphibolite facies of metamorphism
	PEsq	Quartzites rocks
	PEsy	Undifferentiated Syenitic rocks
	PEum	Ultramafic rocks - Peridotites, Dunites, Harzburgites and Lherzolites
Lower to Middle Proterozoic	PE1	Basement lower complex - undifferentiated magmatic and metasediments
	PE1_hard	Basement lower complex - undifferentiated magmatic and metasediments (competent facies)
Lower Proterozoic	PEp	Undifferentiated metamorphic rocks
	PEpgns	Undifferentiated gneissic rocks
	PEps	Schistose supercrustal metasediments - amphibolite facies of metamorphism
Archean ?	PE1b	Basement complex - Burji Gneiss (fine foliated biotite gneisses and schists)

Archean	PEx	Undifferentiated Granulite and Mylonitic facies rocks