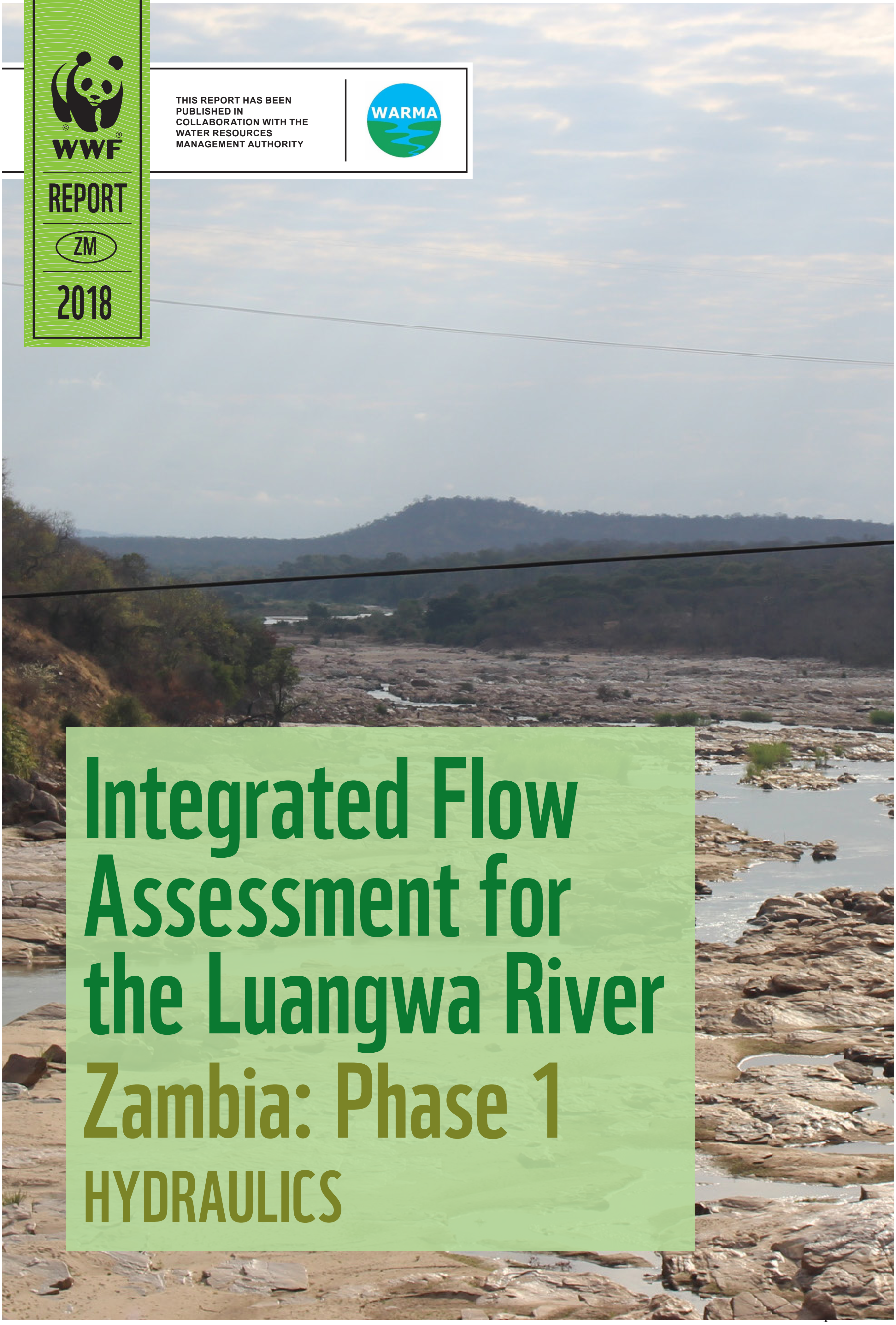

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2018

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WARMA

Integrated Flow Assessment for the Luangwa River

Zambia: Phase 1

HYDRAULICS

Written By: Andrew Birkhead

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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

HYDRAULICS

March 2018

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ABBREVIATIONS

ADP	Acoustic Doppler Profiler
ADAPT	African DAms ProjecT
ALOS	Advanced Land Observing Satellite
AW3D30	ALOS World 3-d 30 (metre)
CRS	Coordinate Reference System
DEM	Digital Elevation Model
DGPS	Differential Geographic Positioning System
EFlow	Environmental Flow
Elevationx	DEM at x m resolution grids (Airbus Defence and Space)
FAO	Food and Agriculture Organization
GIS	Geographical Information System
GCP	Ground Control Point
Globcover	Global Land Cover
ISRIC	International Soil Reference and Information Centre
ISSCAS	Institute of Soil Science, Chinese Academy of Sciences
JAXA	Japan Aerospace Exploration Agency
JRC	Joint Research Centre of the European Commission
LCCS	Land Cover Classification System
LiDAR	LIght Detection And Ranging
mamsl	metres above mean sea level
MODIS	Moderate-Resolution Imaging Spectroradiometer
m3/s	Cubic metres per second
NDVI	Normalised Difference Vegetation Index
NOAA-AVHRR	Advanced Very High Resolution Radiometer of the National Oceanographic and Atmospheric Administration satellite information system
QGIS	Quantum GIS

SAGA	System for Automated Geoscientific Analyses
SPOT	Satellite Pour l'Observation de la Terre (Satellite for observation of Earth)
SRTM	Shuttle Radar Topography Mission
ToR	Terms of Reference
UAV/S	Unmanned Airborne Vehicle or System
UNESCO-IHE	United Nations Educational, Scientific and Cultural Organization - Institute for Water Education
WARMA	Water resources Management Authority
WGS	World Geodetic System
WRB	World Reference Base
WWF	World Wide Fund for Nature
1-d	one-dimensional
2-d	two-dimensional
3-d	three-dimensional

This document is number 5 in a series of reports produced in Phase 1, in the series

01 Inception Report
02 Luangwa Basin Division
03 Water resources
04 Hydrology
05 Hydraulics
06 Fluvial Geomorphology
07 Water Quality
08 Vegetation
09 Invertebrates and fish
10 Mammals, birds and herpetofauna
11 Resource economics and sociology
12 Basin Configuration of Eflows based on a Rapid Basin Planning Tool

THANK YOU

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EXECUTIVE SUMMARY

The WWF, in collaboration with Zambia's water management agency, WARMA, has launched an initiative to address integrated flow management of the Luangwa Basin, with the aim of providing support to WARMA for the development of this basin's catchment management strategy. Core to the strategy will be agreeing on future Environmental Flows (EFlows) for the river system. The Luangwa EFlows Assessment is planned in two phases, with Phase 1 involving the collation and appraisal of available information; the division of the basin based on biophysical and social factors; and a rapid desktop estimate of EFlows. This is one of several Phase 1 reports, and covers the hydraulics component. Hydraulics is integral to holistic EFlow Assessments, since the biota respond to flow through the local hydraulic conditions it creates, such as water depth, velocity and area of inundation.

GENERALLY, SUITABLE HYDRAULIC INFORMATION IS RARELY AVAILABLE AT CHOSEN SITES TO SUPPORT A HOLISTIC EFLOW ASSESSMENT

Following on from the rapid desktop EFlow estimates in Phase 1, 'focus' sites will be selected, for which EFlows at a more comprehensive level will be addressed during Phase 2. The number and location of focus sites are not yet established, and so it is difficult to specify site-specific data requirements and associated hydraulic analyses at this stage. With reference to the Luangwa Basin, however, two broad hydraulically-based conditions exist: rivers where flow is mostly confined to channels with well-defined banks; and more complex floodplain-type systems that incorporate overbank features that are periodically inundated. Generally, suitable hydraulic information is rarely available at chosen sites to support a holistic EFlow Assessment, and field surveys are usually designed to meet the data needs. This is the case for the Luangwa Basin, with searches revealing very few suitable data for use in hydraulic analyses and thus the need for hydraulic surveys in Phase 2. This is particularly so for the complex floodplain section of the Luangwa mainstem, where two of Zambia's most important National Parks are situated.

IT IS EXPECTED THAT AT LEAST ONE OF THE FOCUS SITES WILL BE LOCATED ALONG THE LENGTH OF THE FLOODPLAIN

In this Phase 1 report, the availability of data is discussed with reference to topographic, hydrometric, and remote sensing of floodplain inundation. Regarding the topography of the Luangwa Floodplain, two Digital Elevation Models (DEMs) in the public domain, SRTM30 and AW3D30, are discussed. Of these, the more recently released AW3D30 product appears to provide superior resolution for the floodplain, but would still only aid coarse modelling of how future water developments could affect this important conservation area.

Hydrological information from an (operational) hydrometric station located close to a focus EFlow site provides a useful discharge record, and can be related to observed variations in water level at the EFlow site; this, in turn, can assist the development of a water level-discharge relationship for the site, and hence historic predictions of the area and duration of inundation during the wet season. For potential focus sites centred on the Luangwa Floodplain and along the river's lower reaches, three gauge stations are of interest, but discharge records indicate that the more recent data (last 15 years or so) are largely missing. Linked to discharge records, remote sensing can provide a cost-effective and reliable method for mapping corresponding historical floodplain inundation. The limited recent flood records, however, when combined with the few cloud-free scenes (during the wet season) from the 'optical' remote sensing, mean that an approach based on matching high flows with images of inundation appears to be unpromising.

It is envisaged that the full complement of field data required for hydraulic analyses will need to be collected during at least two field trips to each of the two site-types. Briefly, this will entail one-dimensional (1-d) hydraulic modelling; topographic cross-sectional and water levels surveys during a low flow condition; water level surveys during a medium/high flow condition; and discharge measurements during both the above flow conditions.

It is expected that at least one of the focus sites will be located along the length of the floodplain. The paucity of hydrometric data and remote sensing imagery means that hydraulic information will be strongly reliant on computational modelling. Various matters, some of which are not entirely clear at this stage (e.g. resources available for the Phase 2 assessment) have led me to suggest three alternative approaches for a floodplain-type focus site.

The first of these represents the ideal and most expensive option, and would involve the commissioning of a LiDAR survey of a floodplain reach. Analysis would require 2-d or linked 1-d/2-d hydraulic modelling, which would draw on field data collected over at least two field trips. The field trips would comprise bathymetric surveys of areas submerged at the time of the LiDAR survey; water levels and discharges.

The second approach would involve replacing the LiDAR data with a high to very-high resolution satellite-derived DEM. The Elevation4 and Elevation1 products offer a comparatively (to LiDAR) attractive and cost effective option that may be well-worth pursuing. The hydraulic modelling and additional data collection aspects would be identical to the 'LiDAR-approach'.

The third alternative is to commence with the least data and modelling requirements, and to build on this, if necessary. This would comprise collecting and using topographic information on the active channel, including the tops of the banks, which would identify areas where the river may breach its banks. In this approach, the complex hydraulic behaviour of the floodplain, itself, is not modelled - at least initially, and 1-d hydraulic modelling is suitable. Recommended data collection for this option would also entail at least two field trips, but with the addition of an Unmanned Airborne (or drone) Survey of a river reach several kilometres long to capture the exposed river bed and banks, adjacent channel bifurcations, and ideally, flood channels. If considered necessary, a further development (of this third option) could be linked 2-d modelling of the floodplain using one of the following topographical data sources (in reducing order of preference and cost): LiDAR, Elevation 4, and the relatively coarse but public domain AW3D30 DEM.

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 Basin 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 synthesising all available information on the Luangwa Basin, leading to an initial formal division of the basin 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 basin, as an input to basin development plans.

1.2 ROLE OF HYDRAULICS IN THIS ASSESSMENT

The following excerpt, adapted from Birkhead (2010), describes the roles of hydrology and hydraulics in Integrated Flow Assessments as proposed for the Luangwa River Basin during Phase 2 of this study:

RIVERINE VEGETATION BOTH RESPONDS TO AND INFLUENCES FLOW AND SEDIMENT BEHAVIOUR

Environmental Flow Assessments, a component of Integrated Flow Assessments, provide the means for predicting the consequences of our actions on ecosystem health or ecological status. Determinants of riverine ecological status include abiotic drivers (physical and chemical) and biological responses. Physicochemical drivers include the temporal and spatial distribution of river flow - which is the fundamental management variable, water chemistry, and river form or morphology. River morphology, in turn, depends on catchment geology, land-use and hydrology (all of which influence sediment supply), hydraulics and vegetation, and determines the physicochemical template for biological processes. Changes in natural flow and sediment regimes of riverine systems (incorporating floodplains) may be due to changes in land-use, the construction of impoundments, flow abstractions (including groundwater) and temporal modifications (e.g. hydropower) and return flows. In-channel structures (e.g. impoundments, structures for abstractions and return flows, flood and bank protection, construction of artificial habitats) also alter the flow and sediment regimes, but these may have more localised influences depending on their scale. Riverine vegetation both responds to and influences flow and sediment behaviour, resulting in a feedback relationship *between vegetation, flow and river morphology. The biota responds to discharge through local hydraulic conditions, such as depth, velocity and inundated area. It is therefore necessary to understand how these flow variables are related, so that management of drivers provides the required ecologically relevant hydraulic habitat. Hydraulic analyses are therefore an integral part of environmental and integrated river management.*

1.3 TERMS OF REFERENCE

The Terms of Reference (ToR) for this assessment requires completion of the following tasks.

1.3.1 Task 1

- Establish the existence and availability of maps, aerial photos, satellite imagery and similar of the Luangwa River system, and their costs and usefulness in terms of hydraulic and sediment modelling of the river system for Phase 2 of an Integrated Flow Assessment for the basin. Useful points of enquiry would be with WWF-Netherlands, WWF-SA, TNC, UNESCO, ADAPT, SA Space Agency and others that have the potential to help. Develop a comprehensive inventory of what is or could be available, under what conditions, and the cost, location and contact details. Provide a detailed but accessible explanation of what the different types of information could contribute to the Flows Assessment.

- Review all available information on the hydraulics and hydraulic modelling of the Luangwa River system.

- Write a report.

1.3.2 Task 2

- Recommend and justify how hydraulic modelling of focus sites (to be identified later) should proceed in Phase 2. Provide a workplan and budget.

- Make input to the Phase 2 Planning Report as requested.

1.3.3 Summary of deliverables

- A report that provides:

  - ◊ A critical analysis of the types and availability of spatial information available for the Luangwa Basin that is relevant to hydraulic modelling of the system.

  - ◊ A review of any hydraulic information on the system.

- Contributions as requested to the planning of Luangwa Phase 2.

1.4 KEY DELIVERABLES AND REPORT LAYOUT

This Specialist Report is the key deliverable. Accompanying products include electronic copies of catalogued reference material and data (refer to Sections 2.1, 2.2 and 8).

The report is sub-divided into the following three main sections following the ToR: Data acquisition and storage (Section 2); Review and assessment of data and modelling (Section 3); Suggested modelling approaches and supporting data collection (Section 4).

2. DATE ACQUISITION AND STORAGE

2.1 STORAGE OF REFERENCE MATERIAL

All reference material referred to in this hydraulic assessment, in the form of reports, documents, theses, journal and conference articles as well as presentations, have been loaded into the Zotero[1] reference management software. Zotero supports the exporting of collections in a number of formats[2], which may subsequently be imported into alternative reference management software (e.g. Mendeley or EndNote). For all reference material cited in this assessment, electronic copies of the files (primarily Adobe (.pdf) and MSWord) are included with the exported collection, and are provided as products of this assessment.

DATA ARCHIVES ARE STORED ELECTRONICALLY IN FOLDERS, NAMED ACCORDING TO THE SOURCE

2.2 DATA ARCHIVING

Data archives are stored electronically in folders, named according to the source[3]. Where data can be linked to specific studies and associated reference material, ‘notes’ or ’tags’ are provided in the catalogued references (refer to Section 2.1) to direct the user to the accompanying data. A list of collated data (sources and format) is given in Section 8.

[1]Zotero is public domain and open-source reference management software to manage bibliographic data and related research materials (such as PDF files). Notable features include web browser integration, online syncing, generation of in-text citations, footnotes and bibliographies, as well as integration with word processing. https://www.zotero.org/

[2]BibLaTex, Bibliontology RDF, BibTex, Bookmarks, COinS, CSL JSON, CSV, EndNote XML, MODS, Refer/BibIX, RefWorks tagged, RIS, Simple EverNote Export, TEI, Unqualified Dublin Core RDF, Wikepedia Citation Templates, Zotero RDF

[3]where these are known

3. REVIEW AND ASSESSMENT OF DATA AND MODELLING

3.1 BACKGROUND TO BASIN DIVISION, EFLOW AND FOCUS SITES IN THE LUANGWA RIVER

The Luangwa River Basin has been divided into fifteen homogeneous areas (King and Ewart-Smith, WWF/FRESHWATER/2/2016), with 21 sites representing these areas. The naturalised and present day monthly and daily hydrological time series have been modelled for all 21 sites (Howard and Nyirenda, WWF/FRESHWATER/4/2016). This has led to the assessment of environmental flows at these EFlow sites at a desktop level (WWF/FRESHWATER/12/2016) to support different ecological conditions, thereby providing information on the potential for future water resource developments across the basin. This, in-turn, will result in the selection of so called 'focus' sites, for which EFlows at a more comprehensive level (i.e. higher certainty) will be addressed during Phase 2 of the integrated flow assessment. As this report is part of the Phase 1 process, the number and location of focus EFlow sites are not yet established and cannot be reported here.

The role of hydraulics in EFlow Assessments was briefly explained in the Introduction, and applies to focus EFlow sites for holistic assessments during Phase 2. In holistic methodologies, important and/or critical flow components are identified in terms of criteria such as flow magnitude and timing, for all attributes of the riverine ecosystem (Tharme, 2000). Fundamentally, the hydraulic requirements of holistic methods are identical (or at least, similar), and involve the characterization of the discharge-related ecologically relevant hydraulic habitat for field sites along river systems. Generally, the selection of focus sites should be guided by considerations such as accessibility; diversity of physical habitat for aquatic and riparian biota; suitability of sites for hydraulic modelling over a range of flows, especially low flows; and river sections that are critical for ecosystem functioning (Rowlston et al., 2000; Birkhead, 2010).

A SITE THAT IS DIFFICULT TO CHARACTERISE HYDRAULICALLY IS LIKELY TO PRODUCE INFORMATION OF HIGH UNCERTAINTY

Since the purpose of an EFlow Assessment is to determine a flow regime that will maintain the river in a certain ecological condition, biotic considerations tend to dominate site selection. Sites providing indicators of biotic response to flow variation commonly display a high degree of physical and hydraulic diversity, which is complex to characterise. While hydraulic considerations cannot benefit from pre-eminence in site selection, it is important that they influence the process to the extent that chosen focus sites are not of such hydraulic complexity that reliable analysis and prediction are impractical. This is even more so when hydraulic data are few. A site that is difficult to characterise hydraulically is likely to produce information of high uncertainty, with consequent implications for the EFlow Assessment. This is important, since the purpose of focus sites in the Luangwa study is to support comprehensive EFlow Assessments, i.e. with higher levels of certainty.

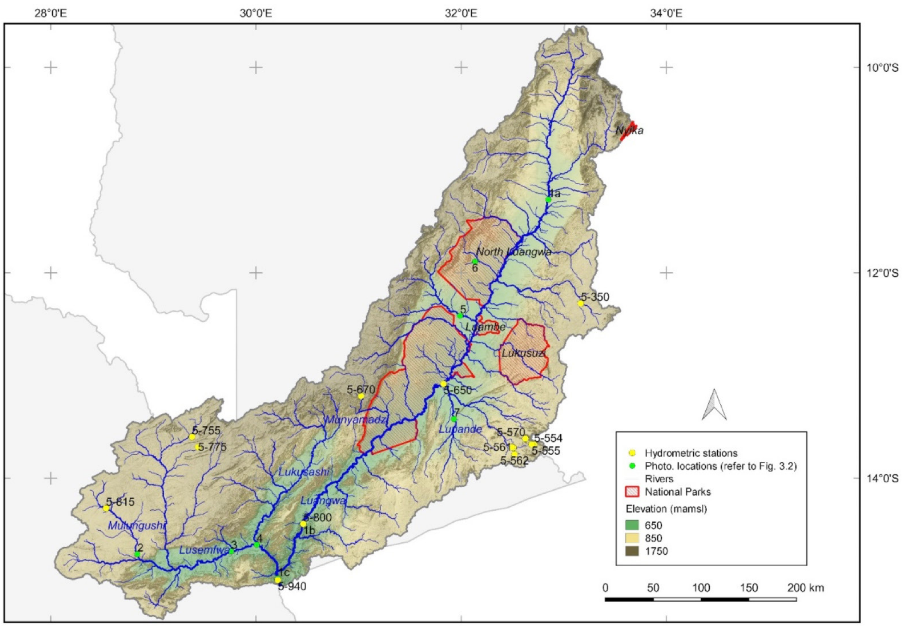
Regarding field sites chosen for hydraulic characterisations, two broad distinctions can be made: rivers where conveyance (or flow) is mostly confined to channels with well-defined banks; and floodplain-type systems that incorporate overbank features such as, inter alia, paleo-channels, wetlands, marshes, pans and lakes, which are activated during higher flows or floods. It is easier to collect data and perform analyses for the former more-confined situation; the generation of hydraulic information is more demanding for the latter floodplain-type systems. Generally, suitable[4] hydraulic information is rarely available at chosen sites to support holistic EFlow Assessment, and field surveys are usually designed to meet the needs[5] of the assessment. This is the case for the Luangwa Basin, with searches revealing very few suitable data to support hydraulic analyses for an EFlow Assessment.

At the basin division workshop[6], three non-negotiable conditions concerning ecological condition were suggested: Category A condition in the Lusemfwa and Luangwa headwaters; at least Category B along the Luangwa River main-stem upstream and through the National Parks; and at least Category C at the Zambezi River confluence[7] (Figure 3.1).

It is therefore reasonable to expect that at least one of the focus sites will be along the middle reaches of the Luangwa River to include its well-known and ecologically important floodplain, illustrated in the photo set of Figure 3.2.

Figure 3.1

Shaded relief of the Luangwa Basin showing most of its major rivers, hydrometric stations, National Parks, and photograph locations (refer to the photo-set in Figure 3.3); produced using the SRTM30 DEM (CRS WGS 84)



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[4] in terms of, for example, spatial resolution of topographic surveys, rating (stage-discharge) information, etc.

[5] including the available time frame for data collection; the desired level of certainty; allocated/available financial resources; and site characteristics, which all are, in-turn, a compromise between biotic and hydraulic considerations as discussed previously

[6] December 2015, refer to WWF/FRESHWATER/2/2016)

[7] J. King, email 12/01/2016

Figure 3.2

Photo-set of the Luangwa River Floodplain in its middle reaches, showing its meandering incised active channel, cut-off oxbow lakes, lateral sand bars and well-vegetated riparian and floodplain zone

THE TRIBUTARIES FLOWING INTO THE LUANGWA RIVER TRAVERSE ESCARPMENTS

A photo set of some other rivers in the Luangwa Basin is provided in Figure 3.3, with photo locations given in Figure 3.1. These examples reveal that other potential focus sites are likely to be characterised by rivers with more-confined channels. The photographs show the distinctly alluvial nature (sands) of the Luangwa and its tributaries flowing across the alluvial sediments of the Luangwa Rift Valley. The tributaries flowing into the Luangwa River traverse escarpments associated with the south-central African Plateau[8] as well as the plateau between the Luangwa and Lake Malawi Rift Valleys[9]. The availability of data is addressed in the next section with reference to these two hydraulically-based distinctions for potential focus sites.

3.2 AVAILABILITY OF DATA

The availability of information is described under four types: topographic, hydrometric, remote sensing for the purpose of floodplain mapping, and land use/cover and soil data. The latter is not specifically relevant to the hydraulics sub-component, but is in support of data for the “sediment modelling of the river system”, referred to in Task 1 of the ToR.

3.2.1 Topographic

No topographic information in the form of field surveys has been discovered for rivers in the Luangwa Basin. It is possible that historic surveys were carried out for some of the water and energy resource developments in the basin (e.g. Mulungushi and Mita Hills Dams and the hydropower plants associated with them, Lake Lusiwasi, etc.). Given, however, the date of these developments (early to mid-1900s) and environmental disturbances that would be associated with the infrastructures, these data will be of little benefit to an EFlows Assessment and were not pursued.

The near-worldwide Shuttle Radar Topography Mission (SRTM)[10] Digital Elevation Model (DEM) is a valuable topographical data source, and a 1 arc-second version (typically 30 m resolution) was recently[11] released for Africa. The SRTM-DEM was found to have an absolute error of around 5 m on the African continent, while for the southern part of Zambia these errors are even a bit smaller (Rodriguez et al., 2005 and Farr et al., 2007, as cited by Meier, 2012). The relief map in Figure 3.1 was produced using the SRTM30 DEM, which provides the most accurate globally - complete elevation data source in the public domain, from which aspect - an important determinant of sediment yield - can be easily computed.

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[8]generally south-east flowing tributaries

[9]generally north-west flowing tributaries

[10]refer to http://srtm.usgs.gov/

[11]latter part of 2014; previous versions were approximately 90 m resolution

Figure 3.3 Photo set of some rivers in the Luangwa Basin - refer to Figure 3.1 for photograph locations (source: Google Earth)

IT IS VERY USEFUL TO HAVE HISTORICALLY MEASURED WATER LEVELS

The Japan Aerospace Exploration Agency (JAXA) is processing data images from its Advanced Land Observing Satellite (ALOS) to produce a global 3D map (AW3D) at 5 m resolution with 5 m vertical accuracy (Section 4.2). JAXA is also preparing a 30 m version of the DEM (AW3D30) which is available in the public domain[12]. It is available for the Luangwa Floodplain, and appears to provide superior resolution over SRTM30, as inferred from the DEMs in Figure 3.4.

3.2.2 Hydrometric

The locations of hydrometric stations in the Luangwa Basin, and used in the associated hydrological study (Howard and Nyirenda, 2016), are plotted in Figure 3.1. Hydrological information from a station located close to a focus EFlow site provides useful historical measurement-based[13] (daily) data[14]. For the hydraulic sub-study, the three stations positioned along the main-stem Luangwa in its middle to lower reaches are of specific interest for potential focus sites required to represent or characterise conditions[15] associated with the floodplains reaches. These are all rated ‘natural’[16] river sections, and include 5-650 (Mfuwe); 5-800 (Ndevu Camp) and 5-940 (Great East Road Bridge). The value of rated sections is that they present no (or at least, little) disturbance to the river morphology, and so focus sites, if required, can be positioned close to them to make use of any hydraulic information. Unstable river sections such as these will change somewhat, and so natural morphological dynamics need to be considered. Nonetheless, it is very useful to have historically measured water levels and associated (calculated) discharges at or near focus EFlow sites. Records of the rating data, average daily water levels and discharges for the above three stations are included with the collated data (refer to Appendix A Collated data).

Discharge hydrographs (daily) for the period 1980 to 2009 for the three main-stem Luangwa River Stations are plotted in Figure 3.6. Unfortunately, the more recent hydrometric data are largely missing, with no flood data since about the mid-1990s for the Mfuwe Station (5-650) in the floodplain (South Luangwa National Park). The most complete record is for the station at the Great East Road Bridge (5-940), with observations commencing in 1948, but also with considerable missing records over the last 15 years.

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[12]It is available for southern Africa, but has missing data

[13]derived from measured stage and stage-discharge relationships

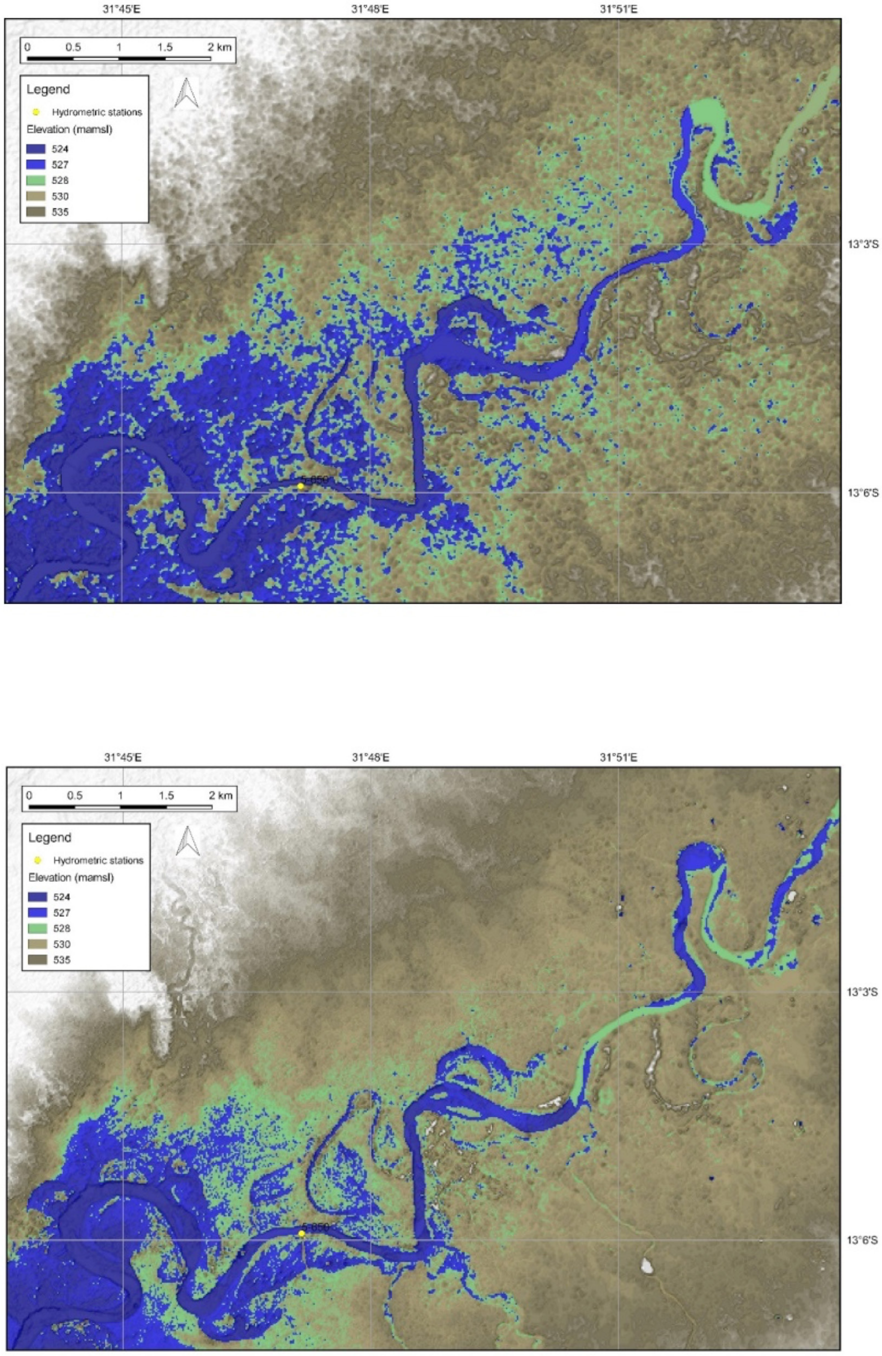
[14]particularly important when hydrology comprises monthly modelled timeseries, disaggregated to give daily discharges

[15]hydrological, morphological, hydraulic and biotic

[16]i.e. no weir structures

Figure 3.4

Comparison between the SRTM30 (top) and AW3D30 (bottom) DEMs[17] for a section of the Luangwa Floodplain near the Mfuwe hydrometric station (South Luangwa National Park): AW3D30 appears to provide superior resolution; cf. floodplain features in Figure 4.3



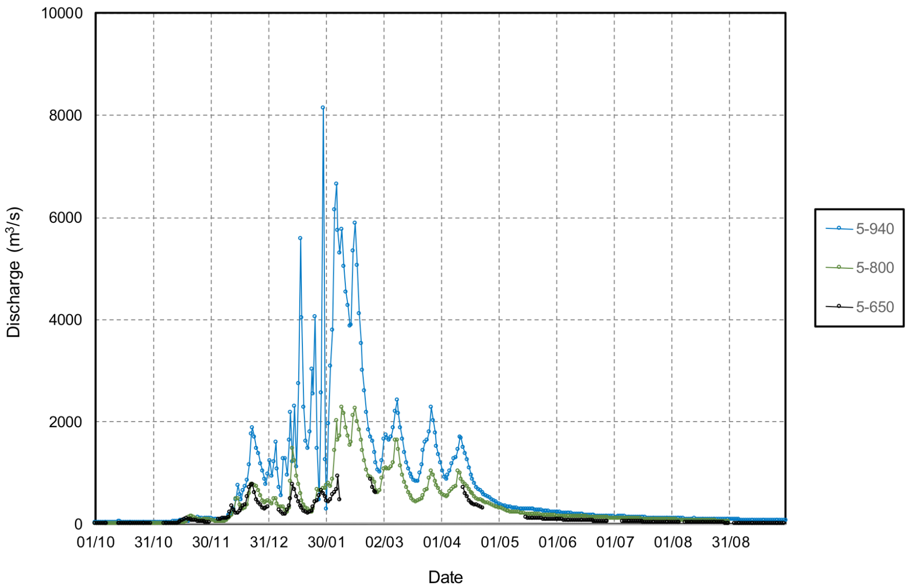
[17]The SRTM took place in February 2000; ALOS was operational from launch in 2006 to 2011 (when it lost power) and the AW3D DEM is thus for some date (or composite dates) within this 5-year period.

3.2.3 Remote sensing of floodplain inundation

Remote sensing can provide a cost-effective method for mapping and monitoring flood inundation areal extent across the Luangwa Floodplain. Multispectral sensors appear to provide more reliable data than radar, if sufficient cloud-free scenes can be procured. Multispectral imagery in the public domain and at suitable resolutions for indicating inundation of floodplain features include Landsat (recent satellites: 30 m resolution) and Sentinel-2 (20 m). Unfortunately, the Sentinel-2 archive is limited, and many of the available Landsat scenes suffer from extensive cloud cover during the wet season. From the available Landsat archive, the two scene dates corresponding to the most widespread inundation were 17/02/1985 and 17/02/2002 (Landsat 5[18] and 7, respectively), and are reproduced in Figure 3.7. Unfortunately, no gauged discharge data are available at the Mfuwe Station for either dates[19]. The discharge hydrographs plotted in Figure 3.5 infer rapid runoff-response of the basin. Consequently, scene dates must fall within likely limited flooding windows, to capture inundation patterns.

Figure 3.5

Measurement-based daily discharge hydrographs from the Mfuwe (5-650), Ndevu Camp (5-800), and Great East Road Bridge (5-940) Stations for the 1984/85 hydrological year

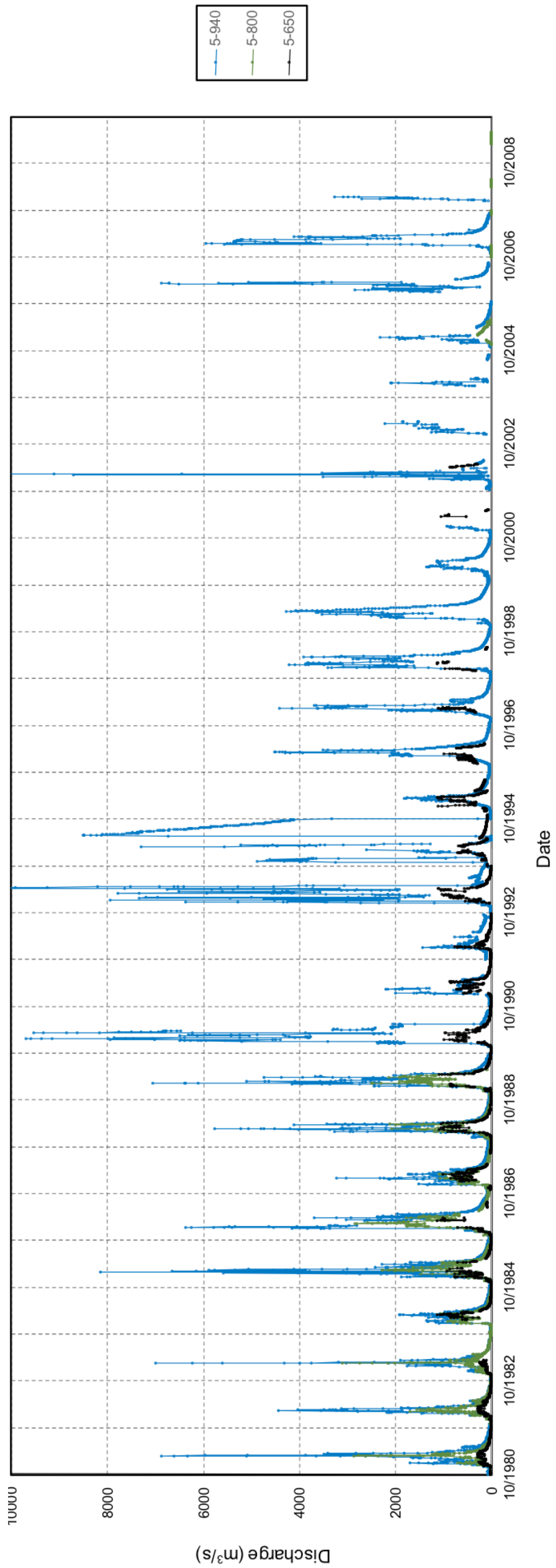


[18]Multispectral Scanner (MSS) sensor with 60 m resolution in the visible and near infrared (NIR) bands; Thematic Mapper (TM) sensor with 30 m resolution in all bands apart from the thermal (but resampled to 30m)

[19]For the 1985 scene, the gauged discharge further downstream at Ndevu Camp was approximately 1800 m3/s.

Figure 3.6

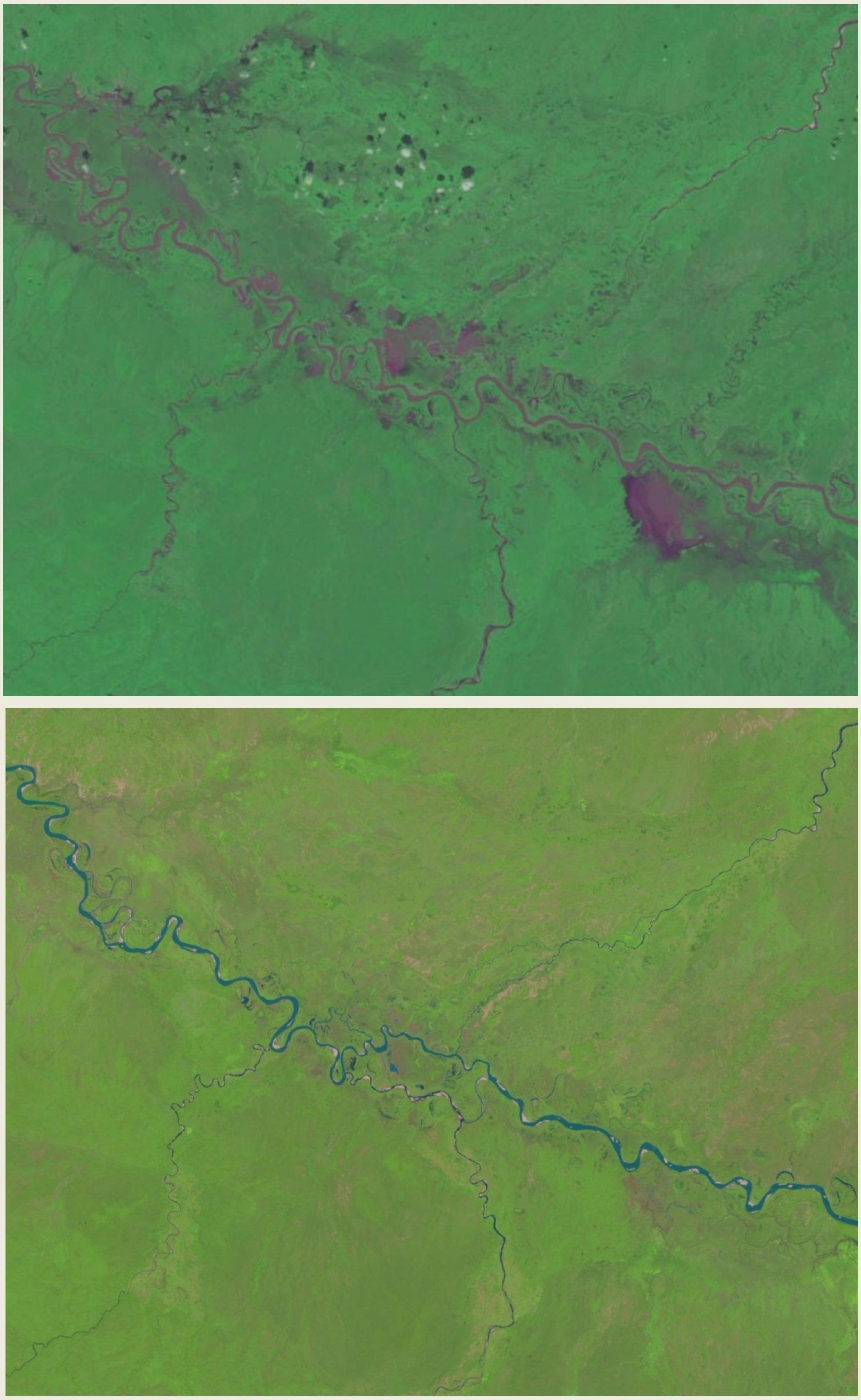
Discharge hydrographs for the period 1980 to 2009 for the three hydrometric stations along the middle and lower Luangwa River (Figure 3.1)



[20]Measurement-based

Figure 3.7

Landsat 5 (up) and 7 (down) 'natural colour' images of the Luangwa floodplain. Scene dates are 17/02/1985 and 12/03/2002 respectively



Obtaining higher spatial resolution multi-spectral commercial imagery such as SPOT 5 or RapidEye (5 m resolutions) is not deemed worthwhile, since it is costly; cloud cover remains a problem; and there is effectively no gauged data in the floodplain since the mid-1990s (Figure 3.6). This precludes the development of empirical relationships between flood discharges and (remotely-sensed) inundation patterns. SPOT 1, which was operational between 1986 and 1990, and has a 20 m spatial resolution, appears to be a better option, but again has cost implications with uncertain value.

3.2.4 Land use/cover and soil types

The following data sources for land use/cover and soil types may be useful for assessing sediment yield in the Luangwa Basin .

Land use and cover information at the spatial scale relevant to the Luangwa Basin is available as a satellite-based gridded Global Land Cover (GLC) product, at a 1 km resolution.

The Globcover national land cover map for Zambia is available at 300 m resolution, illustrated in Figure 4.1 for the Luangwa Basin. The national land covers are derived from the original raster-based Globcover regional (Africa) archive, and have been post-processed to generate a vector version at national extent with the Land Cover Classification System (LCCS) regional legend (46 classes).

For analyses of recent changes in land use and land/vegetation cover, Moderate-Resolution Imaging Spectroradiometer (MODIS) Normalised Difference Vegetation Index (NDVI) products can be used, or alternatively for longer time series, NOAA-AVHRR derived vegetation products.

NO REFERENCE HAS BEEN FOUND TO PREVIOUS HYDRAULIC MODELLING STUDIES FOR RIVERS IN THE LUANGWA BASIN

Sources for soil maps include:

- The map produced by the Food and Agriculture Organization (FAO) of the United Nations at a resolution of 10 km (FAO, 1995). A new version (1.2 at 30 arc-second25) of this map is available from the Harmonized World Soil Database of the FAO, which is the result of a collaboration between the FAO and IIASA, ISRIC-World Soil Information, Institute of Soil Science, Chinese Academy of Sciences (ISSCAS), and the Joint Research Centre of the European Commission (JRC)26.
- Soil property maps for Africa are also available at 1 km resolution from the International Soil Reference and Information Centre (ISRIC)[27], illustrated in Figure 4.2 for the Luangwa Basin.

3.3 PREVIOUS HYDRAULIC MODELLING STUDIES

No reference has been found to previous hydraulic modelling studies for rivers in the Luangwa Basin that can be used to benefit the EFlows Assessment.

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[21]The availability of radar remote sensing imagery should be assessed at the initiation of Phase 2, although limited flow records remain a constraint.

[22]SPOT 5 launched 2002, RapidEye satellites were operational from 2009

[23]and have been provided to the specialist responsible for the geomorphological component of this project

[24]Advanced Very High Resolution Radiometer of the of the National Oceanographic and Atmospheric Administration satellite information system

[25]approximately 1 km

[26]http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/

[27]www.isric.org; ISRIC SoilGrids1km visualisation and distribution website: http://soilgrids.org/

4. SUGGESTED MODELLING APPROACHES FOR PHASE 2 AND SUPPORTING DATA COLLECTION

The previous chapter clarifies the general data paucity to support the hydraulics sub-component of a holistic EFlows Assessment for focus river sites in the Luangwa Basin. Therefore, the field data required in a hydraulics study for a comprehensive assessment will need to be collected during Phase 2, commensurate with whatever modelling approaches are agreed for developing hydraulic information. The recommended approaches and data needs are discussed for the two (hydraulically) different potential focus sites: i.e. those where conveyance is mainly confined to active channels; and the Luangwa channel/floodplain system, where an incised active channel meanders through an episodically inundated floodplain.

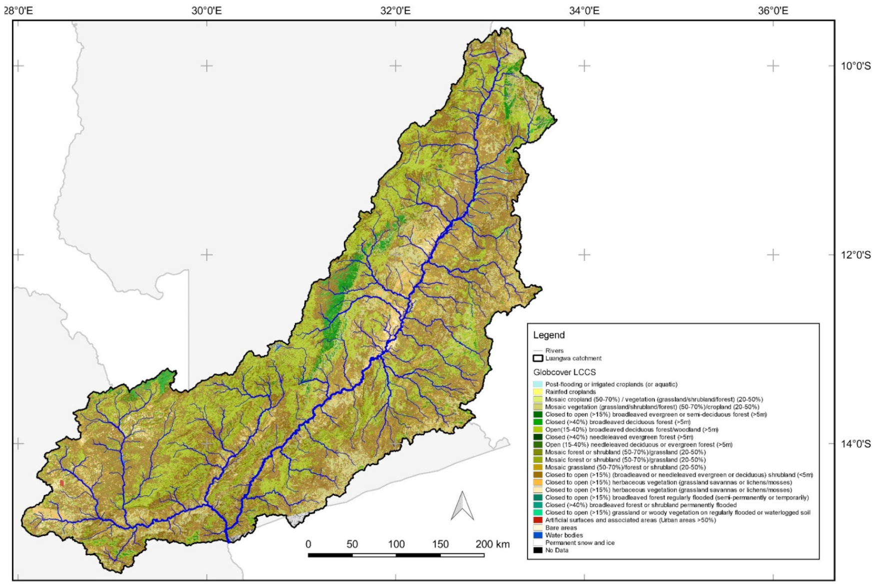

Figure 4.1

Globcover LCCS at 300 m resolution for the Luangwa Basin, Zambia (shape file data source: http://www.glcn.org)

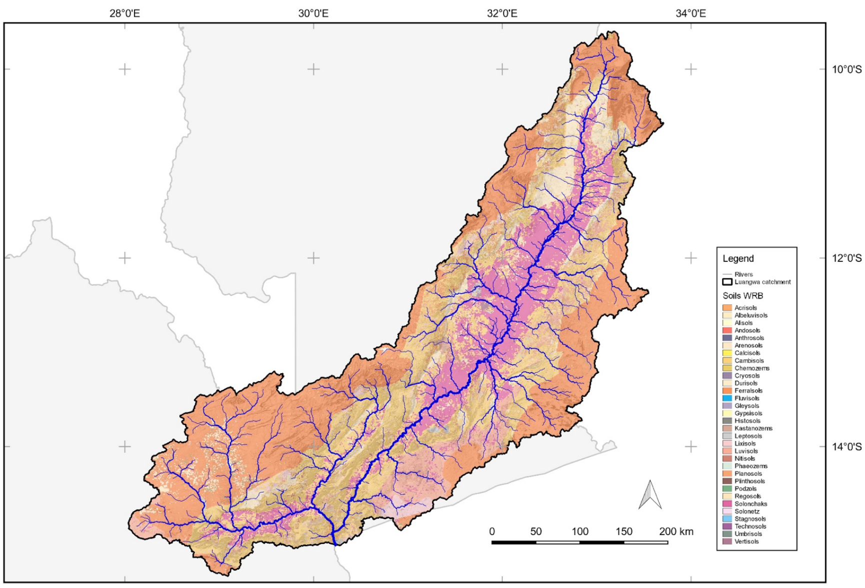

Figure 4.2

Soil map at 1 km resolution for the Luangwa Basin, Zambia (raster files data source: http://www.soilgrids.org/

4.1 CHANNEL-TYPE FOCUS SITES

Of the two distinctly different types of focus sites, the confined channel-type site is hydraulically less complex and so much easier to model. The full complement of field data required for hydraulic analyses will need to be collected during at least two field trips to any such focus site. Modelling approaches and associated data requirements for comprehensive assessment have been described in detail by Birkhead (2010), and for the Luangwa EFlows Assessment should entail at least the following:

- one-dimensional (1-d) hydraulic modelling using single or multiple cross-sectional profiles as the morphological characteristics and biotic requirements necessitate
- topographic cross-sectional and water level surveys[28] during a low flow condition, which should be the first of at least two field trips and combined with the biological/geomorphological team's sampling trip
- water level surveys during a medium/high flow condition
- discharge measurements[29] during both the above (low and medium/high) flow situations, using either a hand-held flow meter[30] or an Acoustic Doppler Profiler (ADP). [31]

THE HYDRAULIC MODELLING APPROACHES AND DATA NEEDS DISCUSSED IN BIRKHEAD (2010) HAVE RECEIVED WIDESPREAD APPLICATION

The hydraulic modelling approaches and data needs discussed in Birkhead (2010) have received widespread application in support of EFlow Assessments in southern Africa (e.g. Angola; Namibia; Lesotho; Mozambique; South Africa; Swaziland and Zambia) as well as further afield (e.g. the Sudan, Pakistan and Peru).

4.2 CHANNEL/FLOODPLAIN-TYPE FOCUS SITE ALONG THE LUANGWA FLOODPLAIN

As discussed previously, it is expected that at least one of the focus sites will be located along the length of the Luangwa Floodplain.

Implications of the data review in Section 3.2 are that empirical correlations between historical flood flows and floodplain inundation (as mapped using remote sensing) could be difficult and unreliable. This is not only due to data

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[28]instrumentation: total station or Differential Geographic Positioning System (DGPS)

[29]Automatic water level recorders (data loggers) installed at focus sites (if site conditions permit for secure attachment and safe from vandalism) can provide valuable continuous water level information, and if located close to an operational gauging station, then well-described stage-discharge relationships over a range of flows.

[30]typically, propeller- or electromagnetic-type instrumentation

[31]The choice of instrumentation is based on whether the river is wadeable or not. Given the widespread presence of (particularly) crocodiles and hippopotami in the Luangwa River, an ADP operated from a boat is the desired choice for focus sites on the Luangwa mainstem and lower reaches of its tributaries.

paucity, but also because the physical floodplain template (and its associated morphological features such as, inter alia, abandoned channels, pans and cut-off oxbow lakes) is highly dynamic (note the changes in channel planform in the 17-year time-lapse illustrated in Figure 3.7). Also, such empirically-based relationships have generally limited predictive capabilities for assessing environmental consequences of different water-resource development scenarios. Visual interpretation of the extensive flooding in the 1985 satellite image (Figure 3.7) indicates that widespread inundation is not only due to overtopping of the incised Luangwa River channel, but most likely also the result of lateral (tributary) inflows directly onto the floodplain, as well as intercepted rainfall.

Given this, the provision of hydraulic information to support a holistic EFlow Assessment for the floodplain needs to be strongly reliant on modelling of the focus site. Such a site should ostensibly incorporate the diversity of floodplain features and associated hydraulic habitats, illustrated in the photo-set of Figure 3.2 and aerial view in Figure 4.3. Two-dimensional (2-d) hydraulic modelling is necessary for the floodplain, although a one-dimensional (1-d) model could be used for the active channel. Given the torturous active channel pattern[32], however, 2-d modelling is preferable throughout. To be representative, a focus site along the floodplain needs to be at least several river-kilometres long, and include the full floodplain width. Topographic data requirements for 2-d modelling are considerably greater than for 1-d, and a floodplain DEM is necessary.

The 1 arc-second (approximately 30 m resolution) SRTM30 DEM, discussed in Section 3.2.1, is a valuable source of global topographical data. Even though its relative vertical accuracies are expected to be better than absolute values, it is nonetheless considered too coarse for use in hydraulic flow modelling of aquatic habitats over mild-gradient topographies. The recently released AW3D30 DEM (Figure 3.4), however, could probably be used to develop a coarse 2-d hydrodynamic model for the floodplain. More accurate data sources also need to be investigated.

Figure 4.3

Aerial view (source: Google Earth) of the Luangwa Floodplain in the south Luangwa National Park, approximately centred on the Mfuwe Bridge (Hydrometric Station 5-650 - Figure 3.1)

[32]producing considerable cross-channel variations in velocity

Three possibilities are (with indicative costs in Table 4.1):

- Airborne laser scanning or LiDAR. This has excellent accuracy but is very costly. Generally, LiDAR surveys do not penetrate water, so a complimentary method is still required for the channel bathymetry at the time of the flying[33].

- Satellite-derived, commercial 3-d elevation models, including[34],

◊ high resolution elevation products:

» Elevation12 WorldDEM, derived from TerraSAR-X and TanDEM-X radar satellite missions with a vertical[35] accuracy of 2 m at 12 m grid spacing

» Elevation10, derived from TerraSAR-X with a relative vertical accuracy of 5 m at 10 m grid spacing

» AW3D, derived from ALOS imagery with a vertical accuracy of 5 m at a grid spacing of 5 m.

◊ very high resolution elevation products:

» Elevation4 and Elevation1, based on Pléides stereo optical satellite data, down to vertical relative accuracy of 2 m (4 m grid spacing) and 1.5 m (1 m grid spacing), respectively. Although approximate costs (pricelists) are in the range US$ 7,000 to 12,000 (Table 4.1), this could evidently be reduced to the order of US$ 2,500 if only stereo primary DEM data (0.5 m grid) are supplied and further processing is done in-house (i.e. derivation of the DEM, surface correction using Ground Control Points (GCP), etc.)[36].

- Terrain modelling using imagery collected by Unmanned Airborne Vehicles (UAVs) or drones[37]. For the Luangwa Floodplain, this would involve the use of a fixed wing[38] UAV for vertical imaging along a series of pre-determined flight paths. The definition and topographic accuracy of the active channel banks could be enhanced with variable angle viewing capabilities of a multi-rotor UAV. The challenge for surveying the Luangwa Floodplain is in obtaining a sufficiently representative sample of this extensive floodplain system. Given that it is quite wide (order of a few kilometres), approximately 5 km^2 probably represents the minimum coverage, whilst 10 km^2 would be more appropriate. A very approximate cost to produce a 3-d terrain model for an area of the floodplain covering at least 5 km2 would be in the range US$ 10,000 to 15,000[39].

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[36]personal communication, Airbus Defence and Space

[37]Zambian restrictions governing the use of UAVs need to be considered

[38]faster travel speed and hence greater areal coverage

Neither of the above methods for acquiring a DEM provides any bathymetric information for submerged habitats (active channel of the Luangwa River and ponded lakes in the floodplain) at the time of the aerial surveys/satellite imaging. For these, depths could be collected bathymetrically, and merged with the 'terrestrial' topography. Safe access to aquatic habitats is a concern, however, due to the high density of hippopotami and presence of crocodiles (Figure 4.4), and it may not be possible to survey many of the floodplain lakes or gain access to reaches of the active channel.

Table 4.1

Indicative costs of various commercial DEM products

DEM data source	Grid (m)	Area (km²)	Minimum width (km)	Indicative cost (US$)
LiDAR[40]	Point cloud	50	floodplain extent	40,000
		100		42,000
		200		45,000
Elevation1	1	100[1]	10	12,000
Elevation4	4	100[1]	10	7,000
ALOS World 3D (AW3D)	5	400[1]	?	6,000[41]
Elevation10	10	500[1]	20	23,000
Elevation12 WorldDEM	12	500[1]	10	11,000

[1]Minimum area; Elevation products are supplied by Airbus Defence and Space; for Elevation1 and 4 products see Footnote[42]

Figure 4.4

The Luangwa River: National Parks in the Luangwa Floodplain have high populations of hippopotami, and crocodiles are also present

[39]This excludes Ground Control Points (GCPs) which would need to be part of the channel cross-section/ bathymetric surveys, as they make use of the same instrumentation.

[40]source: Southern Mapping Company (http://www.saeec.org.za/members/southern-mapping-company). Southern Mapping has recently completed a survey for the WWF in the DRC, for carbon auditing - further details can be supplied on request.

[41]as a referenced price, Level 3 DTM of 'Standard 3D topographic data'

[42]This excludes GCP, a minimum of five being required and provided by the customer

4.2.1 Approaches for developing suitable hydraulic information

Finding a cost-effective approach for modelling the hydraulic behaviour of the Luangwa River/Floodplain system, in support of a comprehensive EFlows Assessment, is a challenge. Ideally, a 2-d hydraulic model, covering a reasonably extensive area (or focus site) is required. This is, however, juxtaposed against many further considerations:

- The lack of observed hydrometric information for the floodplain, particularly during recent times (refer to Figure 3.6). Consequently, simulated hydraulic behaviour may rely strongly on modelling and characteristic parameter values.

- As highlighted in the previous section, the cost of acquiring suitably accurate topographical information for the floodplain, or a portion thereof, can be substantial.

- The sufficiency, or otherwise, in terms of vertical accuracy of commercial topographical satellite-based data for the floodplain, is not known a-priori (i.e. it is only truly evident after the data have been purchased from, processed and provided by the supplier).

- The potential role of tributaries in contributing to floodplain inundation through overtopping of their banks, upstream of (active channel) confluences. Associated with this, the reliance on hydrological modelling, at a monthly time-scale, with subsequent daily disaggregation.

- The highly dynamic nature of the active channel planform (e.g. Astle et al., 1969 and Gilvear et al., 2000) raises the question of whether or not highly accurate surveys of this mobile alluvial channel, for a specific point in time, are necessary.

These, and other considerations which are not entirely clear at this stage (e.g. resource constraints for the assessment), have led to the suggestion of the following three alternative approaches.

4.2.1.1 LiDAR-based DEM approach

This option would be the ideal and most expensive one. The data/modelling challenge would be addressed through commissioning a LiDAR survey of a sufficiently large[43] sample (order of 100 km2) of the Luangwa Floodplain. If carried out during the low-flow season of 2016, drought (El Niño) conditions still prevalent over southern Africa should result in coverage of exposed aquatic habitats that are usually submerged and so rarely seen. The LiDAR data would still need to be augmented, however, with additional field surveying of submerged topographies.

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[43] to be representative

Using the LiDAR data as a template, the study would involve the following modelling and additional data collection aspects:

- Two-dimensional or linked 1-d (channel)/2-d (floodplain) hydraulic modelling of a river/floodplain reach. This would draw information from:
- At least two field trips to the site at different flow conditions, when the following data would be collected:
    - ◊ at a low flow condition: water levels[44] and discharge[45]
    - ◊ at a medium/high flow condition:
        - water levels and discharge
        - bathymetric surveys[46] of the active channel and other aquatic habitats submerged at the time of the LiDAR survey[47].

4.2.1.2 Satellite-based DEM approach

As noted above, acquisition of LiDAR data is costly. Topographic data from LiDAR could, however, be replaced by high to very high resolution satellite-based products, for example, Elevation4, which has a relative vertical accuracy of approximately 2 m. These DEMs are derived photogrammetrically[48], and therefore generally represent Digital Surface Models (or DSMs), which don't distinguish terrain (ground surface) from superimposed vegetation surfaces[49]. The hydraulic modelling and additional data collection aspects listed above for the LiDAR-approach would be identical. Cautionary notes, however, are: firstly, the vertical accuracy of the DEM and its suitability would only become truly apparent when procured; secondly, considerable (active) channel change may have taken place since the remote sensing images were acquired[50], which confuses the merging of (more recent) field survey data with the satellite-derived DEM, particularly along channel margins; thirdly, concomitantly more field survey data may be required to patch the lower resolution DEM than would be necessary for the LiDAR DEM[51]. The Elevation4 and Elevation1 products nonetheless offer a comparatively attractive and considerably more cost-effective option (up to 1/6th the price of LiDAR) that may be well-worth pursuing. Furthermore, if

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[44] instrumentation: total station and/or Differential Geographic Positioning System (DGPS)

[45] Acoustic Doppler Profiler

[46] integrated depth sounding (sonar) and Differential Geographic Positioning (DGPS) instrumentation, operated from a motorised boat

[47] The extent to which this is necessary would only become apparent after appraisal of the LiDAR data, but most likely best done during this higher flow condition due to permit rapid coverage of habitats.

[48] the science of making measurements from photographs

[49] Digital Terrain Models (DTMs) may be derived from them

[50] For Elevation 1 and 4 products, the satellite imaging appears to be 'tasked', and is therefore recent

[51] There is also the potential of LiDAR providing some penetration of shallow clear water habitats

Pléiades[52] stereo optical satellite data products are supplied in primary format, and there is capacity for post-processing 'in-house', then it appears that the cost could be markedly lower[53]. The suitability of the DEM for floodplain modelling (in terms of resolution) appears very encouraging, and although sample data for the Luangwa Floodplain could not be acquired (since it requires satellite 'tasking'), Airbus Defence and Space provided sample Elevation 4 data for appraisal.

4.2.1.3 Approach directed to characterising the flow behaviour of the active channel and onset of overtopping; floodplain modelling an addition, if necessary.

In this third suggested approach for deriving suitable hydraulic information to inform an EFlows Assessment for the Luangwa River/Floodplain, the premise is to commence with least data and modelling requirements, and build on this, if necessary. This is contextualised against a background of conceptualised processes influencing floodplain inundation, and perceived hydrological influence/s of potential future water resource developments on the Luangwa's flooding.

FLOODPLAIN INUNDATION IS LIKELY ASSOCIATED WITH THE BREACHING OF RIVER BANKS BY FLOODWATERS

The photo set in Figure 3.2 illustrates the incised, meandering Luangwa River flowing through its floodplain. The channel planform is highly dynamic and includes active lateral movement and the abandoning of torturous planform geometries, many of which have formed cut-off oxbow lakes. The initiation of floodplain inundation is likely associated with the breaching of river banks by floodwaters, at over-bank locations associated with abandoned channels planforms and local topographic depressions. At flows exceeding so-called bank-full conditions, large increases in discharge are concomitant with small increases in water level, but widespread flooding. Therefore, collecting and using topographic information on the active channel which includes the tops of the banks[54], in a 1-d hydraulic model, would allow the characterisation of flow behaviour up to the initiation of floodplain activation. In this approach, the (complex) hydraulic behaviour of the floodplain, itself, is not modelled; it requires substantially less topographic data, and 1-d hydraulic modelling is suitable. The benefit of this approach should be considered within the context of how frequently the Luangwa Floodplain inundates, and the likely processes responsible for flooding.

Interestingly, Figure 3.7 shows the only two available Landsat scenes where extensive inundation has been captured, with these extracted from a reasonably long archive (decades). From this, it can be deduced that flooding is unlikely an annual occurrence. This conclusion needs to be tempered, however, considering the paucity of useful imagery. Cloud cover may have negated other potentially useful scenes, and furthermore, the revisit time of Landsat satellites could be incommensurate with short flood-durations associated with rapid hydrological response of the basin. Numerous tributaries flow into the Luangwa, generally draining north-west and south-

[52]The Pléiades constellation is composed of two very-high-resolution optical Earth-imaging satellites

[53]approximately US$ 2,500 for primary data (personal communication Airbus Defense and Space)

[54]to define breach locations

east (Figure 3.1). To substantially alter the Luangwa's high-flow hydrology, large storage reservoirs would need to be constructed in the middle-to-upper reaches[56] of a few of its major tributaries. Therefore, whether or not the high/flood flows thought to be responsible for floodplain inundation can be materially reduced by possible future upstream water resource developments should be assessed through a hydrological and water resource development analysis. If this is indeed unlikely, then the question to be posed is whether it is necessary to develop a sophisticated multi-dimensional hydraulic model (with its associated data requirements), for the overbank region of a focus EFlow site.

NUMEROUS TRIBUTARIES FLOW INTO THE LUANGWA, GENERALLY DRAINING NORTH-WEST AND SOUTH-EAST

If such a tailored approach (i.e. directing data collection and modelling activities first to the active channel) is deemed appropriate for a focus floodplain site, then the hydraulic study could involve the following:

- One-dimensional (channel) modelling of a reach within a wider[57] focus site.
- Two field trips to the site at different flow conditions, when the following data would be collected:

  • oat a low flow condition:

  ◇ a UAV survey of a river reach several kilometres long[58], with stereo imaging of exposed bed and banks, adjacent channel bifurcations, and ideally, flood channels

  ◇ depending on the success of the above UAV-based terrain modelling, manual surveys of linked channel cross-sections[59]

  ◇ water levels and discharge

  • at a medium/high flow condition:

  ◇ water levels and discharge

  ◇ depending on the success of topographic data collection at low flow conditions (above), augment data with bathymetric[60] surveys of the channel bed (submerged at the time of the UAV survey).

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[55]16 days for Landsat 8 with an 8-day offset from Landsat 7

[56]since the lower-altitude rift valley-infill is not suited to reservoir construction (mild gradient and deep alluvial deposits)

[57]i.e. including the lateral extent of the floodplain

[58]a minimum of 10 to 15 km, to account for longitudinal variability in breaching

[59]subject to the use of a motorised boat and safe access to the river

[60]integrated depth sounding (sonar) and Differential Geographic Positioning (DGPS) instrumentation, operated from a motorised boat

5. CONCLUSIONS

It is difficult at this stage to suggest one approach and its related data needs and field collection activities, since there are still many uncertainties at the time of writing (e.g. available resources for acquiring a floodplain DEM and for field data collection; whether the river can be safely accessed from a boat at the focus site; if it is appropriate, for the reasons given, to exclude hydraulic modelling of the floodplain, etc.). Whichever approach is adopted, however, data collection and modelling activities for a focus EFlow site along the Luangwa Floodplain will be sizeable (likely lengthy field time during two trips, with the use of sophisticated survey techniques, viz. ADP; DGPS; UAVs; etc., and concomitant post-processing activities).

6. RECOMMENDATIONS

A final recommendation and indicative budgets for the preferred hydraulics approach (or perhaps various options) is required, and will be developed through further consultation with the project leader and specialists responsible for other components of this Phase 1 EFlows Assessment. These will be included in the Final/Phase 2 Planning Report of the Phase 1 Report Series.

Notwithstanding the above, it is worth adding the recommendation of one of the reviewers of this report. This is, that given the paucity of information, there is a risk of developing a hydraulic model with a high uncertainty. The recommendation is therefore to initiate Phase 2 with a data collection campaign, of up to one year, that would include surveys of channel cross-sections/bed bathymetry and bank topography; the survey of GCPs within the floodplain; flow and sediment discharge measurements. Essentially, this is the 'tailored approach' discussed in Section 4.2.1.3, with the addition of GCP surveys for potential inclusion of the floodplain in the modelling. Data collection activities should support modelling approaches, and this recommendation is also compatible with the 'Satellite-based DEM approach' (Section 4.2.1.2). If a LiDAR-based DEM approach is favoured, however, some of these data collection activities are unnecessary (refer to Section 4.2.1.1).

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APPENDIX A.
COLLATED DATA

Data type	Source	Format	Folder path
Hydrometric			
Rating, daily water levels and discharge for stations: 5-650, 5-800 and 5-940	DWA Zambia	ASCII text files	/Collated data/ Hydrometric
Digital Elevation Model (DEM)			
SRTM30 (30 m)	USGS Earth Explorer	GIS raster (.tif)1	/Collated data/DEM
AW3D30 (30 m)	JAXA	GIS raster (.tif)2	/Collated data/DEM
Remote sensing (multispectral)			
Landsat LM5 and LE7	USGS Earth Explorer	GIS raster (.tif)3	/Collated data/Remote sensing/LANDSAT
Land use/cover and soil maps			
Globcover (300 m)	GLCN	GIS shape & legend (.xls)	/Collated data/Land use/Globcover
SoilGrid (1 km)	ISRIC	GIS raster (.tif) & taxonomy (.xlsx)	/Collated data/Soils/ ISRIC/SoilGrid
Africa Soil Profiles database v1.2	ISRIC	GIS shape	/Collated data/Soils/ ISRIC/AfSPv1.2

Luangwa River in the rainy season

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 and the current rhythm and scale of development

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