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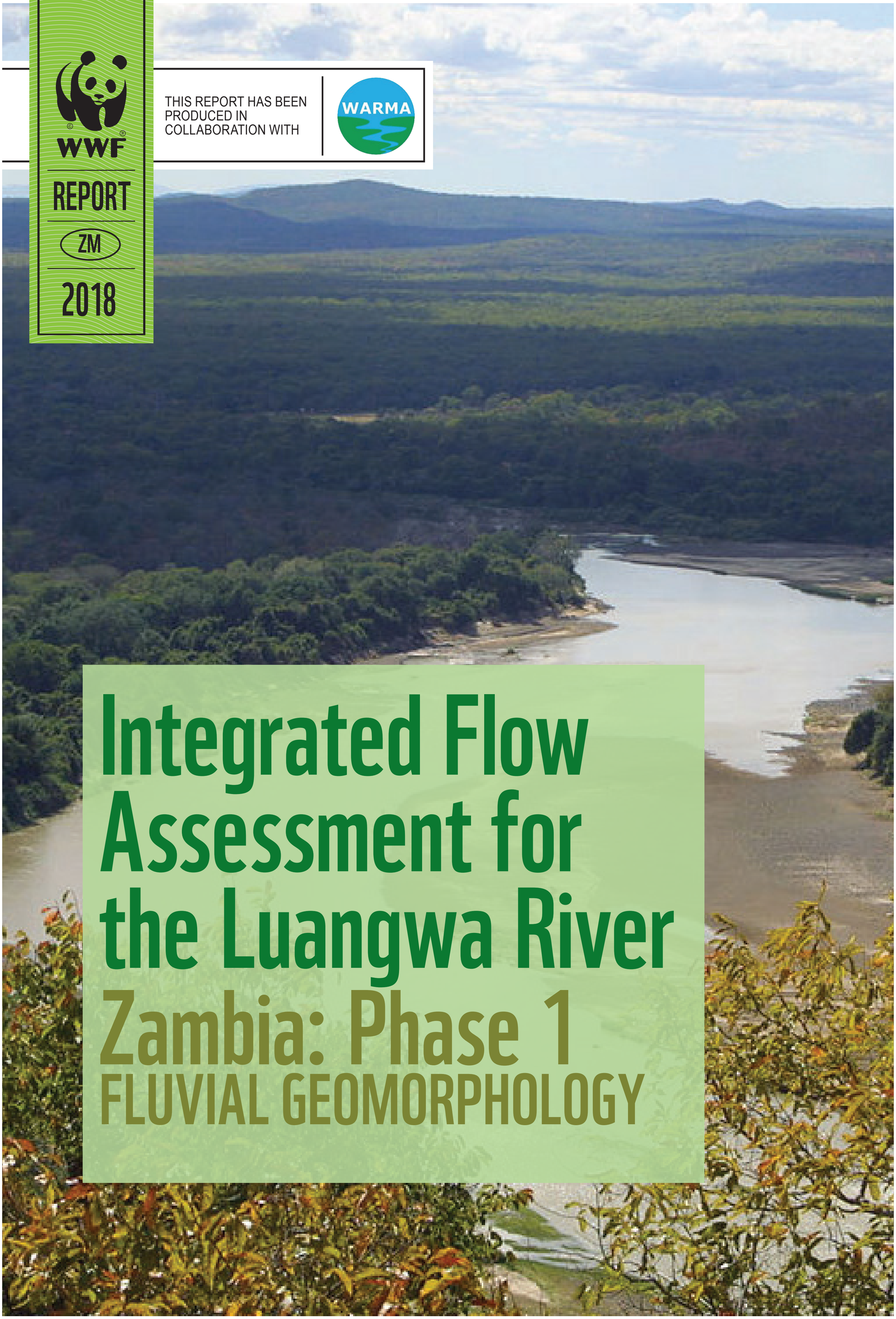

Integrated Flow Assessment for the Luangwa River

Zambia: Phase 1

FLUVIAL GEOMORPHOLOGY

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WWF's mission is to stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature, by: conserving the world's biological diversity, ensuring that the use of renewable natural resources is sustainable, and promoting the reduction of pollution and wasteful consumption.

FLUVIAL GEOMORPHOLOGY

March 2018

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ABBREVIATIONS

DWA	Department of Water Affairs (Zambia)
DWAF	Department of Water Affairs and Forestry (South Africa)
EFlow	environmental flow
FFEM	French fund for the Global Environment
GERB	Great Eastern Road Bridge
HU	Homogenous Unit
JICA	Japan International Cooperation Agency
NWRMP	National Water Resources Master Plan (Zambia)
PES	Present Ecological State
SAFRASS	The Southern African River Assessment Scheme
WARMA	Water Resource Management Authority of Zambia
WWF	Worldwide Fund for Nature
YEC	Yachiyo Engineering
ZRA	Zambian River Authority

This document is number 6 in a series of reports produced in Phase 1, in the series:

01 Inception Report

02 Luangwa Basin Division

03 Water Resources

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THANK YOU

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EXECUTIVE SUMMARY

Background and scope of study
This report forms part of the first phase of the Luangwa EFlows Assessment launched by the World Wide Fund for Nature (WWF) in collaboration with Zambia's Water Resources Management Authority (WARMA). Phase 1 consists of locating and synthesising all available information on the Luangwa Catchment, leading to an initial formal division of the catchment into homogeneous biophysical and social areas. Geomorphology, the focus of this report, encompasses the physical habitat and processes of formation and maintenance of the physical habitat in river environments. Sediment yield of the basin was also a key part of the review.

A key aspect of the work was the sourcing, collation, review and analysis of available literature and data to be able to undertake the geomorphological and land-use assessment of the Luangwa Catchment, and travel to and attendance of a basin division workshop in Lusaka in December 2015. The tasks specifically required that the Luangwa River system be divided into homogenous geomorphological river zones in order to undertake a preliminary assessment of the Present Ecological Condition of these zones from the geomorphological perspective.

A second task was the review of available data and undertaking of a qualitative (or, if available data permitting, quantitative) sediment yield analysis for the catchment, and a brief overview of land-use within the catchment. The resultant Specialist Report (this report) is the key deliverable, together with an electronic database with scientific publications, reports and GIS data which were identified and collated as part of this review and analysis. Based on the findings, recommendations for the envisaged Phase 2 study, a detailed Environmental Flow study, were to be provided. A total of 20 days was allocated to the completion of all work, including travel and workshop attendance.

Approach

The identification of Geomorphological Zones within the Luangwa Catchment was undertaken using a hierarchical classification system for southern African rivers (Rowntree and Wadeson, 1999) as the basis for identifying and delineating areas of similar habitat types and river morphology at the zone scale. The key determinant of zone delineation is longitudinal river channel gradient, which has been shown to be well correlated with many channel properties including channel planform or type, bed material and reach type (Rowntree et al., 2000). Planform (river morphology) characteristics were then used to refine the delineation of the zones.

Land-use in the Luangwa Catchment was assessed using available literature, free land-cover data (the FAO's Global Landcover 2009 dataset) and extensive analysis of recent Google Earth imagery to inform a brief overview of land-use activities within the catchment.

The Present Ecological State (or current ecological condition) was estimated for a series of Homogenous Units that were delineated for the basin at the Lusaka basin division workshop in December 2015. Available literature sources, Google Earth imagery and discussions with regional experts at the December 2015 workshop were used to estimate the present day geomorphological condition of these Homogenous Units. This estimate considered the key criteria of the Geomorphological Assessment Index (Rowntree and du Preez, in press). Output scores are grouped into 6 Categories ranging from A (essentially the historical natural condition) to F (representing the most extremely degraded condition possible for a river).

Estimation of sediment loads and yields was undertaken for the Luangwa Catchment. Determining the sediment load of a river at the catchment or basin scale is one of the main challenges in fluvial geomorphologic research (de Vente et al., 2006). Catchment sediment yield, derived from soil loss equations, provides an estimate of the potential soil lost from surface soil erosion, whereas sediment loads for a river, which are more accurate, are obtained through measured sediment discharge in a river channel (or better, if possible from sediment trapped in dams).

An extensive literature search of regional and within-catchment studies was undertaken, which identified estimates of both catchment sediment yield and sediment load. Due to limitations in available data for sediment yield mapping, a qualitative approach for identifying erosion risk across the basin was undertaken to identify areas of likely high sediment yield. Available desktop data were used for this analysis.

OUTPUT SCORES ARE GROUPED INTO 6 CATEGORIES RANGING FROM A (ESSENTIALLY THE HISTORICAL NATURAL CONDITION) TO F (REPRESENTING THE MOST EXTREMELY DEGRADED CONDITION POSSIBLE FOR A RIVER)

THE LUANGWA CATCHMENT

The Luangwa River is an important tributary of the Zambezi, contributing approximately 28 km3 of flow annually at the confluence upstream of Cahora Bassa Dam. The 165,000km2 Luangwa Catchment is formed by a 700 km long extension off the Western Branch of the East African Rift system (Dixey, 1937), where elevation ranges from 330 masl to more than 2000 masl in the headwaters. The catchment has two main topographic units – the plateau above the escarpment of the Rift Valley, and the Rift Valley floor itself.

The upper plateau, typically at 800 to 1100 masl, has soils that are largely derived from the basement complex, dominated by granites and gneiss, and rainfall is generally higher than 800 mm per annum. On the Rift Valley floor, rainfall is generally lower and Luvisols, Solonetz and Leptosols are common soils, with Vertisols dominating the extensive floodplains.

GEOMORPHOLOGICAL ZONES OF THE LUANGWA RIVER SYSTEM

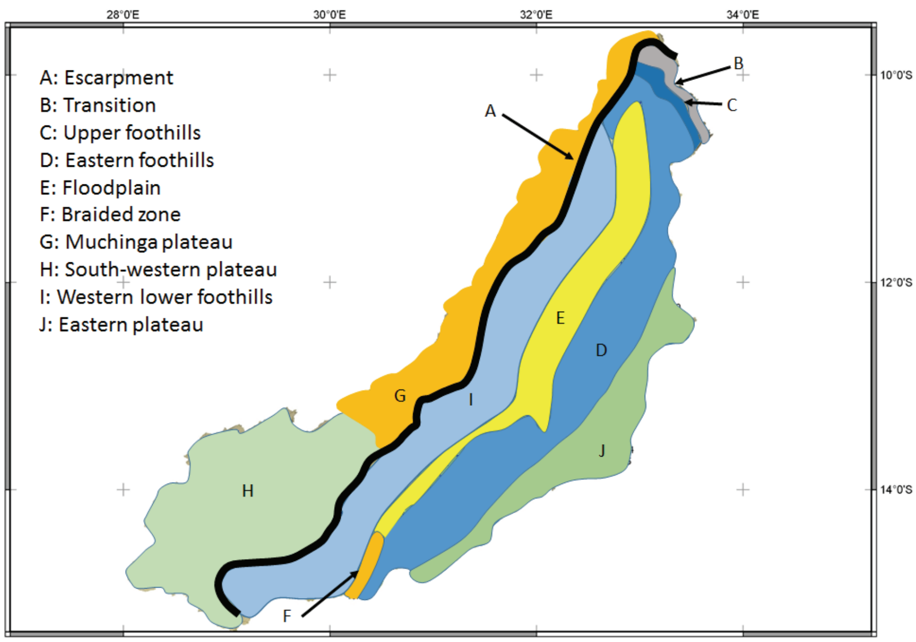
Longitudinal analysis of the mainstem Luangwa and key tributaries identified several major river zone types. The Luangwa Valley is dominated by a central zone of lowland rivers which is characterized by alluvial meandering floodplains and, further downstream towards the confluence with the Zambezi, a lowland braided zone.

Outside of this central lowland zone, upper and lower foothill zone types are dominant, with occasional short sections of mountain stream (associated with the steep escarpment area) and transitional zone types over the steepest areas of the catchment.

Based on the major topographical breaks, typical longitudinal river zone types, coarse land-use patterns and morphology of the river types, ten main morphological river zones were delineated within the Luangwa Catchment (Figure 5.4). Descriptions of the zones were derived primarily from available Google Earth imagery and used to inform the Present Ecological State assessment of the basin.

Figure A

Main geomorphological zones of the Luangwa River system



LAND USE WITHIN THE LUANGWA CATCHMENT

The FAO's 2009 Global Land cover database, Google Earth imagery, published studies and discussions with regional experts identified several key landuse activities in the catchment, namely: commercial agriculture; subsistence and small-scale farming; tourism and conservation; mining; charcoal production, and hydropower electricity generation on the south-eastern escarpment.

Small-scale, often shifting, agriculture is the main source of livelihood and income for the majority of rural Zambians (USAID, 2008). Small-scale subsistence and emerging farming practices are widespread across the plateau areas of the catchment, with larger scale commercial agriculture concentrated in the south-west plateau zone (the Lunsemfwa catchment) and to a lesser extent on the eastern plateau zone. In the valley below the escarpment, conservation and tourism are the dominant landuse activities. North and South Luangwa National Parks are the largest and most famous of the national parks here, with extensive game management areas and forestry reserves across much of the remaining valley floor.

The FAO estimates that Zambia has the fourth highest rate of deforestation in the world (USAID, 2011). Clearing for small-scale agriculture (USAID, 2011) and the production of charcoal (UNEP, 2015) are the key drivers of deforestation. Hydropower and mining activities are limited at the moment – both largely restricted to the eastern and south-eastern plateau regions of the catchment respectively.

DIVISION OF THE CATCHMENT AND PRESENT ECOLOGICAL STATE

The Present Ecological State (PES) of the Luangwa Catchment in terms of river geomorphology was estimated for each of the fifteen areas (Homogenous Units or HUs) delineated at the December 2015 Basin Division Workshop in Lusaka (Figure B). The characteristics of each HU, their relation to the geomorphological zones and a brief description of the impacts and estimate of the PES of the watercourses within each HU are summarized in Table A.

Figure B

Homogeneous Units (HUs) recognized within the Luangwa Catchment at a WWF workshop in December 2015

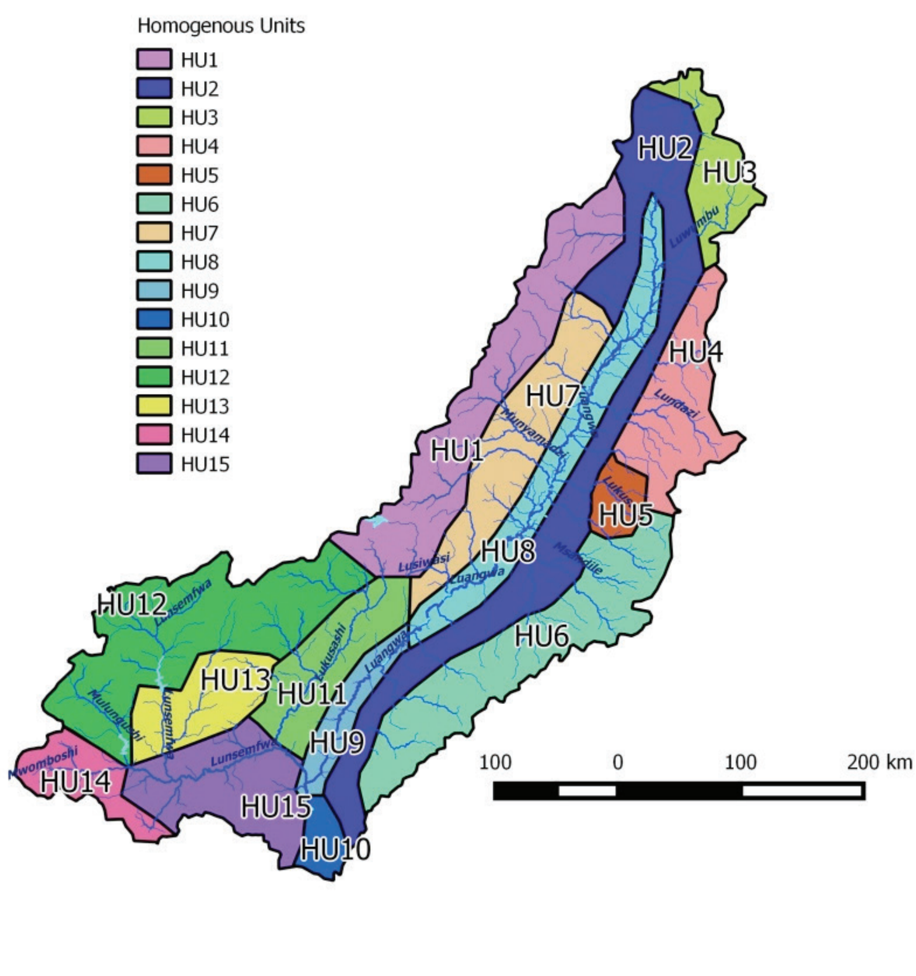


Table 1

Homogeneous Units (Hus) recognized for the Luangwa Catchment and their estimated Present Ecological State for Geomorphology

HU	Location	Description of rivers and watercourses within the HU	PES	Impacts
1	Western plateau (Serenje to Chinsali)	This HU is equivalent to the Muchinga Plateau geomorphological zone. Hilly and fairly well wooded, but largely inaccessible.	A/B	Few impacts - the region is remote and access difficult. Limited clearing for agriculture and charcoal production.
2	Luangwa valley, east bank alluvium	This HU is equivalent to the Eastern Foothills geomophological zone. The river channel flows within an incised macro-channel. The channel bed and bars are increasingly alluvial in nature.	B	Limited use – some areas of fields, but not in any way continuous along the riparian zone. Much protected within game areas.
3	Luangwa source montane area	This HU is equivalent to the Transition and Upper foothills geomorphological zones and a portion of the escarpment zone. Rivers and streams are well wooded, with narrow, steep valleys and small, narrow, deep, fast-flowing rivers in the steep Escarpment Zone. These change to single or multiple anastomosing river reaches in the Transition Zone and thereafter, in the downstream Upper Foothills Zone, to a predominantly a single channel.	B	Remote and steep river sections in the upper section of this HU limit landuse activities and impacts on the rivers. In the lower sections before the protected areas of HU2, intensive clearing of parts of the river have impacted the riparian zone and banks.
4	East bank plateau (Lundazi)	This HU is equivalent to the northern Eastern Plateau geomorphological zone. The larger channels are rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands). These are however often heavily utilised for small scale agriculture.	C	This zone is heavily utilised for agriculture (small scale and subsistence cropping). There is widespread encroachment in to the riparian zones. Reduced flows and increased sediment loads would be expected.
5	Lukusuzi National Park	This HU represents the Lukusuzi National Park in the central part of the Eastern Plateau geomorphological zone. The larger channels are rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands). These are however often heavily utilised for small scale agriculture.	B	The vegetation within the park boundaries is reported to be in good condition, and therefore the rivers and associated drainage lines can be expected to be in a better geomorphological condition than the HUs to the north (HU4) and south (HU6) of this HU.
6	East bank plateau (Petauke to Chipata)	This HU is equivalent to the southern part of the Eastern Plateau geomorphological zone. The larger channels are rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands). These are however heavily utilised for agriculture.	C	Heavily utilised for agriculture (small scale, subsistence and some commercial cropping), with numerous dams present throughout the zone. There is widespread encroachment in to the riparian zones. Reduced flows and increased sediment loads would be expected.
7	Luangwa outer west bank - alluvium	This HU is equivalent to the northern section of the Western Lower Foothills Zone. The streams in this zone are characterised by lowland rivers and lower foothills leading from the western escarpment to the Luangwa floodplain.	A/B	Largely in protected areas and therefore the impacts are limited

8	Luangwa valley meander	This HU is equivalent to the Floodplain geomorphological zone. Reaches of intense meandering are separated by straighter reaches where there is limited lateral movement of the river channel.	A/B	Very limited impacts: there are some small isolated fields in the uppermost section of the zone, but thereafter the river is within protected areas.
9	Luangwa lower mainstem	This HU is equivalent to the lower Floodplain geomorphological zone. The width of the floodplain and intensity of meandering are reduced relative the HU 8 - lateral movement of the river channel is more restricted and tends to a wider, sandier channel.	A/B	Very limited as the majority of the zone is within protected areas.
10	Luangwa catchment outlet	This HU is equivalent to the Braided geomorphological zone. Braided reaches within a confined valley (“gorge”) characterise this zone. High sediment transport section. No wide floodplain is present and there is no meandering.	B	Limited use, but the confined nature of the channel makes this somewhat resistant to adjacent land-use activities. May be impacted by elevated sediments.
11	Lukusashi River sub-catchment	This HU represents a portion of the Western lower foothills geomorphological zone. These are typically lowland and lower foothills river reach types along the lower Lukusashi tributary and associated drainage lines.	B	Largely in protected areas –low population densities in the Rift Valley and therefore these areas tend to correspond with limited agriculture and low impacts.
12	Lunsemfwa – Mulungushi plateau	This HU represents a portion of the South-western Plateau geomorphological zone. Narrow main rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands).	C	This is the most heavily and intensively utilised area in the catchment – flows have decreased and sediments increased, many small and a number of large dams associated with agriculture, and also some hydropower development is in place.
13	Lunsemfwa – Mkushi farm block	This HU represents the central section of the South-western Plateau geomorphological zone. Narrow main rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands).	C	This is less intensively utilised for agriculture than the upstream HU12, but remains impacted by extensive agriculture as well as the upstream flow impacts from agriculture and hydropower.
14	Mwomboshi –Mwapula plateau	This HU represents the southern extremity of the South-western Plateau geomorphological zone. Narrow main rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos.	C	Very little is known about this area from local experts. There is some agriculture which can be expected to have had an impact on the watercourses.
15	Luano Valley	This HU represents the southern portion of the Western lower foothills geomorphological zone with lowland and lower foothills river reach types.	B/C	In this zone, low population densities would limit possible impacts.

ESTIMATES OF SEDIMENT LOADS AND YIELD

There are very limited data to undertake detailed sediment yield modelling. The National Sediment Erosion Hazard mapping for Zambia (Chiti, 1987) identified the very steep escarpment zones of the catchment as areas of likely high sediment erosion.

Attempts at more quantitative sediment yields using available data estimated more than 1000 t/km2/annum in the headwaters, decreasing to values typically in the 400 to 800 t/km2/annum range in the middle and lower reaches (UNEP, 2015), but these results are generally far in excess of anything predicted or previously measured for similar catchments.

Moreover, the results did not corroborate with the Zambian erosion hazard mapping (Chiti, 1987), nor the patterns of clearing for agriculture within the catchment that are known from smaller-scale studies to have increased local erosion rates (Heatwole and Her, 2007).

Another similar earlier study (USDA, 2011) estimated even highersediment yields. Both studies acknowledged the very high uncertainty of their results and attributed this to the limited or absence of, detailed regional and local data and highlighted the need for significant additional long term field measurements and catchment land-use data in order to generate more reliable and accurate results.

As none of the above data and modelling limitations have improved, data remain limited and of a coarse resolution and therefore alternative methods to understand sediment yields from the Luangwa Catchment were investigated.

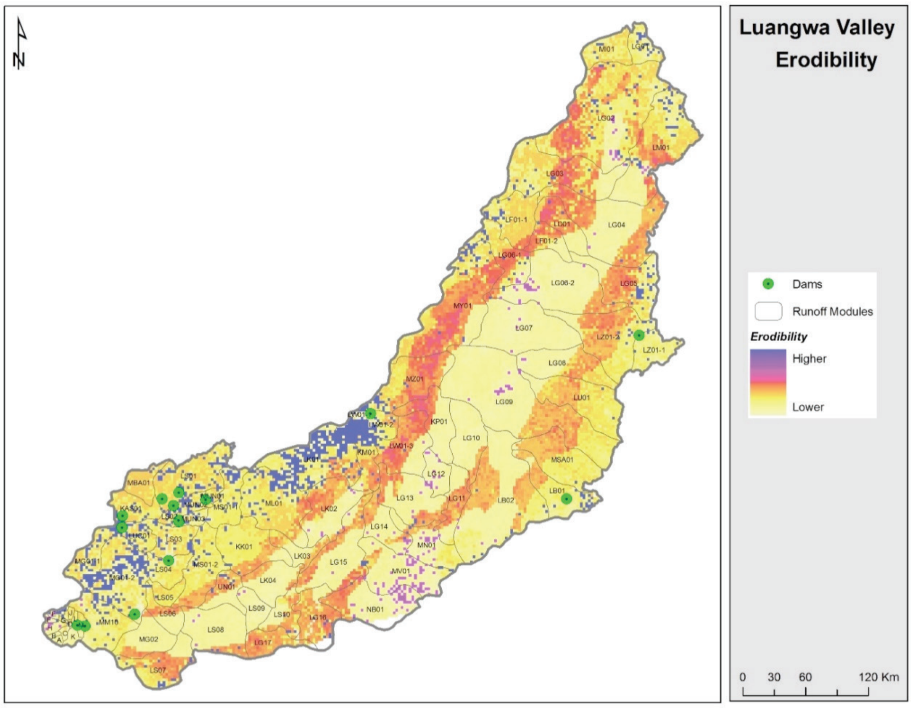
A review of regional river sediment loads studies was undertaken. The 140 t/km2/annum estimate for the Luangwa (Ronco et al., 2010), although based on the very limited sediment load measurements of Hall (1977), is nonetheless based on measured data and is at the lower end of a previous river load estimate for the Luangwa (Bolton, 1984). This estimate is also at the lower end of catchment sediment yield estimates identified from regional and global studies for the Luangwa.

In order to gain a spatial understanding of the erosion in the catchment, a qualitative assessment was undertaken to evaluate erosivity across the catchment. This indicated that areas with a lower clay content as well as poor tree cover have a higher probability of erosion. Clearing of vegetation thus not surprisingly presents a high risk for erosion in the catchment.

Unsurprisingly, the areas with the highest erosion risk correspond with extensive lands cleared for agriculture in the south-western, and to a lesser degree south-eastern, margins of the plateau areas of the catchment. Soils of the central catchment have very low erosion risk due to the low slopes and generally intact vegetation cover within the protected conservation areas of the valley floor. The pattern or erosivity (Figure C) corresponds with the Zambian Erosion Hazard mapping studies.

Figure C

Erosivity of the Luangwa Catchment



CONCLUSIONS AND RECOMMENDATIONS

Data for estimating sediment yield within the basin are simply not available or are too limited to yield reliable quantitative estimates for this large catchment. Some estimates of river sediment load, which have been based on very limited measured sediment discharge data from the 1970's, are likely to represent the most reliable available sediment estimates for the basin at present.

These estimates of sediment load (Ronco et al., 2010) are within the lower range of sediment yields for the basin indicated by global and regional studies, but much uncertainty remains due to the limited measurements and that catchment conditions have changed greatly since the 1970's when these data were collected. Management of the basin, and specifically estimations of dam sedimentation, would benefit from improved and more recent landuse cover information, as the rapid deforestation of the basin is poorly documented and not reflected in these sediment load measurements.

Given the available geomorphological data for the catchment, and the unlikely prospects of generating more detailed sediment yields for the catchment within a reasonable timeframe and budget, the current available data and understanding would be sufficient to support a standard multi-disciplinary holistic EFlows study to investigate the baseline and future consequences of catchment development.

For the evaluation of the geomorphological aspects, methods employed in other large-river EFlow assessments could be used. A minimum of six to seven EFlow sites would be necessary to evaluate the Luangwa Catchment, but ideally more sites would generate a greater understanding of the complex zone types identified across the basin.

1. INTRODUCTION

1.1 BACKGROUND TO THE PROJECT

The World Wide Fund for Nature (WWF), in collaboration with Zambia's Water Resources Management Authority (WARMA), has launched a new initiative to address integrated flow management of the Luangwa Catchment as part of a wider Zambezi flows programme.

The aim is to provide support to WARMA for the development of the Luangwa's Catchment management strategy. A central part of the strategy will be agreeing on future flows for the river system. These flows are widely referred to as Environmental Flows or EFlows. The Luangwa EFlows Assessment is planned to take place in two phases. Phase 1 consists of locating and synthesizing all available information on the Luangwa Catchment, leading to an initial formal division of the catchment into homogeneous biophysical and social areas.

Another major part of Phase 1 is a rapid desktop estimate of EFlows that would support A (pristine) to D (largely modified) conditions at points across the catchment, as an input to catchment development plans.

1.2 ROLE OF GEOMORPHOLOGY IN THIS ASSESSMENT

Fluvial geomorphology encompasses the physical habitat and processes of formation and maintenance of the physical habitat in river environments. Geomorphology provides a critical link between the hydrology and hydraulic processes at a site and how these are translated into the persistence, development or decline of specific instream, riparian or floodplain physical habitats upon which biota and people are dependent.

The translation of the flow, sedimentological and river morphological changes into a description of important physical habitat alterations allows for more integrated predictions of change under different flow scenarios than if only the biota were considered.

At this broad scale of the Phase 1 investigation, the division of the Luangwa Catchment into smaller units or zones of similar biophysical habitat types was an essential step for selecting representative sites across the catchment. These homogeneous zones/areas could then be described as a summary of the large and complex nature of this catchment.

1.3 TERMS OF REFERENCE

The Terms of Reference for the Geomorphology component of the study were the following two key tasks, with a number of sub-tasks as described below. A total of 20 days was allocated to the completion of all tasks.

1.3.1 Task 1

This was the main task for the study, involving the sourcing, collation, review and analysis of available literature and data to be able to undertake the geomorphological and land-use assessment of the Luangwa Catchment, and travel to and attendance of a workshop in Lusaka in December 2015.

Task 1.1	Divide the Luangwa River system into homogenous geomorphological river zones and make a preliminary assessment of the Present Ecological State of these zones from the geomorphological perspective. These findings were presented at the Basin Division workshop held in Lusaka in December, 2015. Information from specialists in many disciplines was used to describe the catchment characteristics and achieve a harmonised catchment division into homogeneous areas, and an agreed Present Ecological Condition for each area.
Task 1.2	Initiate a review of available data and undertake a qualitative (or, if available data permitting, quantitative) sediment yield analysis for the catchment, and a brief overview of land-use within the catchment.
Task 1.3	Write up the results (this report) of the review and analyses for the above tasks.

1.3.2 Task 2

One day was allocated to provide input to planning for Phase 2, including recommendations and justification for how the geomorphological and sediment aspects could proceed in Phase 2 of the study. These recommendations are provided in Section 10 of this report.

1.4 KEY DELIVERABLES AND REPORT LAYOUT

This Specialist Report is the key deliverable, together with an electronic database (in the form of a Dropbox folder) with scientific publications, reports and GIS data which were identified and collated as part of this review and analysis. A summary of the catchment division and initial results were presented in Lusaka in December 2015 at the Basin Delineation workshop.

Those initial results were provided in a Powerpoint presentation at the Lusaka workshop and are presented in full in this document. In this report, Section 2 describes the approaches undertaken for the various tasks. The findings from each task are described in Sections 3 to 8. Section 9 provides concluding remarks and Section 10 recommendations for the geomorphological aspects of a detailed (Phase 2) Environmental Flow (EF) study for the Luangwa.

2. APPROACH

2.1 DIVISION OF THE CATCHMENT IN TO GEOMORPHOLOGICAL ZONES

Geomorphology provides an appropriate basis of classification for describing the physical habitat of riparian and aquatic ecosystems, since the geomorphological processes that shape river channels determine the material from which the channel is formed, the shape of the channel, and the stability of its bed and banks.

The channel geomorphology in turn determines the substrate conditions for the riverine fauna and flora and the hydraulic conditions at any given flow discharge. Structural changes to the river channel (damage to the riparian zone, sediment inputs from catchment erosion or reservoir induced changes in the flow regime) can cause long-term irreversible effects for biota (Kochel, 1988; O'Keeffe 2000).

A hierarchical classification system for southern African rivers (Rowntree and Wadeson, 1999; Rowntree et al., 2000) was used as the basis for identifying and delineating areas of similar habitat types and river morphology at the zone scale (Table 2.1) within the Luangwa Catchment.

Table 2.1

A spatially scaled classification of river units (after Rowntree and Wadeson, 1999)

Hierarchical Unit	Description	Scale
Catchment	The catchment or basin is the land surface which contributes water and sediment to any given stream network.	Can be applied to the whole river system, from source to mouth, or to a lower order catchment above a specified point of interest.
Segment	A segment is a length of channel along which there is no significant change in the flow discharge or sediment load.	Segment boundaries will tend to be co-incident with major tributary junctions or major continental-scale geomorphological features.
Zone	A zone is a sector of the river long profile, which has a distinct valley form and valley slope.	Sectors of the river long profile (generally tens to sometimes hundreds of kilometres)
Reach	A length of river characterised by particular channel pattern and morphology, resulting from a uniform set of local constraints on channel form.	Hundreds to thousands of meters.
Morphological Unit	The morphological units are the basic structures comprising the channel morphology and may be either erosional or depositional features.	Morphological units occur at a scale of an order similar to that of the channel width.
Hydraulic biotope	Hydraulic biotopes are spatially distinct instream flow environments with characteristic hydraulic attributes.	Hydraulic biotopes occur at a spatial scale of the order of 1 m2 to 100 m2 and are discharge dependent.

2.1.1 Zone Delineation

At the zone scale of the hierarchical classification (Table 2.1), the longitudinal profile or river channel gradient is well correlated with many channel properties including channel planform or type, bed material and reach type (Rowntree et al., 2000). Changes in channel gradient along the longitudinal profile usually mark major morphological changes and thus provide the basis for the delineation of longitudinal zones (Table 2.2).

These breaks can be associated with changes in lithology, result from tectonic activity or be associated with the upstream migration of nick points (Dollar, 1998) and major tributary junctions. Planform (river morphology) characteristics can then be used to refine the delineation of the zones.

Different river planforms have been shown to have differential sensitivity and rates of change to flows and floods (Rountree et al., 2001; Rountree and Rogers, 2004) and can be useful in predicting sensitivity to particular impacts. Kesel (2003) similarly demonstrated that different geomorphic planforms respond to river engineering modifications in different ways.

The smaller units of the classification - reach, morphological unit and hydraulic biotope – are usually applied to specific sites and delineation and description of these smaller scale units has not been undertaken at the catchment scale.

Table 2.2

Typical river zone types in southern Africa (after Rowntree and Wadeson, 1999)

Zone Type	Zone Characteristics	
	Slope	Description
Mountain headwater	>0.1	Very steep, narrow, rapid type river dominated by bedrock and very large boulders. Reach types include rapids, cascades and bedrock falls.
Mountain stream	0.1-0.04	Steep gradient stream dominated by bedrock and boulders, locally cobble or coarse gravels in pools. Reach types include cascades, bedrock fall, step-pool, Approximate equal distribution of 'vertical' and 'horizontal' flow components.
Transitional	0.04-0.02	Moderately steep stream dominated by bedrock or boulder. Reach types include plain-bed, pool-rapid or pool riffle. Confined or semi-confined valley floor with limited flood plain development.
Upper Foothills	0.02-0.005	Moderately steep, cobble-bed or mixed bedrock-cobble bed channel, with plain-bed, pool-riffle or pool-rapid reach types. Length of pools and riffles/ rapids similar. Narrow flood plain of sand, gravel or cobble often present.
Lower Foothills	0.005-0.001	Lower gradient mixed bed alluvial channel with sand and gravel dominating the bed, locally may be bedrock controlled. Reach types typically include pool- riffle or pool-rapid, sand bars common in pools. Pools of significantly greater extent than rapids or riffles. Flood plain often present.
Lowland river	0.001-0.0001	Low gradient alluvial fine bed channel, typically regime reach type. May be confined, but fully developed meandering pattern within a distinct flood plain develops in unconfined reaches where there is an increased silt content in bed or banks.
Lowland floodplain	<0.0001	Meandering, depositional pattern within a poorly defined flood plain develops.

Available electronic topographic data (Garmap Africa Series 2012.2: Southern Africa Topo) were used to generate longitudinal profiles of the mainstem Luangwa (from its source to its confluence with the Zambezi) and other key tributaries such as the Lunsemfwa River at twenty metre contour intervals.

Initial zone breaks or boundaries were refined using Google Earth imagery, slope, channel planform, floodplain width and topography to delineate zones of morphologically similar river zones across the catchment.

2.1.2 Present Ecological State assessment

Using available literature sources as listed in this report, analysis of Google Earth imagery and discussions with regional experts at the December 2015 workshop in Lusaka, the present day geomorphological condition of the main geomorphological zones was estimated.

This estimate considered the key criteria of the Geomorphological Assessment Index (Rowntree and du Preez, in press), a method developed and applied by the South African Department of Water Affairs to score the current condition of river geomorphology as part of river monitoring and environmental flow assessment studies in that country.

The estimate of Present Ecological State enumerates the deviation of the condition of the zone as currently observed from the expected Reference condition. For the purposes of this study, the Reference Condition was set as that condition of the river approximately 100 years ago, prior to increased population pressure, dam construction and associated impacts on the river banks, hydrology and sediment load. Thus limited, low intensity agricultural activities would have been occurring at this time, but the population pressures would have been expected to be much lower.

The output scores are grouped into 6 Categories (Table 2.3), ranging from A (essentially the Reference Condition) to F (representing the most extreme degraded condition possible).

2.2 LAND USE WITHIN THE LUANGWA CATCHMENT

2.2.1 Collation and review of available data

Available literature, land-cover data (the FAO's Global Landcover 2009 dataset) and extensive analysis of recent Google Earth imagery was used to inform this brief overview of land-use activities within the Luangwa Catchment.

The FAO's Global Land Cover Network (GLCN) databases, or Globcover, are cited as the best archive on land cover globally as at 2013 (http://www.glcn.org/databases/lc_gc-africa_en.jsp , accessed December 2015). The source data for this land-cover is based on 2005 imagery at 300 m scale. The Globcover was published in 2008 as result of an initiative launched in 2004 by the European Space Agency (ESA).

Table 2.3

Descriptions of the Present Ecological State (PES) categories used to describe and classify the ecological condition of rivers (adapted from Kleynhans 1996; 1999)

Present Ecological State category	% Score	Description of the habitat
A	90-100%	Still in a Reference Condition.
B	80-90%	Slightly modified from the Reference Condition. A small change in natural habitats and biota has taken place but the ecosystem functions are essentially unchanged.
C	60-80%	Moderately modified from the Reference Condition. Loss and change of natural habitat and biota has occurred, but the basic ecosystem functions are still predominantly unchanged.
D	40-60%	Largely modified from the Reference Condition. A large loss of natural habitat, biota and basic ecosystem functions has occurred.
E	20-40%	Seriously modified from the Reference Condition. The loss of natural habitat, biota and basic ecosystem functions is extensive.
F	0-20%	Critically / Extremely modified from the Reference Condition. The system has been critically modified with an almost complete loss of natural habitat and biota. In the worst instances, basic ecosystem functions have been destroyed and the changes are irreversible.

Literature was sourced from the WWF database provided at the initiation of the study, with further information obtained from searching published scientific literature as well as NGO and international aid agency region and country reports. All relevant literature is cited in this report and fully referenced at the end of the report.

A workshop held in Lusaka in December 2015 with regional and in-country experts delineated zones of similar geomorphological, rainfall, runoff, landuse and biotic characteristics within the Luangwa Catchment. The discussions and information from this workshop provided further information and insight into the land-use characteristics and specific crop types that can be expected within the various homogenous units of the catchment.

2.3 ANALYSIS OF CATCHMENT SEDIMENTS

The focus of the Phase 1 component of the Luangwa Environmental Flows (EFlow) study was to review existing information and generate an understanding of the Luangwa River and Catchment in order to support a more detailed field-based EFlow Assessment in Phase 2 of this study.

A review of data on sediment yield and an assessment of the likely sources of sediment across the catchment were undertaken in this study. Determining the sediment load of a river at the catchment or basin scale is one of the main challenges in fluvial geomorphologic research (de Vente et al., 2006). Catchment sediment yield provides estimates of the potential soil lost from surface soil erosion, with soil loss equations primarily focusing on the losses from agricultural lands that are generally on mid-slope positions in the landscape.

The application of physics-based models (such as the Universal Soil Loss Equation (USLE) methods for catchment sediment yield) for estimating catchment sediment yield has, however, often yielded inaccurate results, especially for larger catchments, for the following reasons:

- The models and approaches rely on very large data requirements that are seldom available at sufficiently low resolution.
- There is a lack of knowledge to describe all processes and process interactions at the catchment scale. Specifically, point sources of sediment (e.g. gullies, mass movements), connectivity and sediment transport within the river network remain difficult to describe in most models (de Vente et al., 2006). Some researchers suggest that more than half of the sediment eroded off slopes is redeposited in valley bottoms and lower slopes in a catchment (Dedkov and Mozzherin, 1996). In the Luangwa, further complexity arises from the high prevalence of dambos. These valley bottom wetlands are highly effective sediment traps typical of the high-lying regions of southern and eastern Africa, but are not well accounted for in global runoff and sediment yield models (Nyirongo, 2009).
- Point sources of sediment from subsoil (gully) erosion have been shown to contribute a substantial portion of sediments in some catchments (Hobgen et al., 2014). Such sources are not accounted for in the USLE or RUSLE modelling approaches.

OTHER STUDIES HAVE SIMILARLY NOTED THE RAINFALL DATA LIMITATIONS IN THE ZAMBEZI CATCHMENT

The sediment yield modelling thus represents the potential soil losses in an area, but may not be representative of the actual sediment load within a river because only the upper soil surface erosion is modelled and other sources and sinks (sediment inputs from erosion gullies or dongas; the within-slope movement or sediment and within-channel erosion and bank and floodplain deposition) are not accounted for.

In the Luangwa, with its extensive floodplains and alluvial tributaries, there would be important sediment sinks throughout the catchment. Whilst the catchment sediment yield may not equate well to understanding actual river sediment loads (as demonstrated for Zambia by Walling et al., 2003), they can provide a broad likely upper limit of potential sediment volumes that are generated from a river catchment.

A far more accurate determination of sediment from a catchment is obtained from the measurement of river sediment loads. Sediment load is determined through measured sediment discharge in a river channel (or from sediment trapped in dams) and provides a far more reliable estimate and understanding of the actual sediment load being delivered to and flowing down a river channel. Such an approach is however dependent on a reliable long-term sediment discharge measurements linked to reliable discharge records.

In situations where verified fine-scale data are not available, qualitative analyses of river catchments allows for high-risk and low-risk erosion zones to be identified using available regional and global databases. In the relatively data-poor Luangwa Catchment, a qualitative analysis using the available soils, land cover, slope and low-resolution rainfall data was undertaken to assess the erosivity[1] of the catchment.

This enabled areas of high and low soil erosion in the catchment to be identified, and thus enabled some determination of likely high and low sediment yield zones to be identified.

An understanding of the sediment and erosion patterns within the Luangwa Catchment were thus investigated using three approaches:

1) At the catchment scale, a review of published studies and NGO reports on regional catchment sediment yields was undertaken. All relevant literature identified is cited in this report. The review highlighted the limited verified field data of soils and rainfall information required for accurate sediment yield determination.
2) An estimate of sediment load in the rivers was identified that had been based on limited measured data of sediment discharges (from the 1970's). This estimate of river sediment load provided an additional estimate of yield from the basin and, unlike the catchment yield estimates, has been based on measured (albeit very limited data points that are now several decades old).
3) In order to refine the spatial understanding within the catchment, erosivity was qualitatively determined based on available soil characteristics, vegetation cover and slope data.

2.3.1 Review of catchment sediment yield data

Catchment sediment yield modelling is reliant on detailed data within a river catchment and is most commonly undertaken using the Universal Soil Loss Equation (USLE) or Revised Universal Soil Loss Equation (RUSLE). These are quantitative soil loss estimation methods developed by the United States Department of Agriculture (USDA) and were based initially on measurements of soil erosion from agricultural lands in the USA cornbelt initiated in the 1930s and 1940s (Renard et al., 2011). These modelling approaches rely on detailed small spatial scale data to determine soil loss. For example, the USLE equation is: **A = R x K x LS x C x P**

Where:
- A is the potential long-term average annual soil loss in tonnes per hectare per annum.
- R is the rainfall and runoff factor which is determined by the intensity and duration of rainfall events.
- K is the soil erodibility factor, a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff. This is a function of soil texture, structure, organic matter and permeability of the surface soil.
- LS is the slope length-gradient factor.
- C is the crop/vegetation and management factor – an indication of the effectiveness of soil and crop management systems in terms of preventing soil loss.
- P is the support practice factor, reflecting the effects of practices that will reduce the amount and rate of the water runoff and thus reduce the amount of erosion.

[1] Erosivity is a measure of the potential ability of soil to be eroded by rain or surface runoff.

Using broad-scale regional and global datasets (Holeman, 1968; Lvovich et al., 1991; Dedkov and Mozzherin, 1996; Walling and Webb, 1996), recent studies of the Luangwa itself (USDA, 2011; UNEP, 2015) and of select sub-catchments within the larger Luangwa Catchment (Heatwole and Her, 2007), a review of catchment yield studies was undertaken. The studies within Zambia, and the Luangwa specifically, consistently highlighted the limited data availability and poor or at times unrealistic results (UNEP, 2015) from the modelling using available data for the Luangwa.

Accurate fine-scale mapping of surface soil characteristics and rainfall intensity information are required for accurate sediment yield mapping. In the available soils database for the Luangwa (ISRIC African soil database, http://www.isric.org), there are only 5 field samples representing the entire 165, 000 km2 catchment, and the broad classifications they yield are a limitation to detailed quantitative studies. Other studies have similarly noted the rainfall data limitations in the Zambezi Catchment (Heatwole and Her, 2007; Kling et al., 2014).

As no new data are available and a very recent study attempting to derive sediment yield estimates for the Luangwa (UNEP, 2015) demonstrated that available data are insufficiently detailed or verified to provide reliable catchment yield estimates, further analysis along these lines was not pursued.

2.3.2 River sediment loads

River sediment loads are determined through the measurement of sediment load in a river and extrapolation of this instantaneous measurement through to annualized sediment yields by correlating sediment discharge with flow volumes. Extrapolation from measured sediment loads using rating curves is probably unreliable unless:

1) Both the bedload and suspended loads are measured and correlated well with discharge
2) Accurate long-term records of discharge are available.

Some caution with this method should be used because:

- Rivers in semi-arid regions have been shown to have highly variable sediment loads relative to discharge. As such there is often no clear sediment-discharge relationship. For instance, Leopold et al. (1964) demonstrated that at the same discharge, sediment loads could vary by two to three orders of magnitude.
- Flow variability in the rivers in semi-arid southern Africa is amongst the highest in the world (MacMahon et al., 1992) and much of the sediment movement occurs in large, infrequent (so-called 'catastrophic') floods that are usually not measured and thus do not appear in the hydrological record. For instance, Erskine and Saynor (1996) demonstrated that, in similar semi-arid regions of Australia, catastrophic flood years (where the peak is 10 times greater than the mean annual flood) can generate anywhere between 11 and 283 times the mean annual sediment yield; they thus demonstrated both a poor correlation of sediment load with discharge, and the importance of the large flood years.
- The correlation of sediment load to discharge often only measures the suspended sediment concentration and ignores the bedload component.

This can result in a significant underestimate of the total load in rivers where bedload is a large, or dominant, component of the load.

In the Luangwa, there are no available long-term sediment measurements that can be linked to the flow record. Only limited measurements of sediment loads have been cited in the published record (Hall, 1977), and raw data are not available from these historic studies.

However, one study which estimated sediment load based on the limited measured records from the 1970s was identified (Ronco et al., 2010) in the literature review. Uncertainty remains around this estimate because of the few data points and short record of sediment discharge, and also because these observed data from the 1970's do not represent the current landuse and deforested condition of the catchment.

2.3.3 Erosivity mapping of the Luangwa Catchment

Regional sediment yields and estimated sediment loads in the Luangwa provide an approximation of the sediment derived from the catchment and flowing down the river. Finer-scale sediment-yield mapping has been attempted (UNEP, 2015) but the results are constrained by insufficient detailed and verified data.

In order to gain a spatial understanding of the areas of the Luangwa Catchment that could be contributing to higher sediment yield, a qualitative assessment was undertaken in this project to evaluate erosivity across the catchment. The likeliness of clay content of the various soil types was considered (soils data derived from the ISRIC (FAO) Soil and Terrain (Soter) database, with soils scores according to clay content), with slope (from LANDSAT DEM) and tree cover (MODIS) factored in.

This desktop study was limited in that the verified available data is of a course scale. In order to provide a more accurate and detailed look into volumetric estimates of sediment yield per sub-catchment, far more fine scaled and detailed verified soil type data, as well as localized rainfall intensity data, are required for the catchment.

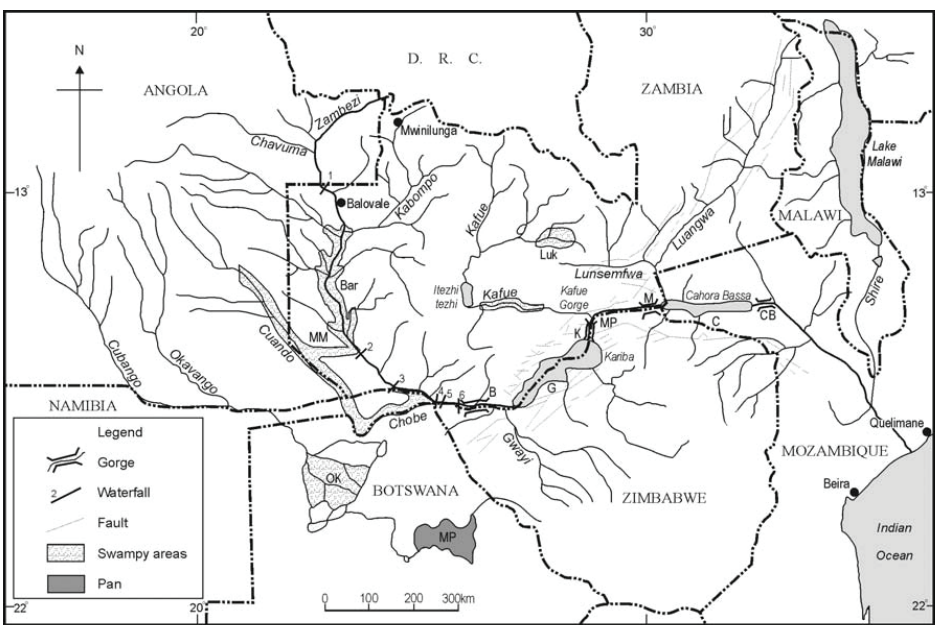
3. GEOLOGICAL HISTORY OF THE LUANGWA CATCHMENT

The Luangwa Valley is formed by a 700 km long extension off the Western Branch of the East African Rift system (Dixey, 1937). This rift valley extension cuts diagonally (south-west to north-east) through the high central plateau of Zambia. The headwaters of the Luangwa are at the northern end of this valley in the Mafinga Hills, a plateau covered by hills situated on the border between Zambia and Malawi (Figure 3.1).

From the upper Jurassic to Cretaceous period, the Luangwa and other main present-day tributaries of the Zambezi flowed southwest and formed the headwaters of the Limpopo River. The Zambezi at this time was a minor, small tributary of the Shire River, and at some period the Luangwa formed a large lake in the valley which rivalled Lake Malawi in size (Moore and Larkin, 2001).

Approximately 65 million years ago, at the end of the Cretaceous, uplift caused the lower Zambezi to erode aggressively westwards, initiating head ward erosion and the progressive capture of the Luangwa, upper Zambezi and Kafue catchments (Timberlake and Childes, 2004).

Figure 3.1
Zambezi River Catchment (source: Moore et al., 2007)



4. DESCRIPTION OF THE LUANGWA CATCHMENT

Today the Zambezi River is the fourth largest river basin in Africa with a catchment area of nearly 1,500,000 km2 (Davies, 1986) and several major tributaries contributing to its estimated 108 km3 annual discharge (Table 4.1). The Zambezi has been divided in to three major segments, (Wellington, 1955; Moore et al., 2007), namely:

- The Upper Zambezi, extending from the headwaters to Victoria Falls
- The Middle Zambezi, extending from Victoria Falls to Cahora Bassa reservoir
- The Lower Zambezi, extending from the Cahora Bassa Gorge across the coastal plain of Mozambique to the Indian Ocean.

The upper segment, upstream of Victoria Falls, is characterised by generally low slopes and river channels with large floodplains and wetlands. The middle segment is known for its extensive gorges, such as Batoka, Kariba and Cahora Bassa, with the confined floodplain of Mana Pools located between Kariba and Cahora Bassa Reservoirs (Figure 3.1). Downstream of Cahora Bassa Dam the river flows into the lower segment - a more than 400 km long stretch of floodplains and delta across the Mozambique coastal belt.

Table 4.1

Mean estimated annual runoff for Zambezi sub-catchments (after Beilfuss and dos Santos, 2001)

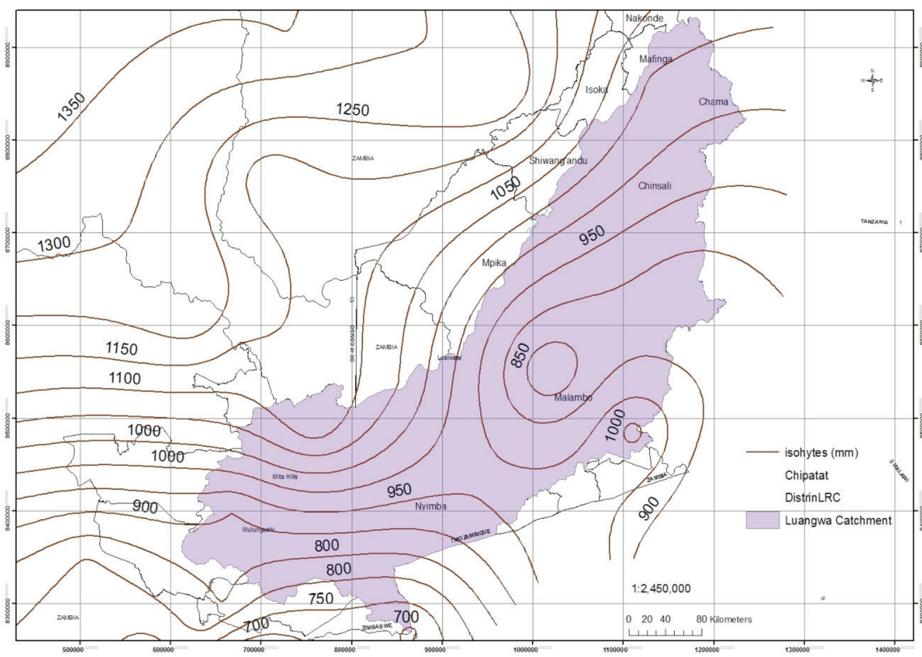
Sub-Catchment	Catchment area (km2)	Mean annual discharge ± 95% C.I. (m3/s)	Mean annual runoff ± 95% C.I. (km3)
Upper Zambezi	507,200	1046 ± 815	32.9 ± 25.7
Gwembe Valley	156,600	222 ± 196	7.2 ± 6.2
Total to Kariba Gorge	***663,800***	***1268 ± 997***	***40 ± 31***
Volume of Kariba Reservoir			*180 km3*
Kafue River	154,200	285 ± 279	9.0 ± 8.8
Luangwa River (including other minor tributaries)	232,000	888 ± 818	28.0 ± 25.8
Total to Cahora Bassa Gorge	***1,050,000***	***2442 ± 1917***	***77 ± 60***
Volume of Cahora Bassa Reservoir			*52 km3*
Plateau Tributaries	177,500	412 ± 365	13.0 ± 11.5
Shire Catchment	154,000	539 ± 422	17.0 ± 13.3
Zangue Catchment	8,500	16 ± 14	0.5 ± 0.4
Total to Zambezi Delta	***1,390,000***	***3424 ± 2675***	***108 ± 84***

The Luangwa River forms an important tributary in the middle segment of the Zambezi, contributing approximately 28 km3 of flow annually to the Zambezi (Table 4.1) at its confluence upstream of Cahora Bassa Dam.

The elevation within the catchment ranges from 330 masl to more than 2000 masl in the headwaters. The Luangwa Catchment can be divided in to two main topographic units – the plateau above the escarpment of the Rift Valley, and the Rift Valley floor itself. Rainfall varies from less than 800 mm per annum on the southern end of the Rift Valley floor, increasing to 900 to 1100 mm per annum along the high escarpment of the northern and western margin of the catchment (Figure 4.1) (refer to Phase 1 Hydrology Report: WWF/FRESHWATER/04/2016).

Figure 4.1

Rainfall distribution across the Luangwa Catchment (source: WARMA)

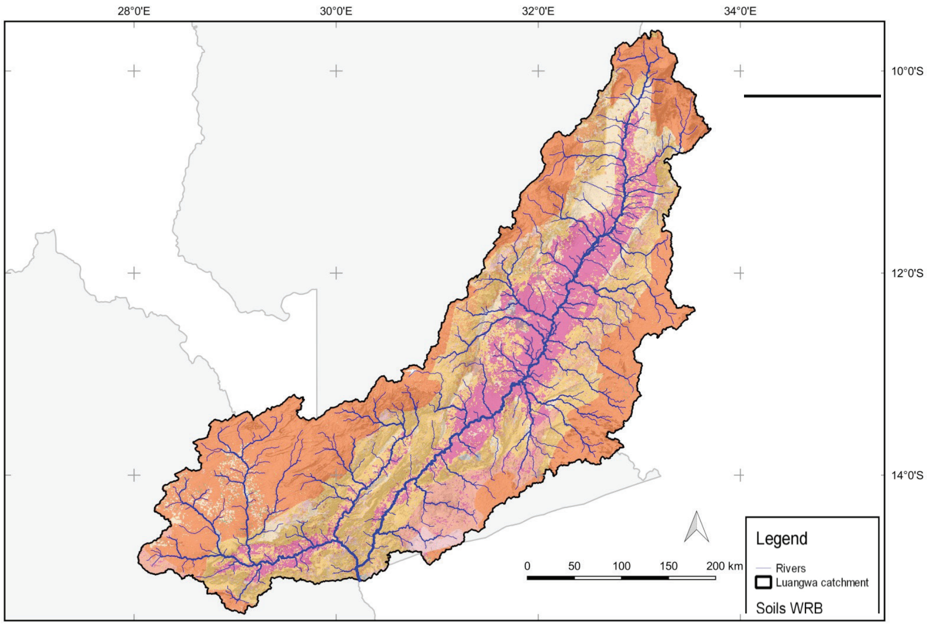


The upper plateau, typically at 800 to 110 masl, has soils that are largely derived from the basement complex, dominated by granites and gneiss, with rainfall that tends to be higher than 800 mm per annum. These soils support the cultivation of sorghum, maize, groundnuts, cow peas and a range of cash crops including tobacco, sunflower, irrigated wheat, soybean and horticultural crops, with shifting (or slash and burn) agricultural practices commonly employed.

Within the small valleys, dambos (seasonally or temporarily saturated valley bottom wetlands) are often present. On the Rift Valley floor, rainfall is generally lower, temperatures higher and food security is problematic due to recurrent crop shortages. Luvisols, Solonetz and Leptosols are common, but it is the Vertisols that dominate the extensive floodplains of the Luangwa Valley (Figure 4.2).

Figure 4.2

Soils of the Luangwa Catchment (source: FAO's soil database classified by the World Reference Base (WRB) for soil resources)



5. GEOMORPHOLOGICAL ZONES OF THE LUANGWA RIVER SYSTEM

Longitudinal analysis of the mainstem Luangwa (Figure 5.1) and key tributaries such as the Lunsemfwa (Figure 5.2) identified several major zones or river morphological types. The Luangwa Valley is dominated by a central zone of lowland rivers (Figure 5.3), which is characterized by alluvial meandering floodplains and, further downstream towards the confluence with the Zambezi, a lowland braided zone.

Outside of this central lowland zone, upper and lower foothill zone types are dominant (Figure 5.3), with occasional short sections of mountain stream (associated with the steep escarpment area) and transitional zone types over the steepest areas of the catchment.

The main Luangwa River headwaters in the northern part of the catchment have mountain stream zone types (the narrow, steep mountain escarpment areas) and this grades in to a transition zone and then upper and lower foothill zones (Figure 5.1).

In the lateral tributaries, upper foothill zones are dominant above the escarpment (edges of the Rift Valley), changing to short, steep mountain stream zones as the rivers flow over the escarpment, followed by a rapid transition to lower foothills and lowland river zones between the escarpment and the mainstem Luangwa on the Rift Valley floor (Figure 5.3).

Figure 5.1

Longitudinal profile and zones of the Luangwa River. An extensive floodplain and braided zone constitute the lowland river zone, which dominates the central basin

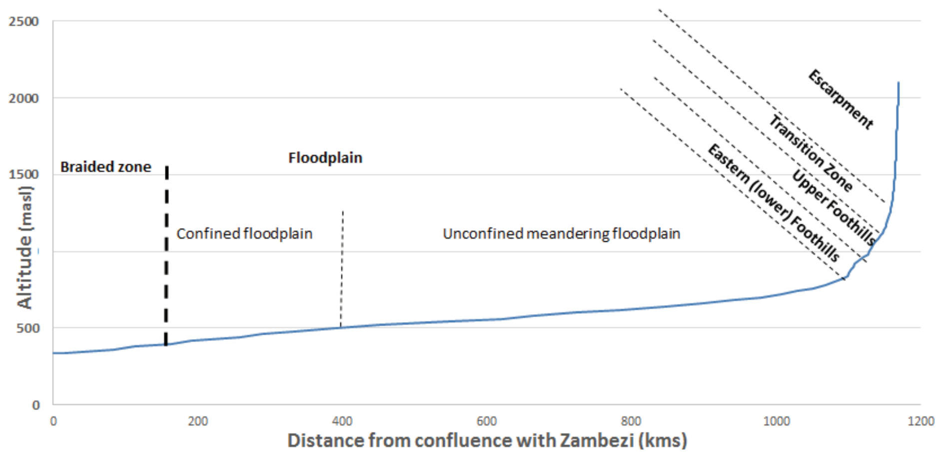


Figure 5.2

Longitudinal profile and zones of the Lunsemfwa River. The escarpment denotes the edge of the Rift Valley

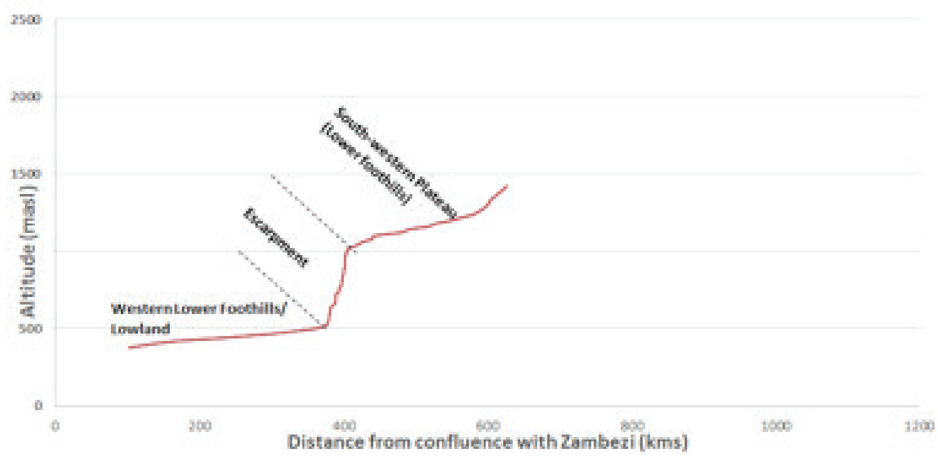
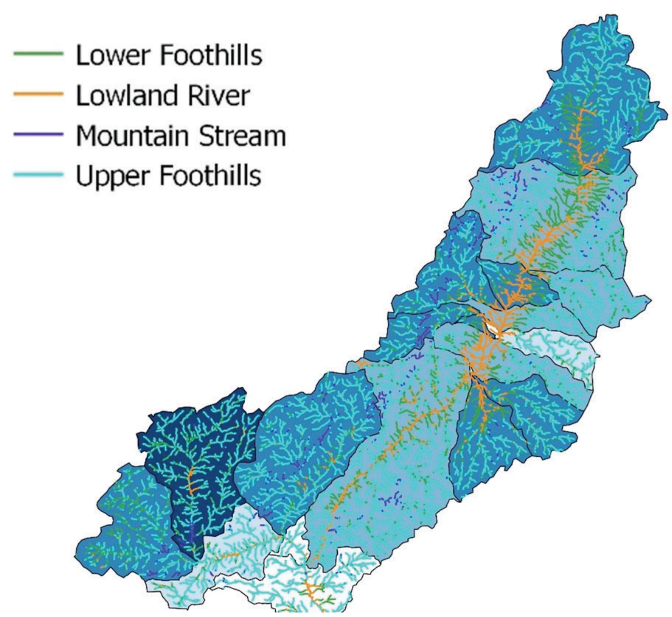


Figure 5.3

Distribution of key river zone types within the Luangwa Catchment. River zone types are classified according to Rowntree and Wadeson (1999)



Based on the major topographical breaks, typical longitudinal river zone types, coarse land-use patterns and morphology of the river types, ten main morphological river zones were delineated within the Luangwa Catchment (Figure 5.4).

The escarpment is most pronounced on the western and northern side of the catchment, separating the high elevation Muchinga Plateau from the central valley floor. This escarpment is typically about 700 m high, but declines to about 450 m along the eastern margin of the valley, where a lower elevation plateau and an extensive zone of foothills have made the transition from the valley floor to the eastern plateau less distinct.

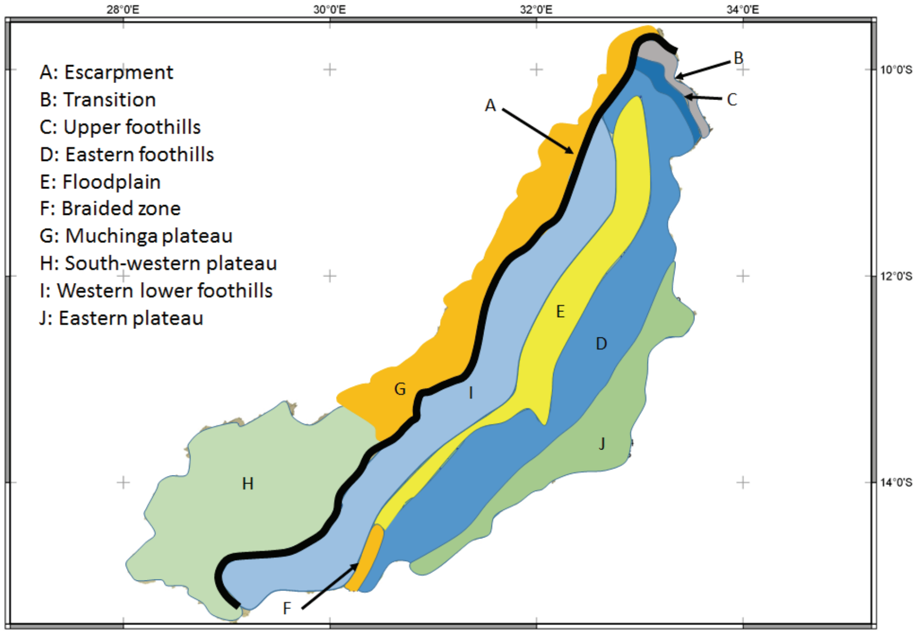
The descriptions of the zones were derived from limited available desktop imagery (Google Earth) and a handful of published studies of rivers within the basin. The characteristics of each zone are described below and summarized in Table 5.1.

Table 5.1

Characteristics of the morphological zones of the Luangwa Catchment

Zone	Characteristics	Land-use
A: Escarpment	Well wooded, very steep sided, narrow, steep valleys with small, narrow, deep, fast-flowing rivers.	Very limited due to inaccessibility.
B: Transition	Single or multiple anastomosing/ anabranching river reaches; some evidence of alluvial fans.	Heavily utilised – riparian and floodplain agriculture is in places intensive and encroaches in to the riparian zone.
C: Upper foothills	Predominantly a single channel which is beginning to meander across the valley floor more than the transition reach. There are anastomosing reaches within this river.	Some areas of fields, but much less intensive use of lands than upstream zone.
D: Eastern foothills	The river channel flows within an incised macro-channel. The channel bed and bars are increasingly alluvial in nature.	Limited use – some areas of fields, but not in any way continuous along the riparian zone. Much protected within game areas.
E: Floodplain	Reaches of intense meandering are separated by straighter reaches where there is limited lateral movement of the river channel. River channel becomes progressively wider and sandier.	Very limited. Some small isolated fields in the uppermost section of the reach; thereafter the majority of the zone is within protected areas.
F: Braided zone	Braided reaches within a confined valley ("gorge") characterise this zone. High sediment transport section. No wide floodplain is present and there is no meandering.	Limited use, but the confined nature of the channel makes this somewhat resistant to adjacent landuse activities. May be impacted by elevated sediments.
G: Muchinga plateau	Hilly and fairly well wooded, but clearing for agriculture and charcoal production is occurring.	Very limited due to inaccessibility.
H: South-western plateau	Narrow main rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands).	Heavily utilised landscape – flows decreased, sediments increased, many small and a number of large dams, hydropower.
I: Western lower foothills	Lowland rivers and lower foothills leading to the Luangwa floodplain.	Largely in protected areas – low impacts.
J: Eastern plateau	Main channels are rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands). These are however often heavily utilised for small scale agriculture.	Heavily utilised for agriculture (small scale and subsistence cropping).

Figure 5.4
Main geomorphological zones of the Luangwa River system



5.1 ESCARPMENT ZONE

The valleys and riparian zones are very steep sided and narrow, and these steep valleys have small, narrow, deep, fast-flowing rivers (Figure 5.5).

Waterfalls are common. Escarpment riparian forest fringes the rivers and streams of this mountainous zone (https://sites.google.com/site/luangwatrees). There is almost no utilization of the landscape due to very steep valleys and general inaccessibility of this mountainous zone.

Figure 5.5
Google Earth oblique image demonstrating the steep, high Escarpment Zone of the headwaters of the Luangwa

5.2 TRANSITION ZONE

Single-channel (Figure 5.6) or multiple-channel anastomosing or anabranching river reaches characterize this zone. There is also some evidence of alluvial fans, indicating that high bedload sediment volumes from the steep upstream reaches are being deposited on the valley floor as this begins to widen and the river slope decreases. There has been extensive clearing of the riparian zones where access is possible. Floodplain agriculture is intensive in some reaches and in places encroaches in to the riparian zone.

Figure 5.6

Google Earth image of the Luangwa River in the Transition Zone

5.3 UPPER FOOTHILLS ZONE

This zone is characterized by predominantly single-channel river reaches, where the channel begins to meander across the valley floor, more so than in the Transition Zone; there are also anastomosing reaches. There has been land clearance in some sections (Figure 5.7), but the clearing of fields adjacent to the river, and encroachment in to the riparian zone, is less intensive than in the upstream zone.

Figure 5.7

Google Earth image of the Luangwa River in the Upper Foothills Zone

5.4 EASTERN FOOTHILLS ZONE

The river channels in this zone – tributaries of the Luangwa – flow within an incised macro-channel. The channel bed and bars are increasingly alluvial in nature (Figure 5.8). Land-use activities are limited, as much of the zone is within protected Game Management Areas or the lower Lukusuzi National Park. Population densities on the Rift Valley floor tend to be low, and clearing is generally limited within and along the riparian zone.

Figure 5.8

Google Earth image of the Luangwa River in the Eastern Foothills Zone

5.5 FLOODPLAIN ZONE

Extensive floodplains occur on the Luangwa as well as the on lower portions of several main tributaries. There is typically a central floodplain with an active meander belt as well as numerous adjacent secondary channels, oxbow lagoons and dambos (Figure 5.9, Figure 5.10). The wide reaches of intense meandering are separated by straighter reaches where there is more limited lateral movement of the river channel. Studies of the Luangwa floodplain have demonstrated the dynamic nature of the channel and riparian zone (Figure 5.11, Figure 5.12). Meander bends can erode across the floodplain at up to 33 m per annum (Gilvear et al., 2000) and this reworking of floodplain sediments is likely to be a significant source of sediment for downstream. The floodplains themselves, however, are very large sediment sinks. Alluvium up to 37 m deep has been reported on the valley floor (ITT, 1992). Tributaries bring in sediment from the side slopes of the Rift Valley, introducing coarser sediment deposits into an otherwise largely sandy matrix (Barham et al., 2011). The interplay of the mainstem Luangwa and its tributaries creates complex erosion and deposition cycles on the floodplain and within the floodplains of the tributaries near the mainstem Luangwa (Colton, 2009; Barham et al., 2011). These are recorded in the many-metres deep sediment deposits.

In the dry season the Luangwa River is reduced to a slow-flowing meandering river, with flow confined to the main channel and winding its way between shallow sand banks. In the rainy season, however, the entire river bed, several km wide in places, is inundated. Water fills the oxbow lagoons and dambos (here occurring as shallow, seasonally or permanently waterlogged, grass-covered depressions), flooding large areas of grassland (www.feow.org, accessed January 2016). Extensive populations of crocodiles and hippopotami occur in the river, and numerous mammals and waterbirds are dependent on the floodplains.

Figure 5.9

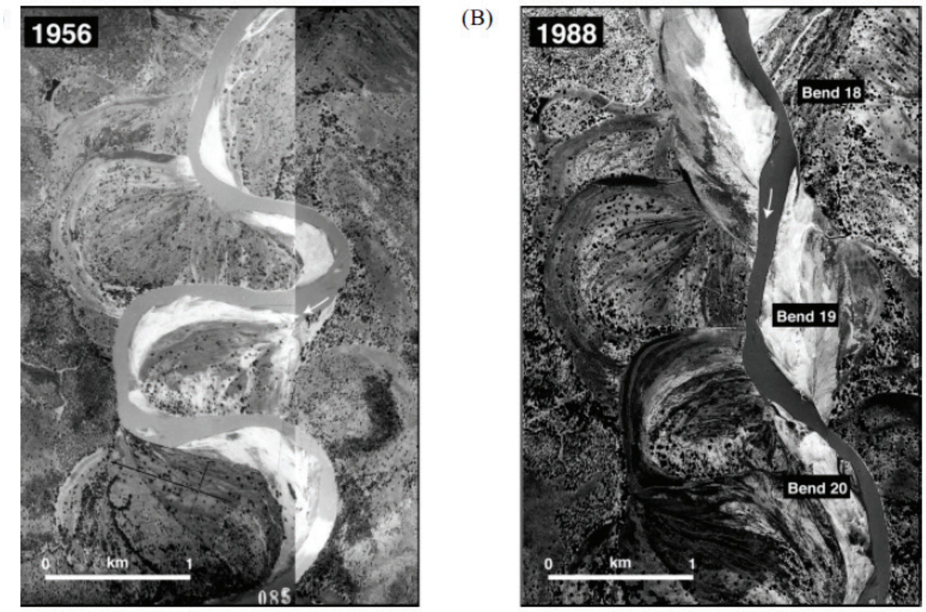
Google Earth image of the Luangwa River in the Floodplain Zone

Figure 5.10

Floodplain channel of the Luangwa (Source: www.panoramio.com/photo/7186852)

Riverine woodland and valley riverine grasslands are the dominant broad vegetation types on the floodplains of the Luangwa and large tributaries. The valley riverine woodland and thicket is associated with the rich alluvial soils deposited adjacent to the Luangwa and its major tributaries. The woodland vegetation along the perennial and seasonal rivers is generally characterized by canopy trees reaching 20 m or higher and a well-developed understory that may extend to form areas of bushland or thicket.

Figure 5.11
Historic aerial photography from 1956 and 1988 of the Luangwa River in the Floodplain Zone (source: Gilvear et al., 2000)



Grasslands are typically located closer to the river (Figure 5.9) in newer soil and more frequently flooded sections of the floodplain. Soil textures range from the well-drained sandy soils of the sandbars to the cracking black clays of the floodplains, with each soil type typically supporting a distinctive grass component (https://sites.google.com/site/luangwatrees):

- On sandy substrata, Cynodon-Eragrostis taller grassland is associated with the sand bars and sandy deposits of the inside bends of the valley's rivers and streams.
- Setaria-Hyparrhenia grasslands and wooded grassland are associated with the brown and black clay loams of the valleys larger rivers' floodplains. On the black cotton clays, Setaria incrassata ('Kasense') grows in pure stands. This riverine grassland frequently grades into wooded grassland.
- Water grass and floating aquatics are found on the seasonally waterlogged clays of the Luangwa River's oxbow lagoons and dambos. These areas can remain under water for most of the rainy season.

Land-use impacts within the zone are negligible. There are some small isolated fields in the uppermost section of the reach, but thereafter the majority of the zone is within protected areas.

Land clearance of the upstream tributary catchments will increase sediment loads, however, and higher sediment loads are linked to accelerated meander rates and more frequent meander cutoffs (Constantine et al., 2014). The increased bed sediment loads may also increase risk of channel avulsion (abandonment of the main channel).

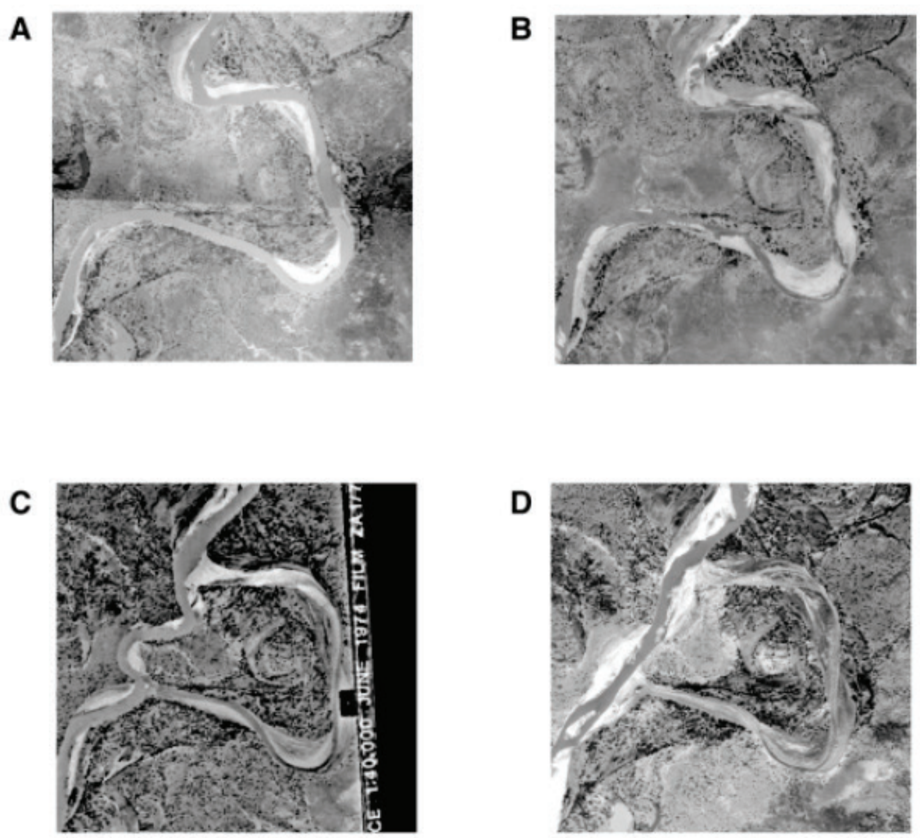


Figure 5.12
Historic aerial photography from 1956 (A), 1967 (B), 1974 (C) and 1988 (D) of the Luangwa River in the Floodplain Zone (source: Gilvear et al., 2000)

5.6 BRAIDED ZONE

Downstream of the floodplain zone the Luangwa enters into a braided zone (Figure 5.13) where the channel flows within a confined valley or gorge. The wide floodplain is absent, as is any meandering of the channel.

Braided river patterns indicate very high bedload transport, where high sediment loads are deposited and stored in large sand bars that move seasonally or during large infrequent inter-annual floods. This bedload component is transported to the Zambezi River.

The confined nature of the channel makes this reach somewhat resistant to adjacent land-use activities and, indeed, land-use within this zone is very limited.

Nevertheless, a change in upstream sediment loads could impact this zone in that decreased sediment loads, such as could be expected from increased dams, would cause a reduction in sediment loads and could cause the abandonment of secondary channels and narrowing and incision of the main channel. This would decrease the physical habitat diversity of the zone.

Figure 5.13

Braided Zone of the lower Luangwa, just upstream of confluence with Zambezi (source: http://www.panoramio.com/user/5554546)

5.7 MUCHINGA PLATEAU ZONE

The headwaters of the tributaries entering the Luangwa from the west arise on the Muchinga Plateau (Figure 5.4). Land-use impacts are limited, as the zone is relatively inaccessible. Some clearing is evident, however, for agriculture and possibly charcoal production. The watercourses are characterized by numerous dambos or valley bottom wetlands (Figure 5.14). The soils of the dambos are poorly drained and compacted, with typically leached unconsolidated illuvial soils that are acid (pH 5-6) and black, dark grey or dark brown in colour. These numerous dambos and drainage channels of the upper escarpment are dominated by grasses - typically Loudetia simplex, Setaria sphacelata, Setaria pumila and several Hyparrhenia species (https://sites.google.com/site/luangwatrees/).

Figure 5.14

Google Earth image of the streams on the Muchinga Plateau Zone. Small rivers and numerous dambos characterise the zone

5.8 SOUTH-WESTERN PLATEAU ZONE

This zone is the high elevation plateau at the south-western edge of the catchment. Extensive wetlands (dambos) characterise the smaller drainage lines, with larger rivers in the bigger drainage lines. The entire zone is heavily utilised by subsistence and small scale farmers (Figure 5.15), with some commercial irrigated agriculture. There are numerous small to medium size irrigation and water-supply dams within the zone, and slopes and riparian zones have been extensively cleared. Studies have noted the high, likely increased, sediment yield from this sub-catchment resulting from extensive and continued clearing of vegetation for agriculture and charcoal production (Heatwole and Her, 2007).

Figure 5.15

Google Earth image of the Lunsemfwa River in the South-Western Plateau Zone. Extensive dambos are present in the small drainage lines

5.9 WESTERN LOWER FOOTHILLS ZONE

The rivers within this zone tend to flow within an incised macro-channel with a restricted floodplain (Figure 5.16) but become increasingly alluvial in nature towards the Luangwa confluence. This zone is dominated by long stretches of lower foothills river types, but occasionally steeper sections of upper foothill reaches are present within this.

In these small upper foothills reaches, multiple-channel anastomosing river patterns (or channel types) occur. Anastomosing reaches tend to have high instream diversity due to the variety of aquatic habitats that are created by the mix of alluvial and bedrock controls within the multiple permanent and seasonal channels. Across the zone, dambos occur on the smaller tributaries and drainage lines.

Much of the zone is within the national parks and/or protected game management areas of the western side of the valley. Land-use clearing, conversion, charcoal production, and therefore land-use utilisation generally, is thus very low, with the exception of areas beside some of the larger rivers between the escapement and the game/protected areas.

Figure 5.16

Google Earth image of the Lunsemfwa River in the Western Lower Foothills Zone

5.10 EASTERN PLATEAU ZONE

This zone represents the northern section of the plateau on the eastern side of the catchment. It is a lower-elevation plateau than that on the north-western side of the catchment. The area is heavily utilised for subsistence and small-scale commercial/emerging farmers (Figure 5.17). Widespread clearing of the slopes has caused increased sediment erosion, and in a study by Heatwole and Her (2007) the likely continued increase in sediment loads arising from continued slope clearance were modelled. Crop fields, forests (Miombo and Mopane) and wetlands (dambos) dominate this landscape, with fields encroaching into forest lands as fertility declines and old fields are abandoned in favour of newly cleared lands (Heatwole and Her, 2007).

Figure 5.17

Google Earth image of a small tributary in the Eastern Plateau Zone

6. LAND USE WITHIN THE LUANGWA CATCHMENT

The FAO's 2009 Global Land cover database, Google Earth imagery, published studies and discussions with regional experts at the December 2015workshp in Lusaka were used to assess and describe land-use characteristics of the catchment.

The main land-use activities within the Luangwa Catchment are:

- Commercial agriculture
- Subsistence and small-scale farming
- Tourism
- Mining
- Charcoal production
- Hydropower electricity generation.

The majority of the catchment is covered by national parks, game management areas and forestry reserves. North and South Luangwa National Parks are the largest and most famous of these. Surrounding these are extensive game management areas. Though data on Zambia's forests are very poor, the country is experiencing a very high deforestation rate, estimated by FAO to be the fourth highest rate of deforestation per capita in the world (USAID, 2011). Expansion of settlements and the over-exploitation of timber resources, together with mining and forest fires, play a role in the loss of forests, but a primary cause is clearing for small-scale agriculture (USAID, 2011). This clearing is also linked to what is probably the main cause – the production of charcoal for cooking fuel (UNEP, 2015).

6.1 CHARCOAL PRODUCTION

Zambia has one of the highest deforestation rates in the world, but it is difficult to distinguish which of the two main land-use activities - shifting agriculture versus charcoal production - is the main driver of deforestation. The land cleared for agriculture may first be used for charcoal production as an additional source of income to the farmer. Alternatively, areas burnt for charcoal might then preferentially be used for agricultural expansion, as there is less labour involved in clearing the land (UNEP, 2015).

Small-scale studies of sub-catchments within the Luangwa Catchment note that the rate of clearing is increasing exponentially (Heatwole and Her, 2007), but no catchment-wide data on land-use conversion or deforestation are available.

Analysis of the Google Earth imagery however confirms that clearing is widespread, but most concentrated near settlements and where there is road access. Large areas of the catchment remain protected in national parks, but clearing for charcoal production is widespread in both communal lands and game management areas (Gumbo et al., 2013). Wignaraja et al. (2010) suggested that most of this wood is procured as an illegal off-take, driving deforestation and unplanned land conversion.

Charcoal is transported to settlements and urban areas primarily for use as fuel for cooking. Although it is clear that charcoal is also being exported to neighbouring countries (Gumbo et al., 2013), the volumes are not known.

6.2 AGRICULTURE

It has been estimated that around 80% of the rural population of Zambia makes a living through subsistence farming on customary land (USAID, 2008). Agriculture contributes to around 21% of Zambia's GDP and 34% of the country's land area is dedicated to large and small-scale agriculture (FAO, 2009; World Bank, 2010). Small-scale agriculture is the main source of livelihood and income for the vast majority of rural Zambians. Pressure to expand the area of the land under agriculture is mounting as the population and demand for food grow (Vinya et al., 2011).

Throughout Zambia small-scale agriculture is characterized by low or stagnant productivity and extractive farming systems that deplete the soils base upon which farmers depend upon for their livelihoods. Subsistence farmers use the traditional 'slash and burn' shifting cultivation locally known as 'chitemene', regularly clearing new fields and abandoning the old ones (UNEP, 2015) as many households cannot afford chemical fertilizers (Bwalya, 2011). The constant shifting fields and clearing of new lands is a major cause of deforestation (Holden, 1993).

The valley floor has comparatively nutrient-rich soils and permanently available water in the form of the Luangwa River, perennial tributaries and springs along the valley's sides (Astle, 1971; Trapnell, 1996), but the soils drain poorly and large areas are prone to flooding. By contrast, the margins of the catchment – those elevated western and eastern fringes on the Zambian central plateau – tend to be characterized by lower-nutrient but better-draining soils (East, 1984; Heatwole and Her, 2007).

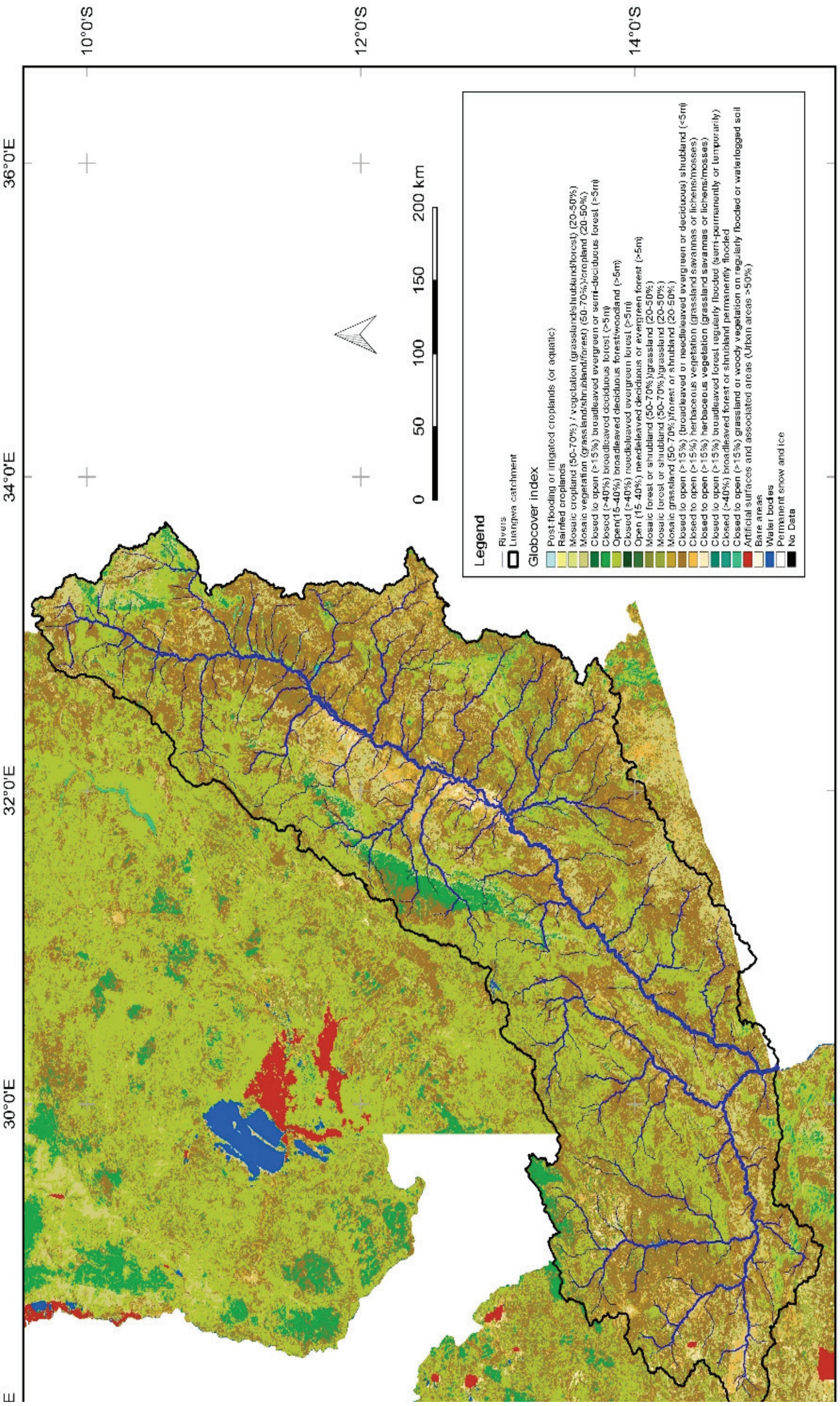
Population densities are higher on the plateau regions of the catchment because of a more moderate climate and lower exposure to disease than in the valley. Clearing of the slopes for agriculture around settlements is most pronounced in the south-western margins of the catchment (in the Lunsemfwa sub-catchment) and the south-eastern margins of the catchment (Figure 6.1). Only 3% of the land in the catchment is used for agriculture (Euroconsult Mott MacDonald, 2007), but this figure is rapidly increasing. Maize and cotton are the dominant crops, but large areas of groundnut, cassava and millet also cultivated.

Whilst small scale subsistence and emerging farming practices are widespread across the plateau areas of the catchment, commercial agriculture is concentrated in the Lunsemfwa sub-catchment in the south-west of the catchment, and to a lesser extent on the eastern plateau regions. WARMA (2015) noted that there is approximately 17,800 ha of land under irrigation in the Luangwa Catchment – the overwhelming majority of which is in the Lunsemfwa sub-catchment - with a further 28,800 ha of planned developments.

They estimated that the future total potential area for irrigated agriculture could be as much as 73,800 ha for the catchment. In the Eastern Province, more than 220 dams are in place to support commercial and small scale agriculture in the eastern plateau region, with a further 165 dams being planned. In the Lunsemfwa sub-catchment, the area of dams more than doubled between 2007 and 2013.

Figure 6.1

Landcover of the Luangwa Catchment (source: FAO's Globcover 2009)



This rapid expansion in agricultural land and infrastructure echoes the high rates of deforestation and land-use conversion discussed above, but studies of cleared slopes in Zambia (Mummeka, 1986; Heatwole and Her, 2007) noted the rapid increase in runoff and decline in infiltration.

Heatwole and Her (2007) highlighted the important role that the dambos play in filtering runoff and providing attenuation from cleared slopes. They suggested that improving the sustainability and productivity of upland cultivation, and continued protection of dambos, would benefit the downstream valley ecosystems.

6.3 OTHER LAND USE ACTIVITIES

Agriculture and the clearing of forests for charcoal production are the main land-use impacts within the catchment and are chiefly responsible for the extensive clearing and deforestation in the catchment. However, other important land uses occur within the catchment and are discussed briefly below.

6.3.1 Hydropower energy generation

Small and medium scale hydropower schemes are operating in the catchment. These are all located in the upper reaches of tributaries on the western fringes of the catchment. The Lunsemfwa Hydropower Scheme operates two hydropower plants with a total installed capacity of 56 MW, with plans to increase the installed capacity to 500 MW by 2020.

ZESCO currently operates a 12 MW hydropower plant, with plans to develop a new linked plant and upgrade the combined capacity to more than 100MW (WARMA, 2015). The oldest hydropower plant, Mita Hills Dam, is an embankment dam near Kabwe that was constructed in the 1950s by the Anglo American Corporation to supply the Broken Hill Mine with electricity.

6.3.2 Towns and settlements

Most of the catchment's population is found on the plateaus between 800 to 1100 masl. Most of the rest of the catchment, particularly the central valley, is designated as national parks or game management areas and has very low population densities. Kabwe, a former mining town in the south-east of the catchment, is the largest town within the catchment, and is located within a large agricultural area. The upland areas of the south east, particularly around the small town of Chipata, are similarly associated with a sprawling area of settlement and agriculture (Euroconsult Mott MacDonald, 2007).

The urban runoff and release of wastewater from these towns and numerous smaller settlements throughout the catchment, as well as extensive peri-urban areas can be expected to have some impacts on downstream water quality, flow and sediments. In addition, settlements in the catchment area associated with the impacts of clearing for agricultural lands and charcoal production described above (refer to the Water Quality report WWF/FRESHWATER/07/2016).

6.3.3 Mining

In the Luangwa Catchment, mining impacts are minor, being largely confined to areas of the south-west of the catchment where there is largely artisanal mining.

These small-scale operations do have an impact on downstream suspended sediment loads in the river, and available data indicate that there are impacts on water quality related to heavy metal contamination above (refer to the Water Quality report WWF/FRESHWATER/07/2016).

6.3.4 Conservation and tourism

The North and South Luangwa National Parks, together with extensive additional protected areas, represent very important national conservation and tourism resources for Zambia. Very large elephant and hippo populations are present within the national parks, together with a wide variety of antelope and predator species (refer to the Wildlife report WWF/FRESHWATER/10/2016).

Tourism is focused within and immediately surrounding these areas, which are along the mainstem Luangwa River. The Lukusuzi National Park is also located within the catchment, but reports suggest that although the vegetation remains in a good condition, the game from this protected area has been hunted out.

Surrounding the national parks, and covering a greater area of the catchment, are very extensive Game Management Areas (GMAs). The GMAs in the Luangwa Catchment often function as buffer zones to the national parks. They are legally protected areas established to control the hunting of wild animals through a licensing system. Human habitation, along with economic activities that are not detrimental to wildlife management, are permitted within these communally owned areas (USAID, 2011).

6.4 SUMMARY

Regardless of the type of land-use activity causing it, deforestation and clearing of lands has a major impact within the catchment. These activities are widespread and increasing. The FAO (2011) estimated average annual rates of deforestation in Zambia to be 167,000 ha per annum or 0.33% of total forest cover between 2000 and 2010, but more commonly cited figures place this at 250,000-300,000 ha per annum (approx. 0.50-0.60% of total forest cover) based on 1965-2005 data (Vinya et. al., 2011; UN-REDD, 2010).

A 2012 study found very high rates of deforestation (0.85% per annum) in the Eastern Province (Chidumayo, 2012), which contains a large proportion of the Luangwa Catchment.

The widespread reduction of vegetation on the slopes of the Luangwa Catchment has been shown to cause higher flood peaks, reduced rainfall infiltration and higher sediment runoff (Heatwole and Her, 2007). The cycle of vegetation clearing and shifting agriculture, soil erosion and resultant loss of fertility has been highlighted as a major limitation to food security and sustainable conservation in Luangwa Catchment (ABCG, 2011).

7. CATCHMENT DIVISION AND PRESENT ECOLOGICAL STATE

At a workshop in Lusaka on 9-10 December 2015, delegates from several disciplines worked together to delineate homogeneous areas within the Luangwa Catchment. Fifteen areas (Homogenous Units or Hus) were recognized based on individual inputs on hydrology, geomorphology, water quality, vegetation, invertebrates, wildlife and water-resource developments (Figure 7.1).The Present Ecological State (PES) of the Luangwa Catchment in terms of river geomorphology was estimated for each of the zones based on available desktop data and discussions with local and regional experts at the workshop.

These estimates are largely based on the data and analyses undertaken in the delineation of the geomorphological zones of the basin (refer to Section 5 of this report). The characteristics of each HU, their relation to the geomorphological zones and a brief description of the impacts in each zone and estimate of the PES of the watercourses within each HU are summarized in Table 7.1.

Figure 7.1

Homogeneous Units (HUs) recognized within the Luangwa Catchment at a WWF workshop in December 2015

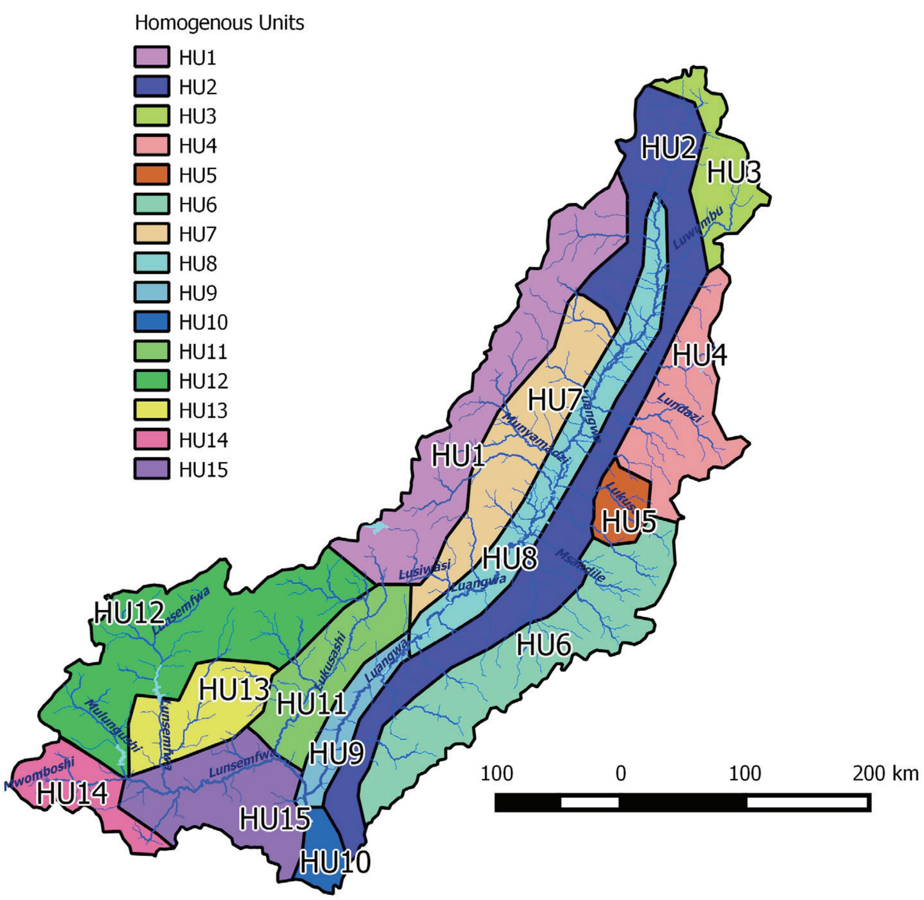


Table 7.1

Homogeneous Units (Hus) recognized for the Luangwa Catchment and their estimated Present Ecological State for Geomorphology

HU	Location	Description of rivers and watercourses within the HU	PES	Impacts
1	Western plateau (Serenje to Chinsali)	This HU is equivalent to the Muchinga Plateau geomorphological zone. Hilly and fairly well wooded, but largely inaccessible.	A/B	Few impacts as the region is fairly remote and access difficult. Limited clearing for agriculture and charcoal production.
2	Luangwa Valley, east bank alluvium	This HU is equivalent to the Eastern Foothills geomorphological zone. The river channel flows within an incised macro-channel. The channel bed and bars are increasingly alluvial in nature.	B	Limited use – some areas of fields, but not in any way continuous along the riparian zone. Much isprotected within game areas.
3	Luangwa source montane area	This HU is equivalent to the Transition and Upper foothills geomorphological zones, as well as a portion of the escarpment zone. Rivers and streams are well wooded, very steep sided, narrow, steep valleys with small, narrow, deep, fast-flowing rivers are present in the steep Escarpment Zone. These change to single or multiple anastomosing/ anabranching river reaches in the Transition Zone. Thereafter, in the subsequent downstream Upper Foothills Zone, the channels becomes predominantly a single channel with limited meandering, with occasional anastomosing reaches.	B	Remote and steep river sections in the upper section of this HU limit landuse activities and impacts on the rivers. In the lower sections before the protected areas of HU2, intensive clearing of parts of the river have impacted the riparian zone and banks.
4	East bank plateau (Lundazi)	This HU is equivalent to the northern part of the Eastern Plateau geomorphological zone. The larger channels are rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands). These are however often heavily utilised for small scale agriculture.	C	This zone is heavily utilised for agriculture (small scale and subsistence cropping). There is widespread encroachment in to the riparian zones and dambos. Reduced flows and increased sediment loads would be expected.
5	Lukusuzi National Park	This HU represents the Lukusuzi National Park in the central part of the Eastern Plateau geomorphological zone. The larger channels are rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands). These are however often heavily utilised for small scale agriculture.	B	The vegetation within the park boundaries is reported to be in good condition, and therefore the rivers and associated drainage lines can be expected to be in a better geomorphological condition than the HU's to the north (HU4) and south (HU6) of this HU.
6	East bank plateau (Petauke to Chipata)	This HU is equivalent to the southern part of the Eastern Plateau geomorphological zone. The larger channels are rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands). These are however heavily utilised for agriculture.	C	Heavily utilised for agriculture (small scale, subsistence and some commercial cropping), with numerous dams present throughout the zone. There is widespread encroachment in to the riparian zones and dambos. Reduced flows and increased sediment loads would be expected.
7	Luangwa outer west bank - alluvium	This HU is equivalent to the northern section of the Western Lower Foothills Zone. The streams in this zone are characterised by lowland rivers and lower foothills leading from the western escarpment to the Luangwa floodplain.	A/B	Largely in protected areas and therefore there impacts are limited.

HU	Location	Description of rivers and watercourses within the HU	PES	Impacts
8	Luangwa valley meander	This HU is equivalent to the Floodplain geomorphological zone. Reaches of intense meandering are separated by straighter reaches where there is limited lateral movement of the river channel.	A/B	Very limited impacts: there are some small isolated fields in the uppermost section of the zone, but thereafter the river is within protected areas.
9	Luangwa lower mainstem	This HU is equivalent to the lower Floodplain geomorphological zone. In this zone the intensity of meandering is slightly reduced relative the HU 8 - lateral movement of the river channel is typically more restricted than HU8 as the river channel tends to a wider, sandier channel.	A/B	Very limited as the majority of the zone is within protected areas.
10	Luangwa catchment outlet	This HU is equivalent to the Braided geomorphological zone. Braided reaches within a confined valley ("gorge") characterise this zone. High sediment transport section. No wide floodplain is present and there is no meandering.	B	Limited use, but the confined nature of the channel makes this somewhat resistant to adjacent landuse activities. May be impacted by elevated sediments.
11	Lukusashi River sub-catchment	This HU represents a portion of the Western lower foothills geomorphological zone. These are typically lowland and lower foothills river reach types along the lower Lukusashi tributary and associated drainage lines.	B	Largely in protected areas – there are very low population densities in the Rift Valley and therefore these areas tend to correspond with limited agriculture and low impacts.
12	Lunsemfwa – Mulungushi plateau	This HU represents a portion of the South-western Plateau geomorphological zone. Narrow main rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands).	C	This is the most heavily and intensively utilised area in the catchment – flows have decreased and sediments increased, many small and a number of large dams associated with agriculture, and also some hydropower development is in place.
13	Lunsemfwa – Mkushi farm block	This HU represents the central section of the South-western Plateau geomorphological zone. Narrow main rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands).	C	This is less intensively utilised for agriculture than the upstream HU12, but remains impacted by extensive agriculture as well as the upstream flow impacts from agriculture and hydropower.
14	Mwomboshi – Mwapula plateau	This HU represents the southern extremity of the South-western Plateau geomorphological zone. Narrow main rivers but the small tributaries and numerous drainage lines are characterised by extensive dambos (valley bottom wetlands).	C	Very little is known about this area from local experts. There is some agriculture which can be expected to have had an impact on the watercourses.
15	Luano Valley	This HU represents the Luano Valley, which is the southernmost portion of the Western lower foothills geomorphological zone. These are typically lowland and lower foothills river reach types.	B/C	In this zone, low population densities would limit possible impacts.

8. ESTIMATES OF SEDIMENT LOADS AND YIELD

Regional to catchment-scale (1) catchment sediment yields, (2) sediment loads within the river and (3) erosivity potential in the Luangwa Catchment were investigated to develop an understanding of sediments within the catchment and river.

8.1 REGIONAL CATCHMENT SEDIMENT YIELD ESTIMATES

Sediment yield from a slope is primarily dependent on rainfall intensity, vegetation cover, slope and surface soil characteristics. Rainfall in the Luangwa Catchment ranges from 800-1250 mm per annum (Euroconsult Mott MacDonald, 2007). The relatively high rainfall of the catchment places it broadly within a moderate sediment yield climate zone where between 100 and 150 tons of sediment per square kilometer per annum (t/km2/annum) could be expected (Figure 8.1).

Several studies (Holeman, 1968; Ward and Corbett, 1990) suggested that these estimates of sediment yield are likely to be on the high end of the range, because the correlation of rainfall to sediment yield is based on a correlation with rainfall derived from 94 stations in the USA (Langbien and Schumm, 1958). This has a relatively young geological landscape where erosion and down-cutting may be more prevalent than under global average conditions.

These estimates are within the range of regional sediment yields predicted by Walling and Webb (1983), however; their global map of sediment yield suggests that the Luangwa region should have a sediment yield within the 50-250 t/km2/annum range. This contrasts strongly with the very high estimates obtained from studies of small to medium catchments from tropical countries adjacent to the Luangwa Valley (Table 8.1).

These studies demonstrate a very wide variety – by several orders of magnitude – of sediment yield. However, these yields (Table 8.1) typically relate to smaller catchments or even small experimental plots. Oyebande (1981) noted a strong decrease in sediment yield with increasing catchment size in Nigeria: catchments larger than 100,000 km2, such as the Luangwa, typically had sediment yields of about 44 t/km2/annum.

This is because larger catchments also tend to contain very large sediment sinks, and therefore the ratio of sediment yield on the slopes to delivery to the river channel is lower. The Luangwa Catchment, at approximately 165,000 km2 in size, can therefore be expected to have a far lower yield than the available estimates and measurements from smaller catchments in the region.

Figure 8.1

The relationship between sediment yield and rainfall (after Langbien and Schumm, 1958)

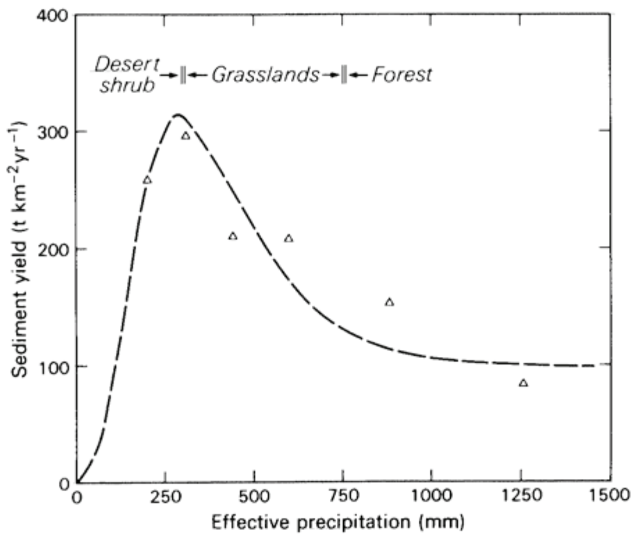


Table 8.1

Estimates and measurements of slope or catchment sediment yield from regional and Luangwa-specific studies

Sed. Yield (t/ km2/annum)	Data Source	Location and method of estimation (if available)
700	Elwell (1971)	A grass-covered experimental plot (4.5% slope) at Henderson, Zimbabwe.
1,080	Elwell and Stocking (1974)	A plot left undisturbed for 8 years after clearing, 4% slope (Matopos, Zimbabwe)
12,700	Elwell (1971)	A bare experimental plot (4% slope) at Henderson, Zimbabwe.
2,100	Walling et al., 2003	63 km2 of the Upper Kayelan catchment, Zambia, a small catchment located west of the Luangwa Catchment. Sediment yield was calculated from continuous turbidity measurements.
25	Stocking, 1977	A large 1990 km2 catchment at Umsweswe, Zimbabwe.
980	Stocking, 1977	A severely eroded sub-catchment of approximately 220 km2 at Umsweswe, Zimbabwe.
287-993	Christiansson (1981)	Measured in neighbouring Tanzania.
1,804	Balek (1977)	Measured in Malawi lowlands
44	Oyebande (1981)	Yield for catchments larger than 100,000 km2 in Nigeria.
Estimates for the Luangwa Catchment.		
50-250	Walling and Webb (1983)	Range of potential sediment yield for the Luangwa Catchment, derived from a global map of sediment yield.
> 400	UNEP, 2015	USLE used to estimate sediment yield for the Luangwa Catchment. High sediment yields estimated. A total value for the Luangwa was not determined, but within-catchment values ranged from more than 1000 t/km2/annum in the headwaters to 400-600 t/km2/annum in the lowlands.
>1,000	USDA, 2011	USLE used to estimate sediment yield for the Luangwa Catchment, which predicted more moderate rates of yield.

8.1.1 Luangwa Catchment sediment yield estimates

The Luangwa Valley has a wide altitudinal range of approximately 330 masl (Euroconsult Mott MacDonald, 2007) to more than 2000 masl in the uppermost headwaters. The especially steep escarpment slopes of the Rift Valley sides are likely to represent higher yield areas within the catchment.

Additionally, the strongly seasonal nature of rainfall would reduce vegetation cover in the dry season, which would tend to increase soil surface erosion and sediment yield. The National Sediment Erosion Hazard mapping for Zambia (Chiti, 1987) not surprisingly identified the very steep escarpment zones of the catchment as areas of likely high sediment erosion (Figure 8.2).

Some attempts at quantifying sediment yield within the Luangwa Catchment itself have been undertaken. A recent UNEP (2015) study attempted to do this, estimating sediment yields of more than 1000 t/km2/annum in the headwaters, decreasing to values typically in the 400 to 800 t/km2/annum range in the middle and lower reaches. Even higher values for some areas equated to an estimated 10 cm soil loss per annum over approximately 25% of the total land area, but no field evidence could be found that supported these very high erosion rates (UNEP, 2015).

The results also did not corroborate the Zambian erosion hazard mapping (Bahr and Bahr, undated; Chiti, 1987) which highlights the expected high erosion along the very steep escarpment zones of the catchment, nor the patterns of clearing for agriculture within the catchment that are known from smaller-scale studies within the catchment (Heatwole and Her, 2007) to have increased local erosion rates.

Except for rapidly eroding small experimental plots reported in Table 8.1, however, the estimated sediment yields for the catchment are far in excess of anything predicted or previously measured for similar sized catchments.

Another similar earlier study (USDA, 2011), also relying on USLE modelling, generated even higher estimated sediment yields (Figure 8.3). Both studies acknowledged the uncertainty of their results and attributed this to the limited, or absence of, detailed regional and local data.

In both cases this resulted in the modelling needing to rely on international data sources to represent conditions within the catchment. Heatwole and Her (2007), in a smaller scale study of selected tributaries within the Luangwa Catchment, similarly noted that the dearth of verified local data and subsequent reliance on regional and global datasets was a limitation.

They highlighted the need for significant additional field and land-use data in order to generate more reliable and accurate results.

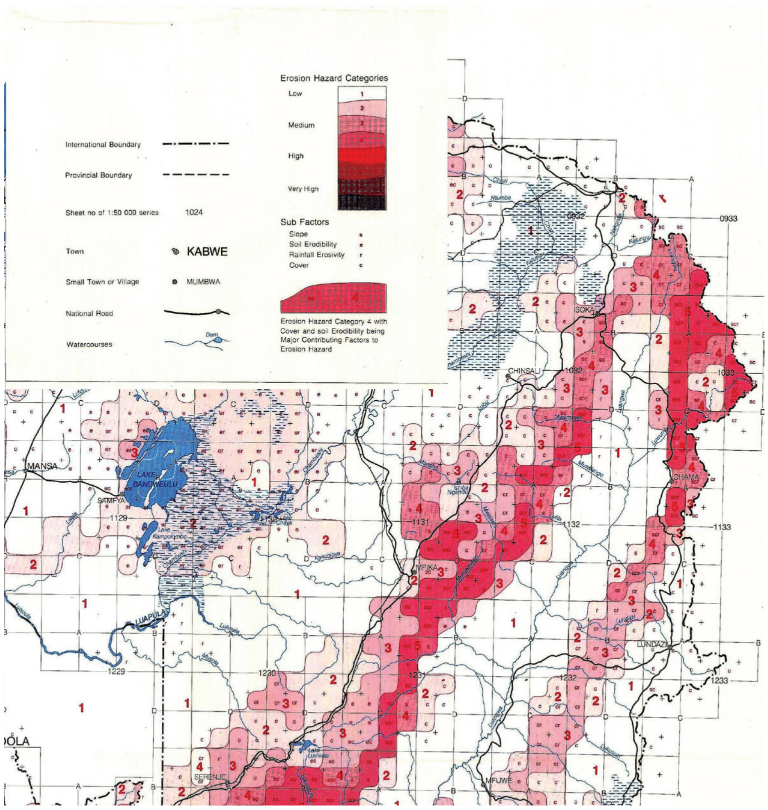


Figure 8.2

Erosion hazard map of the Luangwa valley (source: Bahr and Bahr, undated)

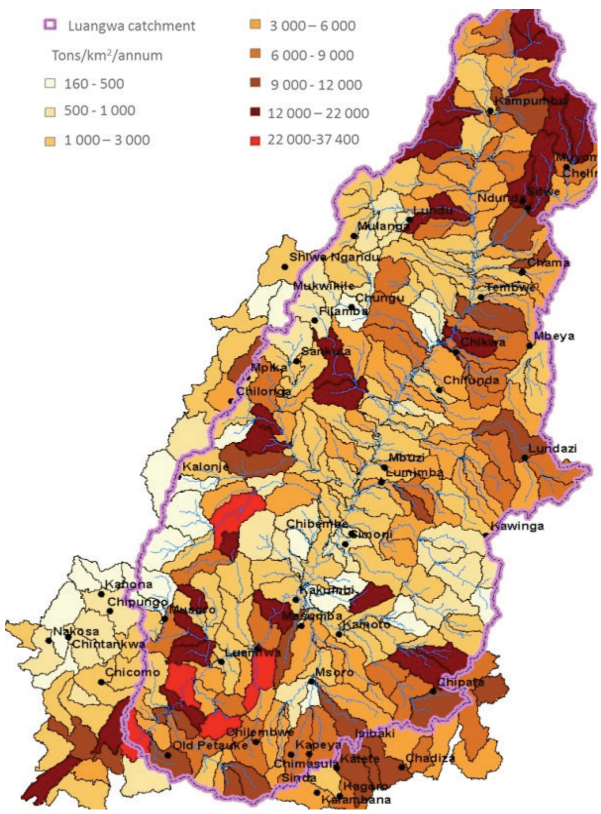


Figure 8.3

The USDA's (2011) estimated mean potential soil loss of the sub-catchments of the Luangwa Catchment (source: USDA, 2011)

Both previous independent attempts at estimating sediment yield from the Luangwa Catchment using catchment sediment yield modelling approaches (the USLE method) have thus produced highly uncertain estimates of sediment yield. In large part, the uncertainty of the modelled results is due to a lack of verified local soil, land-use, land practice and rainfall data.

Especially in Africa, large-scale maps of soil erosion generated from low-resolution data have been criticized for misapplying small-scale agricultural field methods of soil loss estimation to the regional scale (Gardner, 1981; Stocking, 1984), thereby exaggerating soil loss estimates. In addition, the type of land cultivation is a critical factor in explaining sediment yield in large catchments, and this varies considerably in different zones (Dedkov and Mozzherin, 1996).

In a study of a small catchment in the nearby Kafue Catchment in Zambia (Walling et al., 2003), the key factor influencing soil loss was land-use practice. The commonly held practice of applying USA-derived factors to predict soil stability under different land uses in Africa is thus questionable given the vastly different agricultural practices.

Lastly, very limited verified surface soil and detailed rainfall data are available to represent these large areas, and the small scale USLE modelling approach may thus be out of synchronisation with the regionalized, large spatial-scale available data.

As none of the above data and modelling limitations have improved and, particularly in the Luangwa, rainfall, soil, land cover and land-use practice information remains limited and of a coarse resolution, alternative methods to estimate or understand sediment yields from the Luangwa Catchment were investigated.

8.2 RIVER SEDIMENT LOAD

A review of regional studies relating to river sediment loads, and comparison with the limited data for the Luangwa, was undertaken in order to attempt to derive a reliable estimate of river sediment load for the Luangwa River (Table 8.2). Estimates of sediment load are derived from very limited field data, but are within the order of magnitude of sediment yield estimates identified from regional and global studies (Table 8.1), albeit at the lower end of these estimates.

Table 8.2

Estimates and measurements of catchment sediment yield and sediment load for the Luangwa Catchment and River

Sed. yield (t/km2/annum)	Data Source	Method of Estimation
150-1500	Bolton, 1984	Entire Luangwa Catchment – total sediment load at the confluence with the Zambezi based on estimate of deposition within the downstream Cahora Bassa.
140	Ronco et al., 2010	Estimated 14x10^6 m3/annum river sediment load to Zambezi, based on the limited sediment load measurements from 1973-74 by Hall (1977).

In other catchments in Southern Africa, in semi-arid regions where sediment yield and loads would be higher, measured sediment yields (SWECO and Associates, 2003) from catchments (confirmed by the sediment trapped in dams) range from 245 t/km2/annum (Massingir Dam, Mozambique) to 330 t/km2/annum (Corumana Dam, Mozambique). In South Africa, Rooseboom (1992) estimated that the average sediment yield in nine defined sediment yield regions varies between 30 and 330 t/km2/annum, whereas a countrywide reservoir siltation survey in the 1980s in Zimbabwe displayed sediment yield rates of 10 to 704 t/km2/annum (NORAD, 1983), although the higher yields are likely to be associated with small catchments.

Ronco et al.'s (2010) estimate of sediment load of approximately 140 t/km2/annum, being based on the very limited sediment load measurements of Hall (1977)[2] , is nonetheless based on the most measured data and is at the lower end of estimates of the Luangwa's sediment input to the Cahora Bassa reservoir (Bolton, 1984).

The vast difference in measured river sediment loads (Table 8.2) versus estimated catchment yields (Table 8.1) is because of the sediment delivery ratios. For most rivers, the majority of sediment generated on catchment slopes does not end up in the river channel, but is instead deposited at the base of slopes, or in wetlands or floodplains of the river. The total sediment exported from a river catchment is thus far less than the sediment yield of its component slopes (Walling, 1983). In a study of a small catchment in the nearby Kafue Catchment in Zambia (Walling et al., 2003) measured suspended sediment in the river channel was only 9% of the net erosion from the catchment.

8.3 EROSIVITY MAPPING OF THE LUANGWA CATCHMENT

Although we have some estimates of total river sediment loads for the Luangwa Catchment (Table 8.2), data indicating the likely sources are conflicting (Section 8.1). In order to gain a spatial understanding of the areas of the catchment that could be contributing to higher sediment yields, a qualitative assessment was undertaken to evaluate erosivity across the catchment. The results (Figure 8.4) indicate that areas with a lower clay content as well as poor tree cover have a higher probability of erosion (Figure 8.5). Areas with dense tree coverage and high clay content are likely to experience more stable soils and thus have lower erosion probability.

Clearing of vegetation thus presents a high risk for erosion in the catchment. Unsurprisingly, the areas with the highest erosion risk correspond with lands cleared for agriculture in the south-western and, to a lesser degree, south-eastern margins of the plateau areas of the catchment. Soils of the central catchment have very low erosion risk due to the low slopes and generally intact vegetation cover within the protected conservation areas of the valley floor. The pattern or erosivity corresponds with the Zambian Erosion Hazard mapping studies (Figure 8.2).

[2] No details of the single measurements were published. The minimum and maximum values of suspended sediment concentration in the Luangwa were 54 and 1016 g/m3 respectively (Hall, 1977).

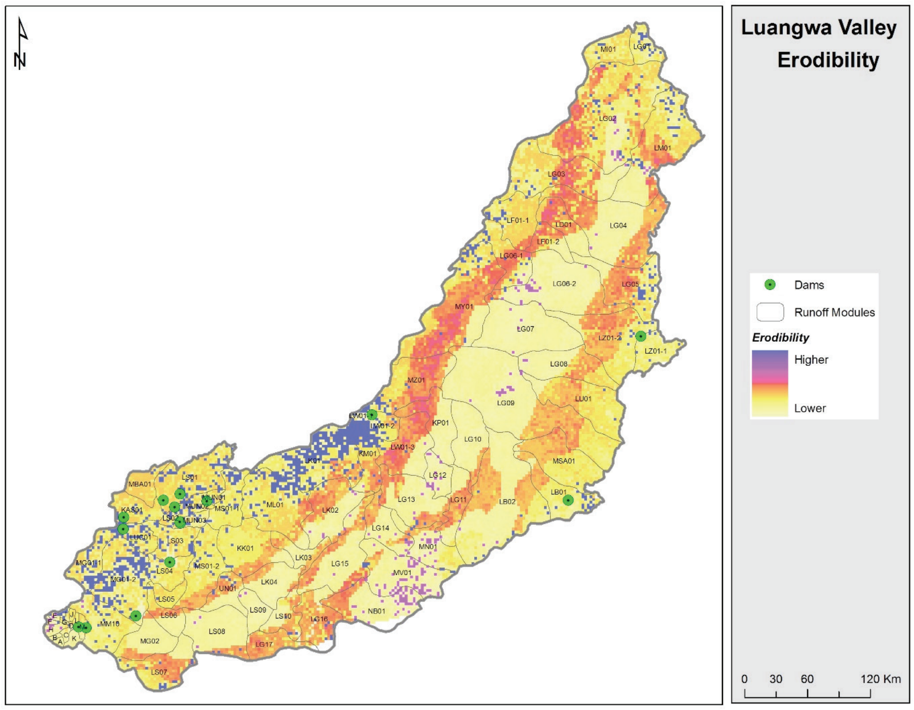


Figure 8.4

Erosivity of the Luangwa Catchment. High-risk erosion areas correspond with land clearance for agriculture in the south-western and, to a lesser degree, south-eastern margins of the plateau areas of the catchment

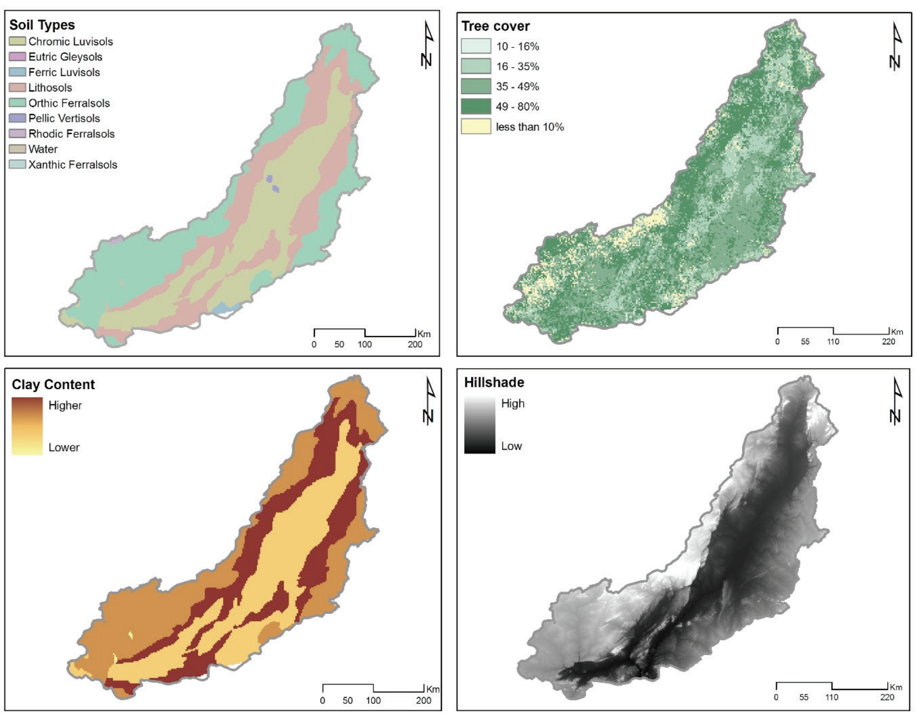


Figure 8.5

Soil type, tree cover, soil clay content and slope data characteristics of the Luangwa Catchment

8.4 SUMMARY OF SEDIMENT YIELD IN THE LUANGWA CATCHMENT

The estimate of total sediment load for the Luangwa River of 140 t/km2/annum (Ronco et al., 2010) is at the lower end of the range suggested by Bolton (1984) and within regional and global estimates of sediment yield for the catchment, but is based on field data collected from the 1970's when landuse impacts across the basin were far lower than present day conditions. Although far lower than recent (USDA, 2011; UNEP, 2015) quantitative estimates of sediment yield for the catchment, the limitations of available data for these studies and others (Heatwole and Her, 2007) affected confidence in the results of the quantitative modelling estimates. Recommendations from these studies noted that, to improve estimates of sediment yield, the following are needed:

- More reliable information is needed on land use.
- Higher-resolution data to describe soils, and much better Zambia-specific data to calibrate soil-erosion models. The accuracy of the USLE was questioned where little or no published research describing field trials on suitable plots has been conducted with cover and management practices typical for Zambia (UNEP, 2015).

Moreover, sediment yield modelling focusses on surface soil losses only, whereas subsoil losses (erosion gullies etc.) can represent substantial sediment sources for rivers and would not be accounted for (e.g. Hobgen et al., 2014).

Data or resources to address these limitations are not yet available. A qualitative assessment of erosivity was thus undertaken for this study to identify areas of likely high sediment yields. The erosivity results (Figure 8.4) highlighted the high-erosion risk areas which unsurprisingly tend to correspond with clearing of lands for agriculture in the south-western and south-eastern margins of the plateau areas of the catchment.

The underlying general pattern of high risk erosion along the escarpment corresponds with earlier erosion hazard mapping studies in Zambia (Figure 8.2).

9. CONCLUSIONS

The development of effective sediment management and control strategies requires an understanding of the sediment dynamics of a catchment and, more particularly, the links between:

- Sediment mobilization from the catchment surface
- Sediment delivery to the channel network and through that network, sediment storage, and the sediment yield at the catchment outlet
- The magnitude of the fluxes involved (Walling et al., 2003).

The catchment sediment budget concept affords an effective framework for assembling such information on sediment sources, sinks, storage and output (e.g. Reid and Dunne, 1996; Walling, 1998). A small-scale study in the nearby Kafue catchment investigating sediment budgets indicated that only 9% of the eroded sediment from the catchment flowed out of the catchment (Walling et al., 2003).

Whilst such data for large catchments are valuable, an intensive programme of field measurements would be needed to obtain a detailed sediment budget for the Luangwa. Such studies will be well beyond the scope of an EFlow study and, given the vast resources needed to collect the necessary detailed baseline data to undertake any detailed sediment yield or load modelling, beyond the reasonable scope and timelines of any EFlow study.

At present, no large dams on the mainstem Luangwa are being considered (as indicated by authorities at the December 2015 workshop in Lusaka), and this considerably lowers the risk in terms of sediment trapping and downstream erosion impacts. Although the available estimates of catchment sediment yield and river sediment load vary widely, and are based on outdated landuse and/or sediment discharge data, areas of high erosivity in the basin have bene identified and this allows for the qualitative consideration of the impact of small dams on tributaries to be factored in to scenarios.

As most of the proposed dams are likely to be hydropower dams located on the escarpment or upper plateau in the headwaters of tributaries, most of the sediment load in the mainstem channel would be unaffected.

Moreover, to account for limited sediment data in EF studies, we use a method (Dollar and Rowntree, 2003) that considers potential bed material transport rather than relying on actual (highly unreliable) load/yield estimates.

The available information, whilst clearly highly variable, would be sufficient to enable reasonable predictions of the direction, and in some part degree, of expected changes due to proposed flow (and at least qualitatively, dam) scenarios in the basin. There is thus sufficient understanding to satisfy the geomorphological inputs of the Phase 2 EFlows study for the Luangwa.

10. RECOMMENDATIONS

Given the available geomorphological data for the catchment, and prospects of generating more detailed sediment yields for the catchment within a reasonable timeframe, the current available data and understanding would be sufficient to support a standard multi-disciplinary holistic EFlow study to investigate the baseline and future consequences of catchment development.

For the evaluation of the geomorphological aspects, methods employed in other large-river EFlow assessments can be utilized, but the prevalence of crocodiles and other dangerous wildlife may place some limitations on the type and extent of field survey work that can be reasonably undertaken. Such limitations will not however constrain the ability of the approach proposed.

Hydraulic information of the selected EFlow sites will be used to evaluate the baseline and potential changes in potential bedload sediment transport using an approach developed for EFlow studies for southern Africa rivers (Dollar and Rowntree, 2003). This modelling approach is especially applicable in alluvial depositional river systems like the Luangwa, where effective discharge ranges are often associated with key depositional habitats. These important discharge classes are identified through a combination of field surveys and desktop sediment transport modelling exercises; the latter uses the approach of Yang (1973).

To assess the individual EFlow sites, detailed vegetation maps (Fanshawe, 1971) are available for the Luangwa. These document the condition of the vegetation and location of the river channel in the 1960s as evidenced from aerial photography at that time. Together with historical aerial photographs from the 1950s and earlier, and more contemporary (Google Earth or similar) imagery, these data can be used to determine the natural dynamics and rates of change of physical habitats at EFlow sites, especially for the floodplain sites, which are known (Gilvear et al., 2000) to be highly dynamic. Historical aerial photography is known to exist for the Luangwa Catchment, but these data tend to be difficult to access and in-country resources would be required to obtain the record of imagery for the EFlow sites. The anticipated budget to undertake the work for the EFlow assessment is tabulated below:

EFlow site selection and descriptions	0.25 days per site
EFlow assessment (fieldwork)	1 day per site
Desktop collation of site imagery/records	0.5 days per site
EFlow PES assessment	0.5 days per site
Data analysis and sediment modelling	1.5 days per site
EFlow workshop (holistic EFlow method)	1 day per site
Scenario analysis	1 day per site
Total per EFlow site:	**5.75 days per site, excluding travel**
Additional for overall EFlow report:	**5-7 days**

A minimum of six to seven EFlow sites would be necessary to evaluate the Luangwa Catchment, but ideally more sites would generate a greater understanding across the complex zone types of the catchment.

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The Luangwa Basin

TOURISM

The South Luangwa National park generates approximately 27,000,000 USD per year in direct spending

HYDROLOGY

The Luangwa River contributes approximately $28Km^3$ of flow to the Zambezi River upstream of Cabora Bassa Dam

CHALLENGES

Water availability is expected to decrease with the combined effects of climate change the current rhythm and scale of development

For more information, contact:

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