Identification of Water Resource Protection Areas (WRPAs) for Zambia

Final Technical Report

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On behalf of World Wide Fund for Nature (WWF) Zambia
In collaboration with Water Resources Management Authority (WARMA), Zambia

11 July 2019

Luangwa River © B. Lehner

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Acknowledgements

This project was financially supported through funding from WWF-Zambia. Data, expertise, and guidance was provided by many colleagues and partner organizations, including Dr. L. Katiyo, F. Chivava, R. Filgueiras, A. Musutu, Dr. B. Ellender (all WWF-Zambia); F. Nyoni, B. Mbale, O. Silembo (all WARMA); Prof. H. Sichingabula, Dr. E. Nyirenda, Prof. C. Katongo (all UNZA); Dr. H. Phiri (Department of Fisheries); G. Shanungu (International Crane Foundation); P. Sichone (Department of National Parks and Wildlife); Dr. N. Rivers-Moore, Dr. B. Paxton (both FRC South Africa); M. Thieme (WWF-US); and B. Geenen (WWF-Netherlands). In particular, the hydrological and freshwater ecological aspects of the study were reviewed by Prof. H. Sichingabula, Dr. E. Nyirenda, Dr. H. Phiri, Prof. C. Katongo, G. Shanungu, P. Sichone, and Dr. K. Banda.

Additional information

Additional information about this project and available data can be found online at

https://wrpa-zambia.weebly.com/

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List of Acronyms/Abbreviations

AEI	Aquatic Ecological Importance
BGR	German Federal Institute for Geosciences and Natural Resources
CLUZ	Conservation Land-Use Zoning
CSI	Connectivity Status Index
CSIR	Council for Scientific and Industrial Research South Africa
DOF	Degree of Fragmentation
DOR	Degree of Regulation
FAO	Food and Agriculture Organization of the United Nations
FFR	Free-flowing River
FRC	Freshwater Research Center
GCM	Global Climate Model
GIS	Geographic Information System
GIZ	German Corporation for International Cooperation
GRanD	Global Reservoir and Dam database
$GOOD^2$	GlObal geOreferenced Database of Dams
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
MCA	multi-criteria analysis
KBA	Key Biodiversity Area
PSL	Potential Sediment Load
RCP	Representative Concentration Pathway
RUSLE	Revised Universal Soil Loss Equation
SADCC	Southern African Development Coordination Conference
sMAPE	symmetric mean absolute percentage error
SSP	Shared Socioeconomic Pathway
WARMA	Water Resources Management Authority
WRPA	Water Resource Protection Area
WWF	World Wide Fund for Nature

1. Introduction

1.1 Abstract

In the Zambian Water Resources Management Act 2011, Water Resource Protection Areas (WRPAs) are defined as areas where special measures are necessary for the protection of a catchment, sub-catchment or geographic area. Three specific selection criteria are listed for the definition of WRPAs: (1) areas of high importance in providing water to users in a catchment; (2) areas of high aquatic ecological importance; and (3) areas that are particularly sensitive to use and anthropogenic impact.

The goal of this project was to develop a methodology and analytical framework to characterize each sub-catchment and river reach of Zambia for their importance regarding these three criteria, to rank them, and to prioritize WRPA candidate sites. In a first step, the 'water provisioning' aspect was assessed by analyzing patterns of runoff generation and human water use; 'aquatic ecological importance' was determined by conducting a freshwater biodiversity and ecosystem assessment, including the use of systematic conservation planning software; and 'sensitive areas' were identified by quantifying erosion potential and sediment transport. We also developed and applied a methodology to identify free-flowing rivers in Zambia, that is, those rivers where aquatic ecosystem functions and services are largely unaffected by changes to fluvial connectivity, including the effects of dams and reservoirs on fragmentation, flow regulation, and sediment trapping. In a second step, the individual criteria were ranked and then combined to provide two resulting maps at the national scale of Zambia, showing the relative importance of (1) sub-catchments and (2) rivers as WRPA nomination sites. This project only analyzed surface water resources while groundwater is addressed through independent approaches.

The results, data and methods presented in this report are intended to support efforts to prioritize water resource protection areas, identify rivers with high conservation value, optimize decision making for infrastructure development, and inform concerted national strategies to maintain and restore important surface water catchment and rivers of Zambia. The actual legislation and associated strategies, mechanisms, and level of water protection in each area are expected to vary depending on local vulnerability, threats and expected impacts. As part of the assessment, hydrologic and freshwater ecology information was compiled into a water resources atlas for Zambia (HydroATLAS-Zambia), which is freely available.

1.2 Background and objectives

The goal of this project was to develop a methodology and analytical framework for delineating and prioritizing Water Resource Protection Areas (WRPAs) for Zambia (see section 1.3 for the definition of WRPAs). The work was conducted in close collaboration between several partners: WWF-Zambia who provided funding for this project and contributed national expertise on freshwater conservation efforts; the Water Resources Management Authority of Zambia (WARMA) who is officially tasked with guiding the nomination of WRPAs; in-country experts from the University of Zambia and other national research institutes and organizations who supported this project through reviews, feedback and their regional expertise; various other stakeholders who supported or informed the development of the methodology; the Freshwater Research Center (FRC; Cape Town, South Africa) and WWF-US (Washington DC) who led the sub-assessment of aquatic ecological importance; and the external consultants Prof. Lehner and Dr. Grill from the Department of Geography, McGill University (Montreal, Canada) who led the large-scale data development and overall scientific design of this project.

This project was conducted over the course of 2 years (June 2017 to June 2019) and was informed by three complementary workshops: an initial introductory workshop hosted by WWF-Zambia (8 June 2017, Lusaka; 21 participants); an interim progress workshop hosted by WWF-Zambia (5 November 2018, Lusaka; 23 participants) which was followed by a 1 day technical capacity building short course (6 November 2018, Lusaka, 15 participants; and a final results workshop hosted by WARMA (29-30 May 2019, Lusaka; 26 participants); see Appendix I for participant lists. The project also relied on experiences from earlier attempts to delineate similar areas within the Zambezi River Basin which did not cover all parts of Zambia (Mwenge Kahinda & Kapangaziwiri 2012; Pence 2012); comparable studies within the global WWF network (e.g., WWF-South Africa & CSIR 2013); and existing scientific literature on the topic of prioritizing catchments for protection and water resource management (see e.g. reviews in Abell et al. 2007, 2017a, 2017b, 2019).

The goal of this project was to delineate and rank sites, both in terms of sub-catchments and river reaches, which can serve as a scientific framework to support the nomination process of candidate WRPA sites using the selection criteria of 'water provisioning', 'aquatic ecological importance', and 'sensitivity to impact'. It is important to note that although a WRPA can relate to protecting both surface water and groundwater resources, it was agreed over the course of the supporting workshops—and in consultation with all parties involved—that this project will only consider surface water resources. This decision was made as groundwater issues are already addressed through a joint collaboration on groundwater vulnerability mapping between the Government of Zambia, the German Federal Institute for Geosciences and Natural Resources (BGR), the German Corporation for International Cooperation (GIZ), and other partners. As such, the results of the surface water resource study presented here are intended to be used in combination with adequate groundwater protection strategies.

Besides the identification of candidate WRPAs, the extensive data preparation and processing steps led to the development of a dedicated database of hydro-environmental sub-catchment and river reach characteristics which are freely available as a stand-alone geospatial database termed HydroATLAS-Zambia (https://wrpa-zambia.weebly.com/hydroatlas-zambia).

1.3 Definition of WRPAs

Prior to the Water Resources Management Act 2011, water legislation in Zambia did not include provisions for delineating protection areas based on the freshwater resource. However, other protected or restricted areas such as national parks, game management areas, forest reserves and commercial fishing areas could be established out of the relevant pieces of legislation, with the accompanying restrictions in land use and human activities. In the new Water Resources Management Act, a Water

Resource Protection Area (WRPA) is defined as an area "where special measures are necessary for the protection of a catchment, sub-catchment or geographic area". The three specific criteria listed for the definition of WRPAs in the Technical Content for the Statutory Instruments for Water Resource Protection Areas for Zambia (2015 draft) are:

- The area is of high importance in providing water to users in a catchment;
- The area is of high aquatic ecological importance; and/or
- The water resources of the area are particularly sensitive to use and anthropogenic impact.

As a fourth and general option, a WRPA can also be designated by any other reason to be cited by the Minister in the declaration of the area. The Minister of Water Resources, Sanitation and Environmental Protection gazettes these areas under technical guidance from the Water Resources Management Authority (WARMA). The actual legislation and associated strategies, mechanisms, and level of water protection in each area are expected to vary depending on local vulnerability, threats and expected impacts.

2. Data and methods

2.1 Overview of methodological approach

In literature, water resource protection areas are generally defined as water resource areas that are providing drinking water and water for ecosystems, and where the water resource needs protection against depletion or contamination (Nel et al. 2009; Karen et al. 2015). Similarly, the concept of 'source water protection' is aiming to protect drinking water at its source by establishing connections between downstream water users and upstream water services (Abell et al. 2019). Source water protection programs are growing in application worldwide, and their objectives expanded beyond water security for people, encompassing biodiversity conservation, climate change adaptation and mitigation, and human health and well-being (Bennett and Ruef, 2016).

Protected areas have been a primary strategy for conserving ecosystems and biodiversity in the past (Butchart et al. 2012), yet it is increasingly recognized that they also contribute to human wellbeing through the provision of ecosystem services, including water provision (Harrison et al. 2016). This dual role is reflected in the global Aichi Biodiversity Targets for 2020, including Target 11 (*"...at least 17 per cent of terrestrial and inland water … especially areas of particular importance for biodiversity and ecosystem services, are conserved…"*) and Target 14 (*"…ecosystems that provide essential services…and contribute to health, livelihoods and well-being, are restored and safeguarded…"*) (CBD 2010). Yet while the identification of critical areas for freshwater conservation is relatively advanced (e.g., Linke et al. 2011), similar methods for hydrologic ecosystem services have only recently received more attention (Brauman 2017) and accurate quantification and mapping approaches at broad scales are urgently needed to prioritize key locations for protection (Mitchell et al. 2019).

Given the lack of established large-scale methods, the national assessment of candidate water resource protection areas (WRPAs) for Zambia is—in part—breaking new scientific ground and represents a novel endeavor which faces the challenge of having few existing studies to compare to. Stakeholder interaction, review, and feedback during the selection process were thus a critical component of the project. The general approach used in this analysis draws from methods that have been applied or proposed in the literature available (for a review see Abell et al. 2017b and 2019). Based on these experiences, the following methodology was designed, presented, and agreed upon through stakeholder interaction during the course of the three supporting workshops (see also Figure 1):

- First, **three individual assessments** were conducted for the three WRPA criteria of 'water provision', 'aquatic ecological importance', and 'sensitivity to impact'. This decision was made in order to allow for the individual results to be used as stand-alone products in follow-up studies or to inform alternative assessments (e.g. focusing on ecological importance only). If the three aspects were merged in a combined assessment from the start, this distinction would not be possible at a later stage.
- Given the inherent large uncertainties in all national-scale data sources used in the assessment, the goal of the three individual assessments was to produce **relative (ranked) results** rather than absolute results. For example, the goal was to identify areas that are providing "more" runoff than other areas and are thus ranked as being more important, instead of attempting to find an absolute runoff threshold above which an area should be nominated to become a WRPA candidate site.
- At the core of the assessment, a **multi-criteria analysis** (MCA) was conducted which combines the results of the individual assessments into a single final map. MCAs are a widely used approach in Geographic Information Science (GIS) with the general aim "to investigate a number of choice possibilities in the light of multiple criteria and conflicting objectives" (Voogd 1983). We mostly employed the simple technique of adding the ranks of individual results using equal weights to create a combined result, or we weighted the criterion of one assessment with a factor derived from another assessment.
- In preparation for the MCA, we first transformed the original values through a **standardization** technique. Standardization is a common pre-processing step in MCAs to produce a normalization of the given values in order to enable meaningful comparisons between criteria that were originally measured on different quantitative scales, and various methods exist (Carver 1991). Here, we chose to standardize most input data using 10 equally spaced quantiles to create ranked scores ranging from 1 to 10. That is, in a set of 500 sub-catchments, those 50 with the highest original values would receive a score of 10, the next 50 a score of 9, etc. A few exceptions applied (as described below), for example in cases where less than 10 original ranks were available, or where a zero rank existed in the data.
- In consultation with WARMA, the decision was made to conduct the prioritization assessment separately for **two spatial units**: (1) for all sub-catchments (polygons) of Zambia; and (2) for all river reaches (lines) of Zambia. This two-fold approach is designed to increase the versatility of the results for the WRPA nomination process, as important distinctions can be made between the watershed aspects of sub-catchments and the fluvial or 'connectivity' aspects of rivers which are expected to ultimately require different protection strategies (e.g. preventing watershed vs. in-stream development).

The final combined results provide a ranked score for each spatial unit within Zambia representing their relative importance in terms of water resources, which can then serve as baseline information for the nomination of candidate WRPA sites. The results are intended to support decision making processes regarding the gazetting of WRPAs, rather than to prescribe scientifically proven minimum requirements of protection. Also, our ranked results need to be combined with additional information, such as local information on land use, risks, or water quality issues to develop comprehensive strategies for integrated water resources management or to select priority areas for interventions. Finally, it is important to note that we do not assume that areas below the top of the national ranking are unimportant in terms of water resources; any site can have local or specific characteristics beyond those assessed in this project which can qualify them as WRPA sites.

As this assessment is based on large-scale data and information, which in part is sourced from coarse-scale global data products, it was imperative to evaluate the uncertainties of the data within the national extent of Zambia and to verify whether the given data quality is sufficient for the intentions of this study. In alignment with the methods and objectives, the data can expose some uncertainties in their (absolute) quantification of environmental characteristics as long as they are deemed adequate for (relative) ranking purposes. Various scientific tests and data evaluations were performed as part of this project (see details below) and the process was supported by stakeholders and in-country experts who provided reviews of the methods and results either independently or as part of the supporting workshops.

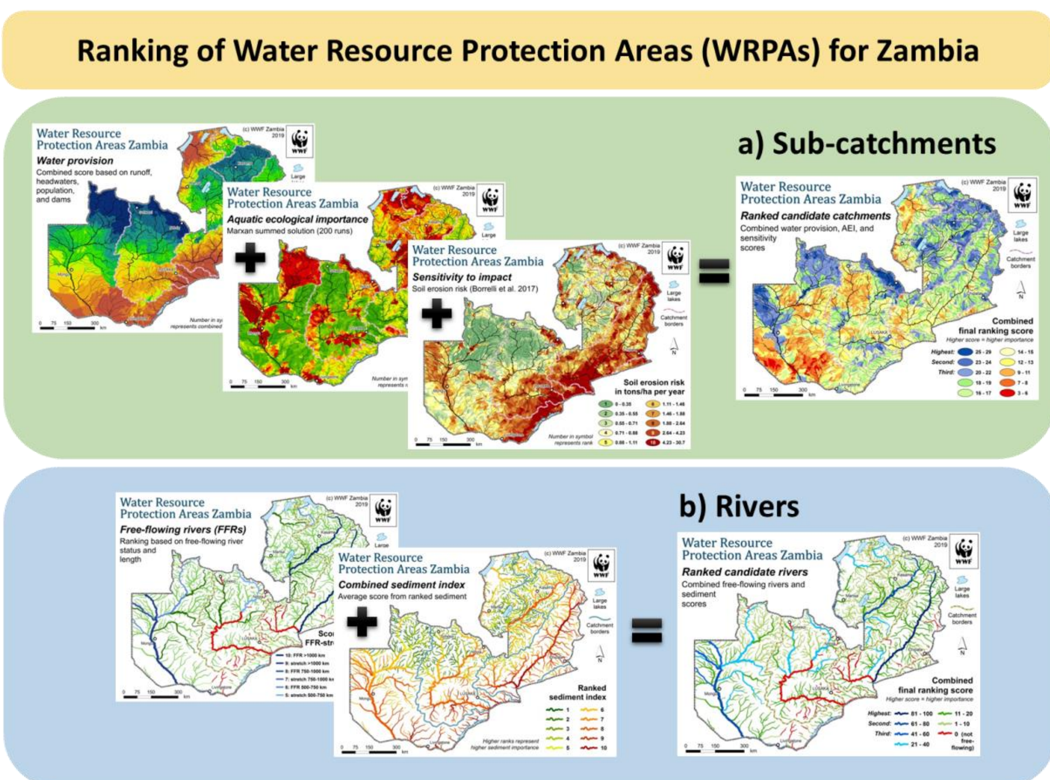

Figure 1: Overview of methodology used to rank candidate sites for water resources protection in Zambia: a) combination of input 3 categories for sub-catchments (water provision, aquatic ecological importance, sensitivity to impact); b) combination of 2 categories for rivers (free-flowing rivers, sediment load).

2.2 Hydrographic data framework

2.2.1 HydroSHEDS

In order to conduct the WRPA analysis of Zambia, two sets of spatial units were required: sub-catchment polygons and river reach lines (note that we define a river reach as the line segment between two river confluences). In order to provide a consistent and seamless national layer of these spatial units, both were extracted from the global HydroSHEDS database (Lehner et al. 2008). HydroSHEDS is a hydrographic mapping product that was derived from a digital elevation model and auxiliary datasets at an original pixel resolution of 90m. HydroSHEDS provides baseline information in a standardized and comprehensive format to support regional and global watershed analyses, hydrological modeling, and freshwater conservation planning. It is currently considered the leading global product in terms of quality and resolution (Stein et al. 2014). HydroSHEDS offers a suite of geo-referenced datasets at multiple scales as seamless global coverages, including catchment areas and discharge estimates. More information on the global HydroSHEDS database is available at http://www.hydrosheds.org.

For this study at the national extent of Zambia, we used HydroSHEDS at a pixel resolution of 500m. As for sub-catchments, we chose level 10 as the finest spatial breakdown available in HydroSHEDS (the existing levels 11 and 12 do not add any significant subdivisions within Zambia). We extracted all sub-catchments that are part of Zambia (with some catchments at the border slightly exceeding beyond the national boundary), resulting in 5,528 individual polygons with an average area of 141.9 km^2 (std. dev. 77.6 km^2) covering a total area of 784,683 km^2. As for rivers, we extracted a national river network by defining streams as all pixels with an upstream catchment area equal or above 10 km^2 or a long-term average natural discharge equal to or above 100 liters per second. We refrained from including streams below these thresholds as they are increasingly unreliable in their spatial representation through global datasets. These selection criteria resulted in 36,074 individual river reaches (that is, line segments between confluences) with an average length of 4.8 km (std. dev. = 4.0 km), totaling 172,760 km of river network within Zambia. Each river reach is additionally linked to its contributing hydrological area with an average size of ~12 km^2.

2.2.2 HydroROUT

For all river network calculations, that is, for assessing upstream and downstream connections and transport of water or sediments, we applied the global river routing model HydroROUT (Grill et al. 2015) which is built upon the HydroSHEDS database and features a nested multi-scale model approach, advanced implementation of connectivity, and uses an object-oriented vector data structure in a graph-theoretical framework. In particular, HydroROUT was used for the assessment of free-flowing rivers (see section 2.4.3).

2.2.3 HydroATLAS-Zambia

In order to conduct the WRPA project, a large amount of hydro-environmental data had to be processed, compiled, and spatially organized. To facilitate this task, a global database framework called HydroATLAS (Linke et al. 2019) was used and customized for the extent of Zambia and the Zambezi River

Basin. After completion of the WRPA project, this database is made available as a stand-alone product and baseline data repository to support other hydro-environmental applications at national scale.

The goal of HydroATLAS-Zambia is to provide a broad user community with a standardized compendium of hydro-environmental attribute information for all sub-catchments and river reaches of Zambia and the Zambezi River Basin at high spatial resolution. Version 1.0 of HydroATLAS-Zambia offers a set of 35 attributes organized in six categories: hydrology & hydrography; physiography; climate; land cover & use; soils & geology; and anthropogenic influences (Figure 2; Table in Appendix II). HydroATLAS-Zambia derives the hydro-environmental attributes by reformatting original data from well-established global digital maps. Additional national datasets were included as available.

The attributes were then linked to the hierarchically nested sub-basins of HydroSHEDS at multiple scales, as well as to individual river reaches. The sub-catchment and river reach information is offered in two companion datasets: BasinATLAS-Zambia and RiverATLAS-Zambia. The standardized format of HydroATLAS-Zambia ensures easy applicability while the inherent topological information supports basic network functionality such as identifying up- and downstream connections. HydroATLAS-Zambia is fully compatible with other products of the overarching HydroSHEDS project enabling versatile hydro-ecological assessments. HydroATLAS-Zambia is free for any user. More information and the data in GIS format are available online at https://wrpa-zambia.weebly.com/hydroatlas-zambia.

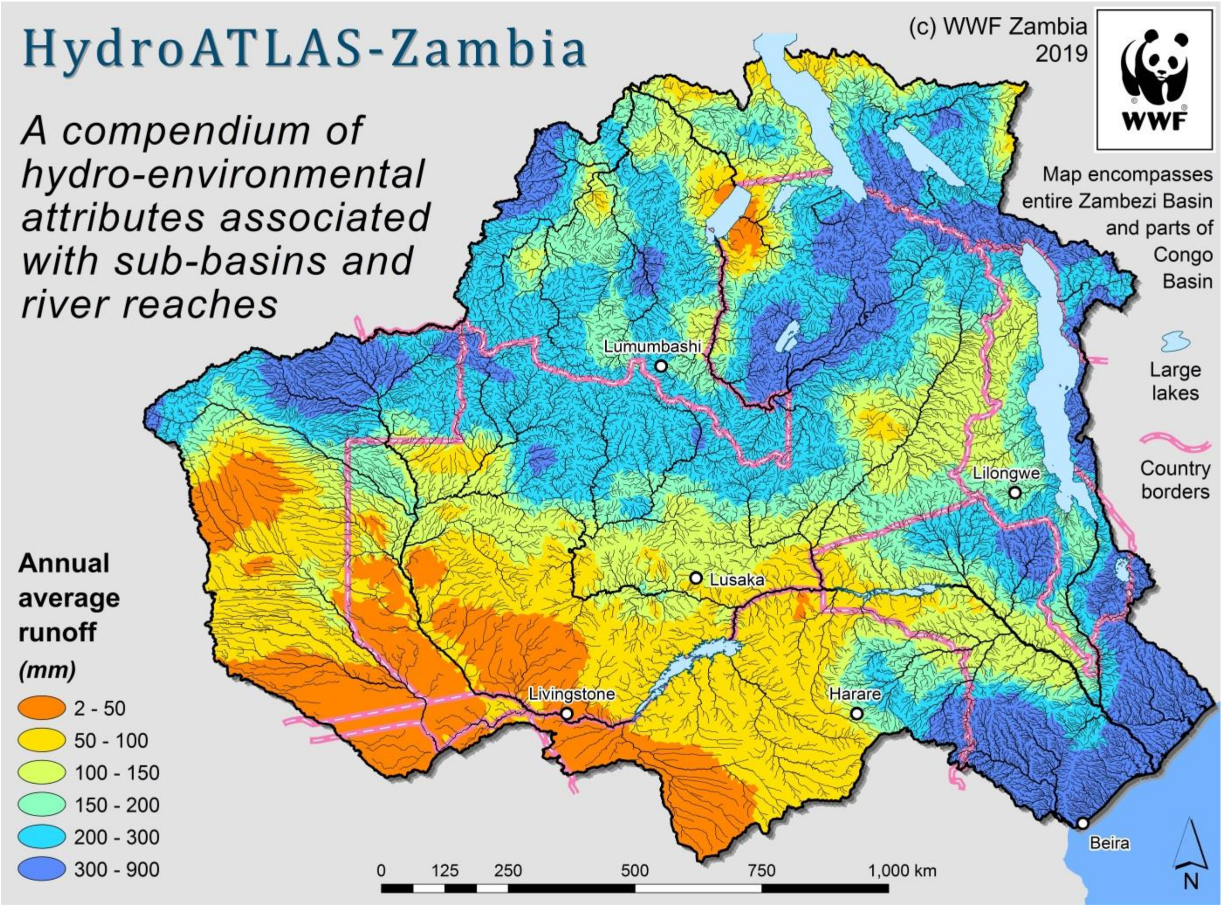

Figure 2: Example data (annual average runoff) contained within the HydroATLAS-Zambia database.

2.3 Criterion 1: Water provision

The importance of each sub-catchment and river reach in Zambia in terms of water provision was assessed following methodological approaches that have been applied or proposed in other studies at large spatial scales (e.g., Green et al. 2015; Abell et. al. 2017b; Mitchell et al. 2019). Following established terminology used for freshwater ecosystem service assessments (Mitchell et al. 2015), water provision was analyzed looking at two distinct elements: the 'capacity' of the landscape to supply water, and the 'demand' for that water by downstream users. When capacity and demand overlap or meet, provision occurs. We thus quantified the capacity of the landscape to provide runoff, estimated the demand for this water by people and agriculture downstream, and connected the downstream demand to upstream areas of capacity by analyzing hydrological connectivity, building on methods outlined in Abell et al. (2017b) and Ouellet Dallaire (Ouellet Dallaire 2018). As a general preposition, we assume that upstream areas with high runoff (that is, high capacity) that serve downstream areas with high demand are the most important for freshwater provision (Luck et al. 2009).

For water capacity, two criteria were used to identify important water source areas: the amount of land surface runoff, and the location of headwater regions. For water demand, also two criteria were used: the demand of water for downstream human populations, and the demand of water for downstream dams (representing agricultural use). The four criteria were then combined in a multi-criteria overlay analysis to derive one priority map of water provision.

2.3.1 Groundwater

Groundwater is acknowledged in this study as a highly important factor for the allocation of water resource protection areas in Zambia. In fact, groundwater issues are already addressed through a joint collaboration on groundwater vulnerability mapping between the Government of Zambia, the German Federal Institute for Geosciences and Natural Resources (BGR), the German Corporation for International Cooperation (GIZ), and other partners. In addition, WARMA has engaged in leading efforts to develop an adequate approach for the identification of groundwater protection zones, following established scientific methodologies (F. Nyoni, WARMA, pers. comm.).

Given the ongoing groundwater research, it was agreed over the course of the supporting workshops—and in consultation with all parties involved—that this project and report will only investigate surface water resources. The groundwater and surface water strategies are considered complementary components and should go hand in hand to achieve an integrated WRPA design. Here, we intentionally refrain from merging the two approaches at this stage to keep the methods distinct, and to allow for an independent focus on one or the other in different regions, as required.

2.3.2 Surface water capacity: runoff

The main source of information for assessing the importance of a sub-catchment regarding the provision of water for downstream uses will be a map of land surface runoff generation at a Zambian scale. There is currently no national high resolution digital runoff map available, and its related representation of river discharge (that is, runoff accumulated along the river network) is measured only at the point locations of existing gauging stations. For this reason, and after thorough validation efforts (see below), the decision has been made to utilize runoff and discharge information at a national scale as provided by a state-of-the-art global hydrological model.

The underpinning hydrological data is originally produced by the global hydrological model WaterGAP (v2.2 as of 2014), and then downscaled to the higher resolution of HydroSHEDS. WaterGAP is a well-documented and validated integrated water balance model that operates at 0.5 degree (~50 km) pixel resolution (Alcamo et al., 2003; Döll et al., 2003 https://en.wikipedia.org/wiki/WaterGAP). It has been used in many global water resource assessments, including the UN World Water Development Reports, the Millennium Ecosystem Assessment, the UN Global Environmental Outlooks as well as several reports of the Intergovernmental Panel on Climate Change. WaterGAP simulates both natural (that is, without human modifications) and anthropogenic runoff and discharge; for the latter, consumptive water use, that is, total water abstractions minus return flows are calculated for agricultural (mostly irrigation), industrial and municipal sectors.

In HydroSHEDS, estimates of average runoff and discharge estimates are available as long-term annual averages (that is, for the time period 1971-2000) and as annual regimes (that is, as long-term average monthly values) at 500m pixel resolution. These values have been derived for every location in the landscape and along the river network through a geospatial downscaling procedure (Lehner and Grill 2013) from the coarse-resolution runoff and discharge layers of the global WaterGAP model. The downscaled runoff and discharge estimates have then been extracted for every sub-catchment and river reach of HydroSHEDS.

For the application within the WRPA assessment, the long-term average runoff estimates of all sub-catchments within Zambia, originally ranging from 5 to 463 mm per year, were standardized to a scale of 1 to 10 (using quantiles). The discharge estimates (Figure 3) were only used as part of the free-flowing river and sediment assessments as described below (sections 2.4.3 and 2.5.2, respectively).

Shortcomings of these downscaled hydrological data are that there is no time series (daily or monthly) available at the high spatial resolution of HydroSHEDS, and that the magnitude of inherent errors caused by the large-scale modeling and downscaling procedures have only been assessed at a global scale. A validation of the downscaled discharge estimates against observations at 3,003 global gauging stations (GRDC 2014), representing river sizes from 0.004 to 180,000 m^3/s, confirmed good overall correlations for long-term average discharges ($R^2 = 0.99$ with 0.2% positive bias and a symmetric mean absolute percentage error sMAPE of 35%, improving to 13% for rivers ≥100 m^3/s).

To expand on this global validation and to add a focus on Zambia, WARMA provided statistical discharge records from 23 gauging stations, including multiple stations along the Kafue and Zambezi Rivers. Represented rivers ranged from small (Muchindamu River with an average discharge of 1.2 m^3/s) to very large (Zambezi River with discharges larger than 1000 m^3/s). It should be noted that one station (Zambezi River at Chirundu Bridge) had only data for a limited time period and seemed to show systematic deviations from other records, which according to WARMA may have been caused by a transition in the data interpretation method; hence this station was excluded from the validation.

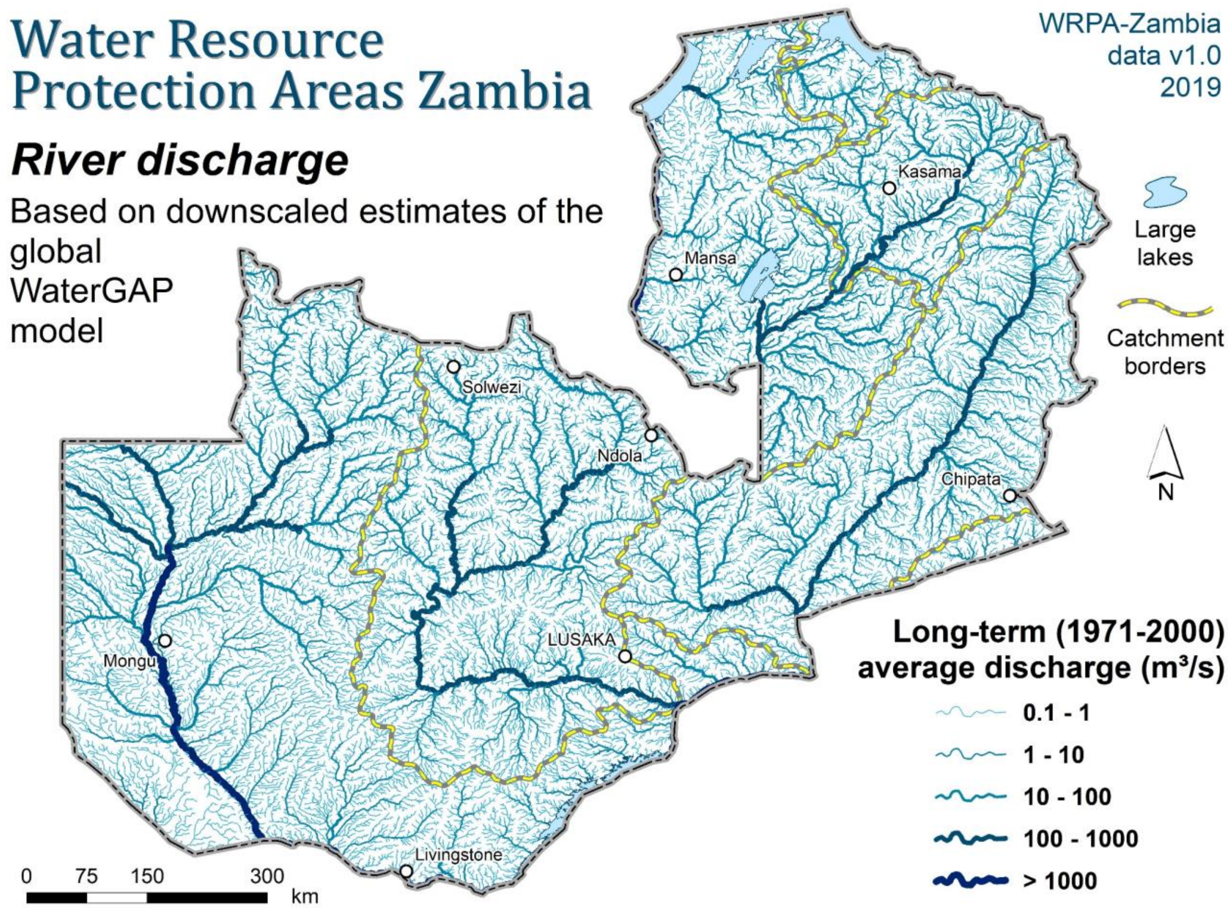

Figure 3: Downscaled discharge estimates available in the HydroSHEDS database.

We visually compared the annual flow regime lines of all 22 stations between recorded (WARMA) and modelled (HydroSHEDS) values. Figure 4 shows four representative examples, illustrating cases with differing levels of correspondence (see Appendix III for all 22 comparisons). The findings showed that despite severe deviations for some stations, the overall annual flow regime was reasonably well depicted by the simulated model results for most stations. We then conducted an additional quantitative comparison where we measured the correlation between all available pairs of data points (measured vs. modelled), using long-term average discharge (22 pairs, that is, 1 per station) as well as long-term monthly averages (12 x 22 = 264 pairs). Figure 5 shows the two resulting scatter plots with R^2 values of 0.95 and 0.86, respectively.

From the validation exercise, and based on reviews and expertise provided by the Zambian hydrologists involved in this project, we concluded that the long-term annual average runoff and discharge estimates available in HydroSHEDS are good proxies to differentiate the general hydrological spatial patterns within Zambia. The long-term monthly averages, on the other hand, show higher uncertainties and should only be used cautiously and in combination with measured data or local hydrological models. It is important to note that given the validation results, no monthly averages were used in the WRPA assessment as presented here; the validation of monthly averages only served the purpose of understanding the overall quality and limitations of the available data.

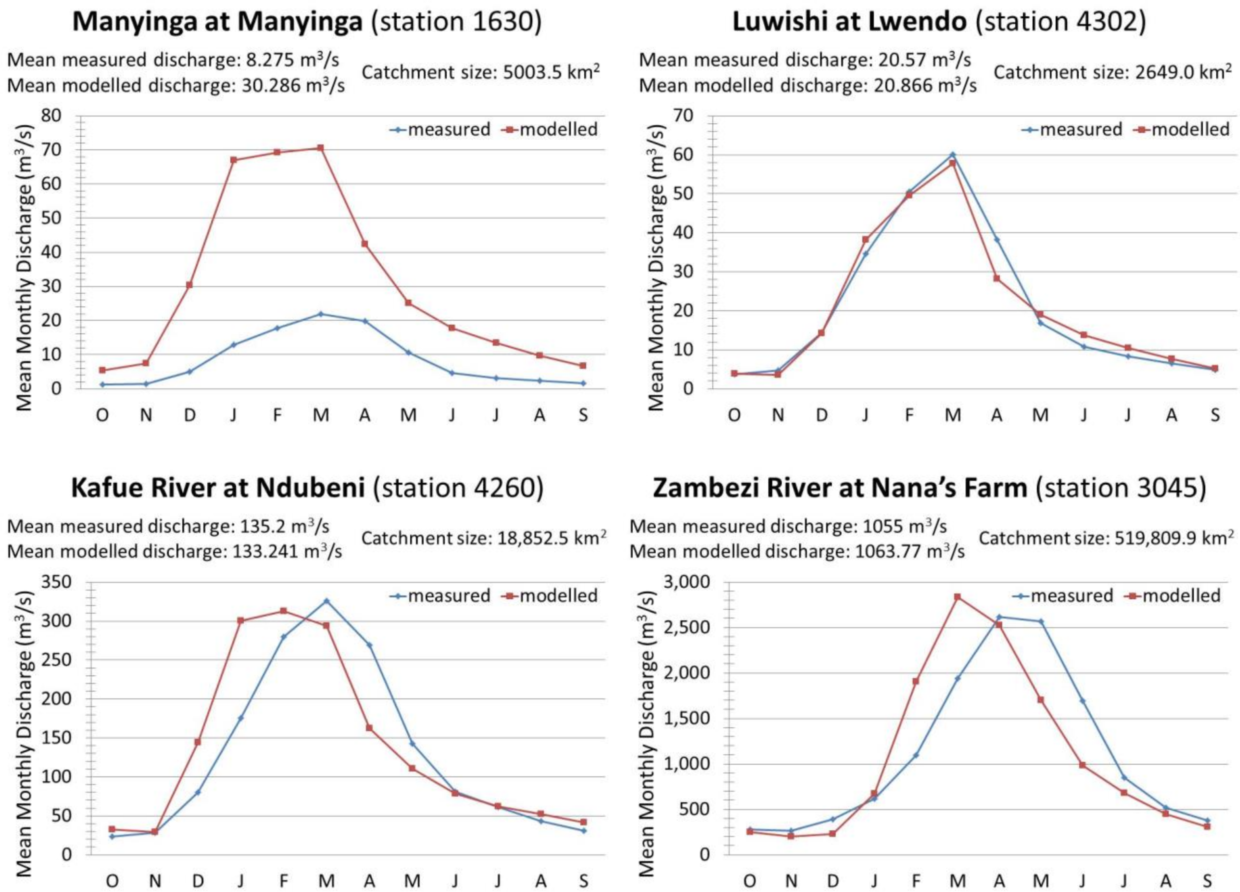

Figure 4: Annual flow regime comparisons between measured (WARMA) and modelled (HydroSHEDS) discharge data. The figure shows four chosen examples. All 22 station results are available in Appendix III.

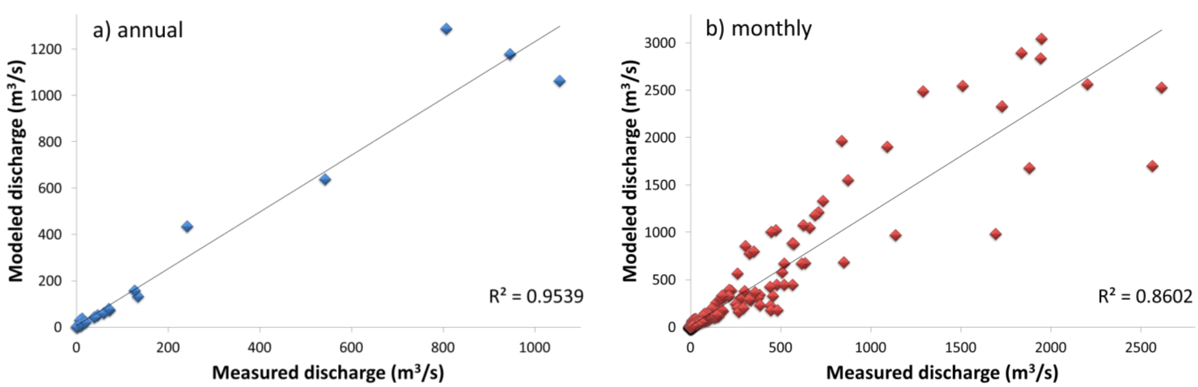

Figure 5: Scatter plots comparing measured (WARMA) against modelled (HydroSHEDS) discharge values at 22 gauging stations in Zambia for a) long-term annual average discharges and b) monthly averages.

2.3.3 Surface water capacity: headwaters

Headwater areas are often considered as particularly important for the provision of water to downstream users and for the overall hydrological characteristics and functioning of a river. The concept generally refers to headwaters as being the source of a river or stream and as such they should be furthest away from the river's estuary or confluence with another river, as measured along the course of the river (https://en.wikipedia.org/wiki/River_source). However, there is no scientifically agreed upon definition of how to depict 'headwater' areas within a watershed. Actual distances are scale dependent, and a small tributary stream may have its own (relative) source water area which would not qualify as a headwater within the larger basin that the stream is nested in.

A different perspective on source water areas is known as "water towers", a term that was first used by Meybeck et al. (2001) to describe high yielding mountain areas that supply disproportionate runoff compared to adjacent lowland areas and its various users. These areas are considered exceptionally important to the economy and human well-being of river basins, especially for downstream areas that often benefit from the abundant runoff (UNEP 2010). However, like the headwater concept, there is ambiguity in the delineation of water towers as there is no clear definition of what constitutes a 'mountainous' or 'high yielding' area.

In order to account for both perspectives in the delineation of headwaters, we combined the two aspects of distance from the river's outlet and the location within mountain regions. For the definition of river outlets, we used the six major catchments of Zambia as identified by WARMA as a guideline (http://www.warma.org.zm/catchments-zambia/): Zambezi, Kafue, Luangwa, Luapula, Chambeshi and Tanganyika (Figure 6); yet we merged the Luapula and Chambeshi catchments as they form one functional unit.

To assess distances, we first calculated the distance of any location within the landscape from the outlet point of its respective catchment by tracing the connection along the river network of HydroSHEDS, and we then assigned these distances to each sub-catchment of Zambia. We then ranked distance values within each major catchment on a scale of 1 to 10 (using quantiles) in order to standardize them and make them comparable at a national scale.

To add the aspect of mountainous source water areas, we selected only catchments with a relatively small total upstream watershed area to restrict the assessment to the source regions of rivers; and we used slope (rather than elevation) as the criterion to identify mountainous terrain. We assigned values ranging from 1 to 3 to those sub-catchments which have (1) less than 1000 km^2 upstream area and more than 1 degree average slope, (2) less than 1000 km^2 upstream area and more than 1.5 degree average slope, and (3) less than 500 km^2 upstream area and more than 2 degrees average slope.

To create a final headwater map which ranks all sub-catchments of Zambia, we added the individual ranks of the distance and mountainous assessments and capped the resulting values at 10.

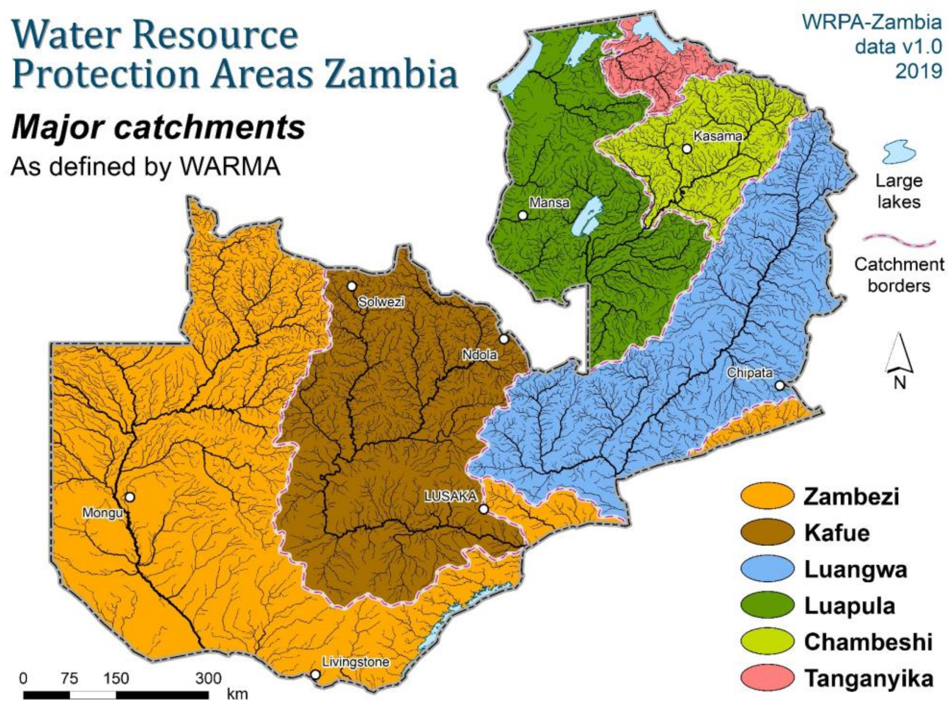

Figure 6: Major catchments of Zambia, as defined by WARMA.

2.3.4 Downstream water demand: population

Surface water for human use, including domestic and municipal purposes, is difficult to quantify as precise statistics of water use in Zambia per person or per sector, separated for surface and groundwater use, are not readily available at high spatial resolution. In the absence of such data, and after consultation with participants in the project workshops, it was agreed upon to rely only on the simplified and relative assumption that more people will use more water. After inspecting various datasets on settlement locations and district population numbers, the spatial resolution and detail of these data were not deemed sufficient for this study. Instead, we utilized the national data for Zambia as provided by the global WorldPop database (Tatem 2017) which offers modelled population numbers at a pixel resolution of 90 m (Figure 7). We used the population grid for the year 2015 for our assessment.

In order to quantify the water demand for populations, we calculated the number of people that are located downstream of any location in the landscape. To do so, we traced the connection of every land pixel along the river network and counted the number of people that are passed along the downstream journey within Zambia (populations outside Zambia were not taken into account). A land pixel with a higher number of downstream people is assumed to have a higher demand for its water resource and is thus considered more important than a pixel with a lower number of downstream people.

To conduct these calculations, we first allocated the given population estimates to the HydroSHEDS river network by summing the population counts within each contributing area of a river reach. We then calculated the total number of downstream people using the 'Flow Length (Downstream)' tool of ArcGIS and assigning the population per reach as the weighting grid. The result is a grid showing the number of downstream people from every pixel in the landscape. To produce a representative value for each sub-catchment, we assigned the average number of downstream people found for all pixels within the sub-catchment. For the application within the WRPA assessment, the resulting values were standardized to a scale of 1 to 10 (using quantiles).

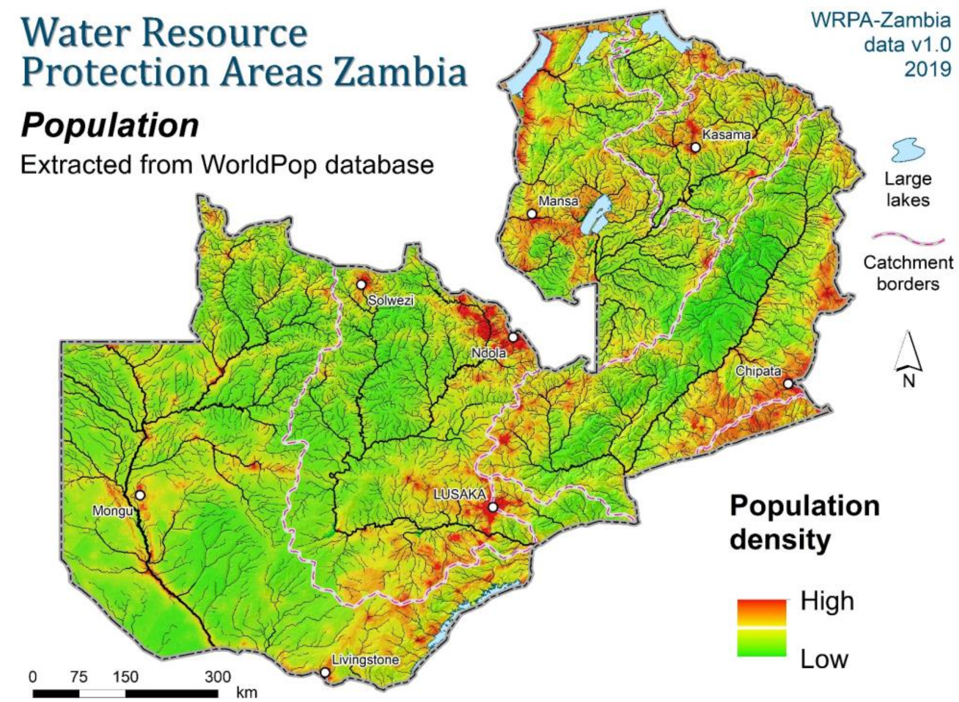

Figure 7: Population per 500 m pixel provided by WorldPop (Tatem 2017).

2.3.5 Downstream water demand: dams

Surface water for agricultural use is typically stored in reservoirs to be abstracted at times of demand. In order to spatially locate this water demand, a dam database for Zambia was compiled in a collaborative effort. An initial version of the database was created using existing locations and attributes of large dams from the Global Reservoir and Dam database (GRanD; Lehner et al. 2011) and locations of medium-sized dams from the GlObal geOreferenced Database of Dams (GOOD[2]; Mulligan et al. 2009). This initial version was then verified and expanded through mapping efforts by WARMA and WWF-Zambia. At the time of conducting this study, the resulting dam database included a total of 1,020 existing dams within Zambia (Figure 8).

In order to quantify the water demand for dams, we calculated the number of dams that are located downstream of any location in the landscape. To do so, we traced the connection of every land pixel along the river network and counted the number of dams that are passed along the downstream journey. A land pixel with a higher number of downstream dams is assumed to have a higher demand for its water resource and is thus considered more important than a pixel with a lower number of downstream dams. It should be noted that ideally, the storage volume of each reservoir should be taken into account in this approach, but this information was not readily available for all dams and was thus not included in the creation of this proxy.

To conduct these calculations, we first snapped the given point locations of dams to the HydroSHEDS river network by allowing a maximum snapping tolerance of one 500 m pixel. We then calculated the number of downstream dams using the 'Flow Length (Downstream)' tool of ArcGIS and assigning the snapped dams as the weighting grid. The result is a grid showing the number of downstream dams from every pixel in the landscape. To produce a representative value for each sub-catchment, we assigned the maximum number of downstream dams found for all pixels within the sub-catchment. For the application within the WRPA assessment, the resulting values, originally ranging from 0 to 18, were standardized to a scale of 0 to 10 by capping them at 10 (as only very few sub-catchments exceeded 10).

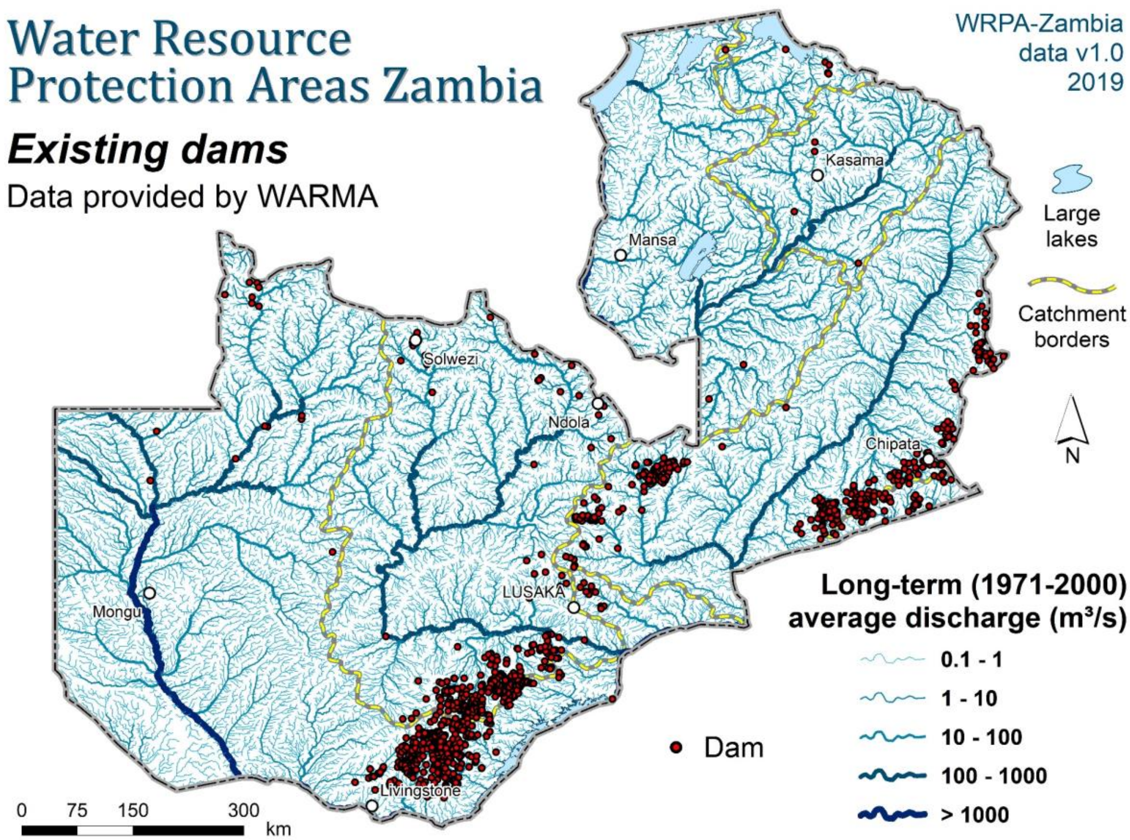

Figure 8: Dam locations within Zambia.

2.3.6 Combination into one surface water provision map

To create a single sub-catchment map of surface water provision, the four normalized input maps (runoff, headwaters, population, and dams) were added, resulting in combined values ranging between 3 and 40. This result was again standardized to a scale of 1 to 10 (using quantiles).

2.4 Criterion 2: Aquatic ecological importance (AEI)

The task of identifying areas of Aquatic Ecological Importance (AEI) was led by the Freshwater Research Centre (FRC) working in collaboration with WWF-Zambia and Zambian fisheries experts. In particular, local expert Dr. Phiri and his team assisted with data collation and the review of preliminary and final WRPA outputs. A detailed technical report is available which fully describes the AEI study, its methods and results (Rivers-Moore and Paxton 2019). Here, we only provide a brief summary of the approach and findings (sections 2.4.1 and 2.4.2). In addition to the FRC-led AEI assessment, a separate study was conducted to identify 'free-flowing rivers' in Zambia (section 2.4.3).

2.4.1 Freshwater species and ecosystem distribution data

In preparation for the AEI study, a comprehensive review was conducted in consultation with relevant stakeholders including WWF-Zambia and in-country experts on the availability and reliability of aquatic biodiversity distribution records, including relevant documentation and studies. The spatial information required for the conservation planning process included a wide range of biodiversity, physiographic and ancillary data in a variety of formats including raster, vector (point, polygon and line), as well as data that needed to be translated into a format readable to a GIS. Data on floodplains/wetlands were provided by the global GIEMS-D15 classified inundation areas (Fluet-Chouinard et al. 2015). For more details on all data sources and characteristics see Rivers-Moore and Paxton (2019).

The species distribution data were supplemented with the Africa-wide IUCN freshwater species assessment data for fish, molluscs, amphibians and odonata (Darwall et al. 2011) and data for aquatic-dependent mammal species compiled through TNC-Zambia for the Development by Design project (Trainor et al. 2017). In addition to the full species complement, threatened and range restricted species as per the IUCN Key Biodiversity (KBA) methodology were included in the assessment (IUCN 2016). All of these features were attributed to the level 10 HydroBASINS planning units (sub-catchments) prior to analysis.

A total of 77 freshwater biodiversity features for Zambia in 11 categories (Figure 9) were included in the final conservation plan. A range of data types was used including species occurrence records, estimated species ranges from the IUCN database, species distribution models, and derived data such as species richness. Species distributions that covered the whole country were excluded and only range-restricted or threatened species were selected, except where species richness indicators were derived. Figure 9 shows the relative contribution and breakdown of biodiversity features used as input to the systematic conservation planning approach, including: (a) proportion of each taxon group and feature; and (b) proportion of IUCN listed taxa.

Freshwater fishes are disproportionately represented in the input layers firstly because of their importance as indicators of broader bioregional as well as local habitat conditions and secondly because, in aquatic ecosystems, they are the taxon group for which data is most readily available. It should also be noted that species were not selected on threat status alone, but on a wider variety of criteria, including input from in-country and regional experts and literature reviews (see Rivers-Moore and Paxton 2019 for details). The choice of which taxa to include or exclude was determined largely by data availability, local knowledge and expertise, as well as knowledge of their threat status, or knowledge of their dependency on aquatic ecosystems. Species richness layers were only calculated for taxon groups such as fish and amphibians for which there were data available on a sufficient number of species for this calculation to be meaningful. Conversely, where very little information was available either with regards to the threat status, importance, repesentivity, or endemicity of species within taxon groups – for instance crabs – only species richness was used.

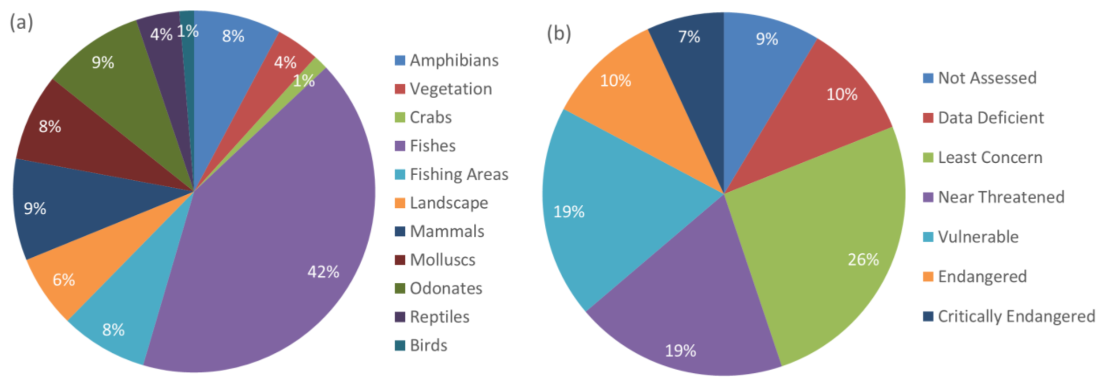

Figure 9: Relative contribution and breakdown of 77 biodiversity features used as input to Marxan: (a) proportion of each taxon group and feature; (b) proportion of IUCN listed taxa. For details see Rivers-Moore & Paxton (2019).

2.4.2 Prioritization using systematic conservation planning approach

To rank AEIs, the six-step systematic conservation planning approach of Margules and Pressey (2000) was followed. To implement this approach, the conservation planning software Marxan was applied, which is designed to select near-optimal reserve configurations based on finding least-cost solutions for all planning units using a simulated annealing optimisation method (Ball and Possingham 2000). The major steps of the process to define AEIs were to define the planning domain and planning units; this was followed by feature attribution and setting of conservation targets (Figure 10). Marxan is supported by a user-friendly front-end interface – the Conservation Land-Use Zoning (CLUZ) software – which was used together with the open-source GIS package QGIS.

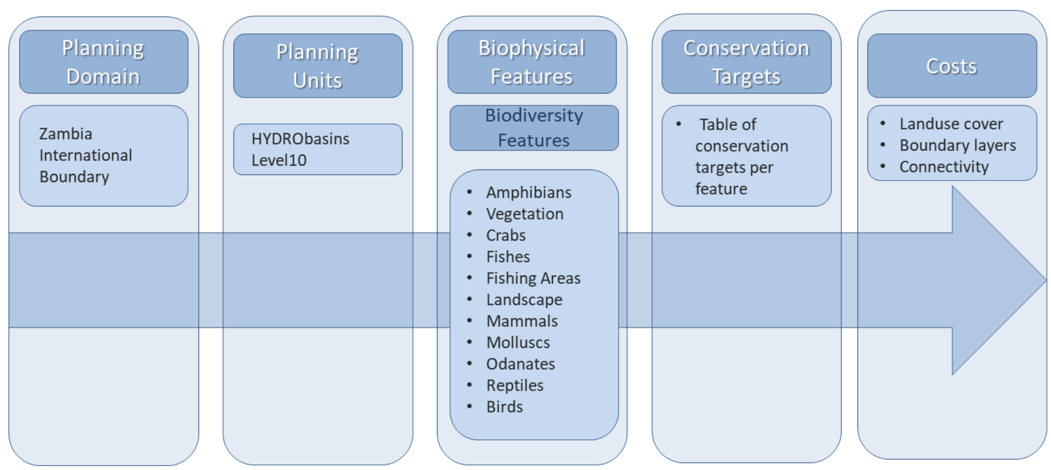

Figure 10: Conservation planning process and phases.

The planning protocol followed for identifying AEIs using Marxan involved the following steps:

1. Collate all available biodiversity features' information in GIS formats and select which features are most representative (range-restricted, endemic or threatened status).
2. Assess the conservation targets appropriate to each species or feature taking account of their IUCN threat or flagship status, the extent of their distribution range within Zambia or their representivity for a particular region.
3. Attribute planning units with 'abundance' data for each biodiversity feature.
4. Assign relative costs to planning units using area as a cost surrogate. Upstream-downstream connectivity between planning units was promoted using distance-weighted boundary costs (based on Linke et al. 2012).
5. The final near-optimal solution was chosen based on running multiple scenarios with different combinations of species targets and species penalty factors.

Marxan assumes that the spatial distribution of data is consistent, and uncertainty in the data is not considered. The optimal solution is influenced by the choice of, and weightings given to, biodiversity features. For this project, the final solution was constrained on the basis of the following exclusions:

- Wetlands were not included, on the basis that these would drive planning unit selection.
- Protected areas were excluded from the planning process, and all planning units were assumed to be equally "available". This decision avoids judgements on management efficiency of protected areas and allows for the estimation of reserve network efficiency in meeting aquatic biodiversity targets.
- Rivers were excluded from the planning process, on the basis that it would be difficult to defend a top-down river type classification as a legitimate surrogate for aquatic communities.

For the WRPA project, 200 Marxan runs were performed and the attribute of "summed solution" was used as the quantitative proxy to represent the importance (and ranking) of each sub-catchment. The summed solution is the number of times a sub-catchment is selected for the conservation portfolio. The resulting values (0 to 200) were standardized (using percentages) into 10 classes ranked from 1 to 10, and 0 was assigned to sub-catchments with a summed solution of 0 (that is, it was never selected).

2.4.3 Free-flowing rivers assessment

A free-flowing river (FFR) is a river where ecosystem functions and services are largely unaffected by changes to the fluvial connectivity allowing an unobstructed exchange of material, species and energy within the river system and surrounding landscapes. FFRs are the freshwater equivalent of wilderness areas and they support many of the most diverse, complex and dynamic ecosystems globally, providing important societal and economic services. For example, floodplains are among the most productive and diverse riverine ecosystems globally (Costanza et al. 1997) and their disconnection from the upstream catchment and/or river channel alters ecosystem services such as natural flood storage, nutrient retention, and flood-recession agriculture (Opperman et al. 2017). FFRs provide a significant source of inland fisheries (McIntyre et al. 2016); and in contrast, built river infrastructure has been linked to declines in freshwater species (Vörösmarty et al. 2010). Acknowledging the importance of river connectivity, a decade ago the Brisbane Declaration (2007) called for the identification and conservation of “a global network of FFRs” and in 2015 the world’s governments committed to “protect and restore water-related ecosystems” under the United Nations’ Sustainable Development Goals (Target 6.6).

Given the importance of free-flowing rivers, it was agreed in the supporting workshops to include them as an independent layer of information for the selection of WRPA candidate sites. A separate FFR assessment was conducted for Zambia and the wider Zambezi region (Grill et al. 2017) which used the same underlying methodological blueprint as a related global FFR study (Grill et al. 2019). The Zambian assessment applied a more local context, various datasets from the global study were improved or adapted, and thresholds were adjusted to better fit the local situation. It should be noted, however, that the global study includes a sediment index which was not incorporated in the earlier Zambian study, and some errors were corrected in the global study (see Figure 11).

In the Zambian FFR approach, four pressure factors were assessed which represent the main human interferences on river connectivity: (a) river fragmentation; (b) flow regulation; (c) water consumption; and (d) infrastructure development in riparian areas and floodplains. To quantify each of the four pressure factors, five representative proxies (pressure indicators) were used: the Degree of Fragmentation (DOF); the Degree of Regulation (DOR); consumptive water use (USE); road density (RDD); and urban development (URB). The five indicators were weighted within a multi-criteria overlay to derive the Connectivity Status Index (CSI) which quantifies connectivity ranging from 0% to 100% for every river reach. Finally, free-flowing rivers were extracted as those rivers with a CSI above 95% over their entire length from source to river outlet. There can also be free-flowing stretches which are parts of free-flowing rivers that are divided by one or more non-free-flowing sections along their course. The river network underpinning this work was provided by the global HydroSHEDS database (Lehner et al. 2008), yet all rivers were removed from the FFR analysis that were shorter than 10 km, showed an average annual river flow of less than 1 m^3/s, or were in arid regions (according to existing physiographic maps) to exclude increasingly uncertain results of smaller and intermittent rivers. These selection criteria reduced the analyzed river network of Zambia to 13,877 reaches with a total length of 67,695 km.

Figure 11 shows the results of the FFR study for Zambia. Overall, 84.6% of the river kilometers analyzed were classified as free-flowing. This relatively high number is the result of a disproportional dominance of small free-flowing rivers (10-100 km) in the river network, compared to fewer longer and larger rivers. There are 11 long rivers (> 500 km) flowing in the study area and six of these were identified as free-flowing, which accounts for about 43.5% by length and 54.5% by number of all analyzed rivers. Remaining long free-flowing rivers are more prevalent in the western part of the Zambezi Basin, where long tributaries are found relatively undisturbed. Another important area is the northeastern part of Zambia, where rivers drain into the Congo Basin, and where a number of long rivers are found. Finally, in the center/east of Zambia the Luangwa River is slightly affected by river fragmentation from downstream dams, and by river regulation from the Lunsemfa River; nevertheless, it still classifies as a very long (>1000 km) free-flowing river in the assessment. The only other two parts of very long free-flowing rivers in Zambia are the Chambeshi/Luapula River and parts of the Cuando/Chobe River that flow along the western country border, yet much of their contributing catchments lie outside of Zambia.

In order to incorporate the results of the FFR assessment into the WRPA project, the following ranking scheme on a scale of 0 to 10 was developed:

10	Free-flowing river	very long (> 1000 km)
9	Free-flowing stretch	very long (> 1000 km)
8	Free-flowing river	long (750 - 1000 km)
7	Free-flowing stretch	long (750 - 1000 km)
6	Free-flowing river	medium length (50 - 750 km)
5	Free-flowing stretch	medium length (500 - 750 km)
4	Free-flowing river	short (250 - 500 km)
3	Free-flowing stretch	short (250 - 500 km)
2	Free-flowing river	very short (< 250 km)
1	Free-flowing stretch	very short (< 250 km)
0	Non-free flowing river or stretch	any length

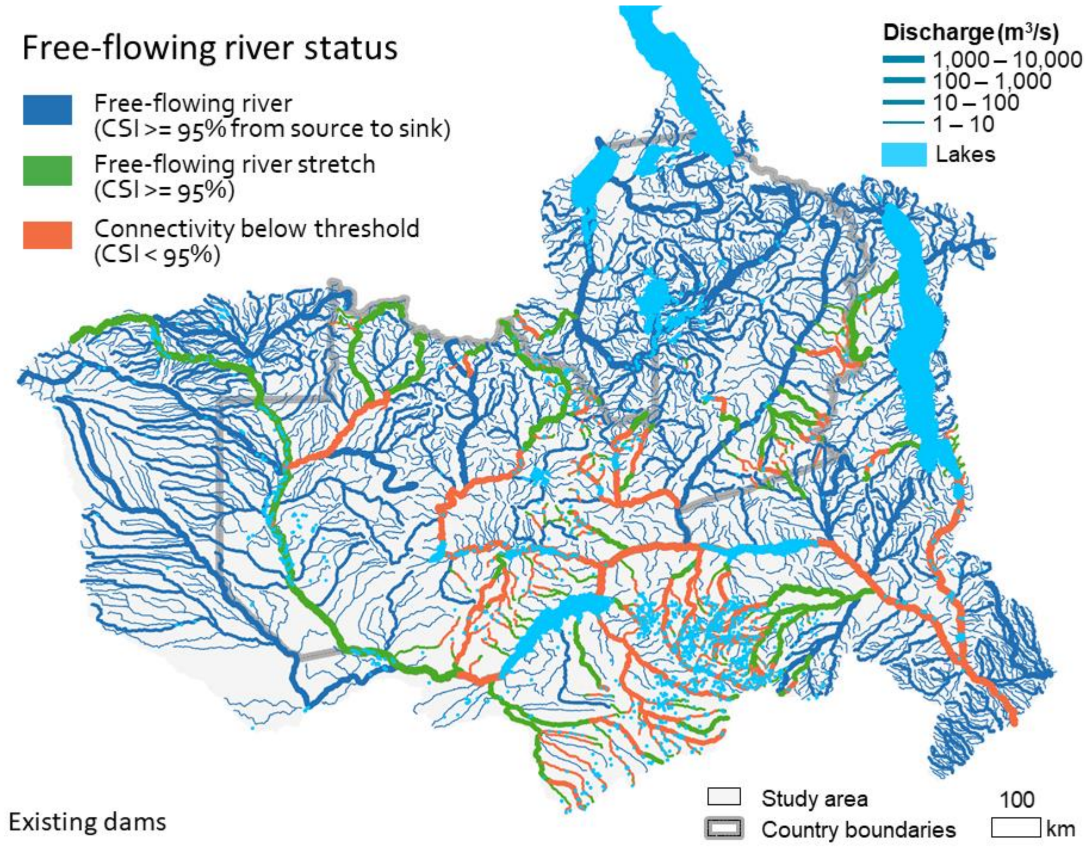

Figure 11: Results of the free-flowing rivers assessment for Zambia (Grill et al. 2017). Map shows the distribution of free-flowing rivers (FFRs), contiguous river stretches with 'good connectivity status' (free-flowing stretch), and impacted rivers with reduced connectivity. Rivers that are not free-flowing over their entire length (that is, partially below the CSI threshold) are divided into stretches with 'good connectivity status' (that is, connectivity status remains above the threshold throughout stretch; green colours) and stretches where the connectivity status is below the CSI threshold (red colours). Note that the Kabompo River (shown as a non-free-flowing eastern tributary of the Zambezi) contains an error and was corrected (as free-flowing) in the WRPA assessment (see Figure 24).

2.5 Criterion 3: Sensitivity to impact

Various factors were considered and discussed during the different workshops to assess the sensitivity of sub-catchments and rivers to use and anthropogenic impact. Water resources and their availability for downstream users, both in terms of quantity, quality, and timing, can be affected by many alterations in the contributing watershed or in the stream channel, including land cover change, land use practices, land degradation, human water use, as well as future climate and socioeconomic changes. We will discuss some of these aspects in more detail in section 2.5.3, but in general, data limitations posed severe constraints on including most of these aspects in the national WRPA assessment.

Given these shortcomings, we used two proxies to rank the sensitivity of different areas to use and anthropogenic impact: soil erosion and in-stream sediment transport.

2.5.1 Soil erosion

Sub-catchments were assumed to be highly sensitive to degradation in their water resource provision if they are prone to soil erosion, not least due to the related negative effects on downstream water quality. There is currently no consistent, high-resolution digital map of the potential risk of soil erosion for Zambia at a national scale. We thus used a high-resolution (250 m) soil erosion map that was developed at the global scale (Borrelli et al. 2017) as a proxy to derive spatial patterns of erosion risk within Zambia. This erosion map is based on the frequently applied Revised Universal Soil Loss Equation (RUSLE) which uses six input factors to predict potential soil loss: rainfall erosivity, soil erodibility, slope length, slope steepness, land cover management, and support practices. Therefore, the map combines natural forcing factors such as topographical conditions of the hill slopes and soil properties with land use, cropping systems and conservation practices, considers mobilization of sediment from sheet and rill erosion, yet neglects denudation and fluvial conveyance processes.

In order to validate the quality of Borrelli's erosion map (shown in Figure 12), a visual comparison was conducted against a national erosion hazard map (in paper format) produced by the Soil and Water Conservation and Land Utilization Coordination Unit of SADCC (Figure 13). Overall, the two maps reveal similar patterns of potential soil loss patterns in Zambia, with some exceptions in smaller regions.

We also conducted a more quantitative assessment of the overall spatial distribution of soil erosion. For this purpose, we accumulated the total soil erosion amounts within 48 select headwater catchments in Africa as provided by Vanmaercke et al. (2014) (average catchment size 685 km^2; all catchments were inspected for being free of lakes, dams, or extensive floodplains to reduce effects of sediment capture). Figure 14 shows that the RUSLE-based accumulated sediment loads were matching the reported values reasonably well, confirming the ability of the erosion map by Borrelli et al. (2017) to distinguish between areas of high and low soil erosion. In fact, most are overestimating the sediment load which is expected as the simple accumulation of soil erosion neglects the effects of sediment deposition on the landscape.

Given these comparisons and statistical evaluations, it was concluded by in-country experts that despite the known limitations of the relatively simplistic RUSLE method in predicting small-scale erosion effects, the estimates by Borrelli et al. (2017) represent a consistent first-level proxy to quantify the spatial variability in potential soil erosion. Hence we deem the results adequate for assessing the level of sensitivity of sub-catchments in Zambia to soil erosion. For the application within the WRPA assessment, the values of average soil erosion (in tons per hectare and year) were standardized to a scale of 1 to 10 (using quantiles).

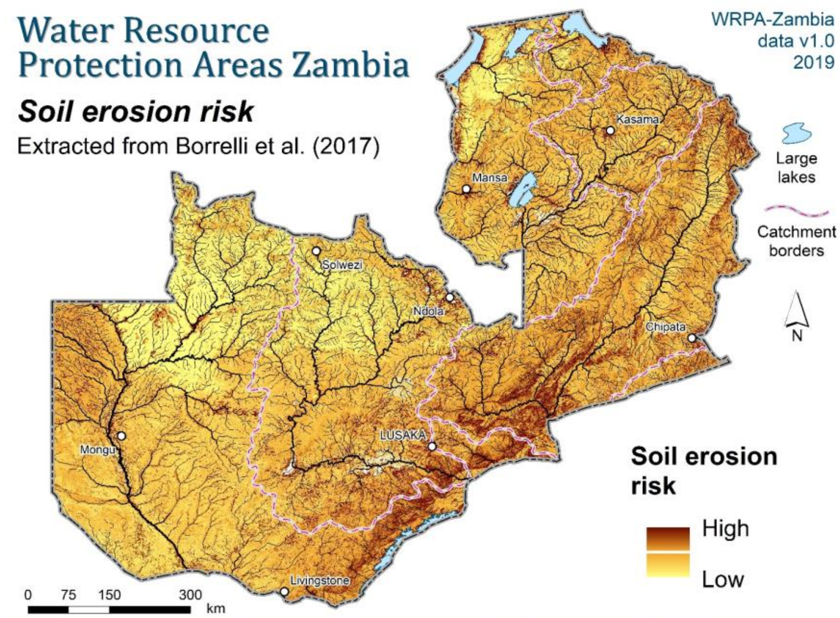

Figure 12: Erosion map by Borrelli et al. (2017), extracted for the extent of Zambia.

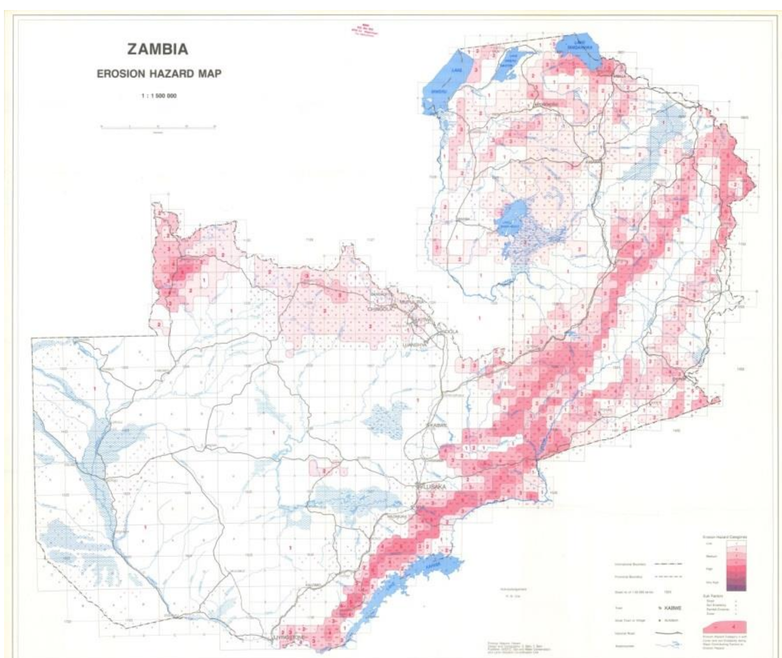

Figure 13: Erosion hazard map of Zambia (credited to R.M. Chiti; Soil and Water Conservation and Land Utilization Coordination Unit of SADCC; not dated). Colour shades from white to dark red represent eight erosion hazard categories ranging from low to very high. Factors included in the assessment were slope, soil erodibility, rainfall erosivity, and land cover.

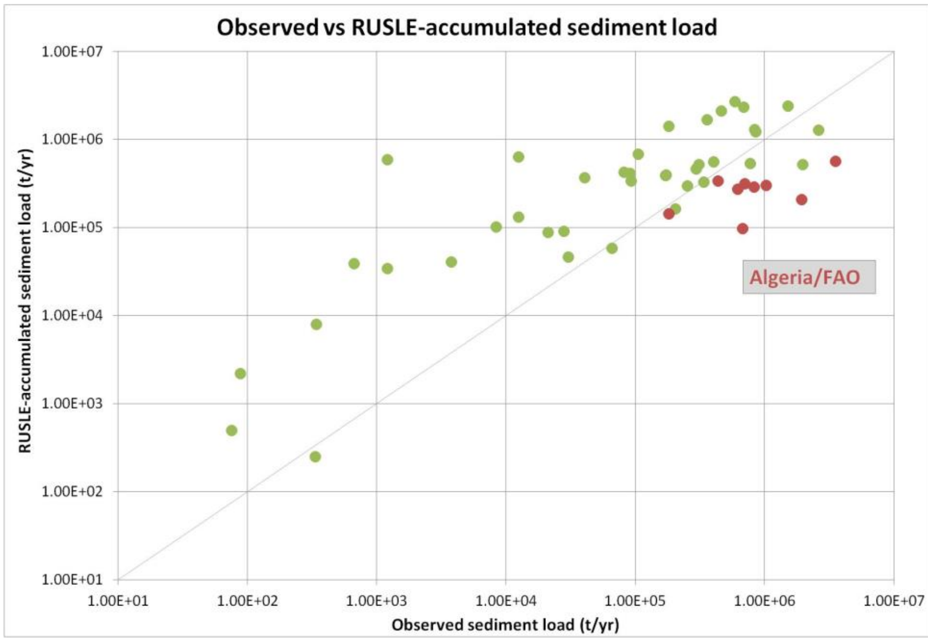

Figure 14: Correlation of observed vs. modelled sediment loads for 48 select catchments in Africa. Observation data were provided by Vanmaercke et al. (2014). Modelled data were calculated as accumulated sum of soil erosion based on Borrelli et al. (2017). Overestimation (that is, points above the 1:1 line) is expected due to the missing consideration of sediment deposition in the landscape in the model results; data for Algeria (originally collected by FAO) are an outlier in that observations seem to consistently exceed modelled sediment loads.

2.5.2 Sediment transport

Soil erosion is also the main source of sediments which are then transported downstream. Sediment content and transport in rivers is important in order to sustain the physical habitat of aquatic ecosystems and is thus critical to be maintained at natural levels and regimes. Sediment connectivity is a key driver for morpho-dynamic processes in small upland streams as well as in large lowland rivers (Constantine et al. 2014). Dams have been shown to capture large amounts of sediments in their reservoir impoundments (Vörösmarty et al. 2003) with the amount of sediment being trapped determined by dam design and operation and the spatial heterogeneity of natural sediment flux in the river network (Schmitt et al. 2018). This sediment capture can trigger a cascade of impacts on fluvio-geomorphological dynamics and processes downstream.

Due to data limitations, the deterministic modelling of sediment transport processes in individual river reaches over large scales remains challenging, and very few large-scale sediment models exist. Here, we utilize novel results derived by the HydroROUT model to quantify the Potential Sediment Load (PSL) at any given point in the global river system (Grill et al. 2019). The model uses the erosion map of Borrelli et al. (2017) to estimate the accumulated suspended sediment load in the river system at each river reach, and accounts for natural sediment trapping in lakes by multiplying the accumulated sediment loads with respective trapping efficiencies following the method proposed by Brune (1953). Details and equations of all calculations are documented in Grill et al. (2019). In addition to sediment load, sediment concentrations were calculated as the ratio between sediment load and average discharge.

To test the quality of our global sediment model results, we compared the PSL estimates against reported data of observed sediment transport at 398 gauging stations globally (Meybeck et al. 2003; Milliman et al. 2011; Vanmaercke et al. 2014; Constantine et al. 2014). Our estimates were able to explain 64% of global and 65% of continental variance in observed sediment load, and more than 83% for three continents (North America, Asia, and Europe). However, the intra-basin variance is most relevant to derive a plausible indicator for natural sediment origins and spatial patterns of sediment connectivity within individual river basins. Within three river basins with multiple observations (Blue Nile and Niger in Africa; Amazon in South America) and for four Asian river basins (Mekong, Irrawaddy, Salween, and Red River), the modelled PSL explains on average 81% of the observed intra-basin variance, indicating a reasonable performance of the global sediment model.

Given the validation results, and after reviews by in-country experts, absolute sediment loads and concentrations were deemed too uncertain to be used directly within the WRPA assessment. However, the relative (ranked) values, that is, the distribution of high versus low sediment rivers was concluded to display reasonable spatial patterns and was thus included in the WRPA assessment. For this purpose, the values of average sediment loads and sediment concentrations were standardized to a scale of 1 to 10 (using quantiles).

While showing some correlation, sediment loads and concentrations are complementary indicators to describe the sediment characteristics of a river. For example, a large river can have relatively low sediment concentrations, yet due to its large discharge volume the total sediment load can still be substantial. On the other hand, small streams will generally be limited in total sediment load, yet they can show strong variation in sediment concentrations. The sensitivity of rivers in terms of sediment transport is equally multifaceted: a dam on a river with high sediment load can trap large amounts of sediments and affect the natural sediment balance far downstream. A dam on a small river, on the other hand, is less likely to cause substantial sediment effects far downstream (due to the limited sediment contribution of the small stream), but it can strongly affect local sediment conditions if it is built on a stream with high sediment concentration. Rivers with low sediment loads and low concentrations are expected to be generally less sensitive to impacts. For this reason, both the results of the ranked sediment loads and the ranked sediment concentrations were used in the WRPA assessment by averaging their respective ranks.

2.5.3 Land use, climate and socioeconomic change

Land use change and land degradation were considered as additional factors affecting the sensitivity of an area to human impact. While no adequate data at a national scale and in good quality could be identified to represent scenarios of future land use change, various large-scale maps exist showing current and historic land use based on land cover classifications derived from remote sensing imagery, including large-scale maps of specific aspects of land cover change such as deforestation. These maps, in principle, could be used to characterize each catchment in terms of natural vs. modified land cover and land use. Yet the interpretation of these maps in terms of ‘sensitivity of an area to impact on water resources’ requires a cautionary approach, as for example different types of agricultural or forest management, which may appear similar on remote sensing imagery, can cause very different responses on the local surface water availability on the ground. It was thus decided in workshop 2 that the identification of candidate WRPAs should be conducted without directly incorporating land use as a layer in the sensitivity assessment. Instead, the risks of local land use practices and potential future development, as well as the ability of various land use management strategies to mitigate these effects should be used in subsequent steps. That is, any candidate WRPA site should be assessed on the ground in terms of its sensitivity to land use change, and the findings should be included in the protection recommendations.

In terms of assessing the effects of climate and socioeconomic change on water resources, several global water balance models exist which can address both aspects. However, these models operate at relatively coarse spatial resolution (10 km x 10 km grid cells or coarser) and depend on scenario assumptions of Global Climate Models (GCMs), Representative Concentration Pathways (RCPs), and Shared Socioeconomic Pathways (SSPs) that represent global rather than regional future developments. It was therefore deemed too uncertain and beyond the scope of this project to downscale these simulations in order to achieve meaningful and reliable results that can inform local water protection or management strategies. Instead, it is recommended that efforts are made to incorporate regional climate model results in future studies.

2.6 Combining all results

Two final result maps were produced from the individually ranked maps as described above: one for sub-catchments and one for river reaches. These two final maps were produced using the following combination techniques:

For sub-catchments, the three individually ranked maps representing the criteria of water provision, aquatic ecological importance, and sensitivity to impact were summed. As each input map was standardized to a range of 1 to 10 (or 0 to 10 for AEI), the summation means that the same weight applies to each criterion, and the resulting final ranking scores range from 2 to 30.

For river reaches, the ranked free-flowing rivers map (range 0 to 10) and the ranked sediment map (that is, standardized and averaged sediment load and sediment concentration maps, range 1 to 10) were used. In this case, the free-flowing river status is considered the dominant criterion, and the sediment characteristics are intended to be a modifier to distinguish between free-flowing rivers with high and low sediment transport. In particular, a river that is not free-flowing should receive a final score of 0 in the combined result even if sediments are present (as it is deemed least important for protection). This combination goal is achieved through multiplication of the two ranked maps which sets all non-FFR reaches to 0 and weighs all FFR scores by the scores of sediment transport. The resulting map shows combined scores ranging from 0 to 100.

3. Results

The Results section presents all in-between and final maps developed during the WRPA project. First, all maps of the three WRPA criteria are shown, separated into water provision (section 3.1), aquatic ecological importance (section 3.2) and sensitivity to impact (section 3.3). These results include both the spatial units of sub-catchments and river reaches. Finally, in section 3.4 the two combined maps of ranked candidate sub-catchments and river reaches are presented.

Many (but not all) maps show a dual legend where the classification of the original values is broken into 10 ranks. These ranks were derived through a standardization process as explained in the Methods section, that is, all sub-catchments or river reaches were ranked and divided into 10 equal quantiles (see Methods for more details).

3.1 Criterion 1: Water provision

This section presents all results related to the criterion of water provision.

Figure 15 shows the ranked land surface runoff map based on the downscaled estimates from the global WaterGAP model. Runoff is generally found to be highest in the north and north-east of Zambia (up to 463 mm per year), while lowest values occur in the south-west (down to 5 mm per year).

Figure 16 and Figure 17 show the distances from the individual outlets of each of the 6 major catchments in Zambia and the identification of source water sub-catchments of hilly terrain. These two results are then combined in Figure 18 to present the ranked headwater areas of Zambia. As expected, main headwater areas are located in the sub-catchments that are furthest upstream in the Zambezi, Kafue, Luangwa, and the combined Luapula/Chambeshi catchments. The initial distance ranking was modified by the terrain characteristics, for example extending the amount of highly ranked headwater regions in the Luangwa catchment in places where steeper slopes are found.

Figure 19 and Figure 20 show the results of the water demand assessment, that is, the identification of the number of downstream people and downstream dams, respectively. Sub-catchments draining from the Zambezi headwater areas show particularly high numbers in downstream people to whom they supply water, followed by the headwaters of the Kafue and Chambeshi. The Luangwa catchment is supplying water to less people downstream due to the lower population density in this region. In terms of dams, most of the Kafue catchment area supplies water to 4 downstream dams while other regions tend to show smaller numbers, with the Luangwa and Chambeshi catchments being mostly free of dams. The main exceptions are found in a series of sub-catchments between Lusaka and Livingstone where a high density of agricultural dams exists.

Finally, Figure 21 presents the combined prioritization of sub-catchments in regard to water provision. The overall spatial pattern mirrors generally that of the runoff and headwater maps, yet with some modifications driven by downstream water use patterns. The highest ranked (or most important) sub-catchments in terms of water provision are found in the headwater regions of the Zambezi, Kafue, and Chambeshi catchments, and to a lesser degree in the Luangwa and Tanganyika catchments.

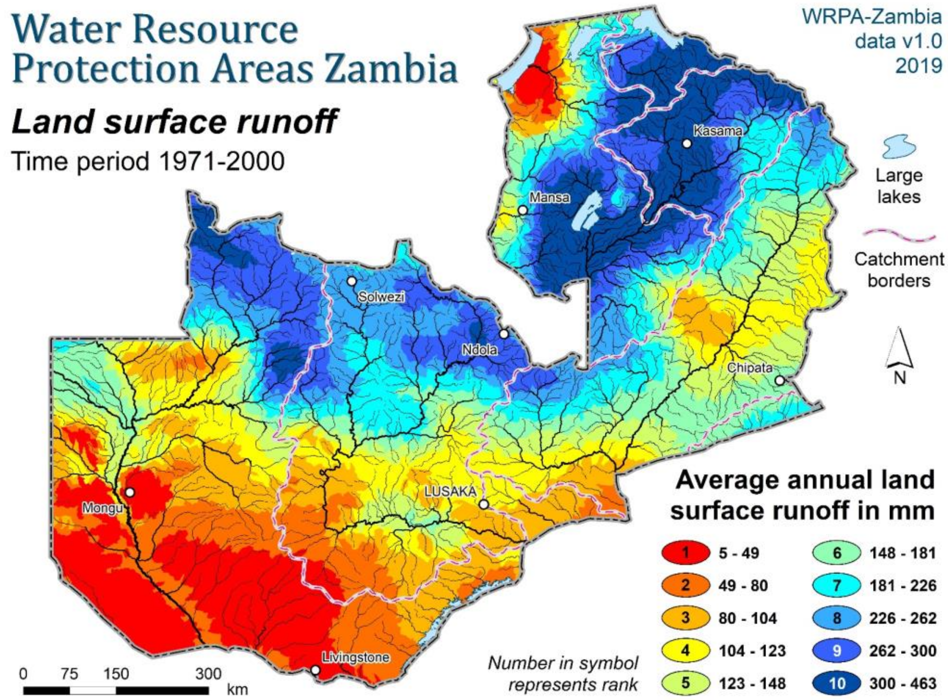

Figure 15: Long-term average land surface runoff as provided by the global hydrological model WaterGAP (version 2.2), downscaled to the sub-catchment units of Zambia.

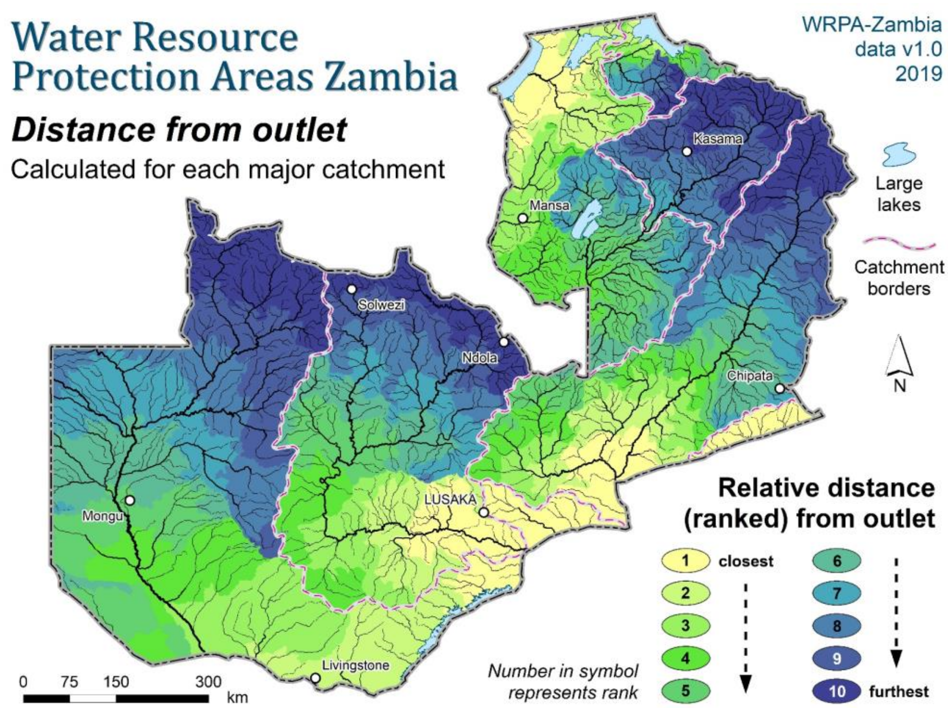

Figure 16: Distance from the outlet of each of the six major catchments in Zambia, calculated along the HydroSHEDS river network.

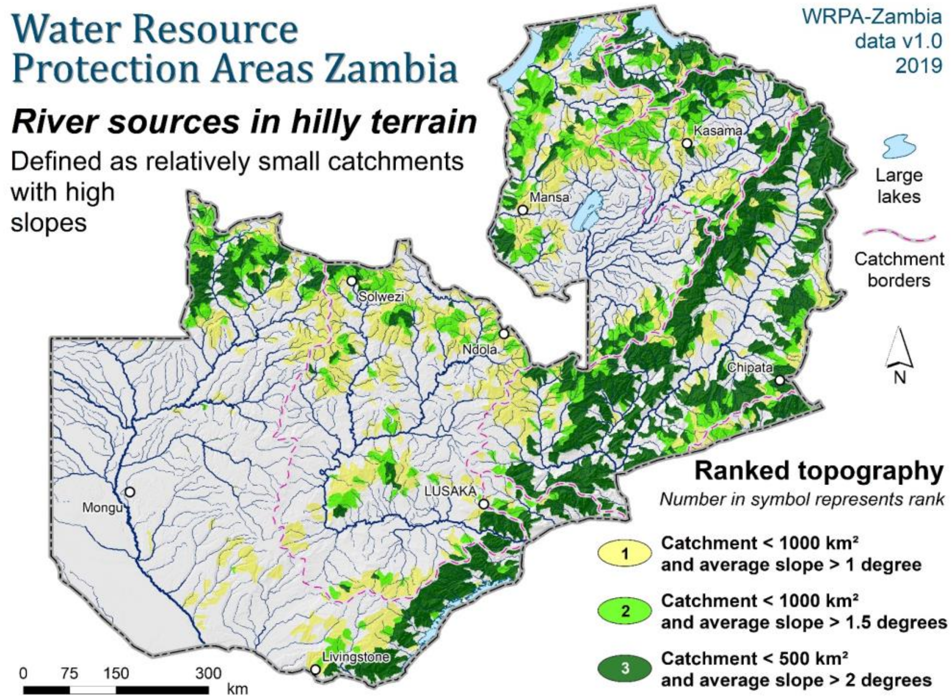

Figure 17: Identification of river source areas in hilly terrain, based on catchment size and slope calculations.

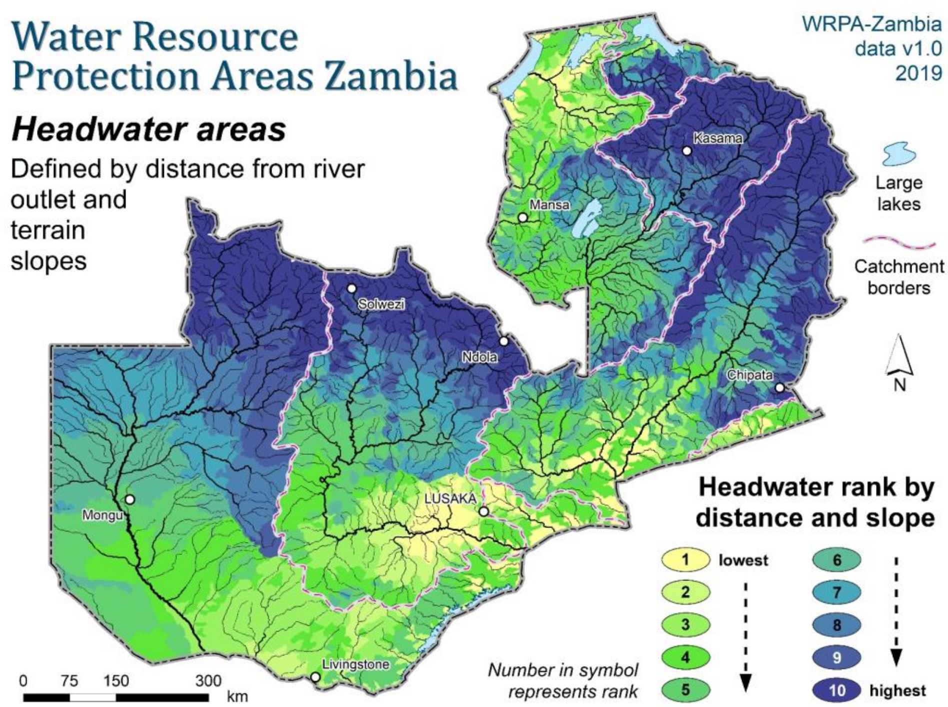

Figure 18: Map of headwater areas in Zambia. The ranking is derived by combining the distances from the main catchment outlets with the river sources in hilly terrain. Higher ranks indicate sub-catchments that are more likely to represent headwater areas.

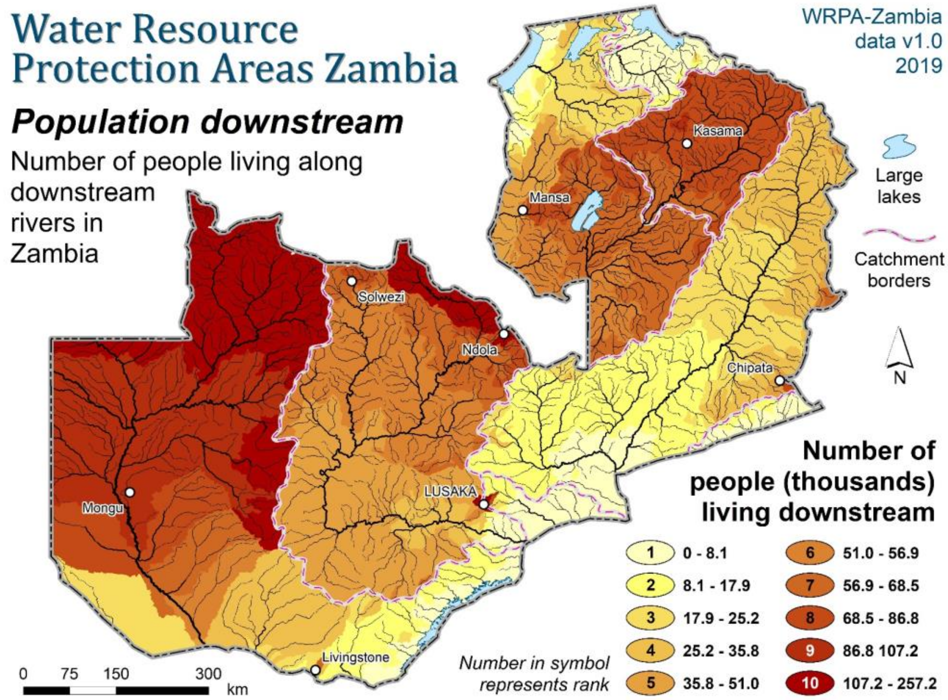

Figure 19: Number of people living downstream, calculated from any location in Zambia. Higher numbers are assumed to indicate higher water demand for human use.

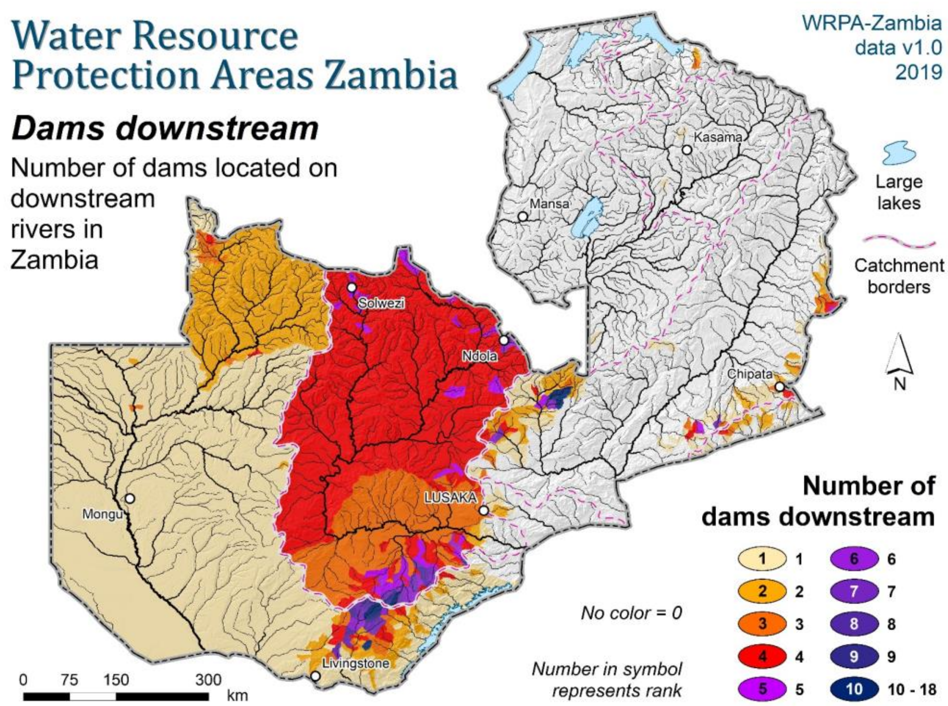

Figure 20: Number of dams found downstream, calculated from any location in Zambia. Higher numbers are assumed to indicate higher water demand for agricultural and human use.

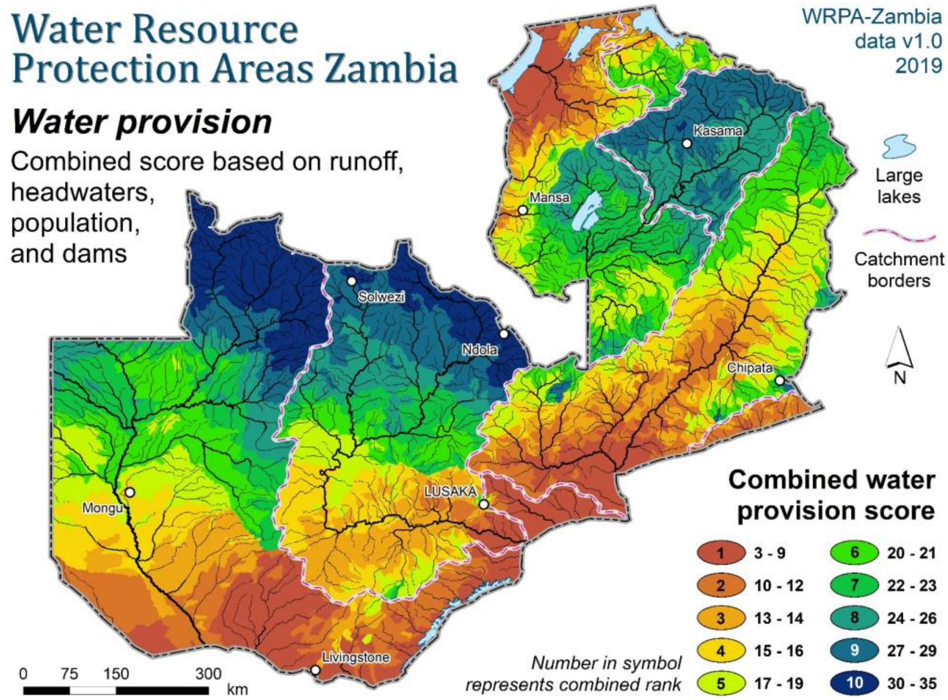

Figure 21: Combined (summed) score of the four individually ranked and standardized input maps of runoff, headwater areas, downstream population and downstream dams. The final score was then standardized again into 10 ranks again quantiles.

3.2 Criterion 2: Aquatic ecological importance (AEI)

3.2.1 Prioritization using systematic conservation planning approach

Figure 22 shows the final map of the Marxan-based AEI assessment representing the summed solution of 200 model runs; all targets were achieved in this solution. Of the total number of planning units selected in the best solution, 21.5% corresponded with protected areas; and of the total area of national parks, 70.6% corresponded with selected AEIs. Thus, a significant proportion of AEIs falls within or is represented by national parks, including portions of the Zambezi floodplain, Kafue National Park, and North and South Luangwa National Parks. However, a number of areas including the uppermost regions of the Kafue headwaters, the Bangweulu swamps and the upper Zambezi are not well covered by the existing protected areas network.

The Zambezian headwaters and the upper reaches of the Kafue are well represented in the selected AEIs, as are the Zambezi and Barotse floodplains. The Bangweulu swamps with the Mweru wa Ntipa, and Lake Tanganyika with its feeder rivers come out as areas of high ecological importance. Among the regions not selected in the final Marxan solution are the upper reaches of the Luangwa River on Muchinga Escarpment. Despite not being selected, stakeholders felt this was a consequence of data deficiency rather than a true reflection of the ecological importance of this region.

The final solution highlighted a number of priority areas that would require intervention to protect important aquatic ecological areas in Zambia. These include the upper Zambezi River catchment; the Zambezi River floodplain; Kafue Flats; areas of the Luangwa River, and Lake Tanganyika. There was good correlation between the identified AEIs and major wetland systems as well as important bird areas. The highlighted AEIs also identify important habitats for large mammals such as lechwe and other large semi-aquatic mammals. The final solution also showed a fairly good congruence with the earlier study by Pence (2012), bearing in mind that this study used the whole of the Zambezi catchment as the planning domain. Furthermore, important fishing areas (river reaches and lakes) are included in the AEI network. Stakeholder feedback confirmed that the final output matched with perceptions and expectations of important biodiversity areas.

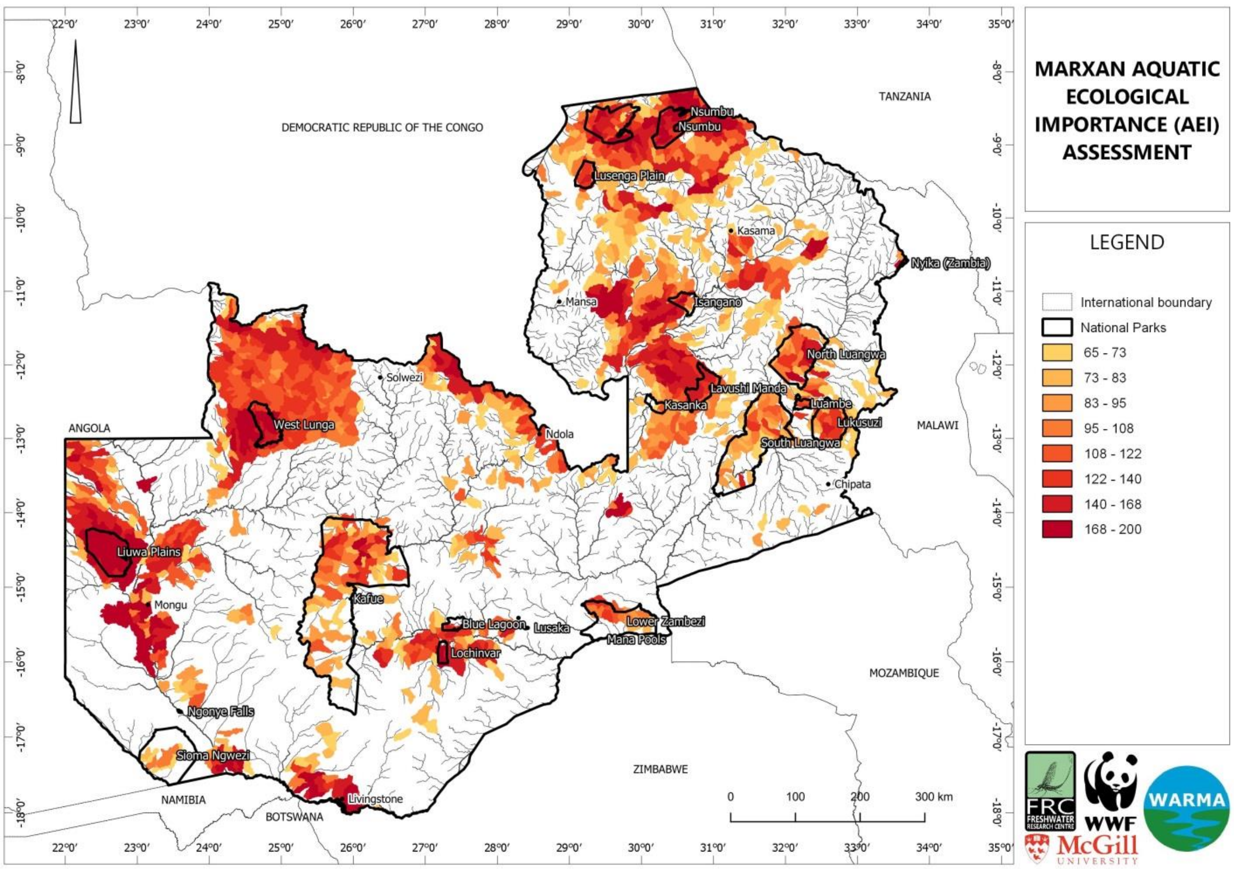

Figure 22: Results of AEI assessment conducted by Rivers-Moore and Paxton (2019). Map shows final Marxan solution for areas of Aquatic Ecological Importance in Zambia for those areas selected over 65 times. Colour codes show the number of times the model selected a sub-catchment based on 200 runs.

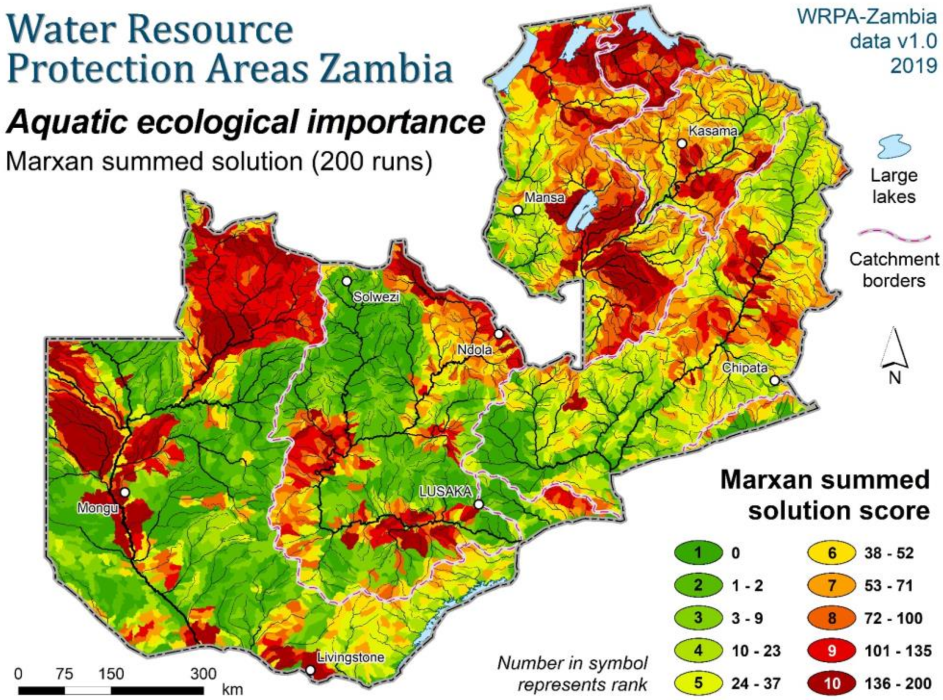

Figure 23: Results of AEI assessment conducted by Rivers-Moore and Paxton (2019), as presented in Figure 22, standardized into 10 ranks using quantiles.

3.2.2 Free-flowing rivers assessment

Figure 24 shows the results of the free-flowing rivers assessment by Grill et al. (2017), with a correction for Kabompo River applied following Grill et al. (2019). Rivers were categorized into 10 ranked classes, based on their FFR status and their length. The highest FFR ranks are achieved by the Luangwa and Chambeshi/Luapula rivers (rank 10), which are very long (>1000 km) and are free-flowing along their entire course from source to sink. The Zambezi River qualifies as a very long free-flowing stretch (rank 9) within Zambia but does not have full FFR status due to the dams on the lower main stem. Note that the highest rank is also achieved by the Cuando/Chobe River, which is not visible in the map as it is only flowing along parts of the western border of Zambia. Several rivers within Zambia are flagged as not free-flowing, in particular the main stem of the Kafue River.

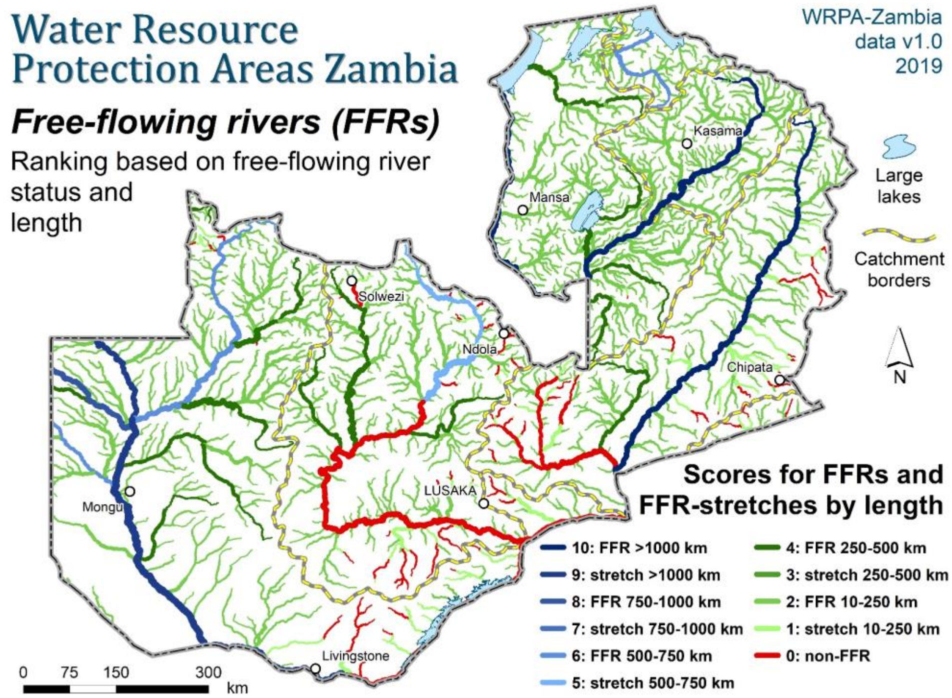

Figure 24: Free-flowing river assessment conducted by Grill et al. (2017), with correction for Kabompo River applied following Grill et al. (2019), ranked into 10 classes based on FFR status and river length.

3.3 Criterion 3: Sensitivity to impact

Figure 25 shows the modeled soil erosion patterns derived from the global database provided by Borrelli et al. (2017). Highest soil erosion risk, with values exceeding 5 tons/ha per year, are found in the Luangwa catchment as well as the lower parts of the Kafue and Zambezi catchments.

Figure 26 and Figure 27 are based on the same erosion data as presented in Figure 25, but the eroded soil quantities were routed along the river network and trapped in lakes where they exist. The routing model calculated sediment load (tons/year) and concentration (grams/liter) which were then ranked into 10 classes using quantiles. The resulting spatial patterns are generally reflecting the inputs from the erosion map, yet an important distinction is apparent between load and concentration maps: sediment loads tend to increase along the course of all rivers and are highest for large river, as the total sediment load is continuously increasing in larger river flows (unless a lake exists). In contrast, concentration values show a different pattern and are more closely mirroring the soil erosion distribution: rivers in high erosion regions show higher sediment concentrations, and vice versa. This leads to cases where rivers can have high sediment loads but low sediment concentrations, such as evident for the Chambeshi River.

Finally, Figure 28 shows the combined sediment index which was calculated as the average between the ranked scores of the sediment load and sediment concentration maps. The most distinct river in terms of displaying both high sediment load and concentration values is the Luangwa River which achieved the highest overall sediment scores.

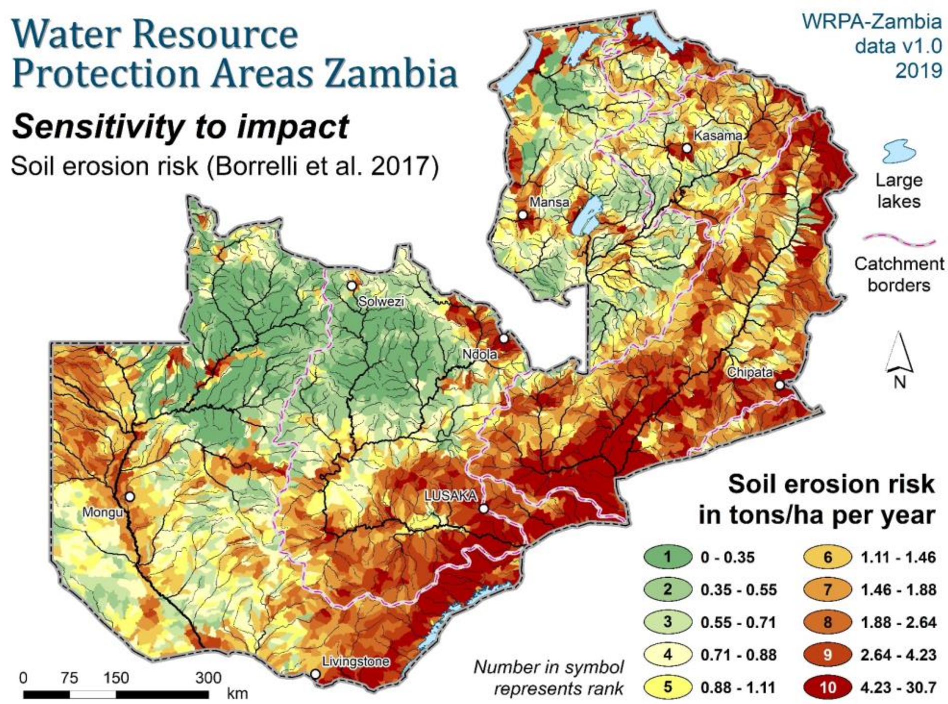

Figure 25: Soil erosion risk of Zambia according to model results provided by Borrelli et al. (2017).

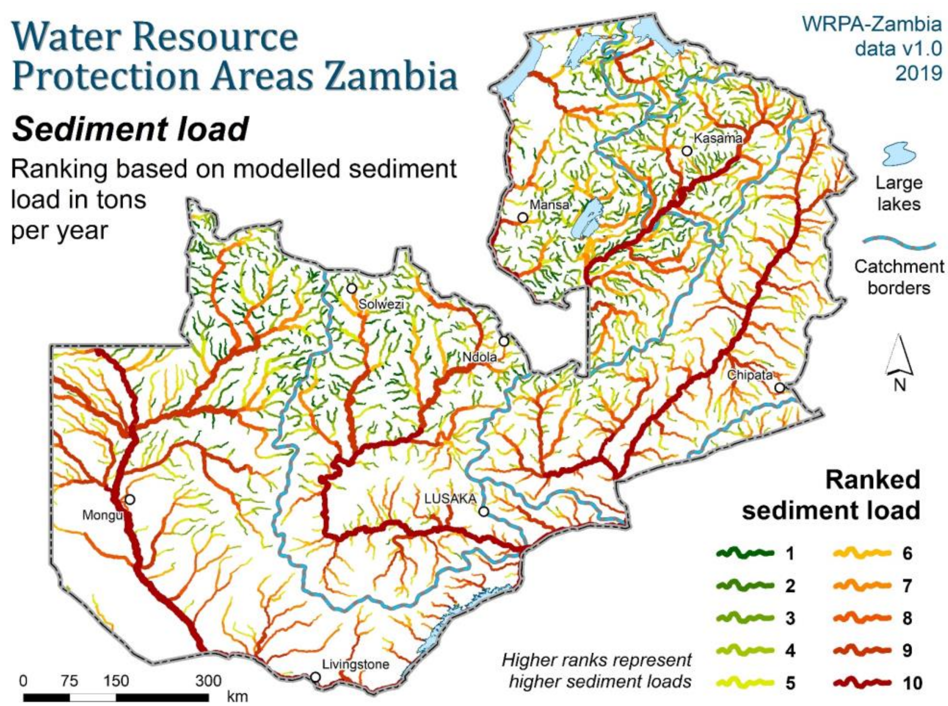

Figure 26: Ranked sediment load as calculated using the soil erosion values of Borrelli et al. (2017), accumulated with the river routing model HydroROUT (Grill et al. 2019). Ranks were created through standardization using quantiles.

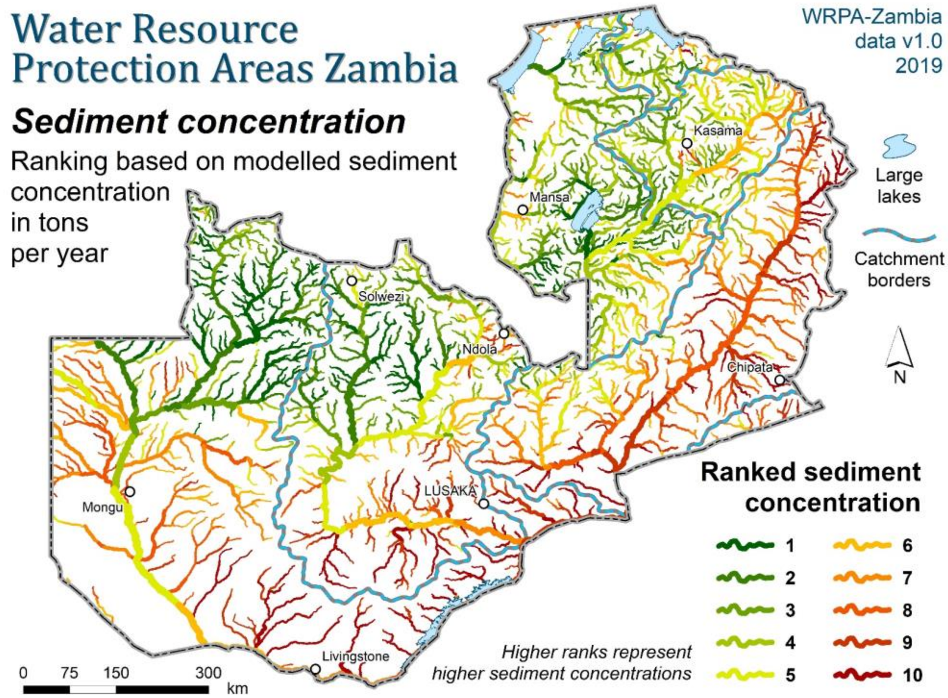

Figure 27: Ranked sediment concentration as calculated using the soil erosion values of Borrelli et al. (2017) and the river routing model HydroROUT (Grill et al. 2019). Sediment concentrations were derived by dividing sediment load (Figure 26) by long-term average discharge. Ranks were created through standardization using quantiles.

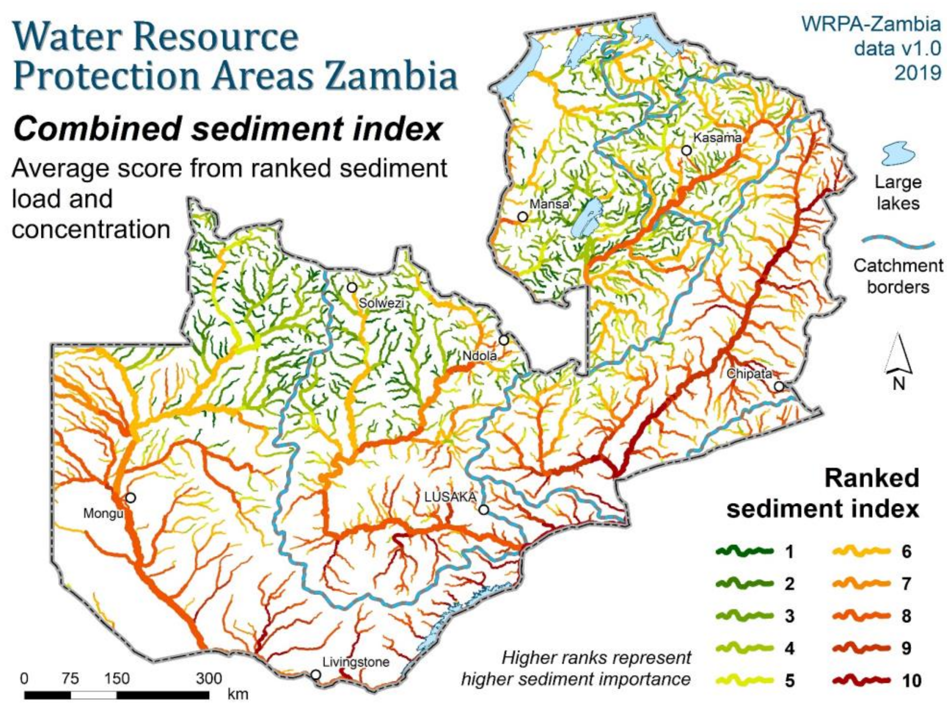

Figure 28: Combined sediment index, calculated as the average between the ranking scores of the sediment load and sediment concentration maps.

3.4 Combining all results

Figure 29 shows the final result of the WRPA assessment for sub-catchments. Larger contiguous areas of multiple sub-catchments that scored highly (blue colours) are found (from west to east) in and around the Liuwa Plains (between and north of the Lungwebungu and Luanginga rivers); in the Barotse Floodplain; in the upper Zambezi headwaters (upper Kabompo, West Lunga and Mwombezhi rivers); in the uppermost Kafue headwaters; in the Bangweulu Lake and Wetlands region; widespread throughout the Chambeshi system; and in a somewhat more dispersed pattern in the Lake Tanganyika headwaters and middle and upper Luangwa headwaters (e.g. North Luangwa Park, Mafinga Hills). Many additional smaller patches of highly ranked sub-catchment are found throughout Zambia.

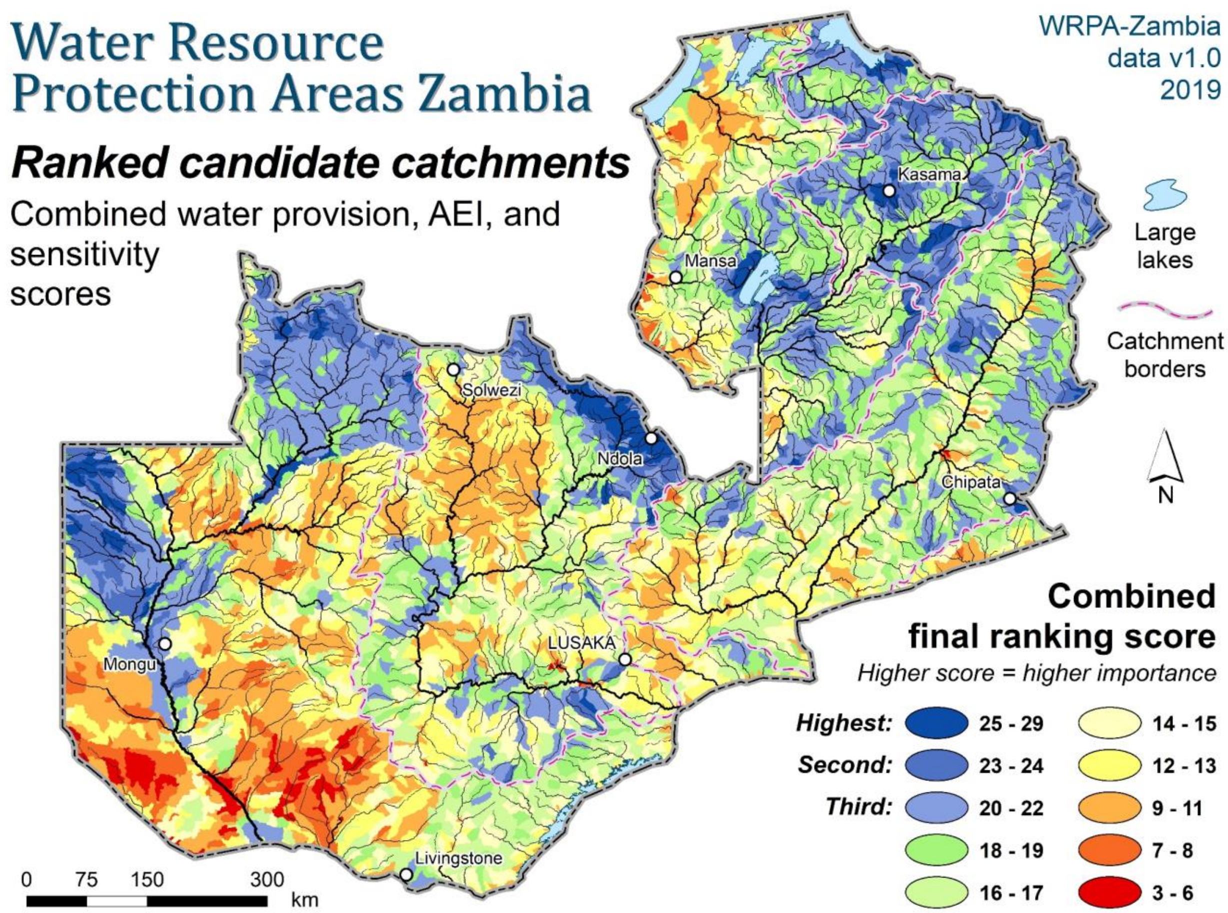

Figure 29: Final result showing the prioritization of WRPA candidate sub-catchments.

Figure 30 shows the final result of the WRPA assessment for rivers. The most distinct river ranked uniquely at the highest level is the Luangwa, which represents the only very long free-flowing river with high sediment loads and concentrations. Protecting this river from any in-stream development that alters its free-flowing status or natural sediment transport is deemed paramount. Other important rivers in terms of connectivity and sediment transport are the Chambeshi/Luapula River and the upper Zambezi River, including its two western tributaries of the Lungwebungu and Luanginga rivers. Other noteworthy examples are formed by several tributaries of the upper Zambezi, including the Kabompo River, and in the upper Kafue system.

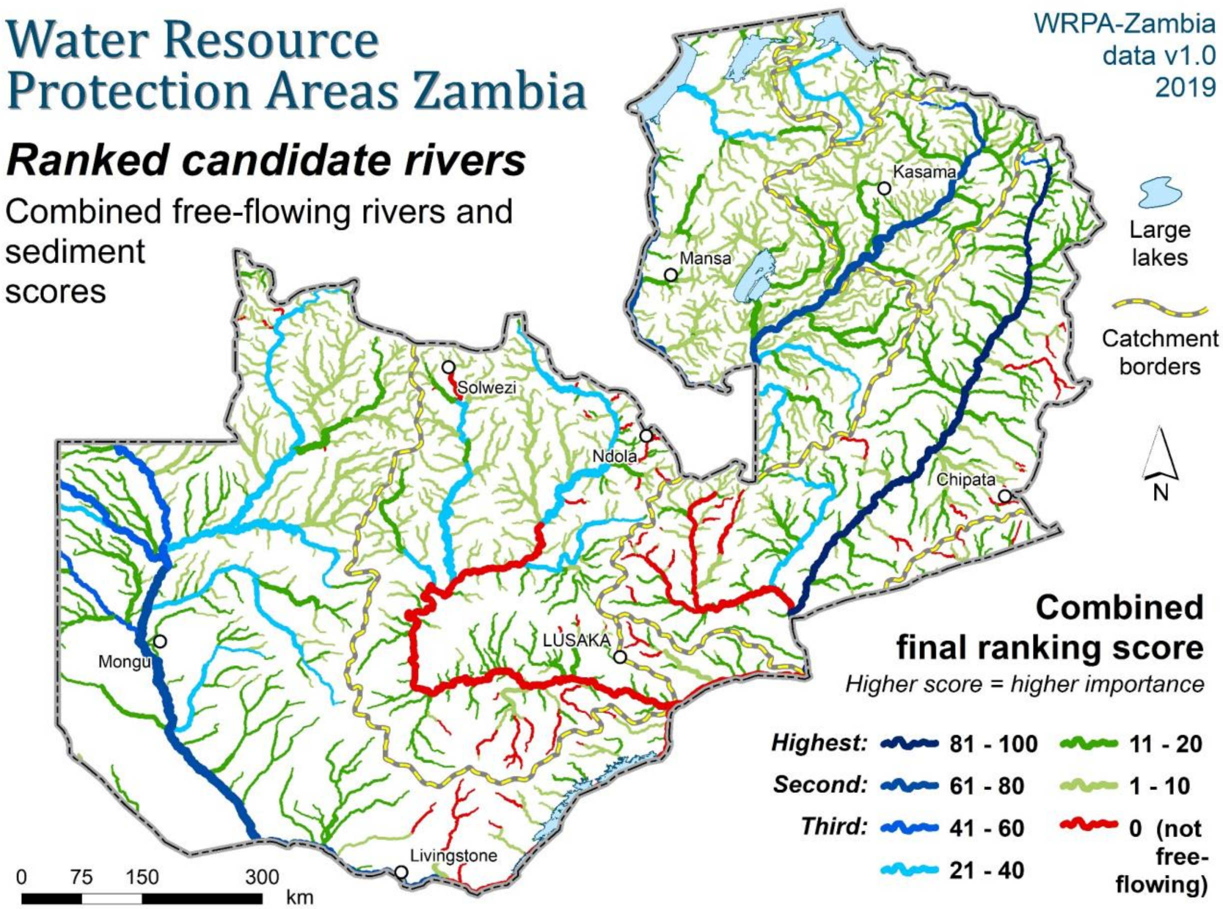

Figure 30: Final result showing the prioritization of WRPA candidate rivers.

4. Discussion and conclusions

The presented two final maps of candidate sub-catchments and rivers represent a "blueprint" of important areas for water resource protection in Zambia. The process of identifying these areas has been iteratively refined through stakeholder engagement in a series of three workshops, and there was general agreement on the appropriateness of the results as a decision-making tool. The presented results, data and methods are expected to play a critical role in prioritizing water resource protection areas, identifying rivers with high conservation value for protection, and optimizing decision making for infrastructure development.

As key findings in terms of candidate sub-catchments, larger contiguous areas of highly ranked areas were found within and north of the Liuwa Plains; in the Barotse Floodplain; in the upper Zambezi headwaters; in the uppermost Kafue Headwaters; in the Bangweulu Lake and Wetlands region; widespread throughout the Chambeshi system; and in a somewhat more dispersed pattern in the Lake Tanganyika headwaters and middle and upper Luangwa headwaters (Figure 29).

River connectivity is a critical component to maintain riverine ecosystem services and functions. To address this specific issue which is often overlooked in catchment based protection strategies, we conducted a separate assessment with a river perspective. The outcomes differ in that rivers are expected to require their own, specific protection strategies. In particular, a river-centered protection strategy may focus on avoiding in-stream or floodplain development, such as the construction of dams and levees, which disconnect the main flow channel from its upstream, downstream and lateral parts. Given the identified importance of the Luangwa River from both a connectivity and sediment perspective (Figure 30), as well as for local and regional wildlife, plans to develop new infrastructure should thus be re-evaluated and accompanied by comprehensive strategic and transboundary impact assessments and should consider alternative development pathways to minimize harmful consequences. Other highly ranked rivers in terms of connectivity and sediment transport within Zambia are formed by the Chambeshi and the upper Zambezi rivers.

Beyond the two final result maps, the applied methodology also generated a set of in-between maps that show separate rankings for the aspects of water provision, aquatic ecological importance, and sensitivity to impact. These individual results can be used independently and can inform subsequent analyses or alternative studies where a more dedicated focus can be placed on one of these aspects rather than all.

The main goal of this project was to identify and prioritize those sub-catchments and river reaches in Zambia that should be considered as candidate sites for protection because they are more important than other sub-catchments or river reaches in terms of water resources. For this reason, the final results are presented on a relative scale following a standardized scoring method, that is, they offer a ranking of the relative importance between locations. While this relative ranking can support decision making processes regarding the prioritization of WRPAs for possible gazetting, it is not capable of prescribing a scientifically proven level of required protection for these locations.

It is important to note that areas which do not score at the top of the national ranking should not be excluded by default from consideration of water resources protection. In fact, any site can be of local importance or exhibit other features not assessed in this study that may qualify them as a candidate WRPA sites. In contrast, if a highly ranked sub-catchment or river reach is already in a protected area, it may not qualify as a candidate WRPA site as the same piece of land cannot be protected by multiple legislations.

Of the total area of national parks, 70.6% corresponded with selected AEIs. However, despite the high correlation of national parks versus identified AEIs, almost 80% of the identified planning units still fall outside of formal protected areas. There are two implications of this finding, namely a) that the existing network of national parks meets not only terrestrial but aquatic conservation goals; but also b) that there remains considerable scope for expanding the conservation area network to protect the remaining 80% of important AEIs not protected by national parks.

Given the large-scale nature of this prioritization effort, it was not a goal to propose local or specific protection strategies or to develop comprehensive methods of integrated water resource management. The mechanisms for actual water protection in each candidate site are expected to vary depending on local vulnerability, threats and associated impacts. Additional field studies will be required to assess these issues which are beyond the scope of this report. Also, existing literature should be consulted which provides recommendations and case studies on how to devise effective protection plans (see e.g. Figure 31 and Abell et al. 2007).

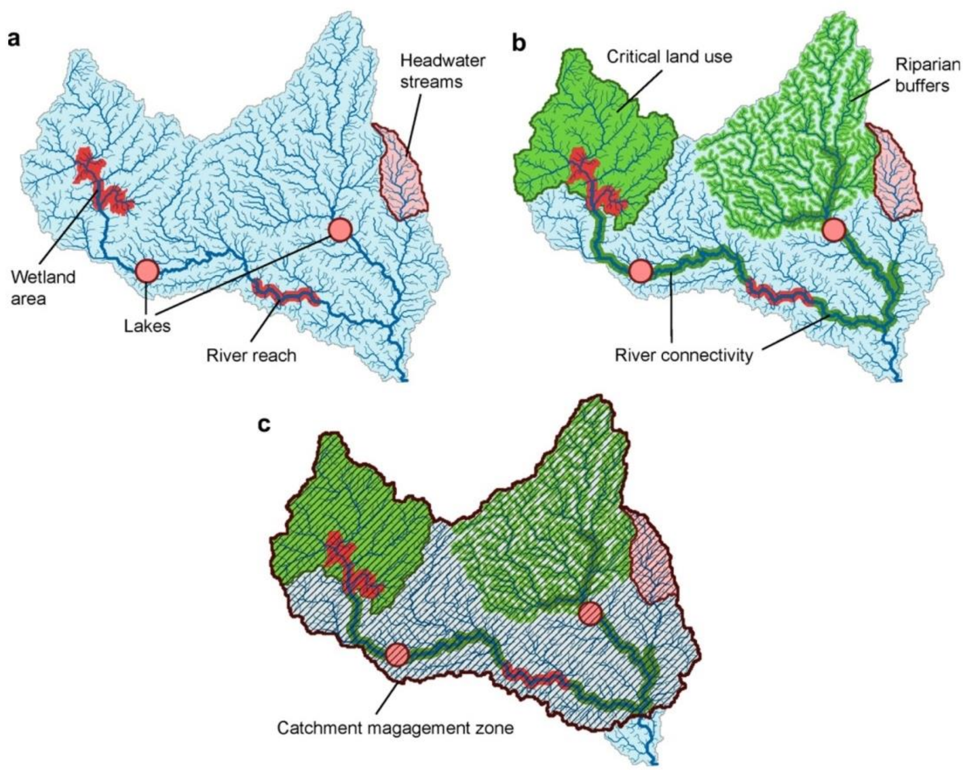

Figure 31: Example for different catchment management strategies that address a) individual local requirements of wetlands, lakes, river reaches, or headwater catchments; b) connectivity between critical locations, and between the landscape (watershed) and the river system; and c) a holistic perspective regarding integrated management of the entire catchment management zone. For more details see Abell et al. (2007).

Already in a preceding report, Mwenge Kahinda & Kapangaziwiri (2012) stated that “the management of limited surface water resources is a great challenge in areas where ground based data are either limited or unavailable. The Zambezi River Basin has a tremendous lack of observed hydrological data indispensable for water resources assessment.” Based on this observation and other shortcomings and limitations identified in this project, in particular due to data gaps at a national scale, we recommend the following actions:

- Planning towards filling in data gaps of any kind.
- Working towards the formal establishment of Key Biodiversity Areas (KBAs) for aquatic ecosystems in Zambia. Based on the biodiversity feature data that can be associated with each identified zone, it would be possible to apply the criteria and thresholds already established in global literature (IUCN 2016).
- Measuring and evaluating indicators of both water security and biodiversity will be critical to establish the conditions under which source water protection activities can contribute to both sets of objectives simultaneously (Abell et al. 2019).

Source water protection offers an integrated approach to invest strategically in areas where biodiversity conservation needs intersect with source water dependency. If designed and implemented with care and at meaningful scales, source water protection activities have good potential for producing both water security and freshwater biodiversity conservation benefits – especially considering the overlap between areas of importance for source water protection and areas of high freshwater biodiversity value (Abell et al. 2019).

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6. Appendices

6.1 Appendix I: Lists of participants at stakeholder workshops

Workshop 1: Waterfalls Lodge, Chongwe District, Lusaka, 8 June 2017

	NAME	SPECIALISATION/POSITION	INSTITUTION	Email
1	Tobias El Fahem	Hydrogeologist, GRESP Programme Manager	BGR/GReSP	pm.gresp@gmail.com
2	Kawawa Banda	Hydrogeologist, Lecturer	University of Zambia	kawawa.banda@unza.zm
3	Alice Nambeye Nchimuya	Environment and Water Quality	WARMA	alicenchimunya@yahoo.com
4	Oscar Silembo	Water Quality & Hydrology, Catchment manager	WARMA	oscarsilembo@yahoo.com
6	Mwiza Muzumara	Hydraulics & Hydrology, Catchment Manager	WARMA	mwizaso@gmail.com
7	Edwin Nyirenda	Hydrologist, Head: Civil Engineering Dept.	University of Zambia	edwinnyirenda@yahoo.com
8	Griffin Shanungu	Wildlife Ecologist	DNPW	griffin@savingcranes.org
9	Harris Phiri	Fish ecologist	Department of Fisheries	harrisphr@live.com
10	Chrispin Simwanza	Principal Inspector	ZEMA	csimwanza@zema.org.zm
11	Happiness Malawo	Hydrologist, Catchment Manager	WARMA	hmalawo@yahoo.com
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13	Tewodros Tena	Water Resources Specialist	BGR/GReSP	tewodros.gresp@gmail.com
14	Jonathan Kampata	Water Resources Operations Manager	WARMA	jkampata@yahoo.com
15	Bernhard Lehner	Hydrologist, PhD McGill University	McGill University	bernhard.lehnr@mcgill.ca
16	Guenther Grill	Geography, PhD McGill University	McGill University	guenther.grill@mail.mcgill.ca
17	Michele Thieme	Director Freshwater Science, WWF US	WWF US	michele.thieme@wwfus.org
18	Raquel Filgueiras	Freshwater Program Manager	WWF	rfilgueiras@wwfzam.org
19	Loreen Katiyo	Water Resources Engineering/Senior Hydrologist	WWF	lkatiyo@wwfzam.org
20	Faith Chivava	Hydroinformatics, GIS Analyst	WWF	fchivava@wwfzam.org
21	Brian Chilambe	GIS Intern	WWF	bchilambe@wwfzam.org

WARMA – Zambia Water Resources Management Authority
ZEMA – Zambia Environmental Management Agency
DNPW – Department of National Parks and Wildlife
TNC – The Nature Conservancy
GReSP - Groundwater Resources Management Support Programme
WWF – World Wide fund for Nature

Workshop 2: Mica Lodge, Kabulonga, Lusaka, 5 November 2018

	NAME	SPECIALISATION/POSITION	INSTITUTION	Email
1	Oscar M. Silembo	Director Water Resources Management & Information	WARMA	oscarsilembo@yahoo.com
2	Edwin Nyirenda	Hydrologist, Head: Civil Engineering Department	University of Zambia	edwinnyirenda@yahoo.com
3	Harris Phiri	Fish ecologist	Department of Fisheries	harrisphr@live.com
4	Beauty Mbale	Water Resources Operations Manager	WARMA	beautyshamboko@yahoo.com
5	Frank Nyoni	Senior Water Quality & Environment Officer	WARMA	fcnj8p@yahoo.com
6	Bernhard Lehner	Hydrologist, Assoc. Prof. of Global Hydrology	McGill University	bernhard.lehner@mcgill.ca
7	Nick Rivers Moore	Ecologist	Freshwater Research Centre	blackfly1@vodamail.co.za
8	Loreen Katiyo	Water Resources Engineering /Senior Hydrologist	WWF	lkatiyo@wwfzam.org
9	Faith Chivava	Hydroinformatics, GIS Analyst	WWF	fchivava@wwfzam.org
10	Dickson Mwelwa	Hydroinformatics Kafue	WARMA	dickson.mwelwa@yahoo.com
11	Chipo Gift Mubambe	Sub-catchment Manager	WARMA	chipogiftm@yahoo.com
12	Adjoa Parker	Senior IWRM Specialist	GIZ	adjoa.parker@giz.de
13	Namafe Namafe	Hydroinformatics	DWRD	namafe86@gmail.com
14	Buchizya Soko	Planner	NWDSEP	buchizya.batat@gov.zm
15	Clara Nanja	Project officer	Birdwatch	clara.nanja@birdwatchzambia.org
16	Goodfellow Mphande	Hydro-Informatics	WARMA	mphane_goodfellow@yahoo.com
17	Singogo Julius	Hydro-Informatics	WARMA	singogojulius@yahool.com
18	Tabo Kaluwa	Planner	NWDSEP	tabokaluwa@gmail.com
19	Muyukwa B. Musolo	Program Adiminstrator	SASSCAL	966118065
20	Chisha A. Nawa	Natural Resurces Planner	DNPW	977987778
21	Joseph Mwelwa	SNR Hydro-Technician	WARMA	977499020
22	Richard Mulenga	GIS specialist	Freelance	966853642
23	Violet Chikule	SNR Hydro-Informative	WARMA	violetvm84@yahoo.co.uk

Capacity building technical short course (GIS/Marxan): WARMA offices, Lusaka, 6 November 2018

	NAME	SPECIALISATION/POSITION	INSTITUTION	Email
1	Faith Chivava	GIS Analyst	WWF	974316836
2	Dickson Mwelwa	Hydro-Informatics	WARMA	976750623
3	Richard Mulenga	GIS Analyst	DOF	966853642
4	Harris Phiri	Fish ecologist	Dept. of Fisheries	harrisphr@live.com
5	Nick Rivers Moore	Ecologist	FRC	blackfly1@vodamail.co.za
6	Regor Mutemba	DEC	WARMA	972671858
7	Chipo G. Mubambe	S.C. Manager	WARMA	955992316
8	Adjoa Parker	Senior IWRM Specialist	GIZ	adjoa.parker@giz.de
9	Goodfellow Mphande	Hydro-Informatics	WARMA	mphane_goodfellow@yahoo.com
10	Singogo Julius	Hydro-Informatics	WARMA	singogojulius@yahool.com
11	Joseph Mwelwa.	SNR Hydro-Technician	WARMA	977499020
12	Violet Chikule	SNR- Hydro-Informatics	WARMA	977370299
13	Monoah Muchanga	Lecturer- Research	UNZA	978156869
14	Kabati K. Chilufya	Fish-researcher	Dept. of Fisheries	974325854
15	Bernhard Lehner	Hydrologist/GIS expert	McGill University	bernhard.lehner@mcgill.ca

Workshop 3: Twangale Park, Chilanga, Lusaka, 29-30 May 2019

1. **Oscar M. Silembo,** Acting Director of Water Resource Management and Information, WARMA
2. **Nachilala Nkombo,** Country Director, WWF Zambia.
3. **Dr. Norman Rigava,** Manager, Conservation,WWF
4. **Dr. Loreen Katiyo,** Interim Freshwater Program Lead
5. **Prof. Bernhard Lehner,** Consultant, McGill University.
6. **Prof. Cyprian Katongo,** Associate Professor, University of Zambia.
7. **Prof Henry M. Sichingabula,** Director, Research & Graduate Studies, University of Zambia.
8. **Dr Edwin Nyirenda,** Lecturer/Researcher, University of Zambia.
9. **Dr Harris Phiri,** Deputy Director- Capture Fisheries, Department of Fisheries.
10. **Bruce Paxton,** Aquatic Ecologist, FRC.
11. **Nick Rivers-Moore,** Aquatic Ecologist, FRC
12. **Beauty S. Mbale,** Senior Hydrologist, WARMA.
13. **Albert Chomba,** Department of Water Resources Development**.**
14. **Frank Nyoni,** Senior Environment & Water Quality Officer, WARMA
15. **Agness Sililo Musutu,** Freshwater Programme Coordinator, WWF Zambia.
16. **Faith Chivava,** GIS Analyst, WWF Zambia.
17. **Griffin Kaize Shanungu,** Programme Coordinator, ICF.
18. **Clara Nanja,** Wetlands Project Officer, BWZ**.**
19. **Violet M. Chikule,** Senior Hydro-Informatics Officer, WARMA.
20. **Richard Musheba,** Planner, Ministry of Water Development, Sanitation & Environmental Protection.
21. **Isabel Miyanda,** Senior Planner**,** Ministry of Water Development, Sanitation & Environ. Protection.
22. **Loziwe N. Chilufya,** Senior Fisheries Research Officer, Department of Fisheries.
23. **Henry Malumo,** Communications, WWF Zambia.
24. **Priscilla Sichone,** Senior Ecologist, DWPW.
25. **Kelvin Songolo,** Intern, WARMA.
26. **Busuma Chama,** Intern, WARMA.

6.2 Appendix II: Attribute list of HydroATLAS-Zambia

The current version 1.0 of HydroATLAS-Zambia includes the following hydro-environmental attributes:

HydroATLAS-Zambia Attributes (Version 1.0)

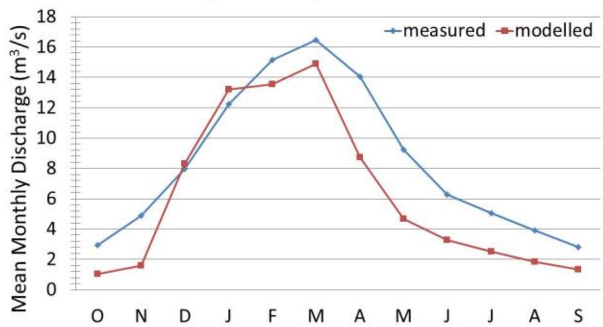
ID	Category	Attribute	Source Data	Reference
H00	Hydrology	Sub-basins	HydroSHEDS	Lehner and Grill 2013
H01	Hydrology	Natural Discharge	WaterGAP v.2.2	Döll et al. 2003
H02	Hydrology	Land Surface Runoff	WaterGAP v.2.2	Döll et al. 2003
H03	Hydrology	Inundation Extent	GIEMS-D15	Fluet-Chouinard et al. 2015
H07	Hydrology	Groundwater Table Depth	Global Groundwater Map	Fan et al. 2013
P01	Physiography	Elevation	EarthEnv-DEM90	Robinson et al. 2014
P02	Physiography	Terrain Slope	EarthEnv-DEM90	Robinson et al. 2014
C01	Climate	Climate Zones	GEnS	Metzger et al. 2013
C02	Climate	Air Temperature	WorldClim	Hijmans et al. 2005
C03	Climate	Precipitation	WorldClim	Hijmans et al. 2005
C04	Climate	Potential Evapotranspiration	Global-PET	Zomer et al. 2008
C05	Climate	Actual Evapotranspiration	Global Soil-Water Balance	Zomer et al. 2008
C06	Climate	Global Aridity Index	Global Aridity Index	Zomer et al. 2008
C07	Climate	Climate Moisture Index	WorldClim & Global-PET	Zomer et al. 2008
L01	Landcover	Land Cover Classes	GLC2000	Bartholomé & Belward 2005
L02	Landcover	Land Cover Extent	GLC2000	Bartholomé & Belward 2005
L06	Landcover	Cropland Extent	EarthStat	Ramankutty et al. 2008
L07	Landcover	Pasture Extent	EarthStat	Ramankutty et al. 2008
L08	Landcover	Irrigated Area Extent	HID	Siebert et al. 2015
L11	Landcover	Protected Area Extent	WDPA	UNEP & IUCN 2014
L12	Landcover	Terrestrial Biomes	TEOW	Dinerstein et al. 2017
L13	Landcover	Terrestrial Ecoregions	TEOW	Dinerstein et al. 2017
L14	Landcover	Freshwater Major Habitat Types	FEOW	Abell et al. 2008
L15	Landcover	Freshwater Ecoregions	FEOW	Abell et al. 2008
S01	Soils	Clay Fraction in Soil	SoilGrids1km	Hengl et al. 2014
S02	Soils	Sand Fraction in Soil	SoilGrids1km	Hengl et al. 2014
S03	Soils	Silt Fraction in Soil	SoilGrids1km	Hengl et al. 2014
S04	Soils	Organic Carbon Content in Soil	SoilGrids1km	Hengl et al. 2014
S05	Soils	Soil Water Content	Global Soil-Water Balance	Trabucco & Zomer 2010
S07	Geology	Karst Area Extent	Rock Outcrops v.3.0	Ford & Williams 2007
A02	Demography	Population Density	WorldPop	Tatem (2017)
A03	Demography	Urban Extent	GHS	Pesaresi et al. 2016
A04	Demography	Nighttime Lights	Nighttime Lights v.4	Doll 2008
A06	Demography	Human Footprint	Human Footprint v.2	Venter et al. 2016
A07	Demography	Global Administrative Boundaries	GADM	University of Berkley 2012

6.3 Appendix III: Comparison of annual flow regimes at 22 gauging stations

The following 22 figures show annual flow regime comparisons between measured (WARMA) and modelled (HydroSHEDS) discharge data.

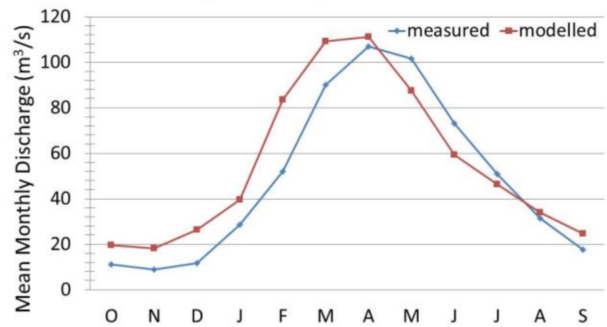
Luakela at Sachibondo (station 1425)

Mean measured discharge: 8.241 m^3/s
Mean modelled discharge: 6.239 m^3/s
Catchment size: 560.7 km^2



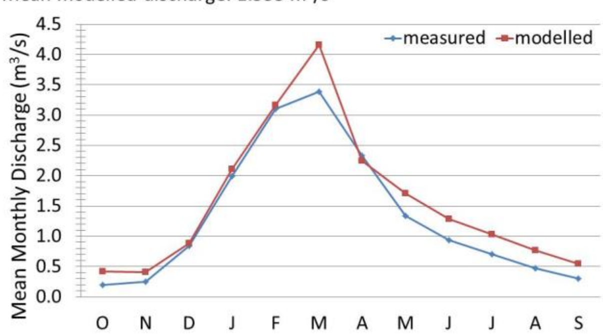
Luanginga at Kalabo (station 2250)

Mean measured discharge: 46.47 m^3/s
Mean modelled discharge: 52.417 m^3/s
Catchment size: 33,114.24 km^2



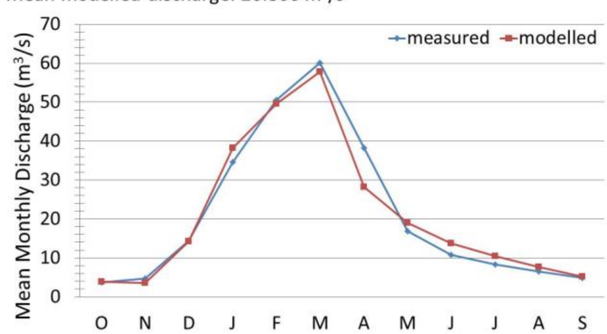
Muchindamu River at Muchindamu (station 4015)

Mean measured discharge: 1.232 m^3/s
Mean modelled discharge: 1.555 m^3/s
Catchment size: 256.7 km^2



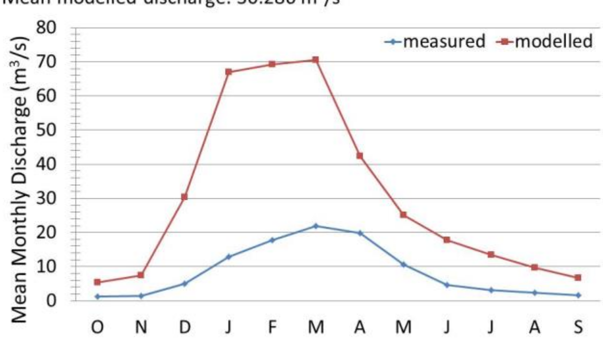
Luwishi at Lwendo (station 4302)

Mean measured discharge: 20.57 m^3/s
Mean modelled discharge: 20.866 m^3/s
Catchment size: 2649.0 km^2



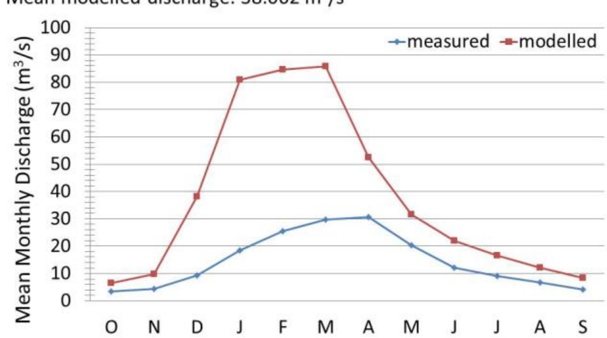
Manyinga at Manyinga (station 1630)

Mean measured discharge: 8.275 m^3/s
Mean modelled discharge: 30.286 m^3/s
Catchment size: 5003.5 km^2



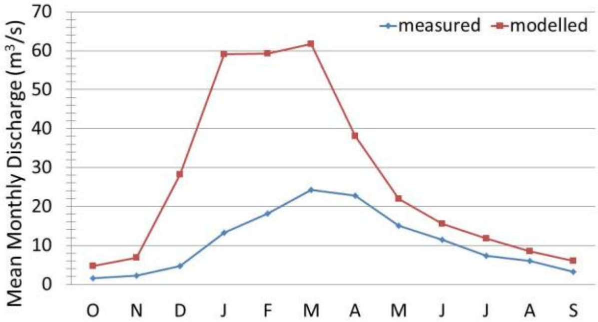
Makondu at Chivatu Village (station 1145)

Mean measured discharge: 12.4 m^3/s
Mean modelled discharge: 38.062 m^3/s
Catchment size: 6156.3 km^2



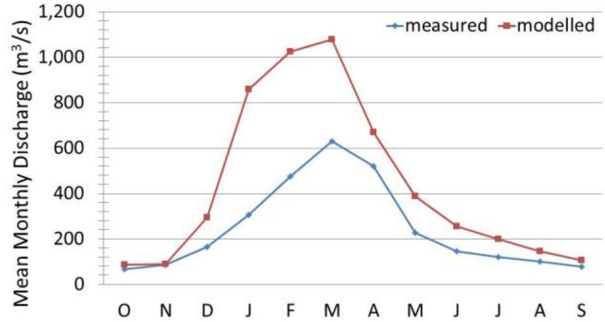
Makondu at Chief Nyakulenga (station 1135)

Mean measured discharge: 14.93 m³/s
Mean modelled discharge: 27.002 m³/s
Catchment size: 3750.6 km²



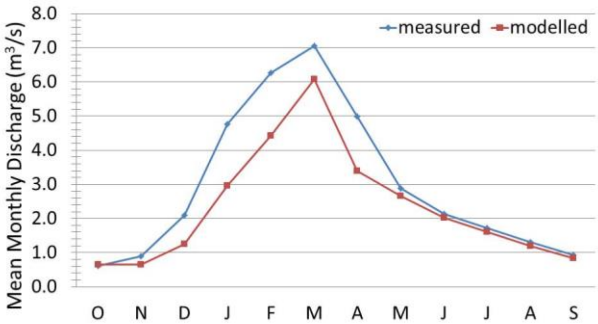
Kabompo at Watopa Pontoon (station 1950)

Mean measured discharge: 242 m³/s
Mean modelled discharge: 434.21 m³/s
Catchment size: 66,706.8 km²



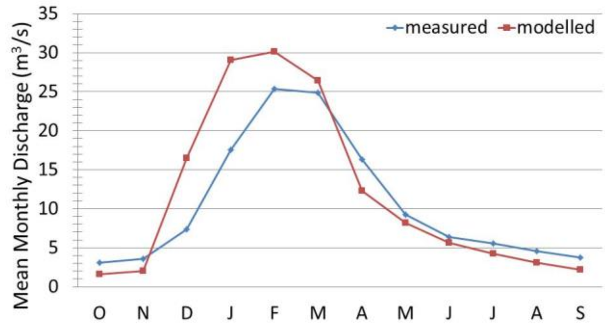
Kafue River at Kipushi Road (station 4005)

Mean measured discharge: 2.942 m³/s
Mean modelled discharge: 2.309 m³/s
Catchment size: 419.6 km²



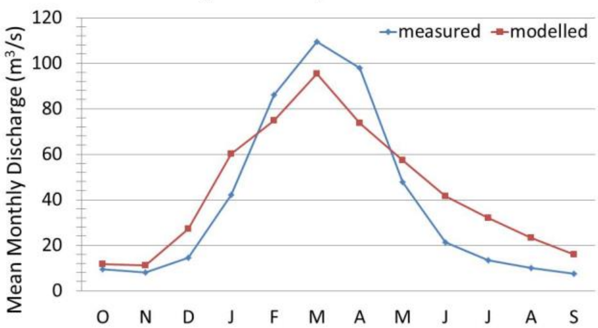
Kafue River at Masaiti Boma (station 4245)

Mean measured discharge: 10.54 m³/s
Mean modelled discharge: 11.723 m³/s
Catchment size: 1404.2 km²



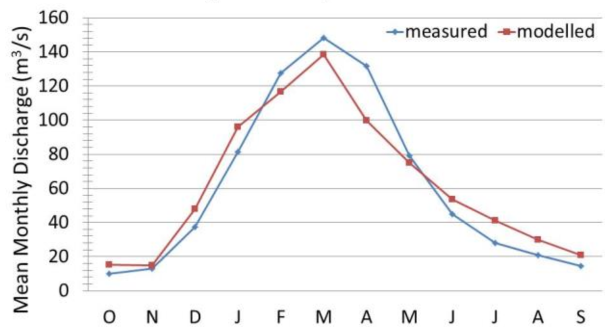
Kafue River at Raglan Farm (station 4050)

Mean measured discharge: 39.26 m³/s
Mean modelled discharge: 42.401 m³/s
Catchment size: 4965.4 km²



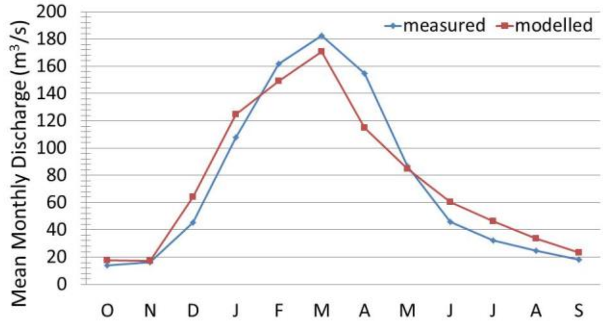
Kafue River at Kafironda (station 4090)

Mean measured discharge: 60.41 m³/s
Mean modelled discharge: 60.636 m³/s
Catchment size: 7076.2 km²



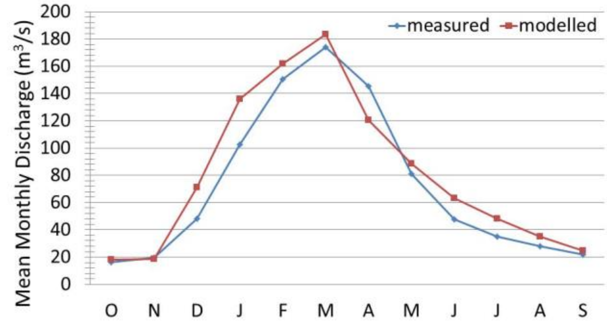
Kafue River at Smith Bridge (station 4130)

Mean measured discharge: 73.11 m³/s
Mean modelled discharge: 73.959 m³/s
Catchment size: 8599.9 km²



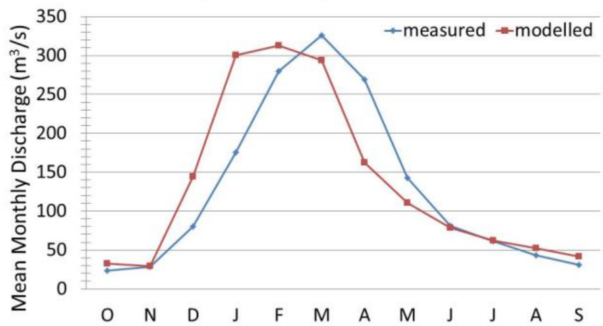
Kafue River at Wusakile Bridge (station 4150)

Mean measured discharge: 71.24 m³/s
Mean modelled discharge: 79.243 m³/s
Catchment size: 9178.3 km²



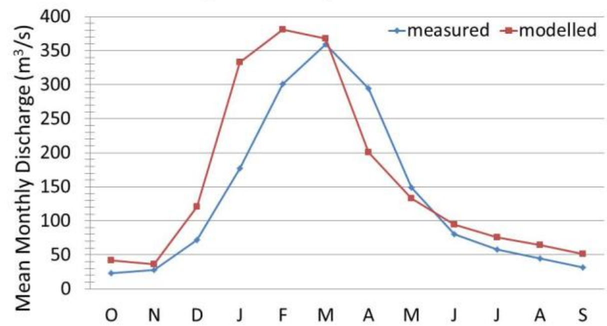
Kafue River at Ndubeni (station 4260)

Mean measured discharge: 135.2 m³/s
Mean modelled discharge: 133.241 m³/s
Catchment size: 18,852.5 km²



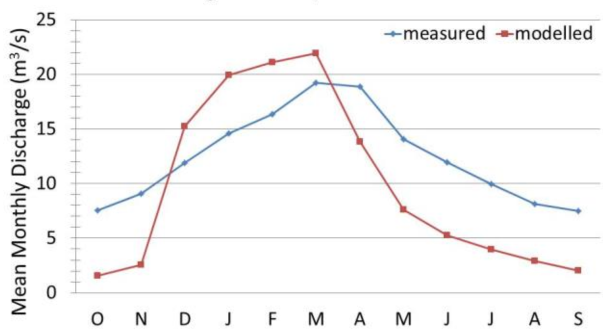
Kafue River at Machiya Ferry (station 4280)

Mean measured discharge: 127.9 m³/s
Mean modelled discharge: 157.307 m³/s
Catchment size: 723,069.0 km²



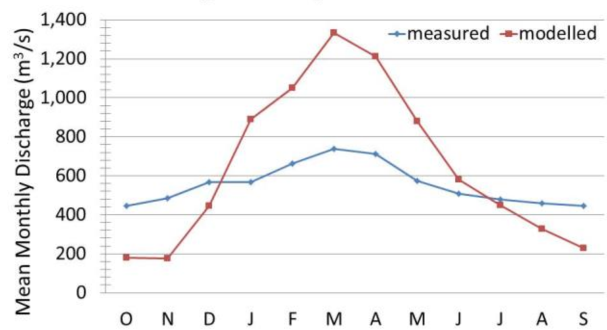
Zambezi at Kaleni Hill Road Bridge (station 1080)

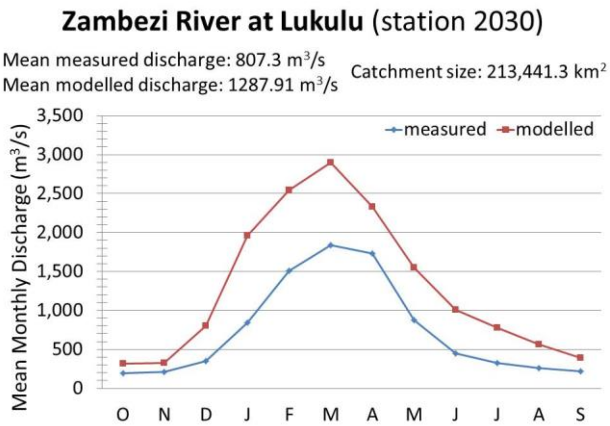
Mean measured discharge: 12.36 m³/s
Mean modelled discharge: 9.834 m³/s
Catchment size: 770.9 km²

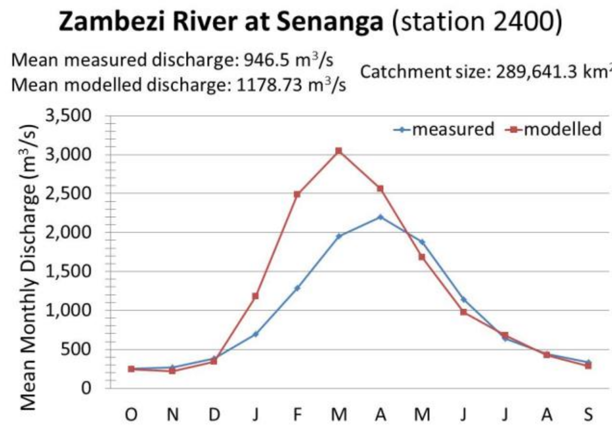


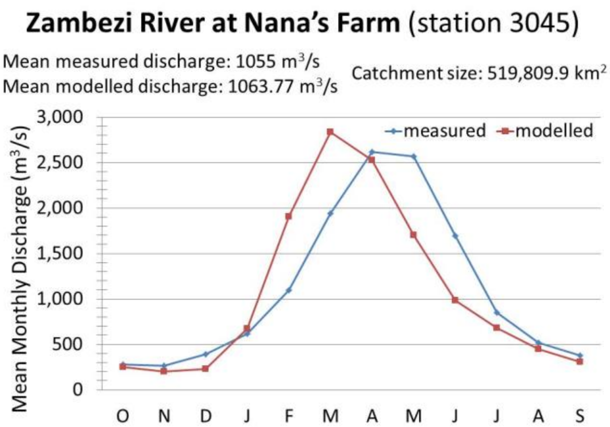
Zambezi at Chavuna Pump House (station 1105)

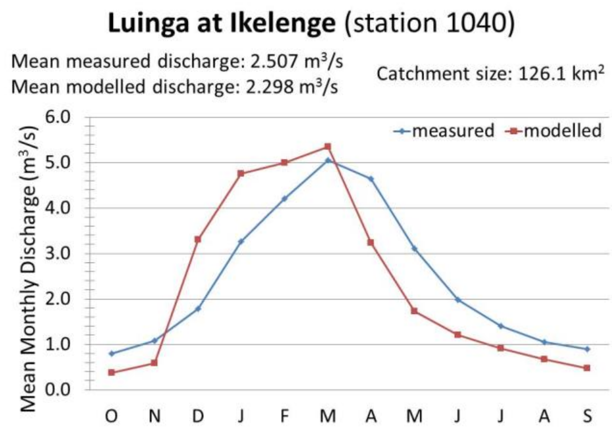
Mean measured discharge: 543.2 m³/s
Mean modelled discharge: 638.16 m³/s
Catchment size: 80,132.8 km²




Zambezi River at Lukulu (station 2030)
Mean measured discharge: 807.3 m3/s
Mean modelled discharge: 1287.91 m3/s
Catchment size: 213,441.3 km2
measured
modelled
Mean Monthly Discharge (m3/s)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
O N D J F M A M J J A S


Zambezi River at Senanga (station 2400)
Mean measured discharge: 946.5 m3/s
Mean modelled discharge: 1178.73 m3/s
Catchment size: 289,641.3 km2
measured
modelled
Mean Monthly Discharge (m3/s)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
O N D J F M A M J J A S


Zambezi River at Nana's Farm (station 3045)
Mean measured discharge: 1055 m3/s
Mean modelled discharge: 1063.77 m3/s
Catchment size: 519,809.9 km2
measured
modelled
Mean Monthly Discharge (m3/s)
3,000
2,500
2,000
1,500
1,000
500
0
O N D J F M A M J J A S


Luinga at Ikelenge (station 1040)
Mean measured discharge: 2.507 m3/s
Mean modelled discharge: 2.298 m3/s
Catchment size: 126.1 km2
measured
modelled
Mean Monthly Discharge (m3/s)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
O N D J F M A M J J A S