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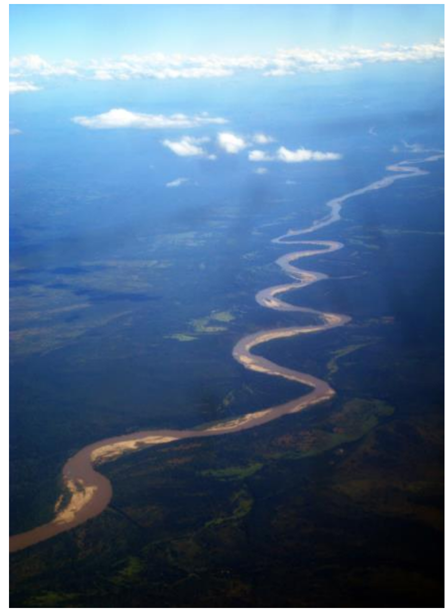

Proposed Ndevu Gorge Power Project: A Preliminary Exploration of Environmental Impacts

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Executive Summary

The proposed Ndevu Gorge Power Project has the potential to irreversibly alter the free-flowing Luangwa River in Eastern Zambia.

We conducted an initial exploration of ecological, hydrologic and nature-based tourism impacts that a dam at Ndevu Gorge could potentially have on the surrounding landscapes of the Luangwa Valley. We used ArcGIS, synthesized existing scientific literature and assessed similar projects in the region. The results of our analyses relied on dam specifications reported in Zambian media (Lusaka Times 2017).

We calculated that the proposed Lake Ndevu would require a dam that could accommodate a water level of 78 m (505 m above sea level). Given the local topography, a secondary retaining wall would also be needed to prevent the reservoir from bypassing the primary dam. The primary dam would be 427 m across and the secondary barrier would measure 1602 m long and at least 17 m high. We estimated that the resulting reservoir would cover 1510 km^2 and have a capacity of 46.8 km^3.

The reservoir would inundate or alter parts of protected areas adjacent to the Luangwa River. The reservoir would inundate 29.5% of the length of the Luangwa River within South Luangwa National Park, at least six safari camps, and as much as 80% of adjacent hunting areas. It would inundate portions of at least six chiefdoms adjacent to the river. The reservoir would inundate much of the length of the Luangwa that these protected areas, hunting areas and chiefdoms currently have access to. It would also reduce the area of valuable wildlife corridor between South Luangwa National Park and Lower Zambezi National Park— which is already bounded by human encroachment on either side of the river— by 50% of its length and 24% of its width.

The dam would likely cause a variety of hydrological impacts upstream and downstream of the reservoir. Potential impacts include: backwater effects, delta formation above the reservoir, channel incision, floodplain isolation and disruption of sediment transport mechanisms. We estimated the backwater zone to extend approximately 16.0 km above the reservoir terminus, affecting the confluence of the Kapamba and Luangwa Rivers and having the potential to impact when and where game drives could occur due to altered flooding regimes. We also estimated that overall, between 6.7 m^3 and 67 million m^3 of sediment, under a 30-year compaction rate, would be deposited annually into the proposed reservoir

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1 Introduction

The Luangwa River, located in the Eastern Province of Zambia, is one of the longest remaining free-flowing rivers in the Zambezi River basin. The Luangwa lies at the bottom of a wide rift valley and is surrounded by natural landscapes and encroaching human development (WB 2010; Watson et al. 2015).

The area has an average annual rainfall of 800 to 1,000 mm, mostly occurring during the wet season from December to April. The natural hydrograph of the river supports seasonal morphological changes to the landscape like oxbow lakes and wetlands, as well as a wide range of rich natural habitats like woodlands, savannah and dambos (Caughley & Goddard 1975; WB 2010).

Along the river are two large national parks: South Luangwa National Park (SLNP) and North Luangwa National Park (ZTA 2017). SLNP is approximately 9,000 km^2 and home to dense concentrations of big game and megafauna, as well as more than 400 of Zambia's 732 species of birds (ZTA 2017). Five game management areas (GMAs) surround the national park, providing an ecological buffer zone. The economy of the Luangwa Valley is primarily based on tourism, agriculture and forest harvesting (WB 2016).

A new dam has been proposed on the Luangwa River (Fig. 1). The Ndevu Gorge Power Project, proposed by MDH South Africa (Pty) Limited, would generate between 235 and 240 MW of power and cost $1.26 billion (Lusaka Times 2017; Zambia Daily Mail 2017).

Hydropower constitutes 90% of Zambia's power supply (ERM 2013). Several large dams already provide Zambia with power from the Zambezi River and its tributaries. Additionally, a new project on the Zambezi at Batoka Gorge ($6 billion, 2,400 MW) is set to commence this year (Lusaka Times 2017). Unlike other rivers in the Zambezi River basin, however, the Luangwa is still a free-flowing system with no dams (WB 2010), presenting a rare opportunity to preserve the natural state of a major waterway (WWF 2016).

The effects of large dams on river systems have been studied extensively (WWF 2004). Freshwater ecosystems are home to a higher concentration of species than

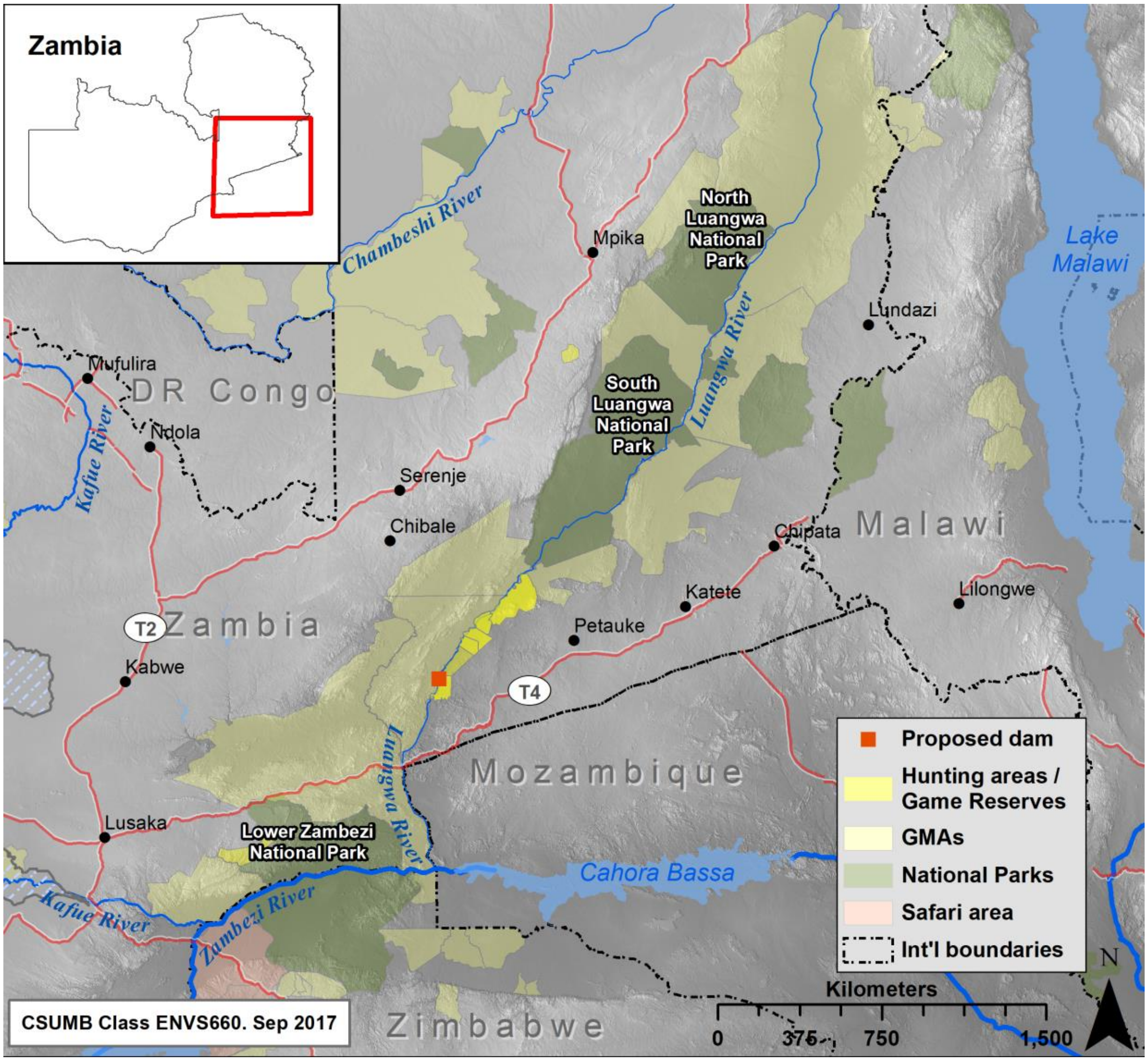

Figure 1. Site of the proposed Ndevu Gorge dam in the Luangwa River Valley, Zambia.

terrestrial and ocean systems, and large dams can disrupt this biodiversity through a variety of mechanisms from hydrologic to human (McAllister et al. 2001).

The purpose of this study was to examine certain potential impacts of the proposed dam on the Luangwa River, surrounding protected areas, local biodiversity, hydrology and sediment transport. Our goal was to examine a broad range of potential impacts to identify areas of concern and further study as plans for the dam develop (Table 1).

Our analysis includes: a geospatial assessment of land cover change resulting from the dam, an analysis of potential impacts to the area's biodiversity and wildlife connectivity, estimated backwater extent and an estimated sedimentation rate of the proposed reservoir.

Table 1. Scope of potential impacts of the proposed dam explored in the preliminary investigation for this report. The topics addressed specifically in this report are indicated with an X.

Potential Impacts		Impacts examined in the study	Location in report
Land Cover Change			
Reservoir Extent	Deduced from provided reservoir length (165 km)	X	Section 2.2
	Overlap with South Luangwa National Park (SLNP)	X	
Spatial relationships	National Parks	X	Section 2.2
	GMAs	X	
	Hunting areas	X	
	Photographic safari areas	X	
	Human encroachment footprint (2010, 2015, …)	X	
	Trans-frontier wildlife connectivity / corridors	X	
Specific forms of land cover change	Power lines	X	Section 2.2
	Roads	X	
	New agriculture - i.e. irrigated agriculture downstream from reservoir supply		
	New towns		
Flow analysis			
Backwater effects	Effects on upstream river depth and morphology of channel and floodplain	X	Section 3.2
	Effect of river gemorphic change on SLNP ecology & econo	X	
Effects on downstream flows/river gradient	Luangwa River downstream of Ndevu Gorge		
Sediment analysis			
Estimate reservoir sedimentation rate	Expected number of years before reservoir fills with sediment	X	Section 4.1
Downstream effects	e.g. down-cutting of main channel by low-sediment flow below dam		
Biodiversity impacts			
Terrestrial wildlife	Terrestrial wildlife connectivity / corridors	X	Section 5.1
	Terrestrial wildlife population distribution		
	Poaching due to increased infrastructure		
Aquatic wildlife	Aquatic habitat connectivity		
	Aquatic ecosystem functioning		
Environmental flow requirements	Timing and volume of water required to maintain healthy aquatic ecosystems		
Ecology-related community impacts			
Impacts on tourism industry	Photographic tourism in SLNP and adjacent GMAs	X	Section 6.1
	Hunting tourism in GMAs and private hunting areas	X	
Impacts on agriculture	Potential for increased agricultural development		
	Identification of any existing local agriculture or wood-cut		
Health issues	Impacts on tsetse fly and tick populations, and mosquito borne diseases		

2 Geospatial Analysis: Reservoir Extent and Land Cover Change

In this section we determine the extent of the reservoir that would result from the construction of a dam at Ndevu Gorge. We show the most likely location for the dam and calculate the water supply level required to produce the reservoir dimensions proposed by developers according to media reports. We then examine how far the reservoir extends into protected areas, hunting areas and chiefdoms as well as provide the basis for examining backwater effects and analyzing wildlife connectivity later in the study.

2.1 Methods

We conducted our geospatial analysis in ArcGIS 10.5 and sourced the following data to complete the analysis:

- Digital elevation model (DEM) raster, 30 m resolution, SRTM Version 2 Arc-Second Global, USGS, Feb. 11-22, 2000 (WGS 1984)
- Extent of human encroachment into natural landscapes mapped by Watson et al. (2015) and extended by F. Watson & P. Millhouser (ZCP, unpublished data) and CSUMB students: V. Larwood, T. Belko, J. Estrada, A. Felipe, J. Simon, L. Boye, D. Frick, M. Thomson, C. Mitchell, S. Myers, A. Cline, A. Diehl and K. Emerick.
- Location of roads, game drives, and camps compiled from various sources including F. Watson (ZCP, unpublished data) and E. Rosenblatt (ZCP, unpublished data).
- Estimated locations of chiefdom boundaries from B. Chilambe, World Wildlife Fund for Nature Zambia, received September 2017
- Dam and reservoir specifications (Lusaka Times 2017; Zambia Daily Mail 2017)
    - Power output: 235 to 240 MW
    - Reservoir length: 165 km
    - Maximum reservoir width: 17 km

2.1.1 Dam specification analysis

We determined the most likely location for the proposed Ndevu Gorge dam by examining the topography of the Luangwa River Valley in ArcGIS. We chose a narrow point at the entrance to a gorge, with a widening upstream of the site – topography typical of other dam sites (Duggal 1996).

Based on the aforementioned media reports, the resulting reservoir would extend 165 km. We measured 165 km upstream from the dam site on the Luangwa River and extracted the elevation of that point. We subtracted the thalweg elevation at the dam site from the thalweg elevation at the end of the 165 km reservoir to determine the water supply height that would create a reservoir of those dimensions.

2.1.2 Watershed delineation

We delineated the Luangwa River watershed above the site of the proposed dam to describe and quantify the area of influence related to the proposed Lake Ndevu. To complete the delineation, we:

- Filled false sinks in the terrain (Fill tool)
- Interpolated DEM values for cells with no data using the mean of neighboring cells (Con and Focal Statistics functions in the Raster Calculator tool)
- Created a map of flow direction based on the DEM (Flow Direction tool) and a map of how flow accumulates across the landscape (Flow Accumulation tool)
- Delineated the watershed based on flow direction and dam location (Watershed tool)
- Calculated the area of resulting watershed (Calculate Field tool)

2.1.3 Reservoir extent

We produced the reservoir extent polygon and specifications using the following steps:

- We calculated the area the reservoir would cover by adding the previously calculated water level to the elevation of the approximate dam coordinates (Raster Calculator tool)
- Converted the resulting raster to a polygon shapefile (Raster to Polygon tool)
- Clipped the polygon to include only areas upstream of the dam sites, excluding downstream areas that met the elevation requirements but would not be included in the reservoir (Clip tool)
- Calculated area and volume of the resulting reservoir (Surface Volume tool, Calculate Geometry) and compared these numbers to media reports of the proposed Lake Ndevu’s length and width.
- Modeled reservoir extents for two other water supply heights to simulate a range of conditions: one at a level that would not require a second

retaining wall, and one larger reservoir modeling a water level 3 meters above full supply (Raster Calculator tool).

We determined which national parks, hunting areas, GMAs and chiefdoms would be subject to inundation by a new reservoir, as well as calculated the length of the impacted river reach within those areas to quantify changes in overall access to the river.

2.1.4 Projections of future infrastructure and land use change

We estimated the location of three electrical power sub-stations for Ndevu Gorge; one located 8 km southeast for initial power transmission and the other two located 97 km and 158 km to the northeast of the dam site. We based these projections on proximity to existing power lines and towns. Due to population size and proximity to mining operations, we projected that Lusaka would be a recipient of power connections. Petauke would be another potential candidate as it already has other major power line connections. We projected that the paths would connect to nearby power line routes already in use. We projected an arterial road would be needed to connect to the substation to The Great East Road (T4) near Nyimba.

We estimated that human encroachment would increase 2 km beyond current development in the next five years based on past rates of growth (Watson et al. 2015). In ArcGIS, we added a 2 km buffer to the current human encroachment data to account for this future development. We considered the limitations of steep terrain and the limited growth of small island communities by using a mask on these portions of the buffer that would not likely see human encroachment.

2.2 Results

The results of these analyses provided both quantitative and visual insight into the impact of the proposed dam and resulting reservoir on upstream protected areas, hunting areas and natural landscapes.

We determined the most likely location for the proposed Ndevu dam to be at approximately 30°27’19’’E, 14°27’7’’S, at the opening of a narrow gorge with a wide valley upstream (Fig. 2).

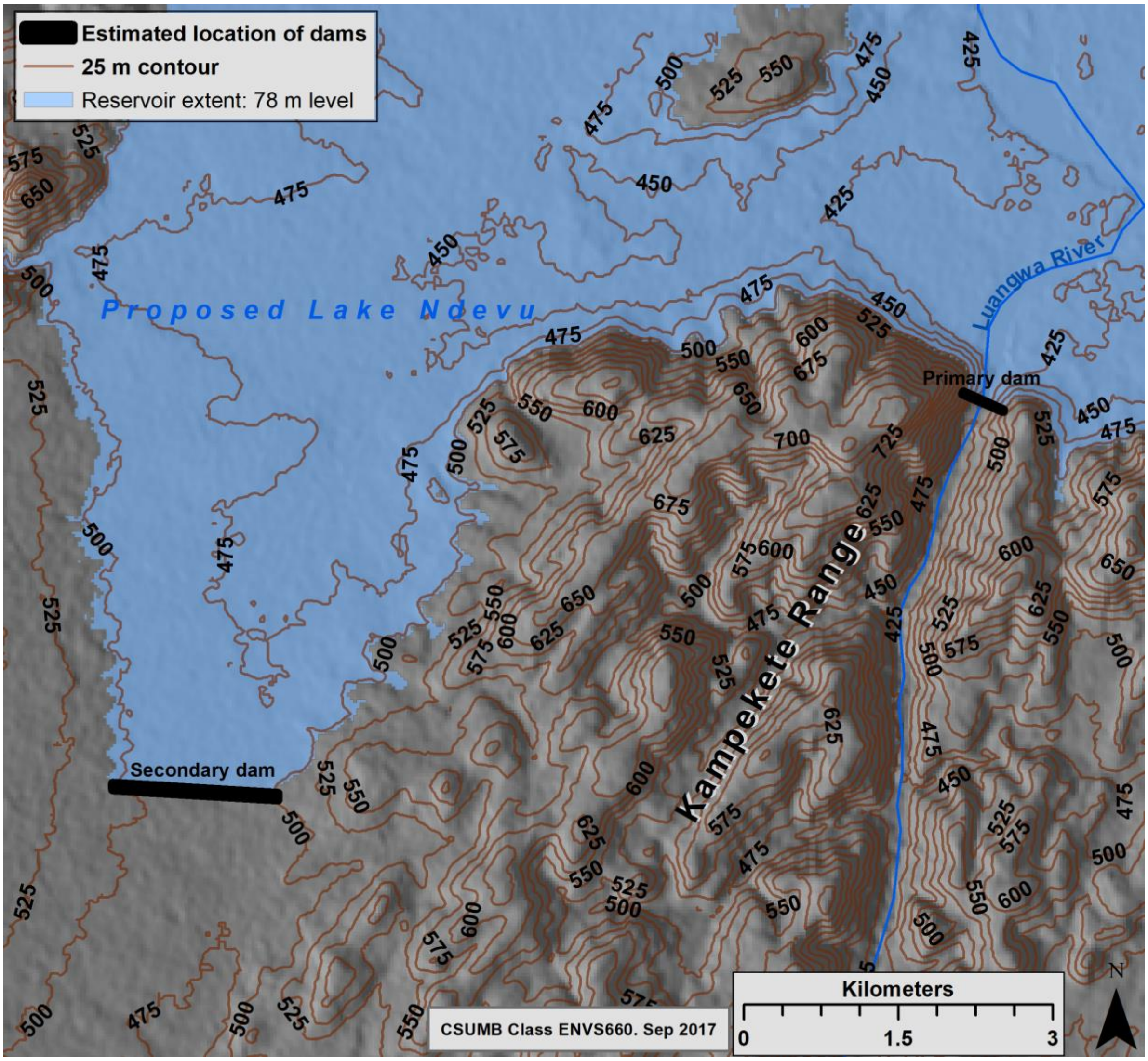

Figure 2. Estimated sites of the proposed dam and secondary wall required for a water level of 78 m (505 m ASL).

The water supply height to create a lake 165 km long would be 78 m (Fig. 4), or 505 m above sea level. At this level, the reservoir would cover 1510 km^2 and hold 47 km^3 of water (Table 2). The watershed analysis yielded a catchment area of 92,492 km^2 for the proposed site (Fig. 3).

As proposed, the water supply level of 78 m (505 m ASL) at full capacity would require a dam wall with a crest length of 427 m across the main stem of the Luangwa River. A secondary 1,602 m-long and at least 17 m-high retaining wall would be required to prevent the reservoir from bypassing the primary dam wall by spilling over a low pass to the west of the Kampekete Range (Fig. 2).

We modeled the extent of two supplementary water supply levels: 61 m and 81 m (488 m and 508 m above sea level, respectively) (Fig. 4) to simulate a range of conditions. A 61 m water level (488 m ASL) would only require the construction of a single dam wall, reducing the amount of infrastructure and human traffic related to construction. Based on the analysis detailed in section 3.2, we anticipated that the water supply could potentially reach 81 m (508 m ASL) in the event of seiching, historic flooding or strong wind forcing. An 81 m water level extends the extent of the reservoir 13 km upstream of the dam (Table 2).

Table 2. Results of GIS analysis including reservoir specifications for Ndevu Gorge Power Project at 78 m (anticipated full water supply level), 61 m (maximum water supply level for one dam wall) and 81 m (water supply level 3 m above full).

	Supply levels (water depth at dam site)		
Parameter	**61 m**	**78 m**	**81 m**
Supply level above sea level (m)	488	505	508
Reservoir size (km^2)	1004.5	1510	1628
Reservoir volume (km^3)	25.9	46.8	53.9
Reservoir length (km)	127.8	165	182
Length of dam wall (m)	427	427	427
Length of second wall (m)	Not Required	1602	1602

We based further analysis on a 78 m (505 m ASL) water supply level.

Protected areas, chiefdoms and hunting areas would be inundated to varying degrees at a water supply level of 78 m.

Six chiefdoms adjacent to the Luangwa River south of South Luangwa National Park would be partially inundated (Fig. 4). Within Mwape, Serenje, Sandwe, Chisomo chiefdoms, the entire reach of Luangwa River would be inundated by the reservoir.

The reservoir would reach 65 km into South Luangwa National Park inundating 29.5% of the total 220 km of river that flow through the park (Fig. 4).

West Petauke and Chisomo GMAs would be affected by the reservoir. West Petauke would be inundated by 11% (Table 3) with 5% of its river reach affected. The river reach in the Chisomo GMA would be completely inundated (Fig. 4).

Hunting areas line the east bank of the Luangwa River for at least 115 km downstream of SLNP. Much of this reach of the Luangwa would be inundated by the reservoir (Fig. 4). Nyamvu Game Ranch would be the most affected in terms of area at 81% inundation (Table 3).

Table 3. Percentage of protected areas and hunting areas that would be inundated by the proposed Ndevu Gorge dam.

Area	Area inundated (km^2)	Total area (km^2)	% area inundated
South Luangwa National Park	244.7	8667.6	2.8
Chisomo GMA	82.9	3602.5	2.3
West Petauke GMA	497.6	4282.4	11.6
Royal Luembe Game Ranch	80.6	140.9	57.2
Nyamvu Game Ranch	103.6	127.9	81
Nyakolwe Game Ranch	179	561.8	31.9
Ndevu Game Ranch	19.6	161.9	12.1
Munyamadzi Game Ranch	67.5	110.1	61.3
Kazumba Conservancy	111.1	197.8	56.2

Several safari and hunting camps would also be inundated including: Ndevu, M'nyamadzi, Nyala, Nyakolwe, Kwena, and Kalamu (Figures 4 and 8).

The dam and reservoir will require considerable infrastructural development and human activity to support the proposed level of power supply (Fig. 5). These projections, while based on currently available data, are meant to give a subjective look at what future potential growth in the area might look like.

The implications of these changes for conservation and nature-based tourism are discussed in sections 5 and 6.

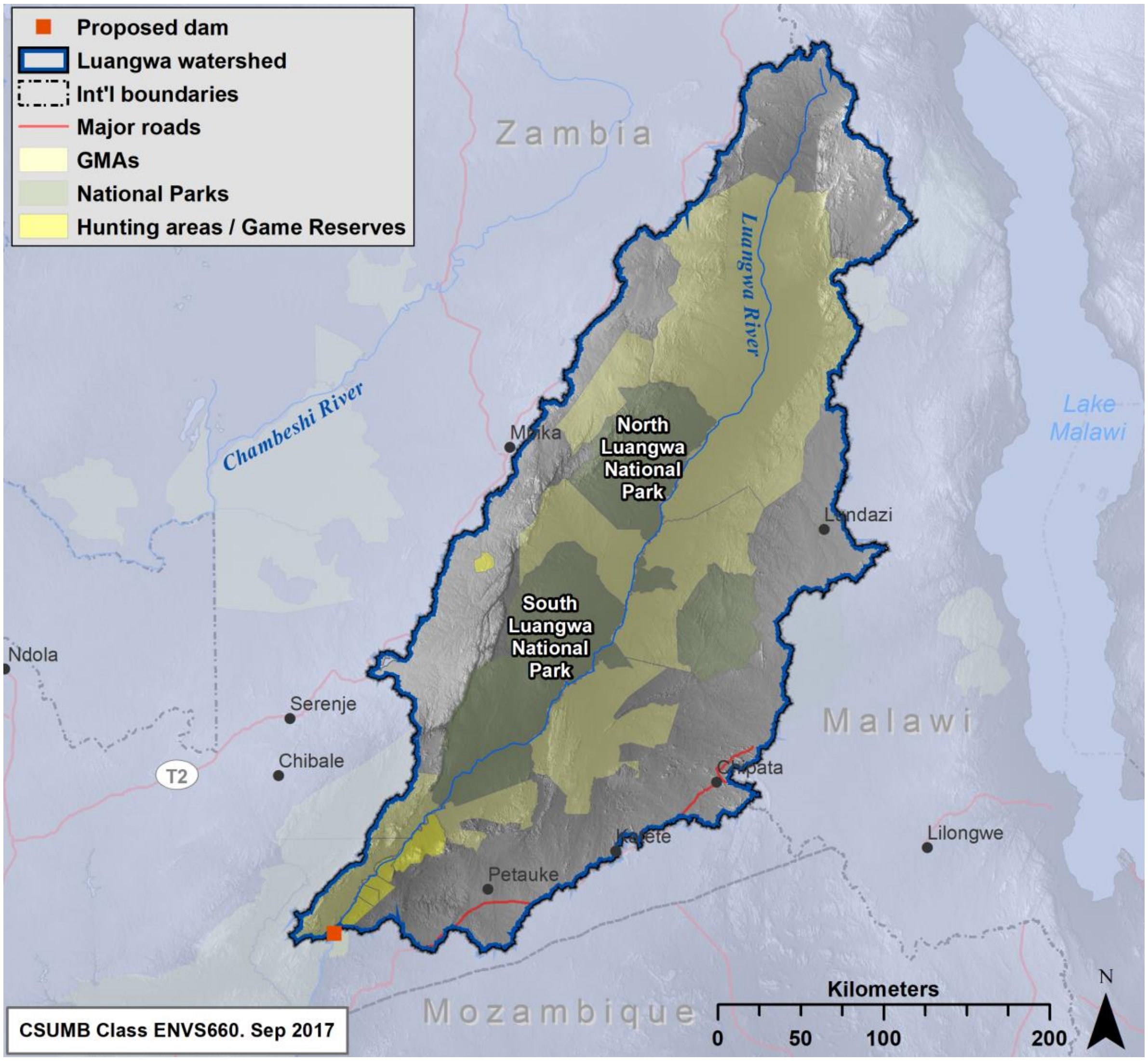

Figure 3. The catchment area above the proposed dam site, located in eastern Zambia, contains portions of several National Parks, game management areas and hunting areas.

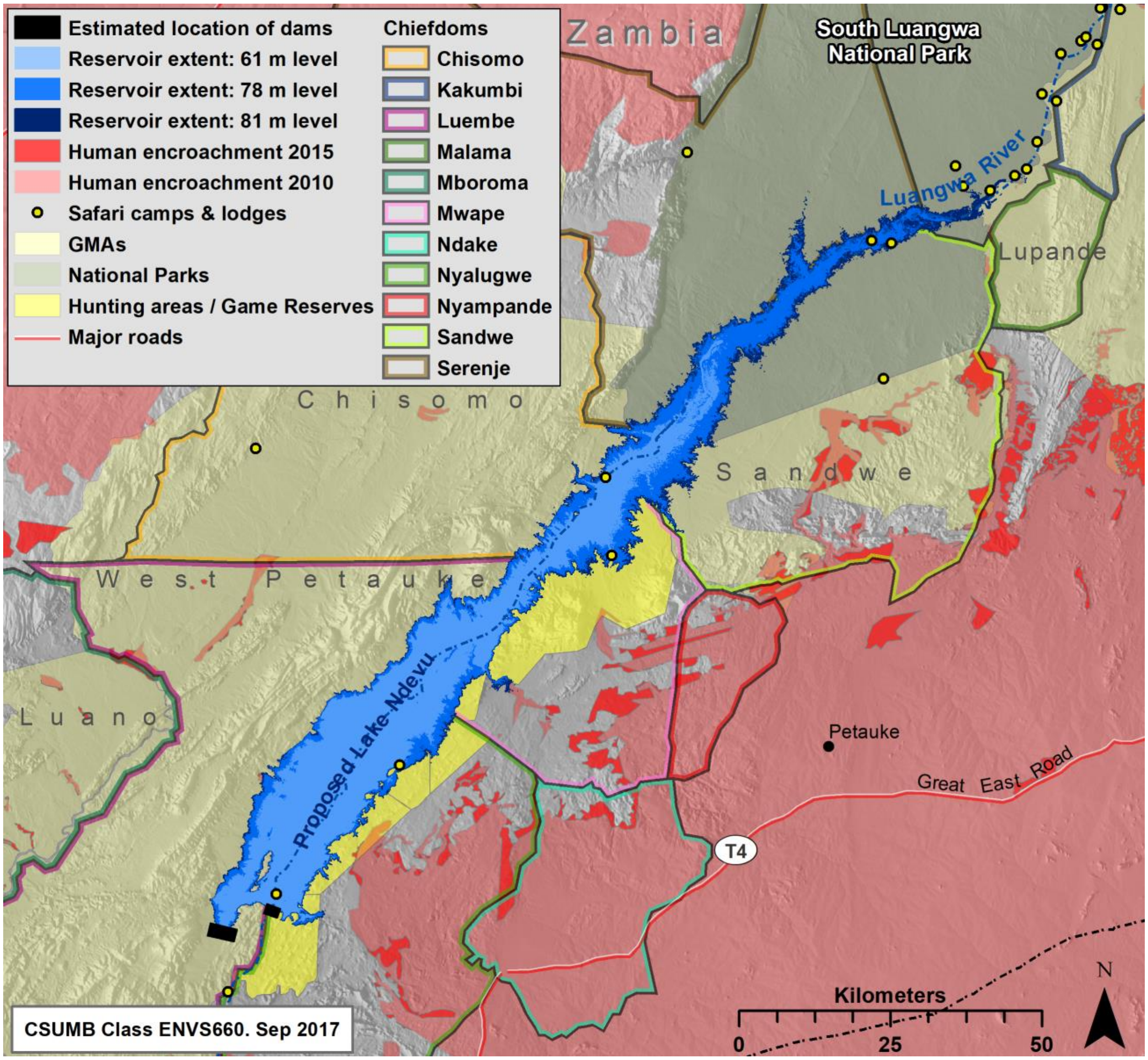

Figure 4. Estimated extent of proposed Lake Ndevu, for water levels of 61 m (488 m ASL), 78 m (505 m ASL) and 81 m (508 m ASL). Human land use in the surrounding area is shown through human encroachment extents and current infrastructure.

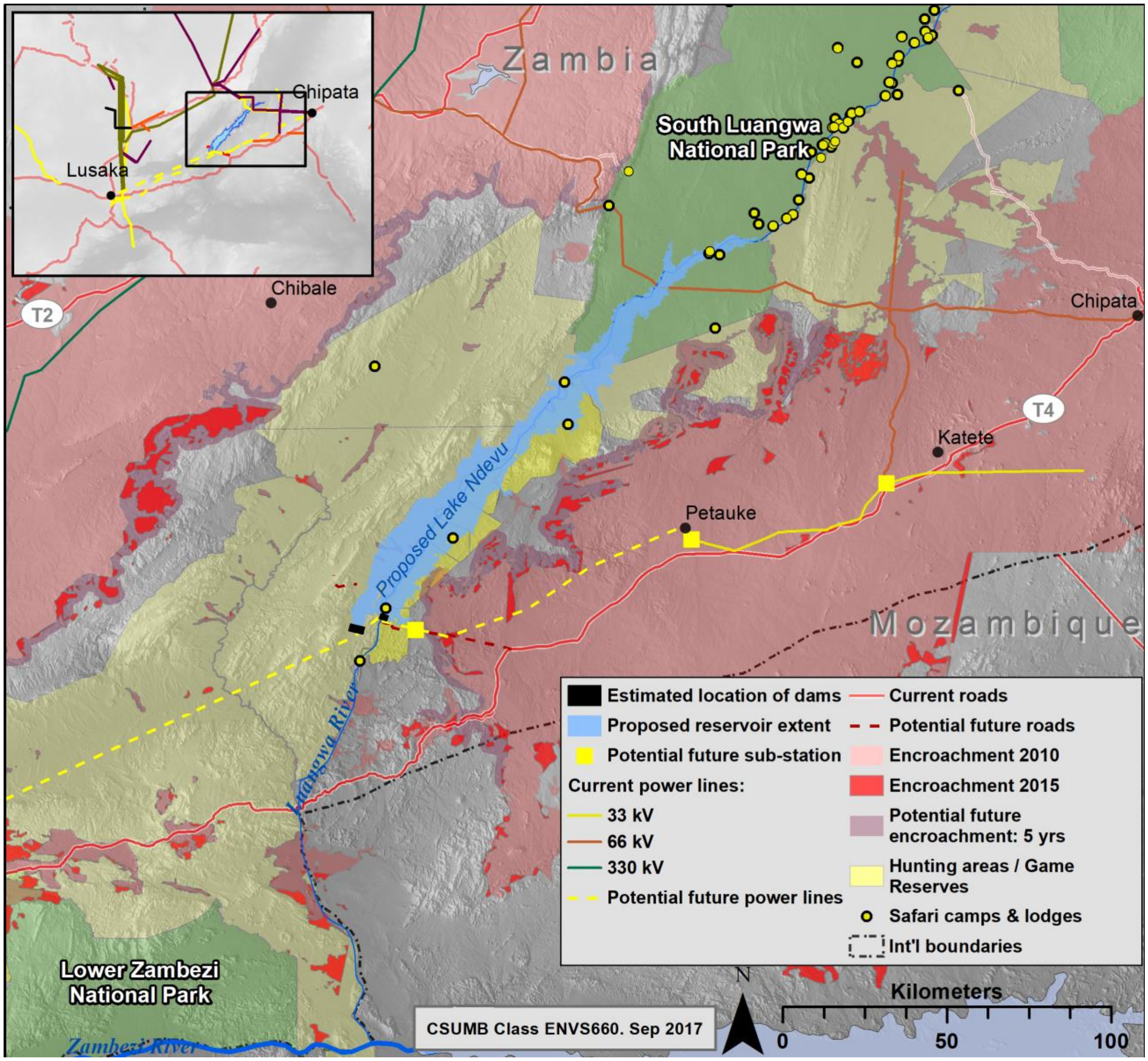

Figure 5. Potential future infrastructure, land use, and human encroachment change five years after construction of the proposed Ndevu dam.

3 Hydrologic Analysis: Backwater Effects

Dams have a variety of hydrologic and geomorphic impacts on a river both below and above a reservoir. Downstream effects can include channel incision and floodplain isolation, in some cases for hundreds of kilometers, while upstream impacts include backwater effects and delta formation (Brandt 2000; Kondolf 1997; Pasanisi et al. 2016; Petts 1979; WWF 2004).

In this section, we describe backwater effects and potential causes for above-normal reservoir operation water levels, explore an example of reservoir impacts on a low-gradient river in Nigeria, and calculate the likely extent of the backwater zone above the proposed Ndevu reservoir terminus on the Luangwa River.

3.1 Backwater Effects and Reservoir Water Level Fluctuations

The section of river directly above a static body of water, such as a reservoir, is known as the backwater zone. This area is characterized by decelerated and nonuniform flow (Lamb et al. 2012). Altered stage/discharge relationships in the backwater zone can change erosion and sediment deposition patterns, which can affect flood magnitude, flood frequency and channel geomorphology (Ganti et al. 2016; Pasanisi et al. 2016; Wang et al. 2005).

All dams are engineered to operate at an optimal water level. Normal reservoir water surface elevation (NRWS) can have direct impacts on flooding extent, capacity effectiveness, flow regulation, and planned water uses (Sun et al. 2011). High flows and wind-generated waves, or seiche waves, can cause large seasonal fluctuations in water surface elevation (USBR 2012). Surface water level fluctuations of dammed rivers can have broad ranges between a few meters up to 100 m, while water level fluctuations of undammed rivers range between a few centimeters and 3 m (Hirsh et al. 2014). Dams are designed to protect against such fluctuations by incorporating a certain amount of freeboard, or vertical distance to the crest of the dam above the NRWS (USBR 2012). Freeboard prevents large waves from overtopping the structure, but also allows water surface elevation to rise above the NRWS level, causing increased flooding in areas adjacent to the normal reservoir footprint.

3.2 Case Study: The Challawa River

The potential backwater effects of the proposed Lake Ndevu may be better understood by examining the backwater zone of an existing reservoir with similar geomorphological features. The Challawa River in Kano State, Nigeria, is similar to the Luangwa River. It has two tributaries directly above its reservoir, a similar channel gradient and comparable sinuosity (Table 4). Within 25 years of the Challawa Gorge Dam being constructed, an 8 km reach above the reservoir experienced noticeable geomorphological changes. The dam has a nominal operating water surface elevation of 521 m (Lehner et al. 2001), but the range of reservoir extents seen in satellite imagery indicates that the water surface level fluctuates considerably depending on the season and year. Notably, the highest water level we estimated was several meters higher than the spillway crest elevation (Fig. 6).

Landsat 7 imagery, taken in September 2001, shows that the reservoir water surface level was high enough to inundate the tributaries flowing into the Challawa River. We determined the water elevation in this image to be approximately 526 m above sea level by extracting the elevation value of the water's surface using a 30 m resolution SRTM DEM Version 2 overlaid with the Landsat imagery. At 526 m, the water surface elevation is above the nominal water surface elevation and is more than 2 m over the spillway crest which is near 524 m above sea level (WB and LCBC 2002). This example of a reservoir whose level has gone higher than the spillway suggests that a 165 m extent for Lake Ndevu might underestimate the full extent of potential geomorphic influence by many kilometers and warrants the analysis of an 81 m water supply level in section 2.

Table 4. Similarities between the Challawa River in Nigeria and the Luangwa River in Zambia measured at a 20 km reach above the Challawa Gorge Dam reservoir and the 20 km reach above the proposed Ndevu Gorge Dam reservoir.

Characteristic	Luangwa River	Challawa River
Channel Length (km)	20	20
Valley Length (km)	16.70	16.08
Sinuosity	1.20	1.24
Gradient (m/km)	0.60	0.40

The Sentinel-2 image taken on January 8, 2017 shows much lower water levels at the Challawa Gorge Dam reservoir (Fig. 6C). The considerable channel rearrangement above the reservoir terminus in this image is a potential effect of fluctuating reservoir water surface elevations and/or backwater effects. If the proposed Ndevu Gorge reservoir is subject to similar changes in water level, the Kapamba confluence could be significantly altered.

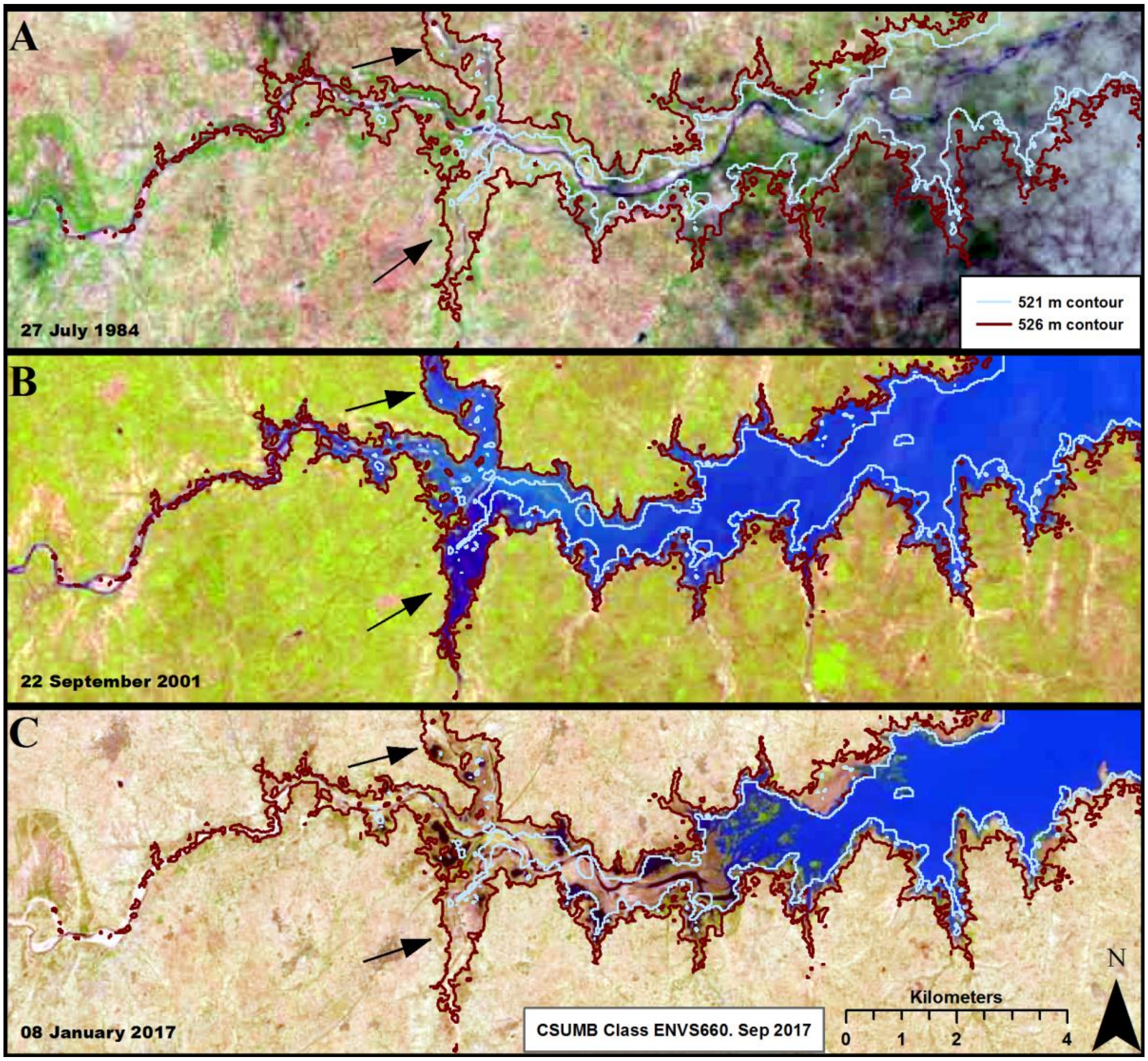

Figure 6. Comparison of Challawa river geomorphology before and after Challawa Gorge Dam construction was completed in 1992. Light blue lines indicate the nominal operating level of 521 m and dark brown lines indicate a water level of 526 m that inundated both tributaries above the reservoir. The Landsat 5 image taken on July 27, 1984 (A) shows the pre-dam river with unrestricted flows. The Landsat 7 image taken on September 22, 2001 (B) shows two upstream tributaries, indicated with black arrows, inundated by water surface elevations that exceeded the nominal operating level. The Sentinel-2 image taken on January 8, 2017 (C) shows evidence of considerable channel rearrangement above the reservoir terminus, a potential effect of fluctuating reservoir water surface elevations above the normal maximum operating level.

3.3 Backwater Effects on the Luangwa River

Since the Kapamba River confluence is an ecologically and economically important region in the Luangwa River Valley and is located approximately 5.5 km upstream of the proposed reservoir terminus, we decided to investigate potential backwater impacts in the area (Fig. 7). If the Luangwa River were dammed, we would expect it to respond similarly to the Challawa River because it, too, has two tributaries entering the mainstem immediately above where the reservoir would be.

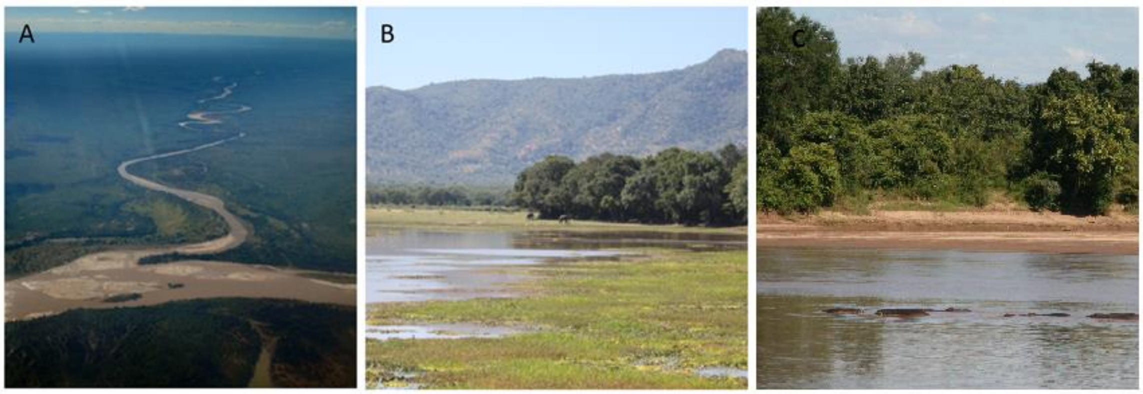

Figure 7. The Kapamba River confluence (A), riverside habitat (B), and hippopotamus in the Luangwa River near the confluence (C). Photographs by Fred Watson.

3.3.1 Methods

In Section 2 we estimated the reservoir at a 78 m water level (505 m above sea level) to reach approximately 64 km into South Luangwa National Park (measuring from the southernmost tip of the park following the floodplain), or approximately 5.5 km south of the Kapamba River confluence. We calculated the length of the backwater zone above the reservoir, L_b km, using the following equation described by Paola and Mohrig (1996):

$$L_b = H / S_{WS}$$

where H is the mean channel depth and S_{WS} is the gradient of the water surface of an unaltered reach immediately upstream of the backwater zone.

We used the mean channel depth for the Luangwa River put forth by Andreadis et al. 2013 in the Global River Bankfull Width and Depth Database. Andreadis et al. calculated river depths using mean annual peak flows from the HydroSHEDS database developed by WWF's Conservation Science Program. We also considered other multiple sources of estimated depth. We analyzed various forms of global terrain data including: SRTM DEM Version 1 (90 m resolution), SRTM DEM Version 2 (30 m resolution), and an ASTER GDEM (30 m resolution), but course resolution made extracting reliable channel morphology data difficult. Another source was an anecdotal observation made by a hunting safari website that indicated a depth of 10 m during the wet season (Mumembe Safaris, date unknown).

3.3.2 Results

Mean channel depth listed for the Luangwa River by Andreadis et al. 2013 was 3.62 m. We estimated water-surface gradient of the 35 km reach above the reservoir by calculating the difference between start and end elevations (7.95 m) and dividing it by reach length (35054 m) to get a channel gradient of 0.23 m/km. A gradient of 0.23 m/km matches what would be expected of a large meandering river when comparing the gradients of the top 20 largest rivers worldwide (Lewin and Ashworth 2014). To calculate these parameters, we focused on the river reach directly above the expected reservoir that had similar meander lengths and sinuosity patterns. The resulting estimated backwater length was approximately 16.0 km beyond the end of the reservoir, which extends past the Kapamba River confluence (Fig. 8).

Table 5. A range of backwater lengths that could be expected on the Luangwa River depending on mean channel depth. All values were calculated using a water surface gradient of 0.23m/km.

Mean Channel Depth (m)	Backwater Length (km)
1	4.4
2	8.8
3	13.2
5	22.0
10	44.1

It is important to note that mean channel depth varies substantially along the Luangwa River (some parts are confined and deep while others are wide and shallow) and minor changes in channel depth inputs on a low gradient river yield quite different backwater lengths using the Paola and Mohrig equation (Table 5). Therefore, a backwater length of 16 km should be considered a coarse estimation for this section of river. Backwater length can vary due to changes in river morphology as well as discharge. Our calculation of 16 km depends on the accuracy of the depth estimate, which can vary year to year. A backwater length of 16 km has a wide margin of error and is subject to these variations.

Likely hydrologic and geomorphic changes within the backwater zone include an increase in river stage, flood duration, sediment deposition and changes in river morphology at the confluence of the Kapamba and Luangwa Rivers. The confluence is an economically and ecologically important area as there are at least six safari and bush camps and the Nyamaluma training camp within a 30 km radius (Fig. 8). Increased flood duration could reduce the length of the season in which game drives could occur, prolong the flooding typical of the wet season and could cause a range of challenges for safari enterprises.

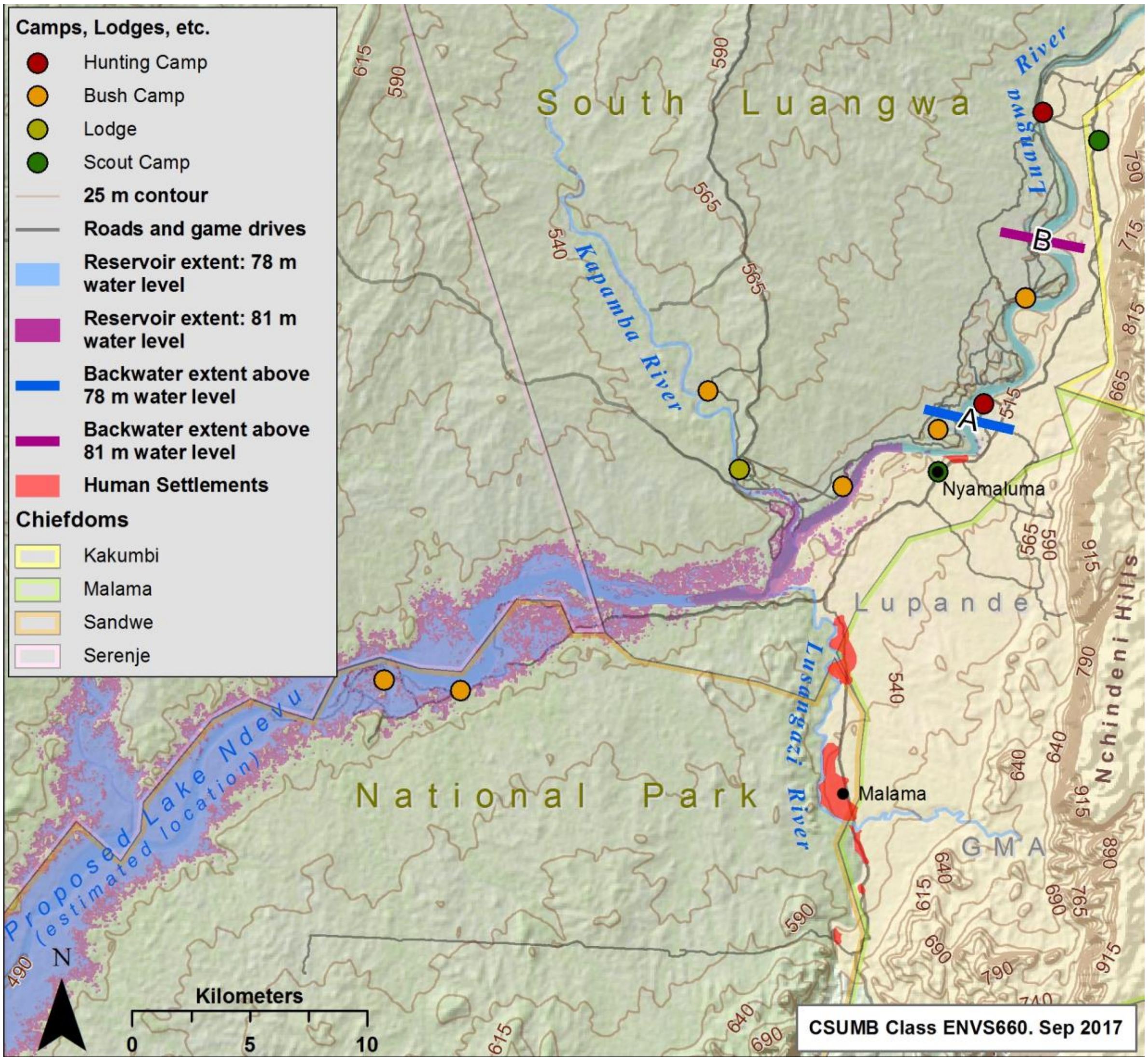

Figure 8. The Kapamba confluence and surrounding area that could be impacted by a backwater zone of 16 km upstream of the reservoir termini at reservoir water surface elevations of 78 m (A) and 81 m (B).

4 Hydrologic Analysis: Sediment

In this section, we estimate the amount of time it would take to fill the predicted volume of the reservoir with sediment. We estimate sediment yield for the Luangwa River above Ndevu Gorge based on previously published scientific literature applicable to the geographic area and use this information to calculate annual volume of sediment transported by the Luangwa.

The Luangwa River is a low-gradient, highly-dynamic, meandering river with medium sinuosity and channel substrates typified by a combination of clay, fine and coarse sands and loamy alluvium (Gilvear et al. 2000). Mobile sediment, combined with high flows during the wet season, cause frequent changes in the Luangwa's dimension and pattern (Gilvear et al. 2000, Fig. 9).

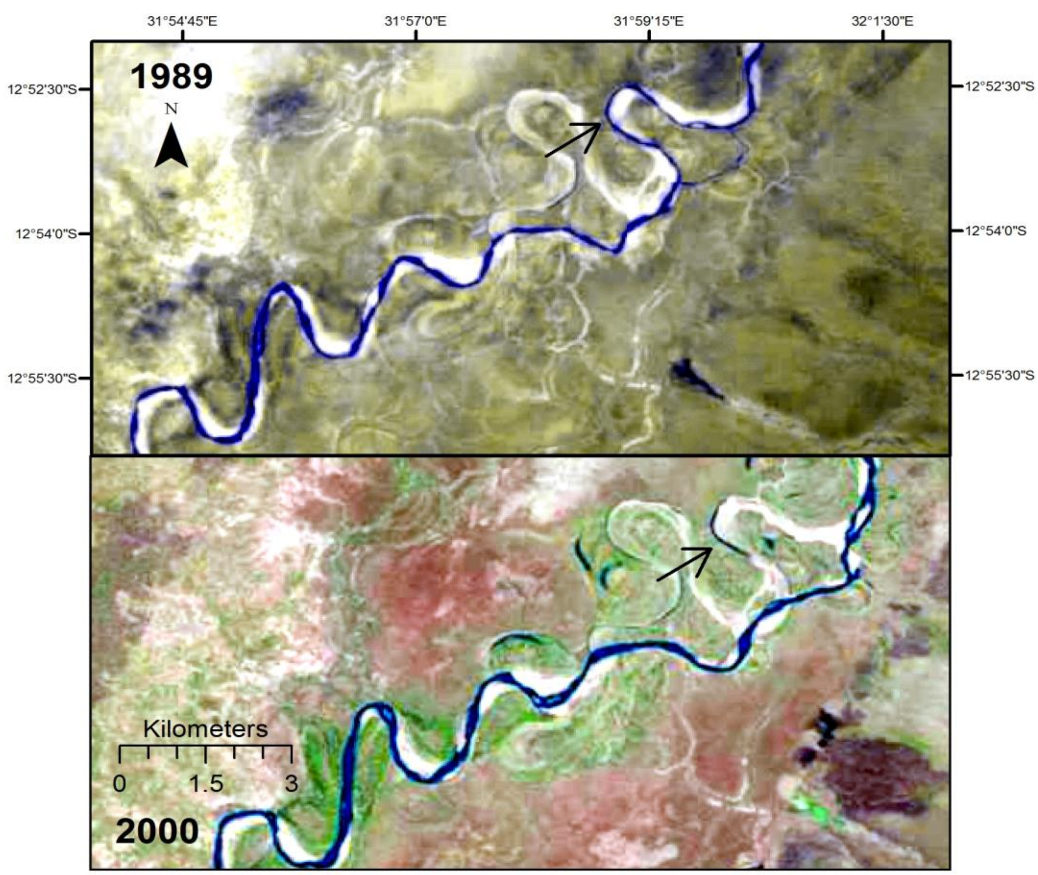

Figure 9. Example of dimension and pattern changes of mobile sediment in the Luangwa River's course, using Landsat 4-5TM imagery compiled from 01 Jan – 31 Dec in both 1989 and 2000.

4.1 Methods and Results

We estimated annual sediment yields as ranging between 100 and 1000 tonnes per square kilometer annually (t km^{-2} y^{-1}) using estimates from a report on sediment loading in the Zambezi basin (Bolton 1984), although specific sediment yield data were not available for the Luangwa itself. We divided the estimated sediment yield by the watershed area above the dam to calculate the annual mass of sediment produced (92,942 km^2, Fig. 2; Table 8). To convert from mass to volume of sediment, we needed to determine the bulk density of the sediment in the Luangwa River using particle size densities for given percentages of sediment types (sand, silt, clay).

Using data from a study on the Luangwa River in 2000 (Gilvear et al.) we estimated that the average sediment composition is approximately: sand 79%, silt 10.5%, and clay 10.5%. We estimated the bulk density of the sediment using the following equation developed by Lara and Pemberton (1965):

$$W = W_c P_c + W_m P_m + W_s P_s$$

where W is density in kilograms per cubic meter, W_c, W_m and W_s are the density coefficients of clay, silt, and sand, respectively, and P_c, P_m and P_s are the percentages of clay, silt, and sand, respectively. We calculated density coefficients for sediment compacted over 30 years (K_c, K_m and K_s) using Lara and Pemberton's methods for estimating compaction over time (1965). We used the 30-year density coefficients (Table 6), and assumed the sediment in the reservoir would always be submerged or nearly submerged (Reservoir Operation Type 1, Table 7).

Table 6. Bulk density coefficients for initial density of sediment (Lara and Pemberton 1965). Bulk density coefficients for 30-year density of sediment were calculated using methods from the same report.

Reservoir Operation	Initial density (t/m^3)			30-year density (t/m^3)		
Type	W_c	W_m	W_s	K_c	K_m	K_s
1	0.42	1.12	1.55	0.32	1.08	1.55
2	0.56	1.14	1.55	0.51	1.13	1.55
3	0.64	1.15	1.55	0.64	1.15	1.55
4	0.96	1.17	1.55	0.96	1.17	1.55

Table 7. Reservoir operation descriptions for selecting appropriate sediment bulk density coefficients as described by Lara and Pemberton (1965).

Reservoir Operation Type	Description
1	Sediment always submerged or nearly submerged
2	Normally moderate to considerable reservoir drawdown
3	Reservoir normally empty
4	Riverbed sediments

We used a 30-year compaction rate to determine a conservative estimate of annual volume input over time (between 6.7 and 67 million m^3/yr). We estimate that it would take 693 to 6,933 years to fill the proposed reservoir, 46.8 km^3, at that rate. By comparison, Lake Kariba is expected to have its "dead" storage capacity filled with sediment, about 116 km^3, in 1,600 to 16,000 years at a rate of 7 to 70 million m^3 per year (Bolton 1984). Though comparatively smaller, Lake Cahora Bassa is predicted to fill its "dead" storage capacity with sediment, about 12.5 km^3, in 60 to 600 years at a rate of 20 to 200 million m^3 per year (Bolton 1984).

The long fill time estimated for Lake Ndevu is consistent with the fact that, among large reservoirs around the world (excluding ones that enlarge existing natural lakes), Lake Ndevu would have a relatively large ratio of reservoir volume to catchment area. Lake Ndevu's ratio would be 0.51 m^3/m^2, compared, for example, to Lake Kariba's 0.27 m^3/m^2 and Lake Cahora Bassa's 0.06 m^3/m^2, from analysis based on GRanD database (Lehner et al. 2011).

Table 8. Parameters used in calculating sedimentation of predicted reservoir.

Sedimentation calculation parameters	
Watershed area (km^2)	92,492
Reservoir volume (km^3)	46.75
Calculated 30-year bulk density (t/m^3)	1.37
High est. sediment yield ($t\ km^{-2}\ y^{-1}$)	1000
Low est. sediment yield ($t\ km^{-2}\ y^{-1}$)	100
High sediment volume (m^3/yr)	67,000,000
Low sediment volume (m^3/yr)	6,700,000

It is thus unlikely that sedimentation of the reservoir is of significant consequence given the large size of the reservoir and the time it would take to fill with sediment.

Operation of the proposed dam will affect how sedimentation of the reservoir impacts efficiency and longevity of power production. River-specific sediment data are necessary to improve accuracy of annual sediment yields and volumes. Although not addressed in this report, the location of sediment accumulation may have greater impact than the seemingly negligible amount of time it takes to fill “dead” storage capacity of the reservoir and could be explored further (Bolton 1984).

5 Biodiversity and Wildlife Connectivity Analysis

Dams in subtropical regions have been found to exert a variety of trophic effects on surrounding ecological systems (WWF 2004). They disconnect rivers from their floodplains and wetlands, slow river flows, disrupt sediment movement, fragment freshwater habitat and disrupt natural flood cycles (WWF 2004).

The proposed Ndevu Gorge dam and resulting Lake Ndevu have the potential to harm plant and animal biodiversity through habitat loss and disruption from increased human activity and development, inundation, loss of natural river function and loss of wildlife connectivity. Inundation of parks, GMAs and hunting areas would cause direct loss of natural habitat that preserves biodiversity. Lake Ndevu may further constrict the Luangwa River wildlife corridor, impacting wildlife movement and dispersal. Added human encroachment and development could increase snaring as well as contribute to habitat loss and prey depletion (Watson et al. 2013 & 2015).

In this section we examine animal species of concern in the Luangwa Valley and how the Ndevu dam might impact their relationship to the landscape. We then quantitatively examine impacts to wildlife connectivity on a regional scale by analyzing changes to the wildlife corridor that connects South Luangwa National Park to Lower Zambezi National Park.

5.1 Luangwa River Valley Biodiversity

The Luangwa River Valley provides a mosaic of diverse habitats including riparian forest, grassed dambos, floodplain grassland and woodlands such as miombo and mopane (Caughley & Goddard, 1975). The natural hydrology of the Luangwa River allows for flooding in the rainy season (December to April) creating seasonal wetlands, oxbow lakes, sandbars and other features that create rich habitat for plants and wildlife.

The Luangwa Valley is home to several species on the International Union for the Conservation of Nature (IUCN) Red List as well as species of national and economic importance.

The **African wild dog** is an IUCN endangered carnivore that requires large ranges and is in steep decline due to snaring and habitat loss (RWCP & IUCN/SSC 2015). They are of ecological importance as an apex predator, and of economic importance to the wildlife tourism industry. African wild dogs require some of the largest ranges of any carnivore in the world (RWCP & IUCN/SSC 2015), making them vulnerable to the habitat loss and land cover change that would accompany the development of the Ndevu Gorge dam. The added human encroachment due to dam construction and power station operation could also lead to increased snaring (Watson et al. 2013). Management and conservation of this highly vulnerable species hinges on gene flow between large ranges, which relies on large protected areas connected by movement corridors (RWCP & IUCN/SSC 2015). Further discussion of the dam's impact on wildlife corridors takes place in the following section.

Grey crowned cranes are listed as endangered by the IUCN due to habitat loss and illegal trade in the exotic pet industry. These cranes favor wetlands and are numerous in the Luangwa River valley (Dodman 2008). They congregate in the seasonal oxbow lakes and small wetland plains afforded by the river's natural processes. This habitat is a breeding site, making Luangwa Valley important for the overall health of crane populations (Dodman 2008). Their distribution includes a distinct range in the region upstream of the Ndevu reservoir (Dodman 2008). The reservoir has the potential to inundate the seasonal oxbow lakes and grasslands that these endangered cranes require for breeding and foraging.

African elephants are classified as vulnerable in on the IUCN red list due to poaching and ivory trade. Populations are decreasing continent-wide by about 8 percent per year due to poaching (Chase et al. 2016). A 2015 study indicates that elephant numbers in the Luangwa River region have slightly decreased since 2008 (DNPW 2016). In South Luangwa National Park in particular, numbers declined from as high as 8,000 in 1995 to less than 2,500 in 2012 (Frederick 2012). SLNP lost almost half its elephants between 2011 and 2012 (Frederick 2012).

Their range extends south of the National Park and throughout the area that would be impacted by the potential dam and reservoir (IUCN 2008). Reservoir inundation would flood their preferred movement corridors, since elephants prefer to move along river corridors during the wet season (Caughley & Goddard 1975),. Their size and charismatic nature elevates African elephants to a keystone role in wildlife tourism. Their extensive range movements necessitate a further look at how Lake Ndevu and resulting habitat change would affect this species and their value to biodiversity and tourism.

Thornicroft's giraffe is endemic to the Luangwa River Valley and was identified as genetically isolated in 2013 (Fennessy 2013). The population is stable and varies from 750 to 1,000 giraffes with none in captivity (Fennessy, 2013). The species range extends through North and South Luangwa National Parks (IUCN 2016). Individual ranges average between 68 to 82 km^2, requiring 2 to 3 kilometers on either side of the river (Berry, 1978). Male Thornicroft's giraffes have been found to cross the Luangwa River during dry season at water depths of 1 m or less (Berry, 1978); a movement important for gene flow and the genetic diversity of the population. The widening and deepening of the river where the reservoir and backwater effects occur may hinder Thornicroft's giraffe from crossing in those parts of its range.

Hippopotamus conservation is a point of contention in Zambia (Lusaka Times, 2016). The IUCN elevated hippos to vulnerable status in 2006 due to habitat loss and poaching for their ivory teeth and meat. Zambia has one of the largest populations of hippos in Africa (IUCN, 2009) and the Luangwa River Valley is home to 62 percent of them (Chomba et al., 2012). In South Luangwa National Park, populations have steadily increased since the 1950s, and remain at or near ecological carrying capacity, with numbers higher during years with more rainfall (Chomba et al. 2012). Hippos are particularly sensitive to human disturbances when coupled with low rainfall (Lewison, 2007).

Hippos are important megafauna to wildlife tourism, and their presence in a river ecosystem is integral to natural processes. Specifically, their dung is rich in nutrients and supports healthy aquatic ecosystems (McCauley et al. 2015).

Hippos prefer riverbends and areas with many meanders due to the sandbars that accumulate for the critical behavior of basking in the warm sun to control body temperature (Chansa et al. 2011). These types of habitats also provide suitable nursery grounds in which to protect their young from lions and other predators. Reservoir inundation and backwater effects would flood these meanders, removing prime hippo habitat and disrupting natural processes that rely on their presence.

African lions are listed as vulnerable on the IUCN Red List and have declined by 43 percent in the last 21 years (Bauer et al. 2016). Their range encompasses North and South Luangwa National Parks and the corridor that links that region to Lower Zambezi National Park (Panthera & WCS 2016). However, they are being extirpated from the outer portions of this range, pinched inward toward protected areas by human encroachment, poaching and prey depletion (Bauer et al. 2016; Panthera & WCS 2016).

Lions are popular targets of trophy hunting and concern over population numbers prompted a hunting ban in 2013 (Rosenblatt et al. 2014). The ban was lifted in 2015 (BBC Africa 2015).

Leopards were elevated to vulnerable on the IUCN Red List in 2016 due to globally declining numbers (Stein et al. 2016). Threats to leopards include habitat fragmentation and loss, prey depletion, poaching and all due to human encroachment and development (Stein et al. 2016). Leopard range includes South and North Luangwa National Parks as well as the corridor that connects those protected areas to Lower Zambezi National Park (Gerngross 2016), and is increasingly pressed into these protected areas by human encroachment resulting in prey depletion (Rosenblatt et al. 2016). Inundation by the proposed reservoir and the increased human encroachment that comes along with it could exacerbate these threats.

5.2 Dam Impacts on Wildlife Connectivity

Large dams and reservoirs have the potential to affect wildlife on a regional and continental scale. Current initiatives in conservation focus on the connection of large protected area like national parks into a functional network of corridors that facilitate dispersal and migration between core habitat areas (RWCP & IUCN/SSC 2015; WSSD Plan 2002). Corridors can mitigate the effects of habitat loss and encourage gene flow between populations (Roever, 2013). These corridors are of particular importance to species with high dispersion and vast ranges like the endangered African wild dog, lions and elephants.

The United Nations provided a framework for sustainable development at a 2002 World Summit on Sustainable Development that commits member nations to "promote the development of national and regional ecological networks and corridors" (WSSD Plan, 2002). Adherence to UN policy would warrant further research on the potential impacts a dam at Ndevu Gorge could have on the critical wildlife corridor in the Luangwa River Valley.

There are several indicators that wildlife utilize the natural corridor between South Luangwa National Park and Lower Zambezi National Park. Patterns of human encroachment (Fig. 5) line the corridor along the Luangwa River, denoting a narrowing pathway of productive landscape that wildlife can use to move between protected areas.

IUCN species reports and assessments for elephants, wild dogs, leopards and lions show ranges that span the two park systems and include the corridor between (IUCN 2008; Gerngross 2016; Panthera & WCS 2016; RWCP & IUCN/SSC 2015).

Hunting and safari camps along the Luangwa south of SLNP claim that elephants, wild dog, leopards and lions can be seen on their private reserves (Mbizi Game Reserve 2016; Munyamadzi Game Reserve 2015; Kirchner 2016) placing these species between the two park systems and supplying further evidence of use of the river as a wildlife corridor. A geotagged photo from 2015 shows a group of wild dogs in the Nyakolwe area, about 20 km south of SLNP (Kirchner 2016). Munyamadzi Game Reserve, located about 70 km south of SLNP, reports an April 2017 sighting of wild dog as well as reports of a pack of 30 in the area (Munyamadzi Game Reserve 2015).

Elephant movement serves as an apt proxy for studying connectivity benefits to biodiversity, because elephant presence is highly correlated with species richness of other megafauna (Epps 2011). Roever (2013) modeled African elephant movement between protected areas and found that evidence supports the existence of a corridor between the Luangwa national parks and Lower Zambezi National Park.

This corridor is particularly important because the Luangwa parks have little connectivity to other major protected areas. High human density in Malawi discourages connectivity in that direction (Roever 2013). The Luangwa -Zambezi corridor is also the Luangwa's sole connection to the Kavango-Zambezi Trans-Frontier Conservation Area (TFCA) system of protected areas.

The reservoir would inundate 50% of the length of the Luangwa River corridor between SLNP and Lower Zambezi and 24% of the width where the risk of human encroachment is the greatest (Fig. 10).

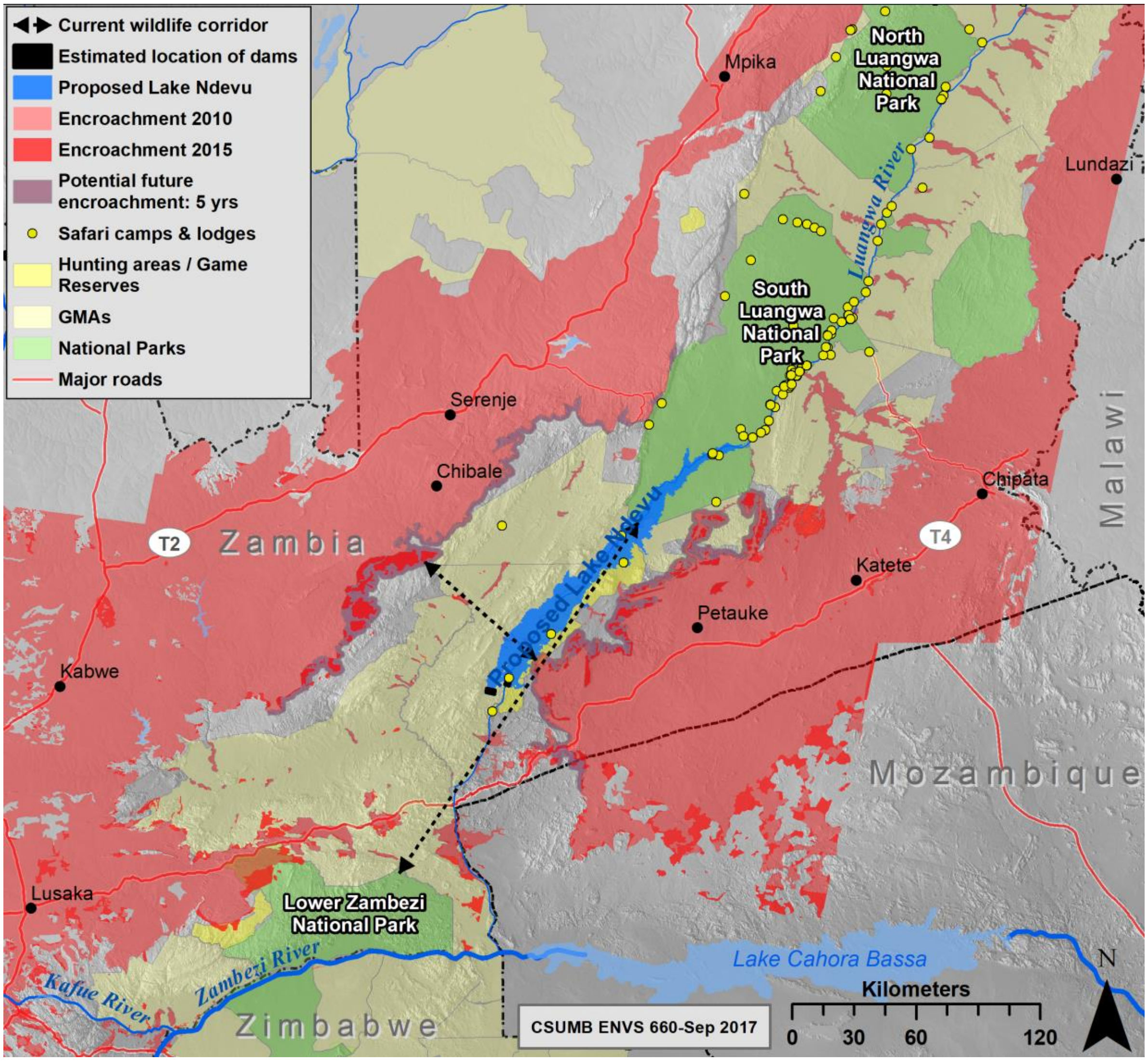

Figure 10. Reservoir inundation and human encroachment in relation to the Luangwa River wildlife corridor. At full reservoir supply and expected levels of human encroachment,

6 Wildlife-Based Tourism Impacts

Nature-based tourism is a large part of Zambia's total economy, fluctuating between 6% to 10% of the GDP and contributing US$ 110 million to US$179 million per year (UNREDD 2015). Over a 20-year period, tourism has steadily grown at an average rate of 12% (Richardson et al. 2012). For every three nature tourists, one full-time job is created (WB 2007). The direct contribution to employment is estimated to provide 124,000 jobs including employment through hotels, travel agents, airlines, restaurants, and other leisure activities supported by tourists (WTTC 2017).

Nature-based tourism in the Luangwa Valley contributes significantly to improved welfare and poverty alleviation (Simasiku et al. 2008). Wildlife creates the potential to generate income opportunities in rural areas not suitable for commercial agriculture. In 2003, SLNP provided employment to 638 permanent employees, also creating 1,200 direct jobs and another 1,200 indirect jobs (UNDP 2004). According to emerging studies, SLNP generates an income value of around US$ 20M from tourist activity. A preliminary World Bank (WB) report cited a study conducted by The Nature Conservancy (TNC) estimating the value of SLNP at US$ 20M, although we could not find details of the TNC study (WB 2016). More recently, a PhD student at the University of Florida is completing a study on the economics of tourism in and around SLNP, and has estimated a similar total value (Chidakel 2017).

Trophy hunting constitutes a large part of Zambia's economy and is permitted in hunting concessions within GMAs as well as private hunting areas and conservancies (Chomba & Nyirenda 2015). Gross earnings from trophy hunting in Zambia generated US$ 18M (Lindsey et al. 2014). Trophy hunting within GMAs generates US$103 ± 97/$km^2$ whereas extensive game ranching earns US$878 ± 226/ km^2 (Lindsey et al. 2014). Wildlife ranching including crocodile farming was valued at US$ 15.7M and employed 2,200 people in 2012 (Lindsey et al. 2013). The turnover from trophy hunting and ecotourism on extensive and fenced game ranches was US$ 11.2M (Lindsey et al. 2013). In comparison, 36 GMAs encompassing an area 29 times larger generated US$ 16M (Lindsey et al. 2014).

The Department of National Parks and Wildlife (DNPW) has 1,556 field staff employees to assist in the management and protection of wildlife resources in GMAs (UNDP, 2004). In 2012, DNPW earned approximately US$ 4.34M from trophy hunting in GMAs (Lindsey et al. 2014). DNPW allocates 50% of animal fees and 20% of concession fees to local Community Resource Boards (CRBs), and those fees are allocated within GMAs to Village Scouts, Chiefs, CRB administration and community projects.

GMAs are classified into five categories based on their capacity to produce revenue from hunting, although more recently a sixth designation—super-prime—has emerged (Simasiku et al. 2008; Watson et al. 2013). Earnings within GMAs are directly linked to consumptive tourism which is dependent on wildlife resources. Communities living within prime GMAs are estimated to have 17% higher incomes compared to households outside of GMAs (Richardson et al. 2012). However, the benefits of living in a GMA are unevenly distributed. Due to habitat loss, unsustainable management and increased poaching 49% of GMAs do not generate earnings (Richardson et al. 2012). Overall, communities living within GMAs are 30% poorer than the national rural average, with few economic opportunities and low agricultural potential; revenue per capita community is US$ 11.9/km^2. (Lindsey et al. 2014).

Numerous societal and economic impacts are likely to arise if the proposed Ndevu Gorge dam is commissioned on the Luangwa River. The inundation is likely to affect SLNP, four GMAs, five game ranches, a hunting conservancy, and numerous safari camps. Human encroachment is already significantly impacting the natural habitat for wildlife. Habitat loss within GMAs is increasing at a rate of 0.69% per year while deforestation of protected areas is expanding at a rate of ~2,500-3,000 km^2 per year (Watson et al. 2015; Vinya et al. 2011).

Recent extended dry seasons and seasonal droughts have resulted in less agricultural output per capita (WB, 2016). Increases in food insecurity and high poverty levels have caused wildlife poaching rates to increase. As a result of declining wildlife populations, DNPW reclassified 24 GMAs in 2008 as depleted, understocked or secondary (Simasiku et al. 2008). Lupande and West Petauke GMAs are classified as super-prime and prime, respectively, based on species richness and relative abundance (Watson et al 2013). Sandwe was reclassified in 2008 due to 30% decrease in species abundance (Simasiku et al. 2008). Chisomo is classified as understocked and does not have consistent earnings from trophy hunting (Chomba & Nyirenda 2015).

If the Ndevu dam were to be constructed, certain GMAs and hunting areas would be partially inundated, and some properties that bordered the river would instead border the lake. The river reach within Chisomo and Sandwe would be 100% inundated and the river reach within West Petauke would be 58% inundated. The uppermost reach of the reservoir, under backwater conditions, would also affect Lower Lupande GMA.

Inundation from the proposed Ndevu Gorge dam would put added pressures on the wildlife resources within GMAs, which are already under ecological stress. Private hunting areas outside the GMAs would see significant inundation including the loss of several camps and roads that support revenue-generating wildlife-based tourism operations.

7 Scoping for Future Work

This study represents a preliminary exploration into potential impacts of a dam at Ndevu Gorge. Should an environmental impact study be conducted, more detailed review of potential impacts should include the following study areas not fully addressed in this report:

- Modelling and simulation of altered river stage & floodplain dynamics in the backwater zone directly upstream of the reservoir terminus
- Analysis of effects on flow downstream of the dam site
- Analysis of effects on downstream sediment transport, including altered stream morphology and nutrient deposition
- Projection of indirect land use change catalyzed by the dam & reservoir, e.g. new towns, roads, powerlines, wood cutting, charcoal burning, and/or irrigated & non-irrigated agriculture in areas that are now in a relatively natural state
- Projection of probable poaching activity associated with changes in land use
- Quantification of economic consequences of environmental impacts, such as effects on photographic and hunting tourism
- Analysis of terrestrial wildlife distribution and movement within the corridor zone between SLNP and LZNP both currently, and under future conditions with additional encroachment of settlement, as well as the reservoir and associated infrastructure
- Analysis of aquatic ecosystems (including aquatic wildlife) supported by the Luangwa River both currently, and under future conditions upstream and downstream of the dam site

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