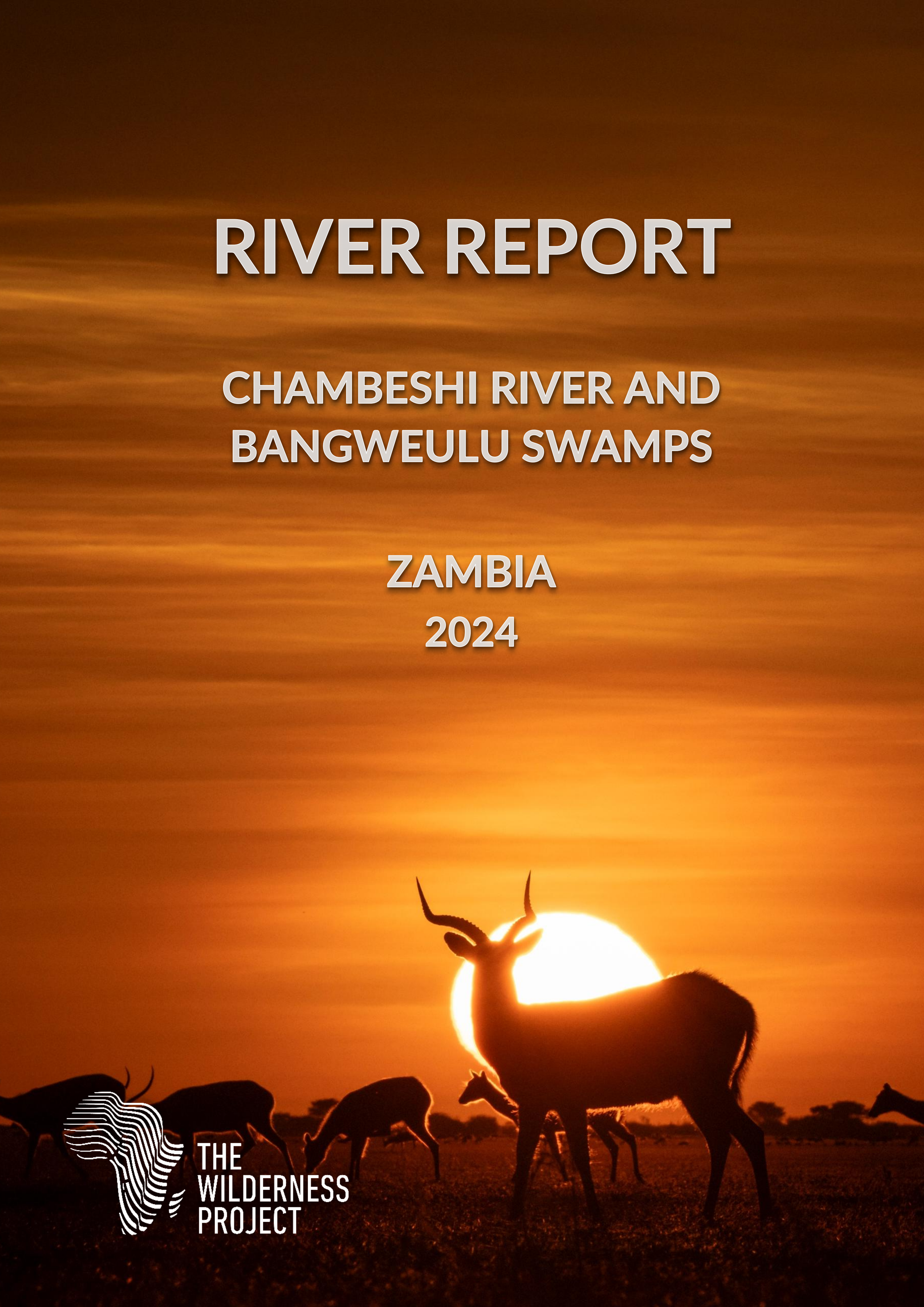
RIVER REPORT

CHAMBESHI RIVER AND BANGWEULU SWAMPS

ZAMBIA
2024



THE WILDERNESS PROJECT

ABOUT THE WILDERNESS PROJECT

By 2035, in partnership with local communities, governments, researchers and NGOs, The Wilderness Project aims to explore, study and better protect 1.2 million square kilometres of irreplaceable African wilderness. Central to this effort is to establish detailed hydrological and ecological baselines of the largely undocumented sources and watersheds of Africa's greatest river basins — Zambezi, Congo, Nile, Chad and Niger.

ACKNOWLEDGEMENTS

Our research transects would be impossible without the collaboration of our various partners, who enable information-sharing, provide local advice, and grant permissions wherever we work. For their continued support along the Chambeshi River, we thank the Department of National Parks and Wildlife, Copperbelt University, African Parks, the Water Resources Management Authority, the University of Zambia, and the Wild Bird Trust. Finally, we extend our gratitude to the traditional custodians who granted us permission to navigate the waters and lands of the Chambeshi—twatotela.

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THE WILDERNESS PROJECT

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EXECUTIVE SUMMARY

The Chambeshi River is the most distant source of the Congo River, originating 4,775 km from the Atlantic Ocean in Zambia's Senga Hills. It is a major water source for the Bangweulu Swamps—an internationally recognized Ramsar site home to the southernmost population of shoebills and two endemic antelopes, the black lechwe and Bangweulu tsessebe. Despite its ecological significance, the Chambeshi River remains largely undocumented, with no modern scientific assessments of its biodiversity, water quality, and hydrology.

To address this gap, The Wilderness Project (TWP) initiated the Chambeshi River research transect in April–May 2024, covering 765 km over 33 days from the river's source to Tuta Bridge near the southwestern outflow of the Bangweulu Swamps. The expedition collected data on human impacts, biodiversity, water quality, and river discharge. Findings are detailed in this report and presented as interactive web maps with 360-degree imagery (link)

Key Findings:

People and Fisheries

People are distributed along most stretches of the river, with several hotspots of human activity near roads, bridges, harbours, and wetland high ground. The average density is **3.38 people/km**, comparable to other Zambian rivers. Fishing activity is widespread, with notable pressure in specific areas, highlighting the need for an **updated fisheries assessment** for both the Chambeshi River and Bangweulu Swamps.

Agriculture and Water Quality Risks

The upper Chambeshi River in Senga Hills experiences **intense agriculture**. Although high wet-season flows dilute pollutants, dry-season eutrophication and pollution have been reported anecdotally. In addition, **The Lulimala River Mouth** showed significantly elevated conductivity and salinity—three times higher than upstream—likely **linked to manganese mining**. These findings emphasize the urgent need for ongoing water quality monitoring, particularly in the upper Chambeshi and Lulimala rivers.

Biodiversity

The Chambeshi Flats showed unexpectedly **high wetland bird densities** (8.45 birds/km vs. 4.91 birds/km in Bangweulu Swamps), likely due to localized bird migrations tracking receding waters. However, terrestrial wildlife was largely absent, aligning with evidence of long-term population declines in the region.

Despite limited sampling effort, our opportunistic fish sampling detected an **estimated 40 species**, with several potentially undescribed species in the upper Chambeshi. Rapids in the Chambeshi Gorge act as a natural biogeographic barrier, restricting fish movement. Ongoing taxonomic and eDNA analyses from 13 sites will provide further insights into ichthyofaunal diversity.

Hydrology and Wetland Function

The Chambeshi River contributes an estimated **40–50% of the Bangweulu Swamps' flow**, with most water originating from its tributaries and the Chambeshi Flats. During the dry season, smaller tributary inputs diminish, and the **storage effect of the Bangweulu Wetlands becomes more pronounced**, reinforcing the **critical role of the Chambeshi-Bangweulu wetland complex as a hydrological buffer** for the broader Luapula system. Contrary to outdated views that wetlands "lose" water through evapotranspiration, Bangweulu plays a **key role in sustaining downstream flows**, supporting biodiversity and human livelihoods.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Background of The Wilderness Project

The Wilderness Project (TWP) is a non-profit organisation that supports research and conservation on rivers in Africa. In 2022, TWP launched the Great Spine of Africa series of expeditions (GSOA) in partnership with the ROLEX Perpetual Planet Initiative. The objective of the programme is to explore and protect over 1.2 million km² of irreplaceable African watersheds and wetlands by 2035. To date, TWP has enabled important research along thousands of kilometers of rivers in Zambia, Angola, Namibia, and Botswana, including the Cassai, Cuando, Lungwebungu, Kafue, and Zambezi Rivers.

TWP collects important baseline data on rivers to support their long-term management and conservation. The overarching goals of TWP are to: i) assess the status of Africa's freshwater ecosystems; ii) identify areas of critical concern or conservation significance; iii) support the efforts of government and NGOs working in the freshwater conservation space; iv) develop local scientific and storytelling capacity; and v) generate targeted interest and funding for the conservation of rivers in Africa.

1.2 Expedition Objectives

In April–May 2024, researchers from TWP conducted a transect of the Chambeshi River from its source in Senga Hills to Tuta bridge, near the outflow of the Bangweulu Swamps — a total distance of 765 km. The expedition aimed to gain a 'snapshot' of the health of the river by collecting biodiversity, human impact, water quality and discharge data. In addition, informative digital content was promoted on various social media platforms to raise awareness about the river. This included a feature in the Call to Earth series — a partnership between Rolex and CNN to report on the environmental challenges facing the planet (link). Finally, capacity building was encouraged by conducting the expedition with a predominantly local team and training them on river expedition, research and guiding approaches.

1.3 Study Site Description

The Chambeshi River is the most distant headstream of the Congo River (Figure 1). It originates as a spring in the Senga Hills of northern Zambia, near the border with Tanzania, before flowing in a south-easterly direction for ~160 km towards the Chambeshi Flats — a large complex of dambos and wet meadows that includes the Luwala Swamp, Bwela Flats and Nashinga Swamp. The Chambeshi Flats regulate the flow of water downstream towards a broad, shallow alluvial pan containing lakes, swamps and floodplains — the Bangweulu Swamps.

The Chambeshi River diverges into the Bangweulu Swamps, reconverging at the southerly outflow as the Luapula River. From this outflow, the Luapula River travels south for a further 180 km before turning a wide arc to the north and flowing into Lake Mweru, which drains into the Luvua River and eventually confluences with the Lualaba branch of the Congo River, enroute to the Atlantic Ocean.

Along its course, the Chambeshi River flows through several distinct biogeographical zones (Table 1). These include the source hills, the steep, rocky and heavily forested areas of the Chambeshi gorge, and two major wetlands. Vegetation surrounding the Chambeshi River consists predominantly of mixed miombo open woodlands and forests, interspersed with grassy glades.

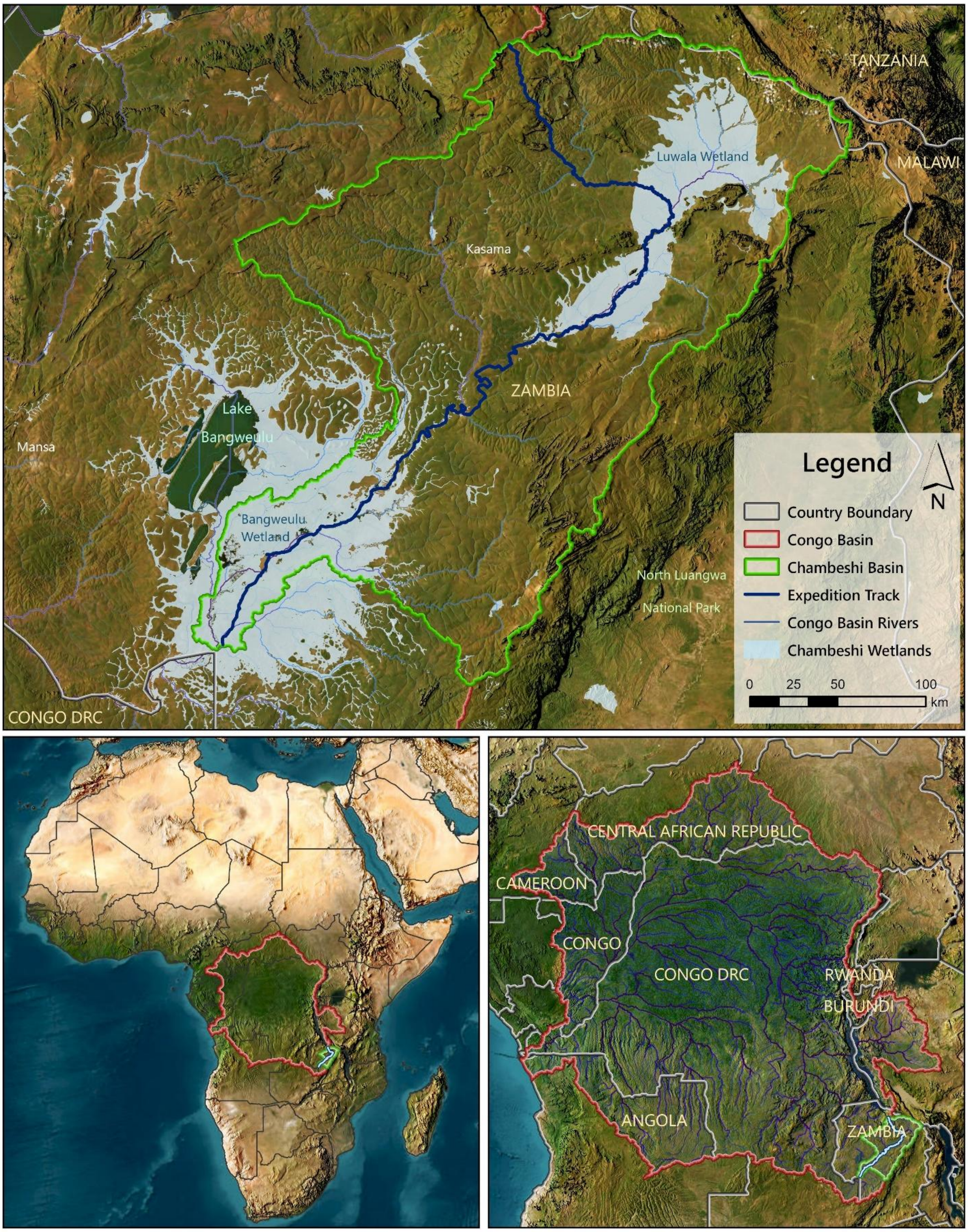

Figure 1. Rainfall in the Senga Hills of northern Zambia enters the Chambeshi River and flows ~4,775 km to the Atlantic Ocean via the Luapula, Luvua and Congo Rivers. The 2024 Chambeshi Expedition followed the first 765 km of this route, as is displayed with a red line in the smaller inset map.

Table 1. The biogeographical areas through which the Chambeshi River flows.

River Section	Description	Photograph
Chambeshi Source	The source area is the first 38 km of the river. Here, the river is small (less than 20 m wide in most sections), with a narrow grassy floodplain that is bordered by miombo woodlands.	
Chambeshi Gorge	The Chambeshi Gorge has a narrow river (less than 20 m wide in most sections) and a steep relief with several large rapids. The river is bordered by riverine forests and grassy glades, with limited wetland habitat.	
Chambeshi Flats	The Chambeshi Flats is a large complex of dambos and wet meadows that includes the Luwala Swamp, Bwela Flats and Nashinga Swamp. The wetland complex is dominated by aquatic grasses that grow in a floodplain up to 70 km wide.	
Lower Chambeshi River	The Lower Chambeshi River is located between the Chambeshi Flats and Bangweulu Swamps. The main channel of the river is generally over 20 m wide in this section and is bordered by trees that occur within a narrow grassy floodplain.	
Bangweulu Swamps	The Bangweulu Swamps is an ~9,850 km^2 extent of submerged aquatic vegetation in open lakes and channels surrounded by dense flooded grasslands and papyrus stands — one of the largest intact wetlands on the planet.	

Conservation Areas

There are several areas of conservation importance in the Bangweulu Swamps, and, although none of these extend to the Chambeshi Flats or upper reaches of the Chambeshi River, they are important for the biodiversity of the greater ecosystem. These include three national parks and six game management areas (GMAs). Collectively, GMAs cover much of the south-eastern Bangweulu Swamps complex (Figure 2).

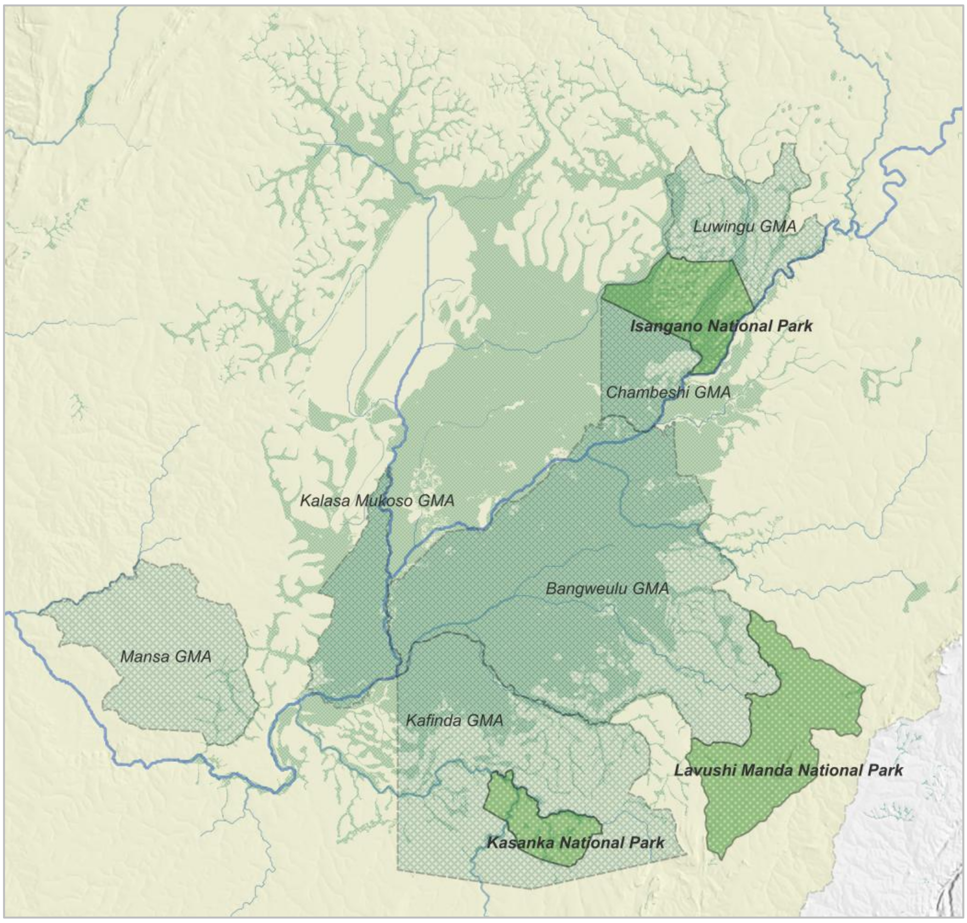

Figure 2. Areas of conservation importance within the Bangweulu Swamps.

Conservation areas in the Bangweulu Swamps offer a refuge for migratory herds of the endemic black lechwe — now extinct from the Chambeshi Flats. In addition, the Bangweulu tsessebe (*Damaliscus superstes*) is an isolated population of sassaby that is endemic to the region. Moreover, the wetlands host a diverse array of wetland-associated birds, including a large population of the endangered wattled crane (*Grus carunculata*) that serves as an indicator of the health of this pristine ecosystem.

Sustainable management of the Bangweulu Swamps supports an immense fishery — the productivity of which is influenced by the regular seasonal inundation of the floodplain vegetation. Much of the wetland falls under customary land tenure and the Bangweulu GMA is cooperatively managed through Community Resource Boards (CRBs), the Department of National Parks and Wildlife (DNPW) and African Parks (AP).

Ongoing Initiatives

There are several ongoing initiatives within the Bangweulu Swamps and the greater Chambeshi River basin. These predominantly aim to reduce the vulnerability of communities to the impacts of climate change and strengthen the ecological integrity of the forests and wetlands. Several of these align with the United Nations Environmental Programme (UNEP) project titled “Building the resilience of local communities in Zambia through the introduction of Ecosystem based Adaptation (EbA) into priority ecosystems, including wetlands and forests"[1]. These include the: i) Water Resources Development Project (WRDP); ii) Transforming Landscapes for Resilience and Development Project (TRALARD); iii) Miombo Eco-Region Conservation Programme (MECP); and the iv) Bangweulu Wetlands Project.

Whilst much of the funding for these projects has been directed towards community development, including improved water resources management and agricultural productivity, a comparatively small amount has been earmarked for the conservation, management and expansion of wilderness areas within the basin. As a result, the protection and expansion of wilderness areas within the Chambeshi basin should be a priority — particularly considering the globally relevant target to conserve 30% of Earth's land and sea by 2030[2]. Within this context, the Bangweulu Wetlands Project emerges as a unique and increasingly important driver of conservation in the area (Figure 3).

Since 2008, African Parks and their partners, in collaboration with DNPW and CRBs, have been the stewards of the Bangweulu Wetlands Project[3]. This project involves several important initiatives, including: i) community programmes and enterprise development projects — particularly beekeeping and sustainable fisheries; ii) indigenous game reintroductions; iii) awareness raising to support the recovery of the black lechwe population; iv) conservation law enforcement training; and v) the establishment of a comprehensive shoebill captive rearing and rehabilitation facility. Among other positive results, these interventions have curbed illegal hunting, prompting a dramatic increase in the black lechwe and tsessebe populations. However, as the number of people living within the Chambeshi basin continues to grow, the protection of this unique ecosystem will increasingly rely on adaptive and inclusive conservation interventions that account for the needs of both people and biodiversity (Figure 4).

Figure 3. The Bangweulu Wetlands Project has played a pivotal role in supporting communities and natural ecosystems in the Bangweulu Swamp and surrounding areas.

[1] *GEF Project Details. Available at: https://www.thegef.org/projects-operations/projects/8034.*
[2] *For more information, see https://www.cop28.com/en/thought-leadership/The-30x30-Biodiversity-Goal-at-COP28.*
[3] *African Parks. 2024. Available at: https://www.africanparks.org/the-parks/bangweulu.*

Figure 4. Francis Musonda of the upper Chambeshi valley displays the afternoon's harvest. These caterpillars are known locally as fikhubala. They are generally dried, salted and cooked prior to consumption.

1.4 Team Members

The expedition team consisted of scientists and local researchers, river specialists, storytellers, filmmakers, guides, and logistics experts, including some of the best expedition talent in Zambia (Table 2).

Table 2. The Chambeshi River Expedition Team


Dr Steve Boyes-
Project Founder


Stephen Mbewe-
Researcher


George Matomola-
Camp Manager


Justin Mulenga-
Local Guide


James Kydd-
Storyteller


Kevias Zulu-
Lead Chef


Matthew Dooley-
Research Lead


Johan van der Westhuizen-
Expedition Lead


Kedila Mbundi-
Camp Chef


Johan 'Vossie' Vorster-
Storyteller


Abdul Al-Habesh-
Logistic Support


Phindile Ntshangase-
Logistic Support


Brian Puleni-
Logistics Assistant


Dominic Mwahamubi-
Boat Captain


Elvis Mwila-
Local Guide


Maans Booysen-
Logistics Lead

1.5 Expedition Safety

All possible avenues for medical support and general safety are put into place prior to conducting an expedition. This includes land support vehicles, which follow the river team for resupplies where possible.

All team members have full medical cover with a medical evacuation protocol being established prior to the expedition start. Moreover, at least two team members are qualified in advanced medical aid with TWP providing important access to medical oversight. For on-the-ground emergencies, the expedition team carries full trauma, resuscitation, and medical kits as well as emergency communication devices including satellite phones, spot trackers, and a BGAN satellite internet unit. Additionally, at least one team member is always on standby during expeditions to relay messages and liaise directly with the relevant authorities.

1.6 Research Design

During the 765 km transect, survey data and 360° imagery were collected continually, with other data at fixed points (Table 3, Figure 5). Survey data included human activity, agriculture, infrastructure, biodiversity and fire. In addition, every ~10 km, water quality was analysed, and aerial fixed-point images were recorded. At ~50–75 km intervals, eDNA samples were collected and a benthic macroinvertebrate survey was conducted. At night, an acoustic bat recorder was deployed, along with several traps for freshwater fish and crustaceans. Finally, where suitable sites were identified, fish sampling was conducted using a dip net and discharge measurements were recorded using an acoustic doppler current profiler (ADCP).

Table 3. Research methodology summary.

Data Collection Frequency	Data Category
Continuous	• GPS track • 360° video • Survey forms relating to human activity, agriculture, infrastructure, biodiversity and fires.
Every 10 km	• Water quality analysis • Fixed point aerial drone surveys
Every ~50–75 km	• Zambian Invertebrate Scoring System (ZISS) sampling • Environmental DNA (eDNA) sampling
Every Night	• Acoustic bat recording • Trap and net deployments for fish and invasive crayfish
Opportunistic	• Fish sampling • Discharge measurement

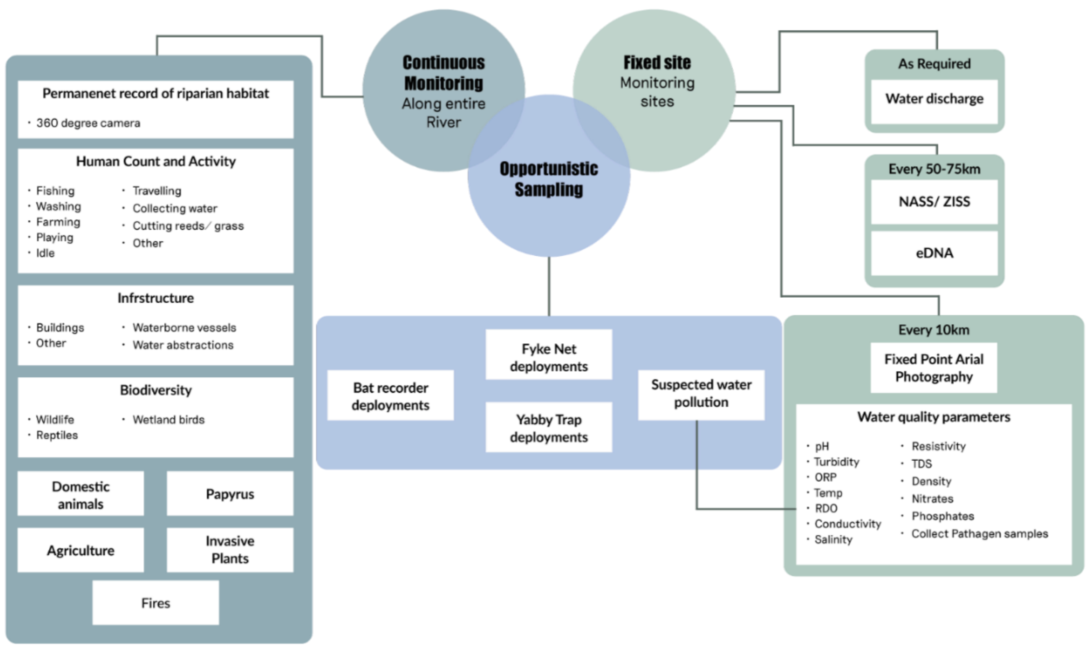

Figure 5. Summary of the data collected on the river.

1.7 Survey Limitations and Potential Data Bias

It is important to note that there are several limitations and potential biases involved with observational data collection on rivers. These may limit the statistical confidence of data analysis and must be considered when interpreting data. The limitations and biases in the data require due consideration when making management decisions or undertaking scientific analyses. For the Chambeshi River Expedition, these limitation and biases include:

- The expedition followed the main river channel and as such oxbow lakes, backwaters and floodplain margins were excluded from the survey.
- Tall vegetation or distance from dry land limited visibility within the wetlands, and particularly within the Bangweulu Swamps.
- Observers only counted what was visible from their vessels.
- Uncontrollable variables such as prevailing weather, team health, rapids, sharp corners in the river, or sand banks may have obscured observations or introduced observer bias.
- Counts are an estimation only.
- Animals needed to be large enough to identify by sight from the river. As such, smaller species of rodents, amphibians, reptiles and insects were excluded from observational data.
- The expedition survey was conducted in April–May 2024 — the wet season in northern Zambia. High rainfall had swelled the river and inundated the floodplains, resulting in underestimations of some data categories, particularly fires, human activity and wetland birds, many of which were concentrated along the wetland margins.
- Survey time was typically restricted to daylight hours (between 08h30–18h00) however some survey-days were longer or shorter depending on field conditions and variables.
- The presence or absence of people along rivers is influenced by the time of day, as people may spend more time by the river in the mornings and evenings when collecting water, bathing or washing clothes. Additionally, human activity is generally higher along rivers on weekends. As a result, human activity densities should be combined with supplementary census information to ensure that they are fully representative of people along the river.
- The expedition was conducted over 33 days, and as a result does not represent the permanent state of the river. It offers a snapshot of the river to which future data can be compared.

Figure 6. Sunrise on the Chambeshi River. Photograph by James Kydd.

2. CONTINUOUS MONITORING

The process of collecting survey data on the transect involved two parties: the observer and the recorder (Figure 8). The observers sat at the back of canoes and visually scanned the river and its banks for relevant observations within 100 m from the river-edge. Sightings of relevance were then relayed to the recorders who used a smartphone to input the data into Survey123 (ESRI). Information obtained for each sighting included the count, the side of the river, and other important notes. From Survey123, data were uploaded to a cloud database for safekeeping. Survey123 forms were created beforehand and set to automatically assign geolocation, date, and time to each entry.

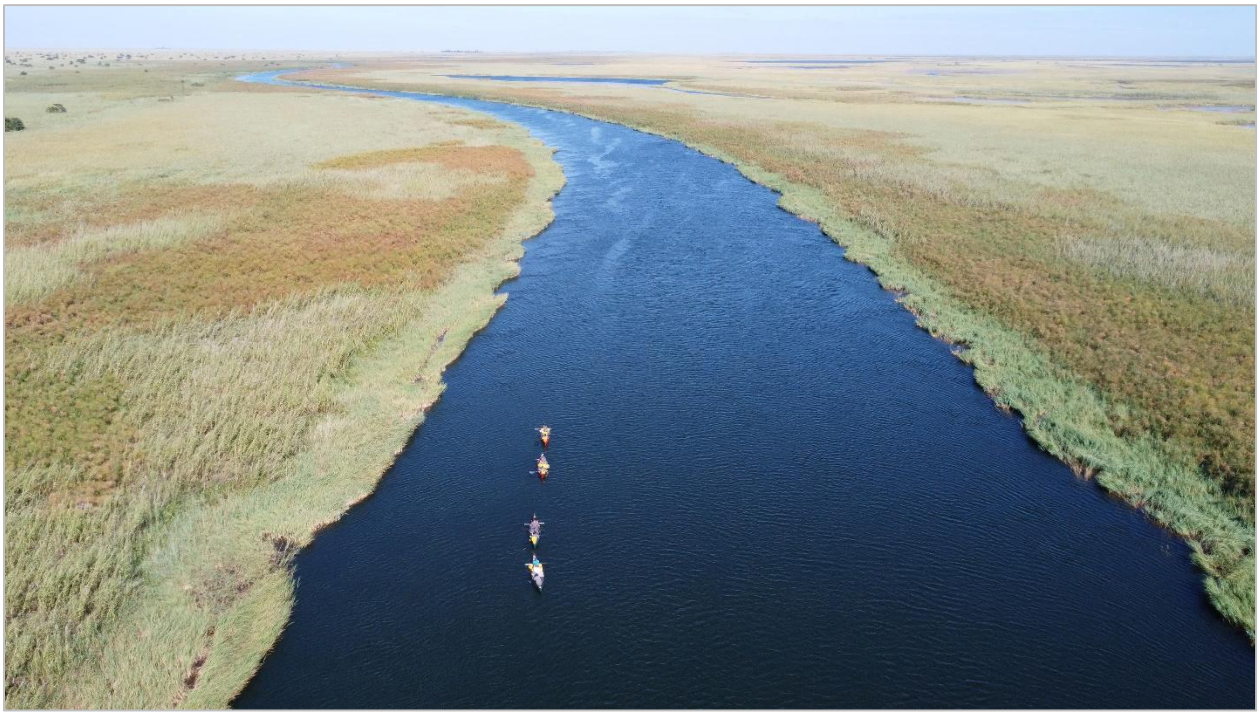

Figure 7. The expedition team travels through the Bangweulu Swamps.

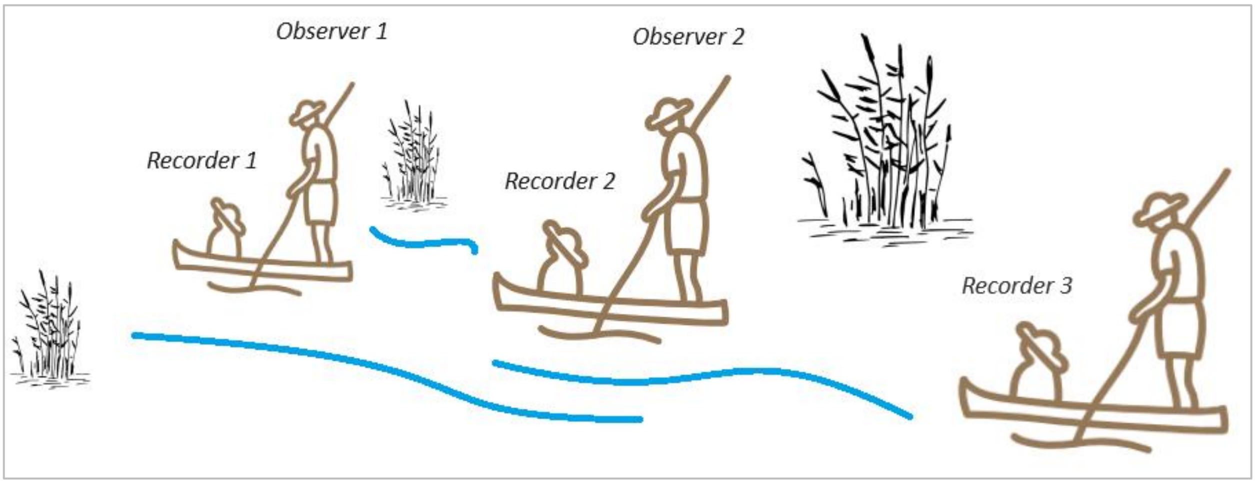

Figure 8. The distribution of observers and recorders within the survey team. Please note that observers on the Chambeshi River transect were seated, not standing.

2.1 Human Activity

Methods: Human Counts and Activity

The presence or absence of people along the Chambeshi River provides an indication of the utilization of the river and associated resources. To this end, all people active within the riparian zone of the river were counted without considering age, sex or ethnicity. An outline of the activities documented on the Chambeshi River is provided below. Going forward, long-term monitoring of the number of people interacting with the river is recommended to provide an indication of the trajectory of general river health.

- **Inactive** People who were present within the riparian zone of the river but were not actively engaged in any of the below activities.
- **Travelling:** People travelling on foot, by motorbike or in a waterborne vessel. For the purposes of this analysis, all parked watercrafts including wooden dugout canoes, fiberglass canoes, motorised boats, barges or other vessels were included in the count.
- **Fishing**: People fishing with nets, traps, hook and line or other means were counted. In addition, those involved in the cleaning or repairing of fishing nets were included. For the purposes of this analysis, all unmanned but deployed fishing equipment was counted.
- **Washing**: People in the process of washing their bodies or clothes.
- **Collecting Water**: People in the process of collecting water from the river.
- **Swimming**: People in the water who were not bathing or washing their clothes.
- **Farming:** People tilling, sowing, harvesting, watering, building enclosures around their farms or other farming related activity.
- **Other:** Other human activities on the Chambeshi River were typically associated with natural resource use, and included collecting and selling firewood, harvesting and transporting reeds and building canoes.

Results and Discussion: Human Counts and Activity

There were 2,588 people along the Chambeshi River transect, equating to an average density of 3.38 people/km (Table 4). This is lower than some other rivers in Zambia, including most of the Zambezi River where human densities are as high as 10.63 people/km. Most people were inactive, travelling, fishing or washing.

Table 4. Summary of human activity on the Chambeshi River

Activity	Number of People
Inactive	1,580
Travelling	519
Fishing	260
Washing	175
Collecting Water	17
Swimming	10
Farming	9
Other	18
Grand Total	2,588

Several hotspots of human activity were identified, all of which corresponded to villages. These are Chandamukulu, Chikulu, Ndasa, Malama, Chandesi, Munyanga and Bwalya Mponda. Several of these hotspots were within the major wetlands along the Chambeshi River. Here, communities live on islands that are largely isolated from the mainland when the river is in flood. As a result, access to healthcare and education is severely reduced for much of the year. To address this, several initiatives have been implemented to improve mobility, including dredging channels through the wetlands and building bridges.

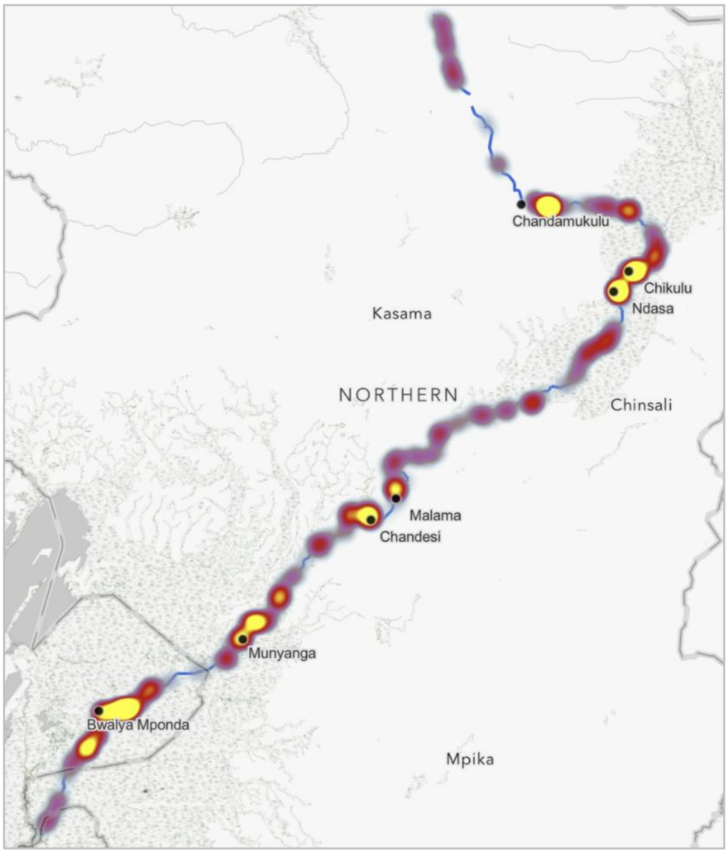

Figure 9. Several villages were associated with high density of people in the riparian zone.

Travelling

Over 90% of transport on the Chambeshi River is conducted with wooden dugout canoes. These are fashioned from large trees and are used predominantly for moving between fishing grounds, tending to nets and crossing the river (Figure 10). Most dugout canoes (58%) were not in use at the time of the survey, suggesting that there is significant unsampled human activity along the river.

Table 5. Parked and in-use vessels along the Chambeshi River.

Type of Vessel	Count
Dugout canoe	
In Use	237
Parked	327
Sub-Total	564
Other Paddle Boats	
In Use	26
Parked	29
Sub-Total	55
Motorised Boats	
In Use	1
Parked	1
Sub-Total	2
Grand Total	**621**

Figure 10. Travel on the Chambeshi River is mostly done by dugout canoe (bottom) and fibreglass paddle boats that are used for transporting goods (top). Wood and charcoal are generally transported into the wetlands with fish exported for sale in surrounding markets.

The density of boats was 1.02 vessels/km — close to the average for rivers in Zambia (1.3 vessels/km). Vessels were uncommon above the Chambeshi Flats because of the small, fast-flowing river (Figure 11). In addition, there was a notable absence of boats in the middle sections of the Chambeshi Flats, probably because of the distance from land. The highest densities of boats were in the Bangweulu Swamps, particularly around Bwalya Mponda and the other islands.

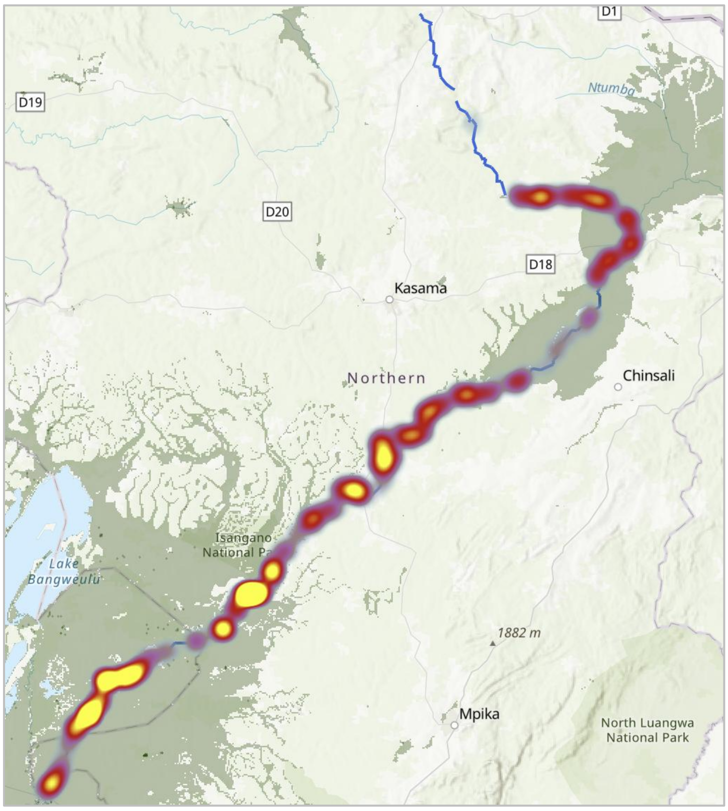

Figure 11. All vessels counted along the Chambeshi River transect.

Fibreglass paddle boats were uncommon on the Chambeshi River, representing just 9% of vessels. Interestingly, these were mostly concentrated upstream-of and within the Bangweulu Swamps where they are used for shipping goods (Figure 12). This supply chain includes the transportation of construction materials and fuelwood, which are in short supply within the wetlands. These commodities are traded with surrounding villages in exchange for fish. In this way, the fishery of the Bangweulu Swamps forms the basis of the local economy, driving the trade in fuelwood and influencing local deforestation dynamics.

There are several large towns near the Chambeshi River, with a combined urban population of nearly 1 million people (Table 6). The rapidly growing population within these towns drives demand for charcoal, fuelwood, construction materials, agricultural produce and fish — much of which is sourced from the Chambeshi River and surrounding terrestrial ecosystems. As a result, land within the catchment has become increasingly converted to human land-uses[4].

Table 6. Urban populations near the Chambeshi River[5].

Town	Population 2010	Population 2022	Change 2010–2022	Growth (%)
Mansa	204,998	327,063	122,065	37
Mbala	110,738	161,595	50,857	31
Kasama	108,828	158,051	49,223	31
Chinsali	86,723	148,997	62,274	42
Mpika	80,551	149,063	68,512	46
TOTAL	**591,838**	**944,769**	**352,931**	**37**

[4] *Chundu ML. et al. 2024. Modelling land use/land cover changes using quad hybrid machine learning model in Bangweulu Wetland and surrounding areas, Zambia. Environmental Challenges, Volume 14.*
[5] *Zambia Statistics Agency. 2022. Zambia Census of Population and Housing.*

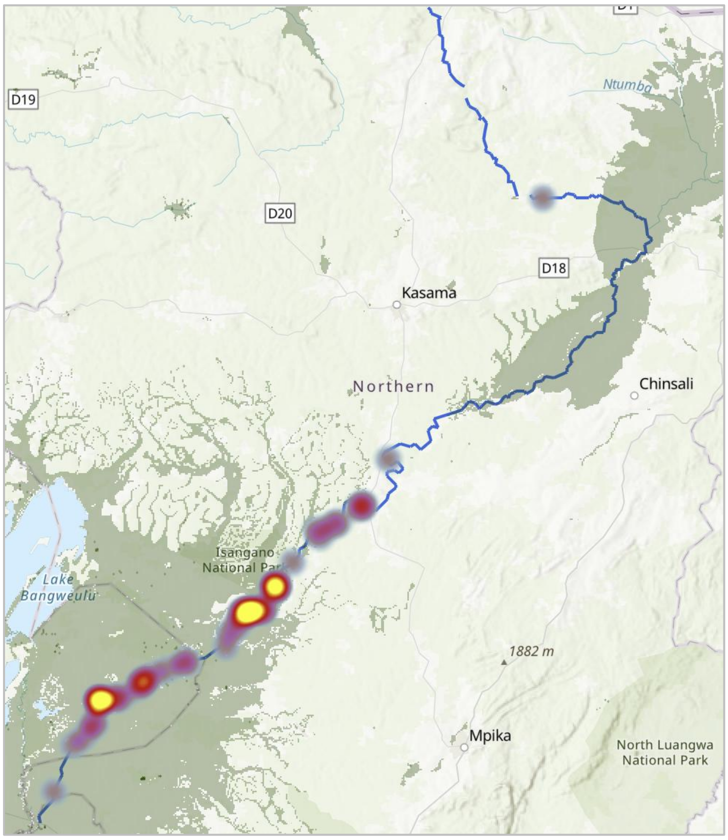

Figure 12. Distribution of fibreglass paddle boats. Most were concentrated near the trade villages of Bwalya Mponda and Munyanga in the northern section of the Bangweulu Swamps.

Sustainable resource-use in the Bangweulu Swamps

Resource and land-use within the Bangweulu Swamps follows seasonal patterns that are driven by the ebb and flow of floodwaters. These influence planting and harvest seasons, fishery and rangeland productivity, ease of movement, and animal migrations. As a result, the livelihoods are intricately linked to the ecosystem services provided by the wetlands. However, threats to the integrity of the wetlands and surrounding catchment — including deforestation for fuelwood and charcoal production, and grassland conversion to cropland — have the potential to cause irreversible damage that reduces the natural services provided by the ecosystem.

Interestingly, the Bangweulu Swamps has a high level of human activity despite its large size and relative inaccessibility compared to other sections of the river. This is because of an archipelago of islands that runs through the centre of the wetlands — the largest of which is Bwalya Mponda (Figure 13). These islands are the home of the Lunga constituency, which represents most of the population within the Bangweulu Swamps.

Figure 13. Islands in the Bangweulu Swamps are hotspots of human activities, including fishing and farming. Note that the greenery surrounding the island is wetland grass with water below it. In addition, the foreground is cultivation of cassava on mounds that keep the tubers from getting waterlogged.

The population living in the Lunga district in the heart of the Bangweulu Swamps has increased from just 24,000 in 2010, to 39,000 in 2022 — a growth rate of 4.2%, more than the national average of 3.4% for rural areas[6]. This growth is most likely because of limited access to reproductive healthcare and family planning given the remote setting of the swamps.

Population density in the Bangweulu Swamps is ~6 people/km — high relative to comparable wetlands in the region. For example, population density in the Okavango Delta in Botswana is just 1.4–3.2 people/km^2 [7]. Moreover, the limited availability of habitable land within the Bangweulu Swamps means that most people live on islands or along the floodplain margins. As a result, human activity is concentrated in these areas, resulting in localised, high intensity fishing, hunting and agriculture.

The demand for staple starch (cassava and maize), fuelwood, dugout canoes and construction materials from the growing population in the Bangweulu Swamps has contributed to an almost 40% decline in forest cover in surrounding areas in 1990–2020[8] (see Land-use and Land-cover Change Analysis Section for further details). This is concerning as these forests are central to the health of the wetlands — they promote infiltration of water to the soil and prevent erosion. As a result, the loss of forest cover can be considered an immediate threat to the entire Bangweulu Swamps ecosystem with the potential to cause permanent damage to the biodiversity and fisheries therein. Ultimately, this will: i) reduce the resilience of livelihoods within the wetlands to the impacts of climate change and further population growth; and ii) reduce the profitability and diversity of sustainable alternative livelihood options, including eco-tourism.

Deforestation has been accompanied by a ~30% reduction in grassland cover within the Bangweulu

[6] *Lunga District Integrate Development Plan*
[7] *Botswana Statistics. 2022. Population and Housing Census.*
[8] *Chundu ML. et al. 2024. Modelling land use/land cover changes using quad hybrid machine learning model in Bangweulu wetland and surrounding areas, Zambia. Environmental Challenges, Volume 14.*

Swamps and adjacent areas in 1990–2020[9]. This is primarily driven by conversion to cropland, which has seen an 80% rise in the same period. Similarly to forests, grasslands reduce the flow of water through the system and form the cornerstone of the system's rich biodiversity. Conversion to cropland exposes surface-soils to leaching and erosion, affecting nutrient dynamics within the system. As a result, the loss of grasslands within the Bangweulu Swamps has the potential to reduce the natural functioning of the ecosystem, thereby reducing the provision of important ecosystem services to surrounding communities.

Recently, the Transforming Landscapes for Resilience and Development Project (TRALARD), has significantly improved navigability of the swamps by deepening and widening of at least 80 km of channels in the wetlands to improve the flow of goods and services (Figure 14). The aim of these activities includes: i) enhancing the resilience of communities to climatic impacts; and ii) improving landscape management. However, further studies should be undertaken to determine the potential impacts of this dredging on the hydrology of the Bangweulu Swamps.

Figure 14. A highway through the swamps — channel dredging in the Bangweulu Swamps improves ease of movement. However, this practice encourages settlement along drainage lines, with the growing population placing resource-use pressure on fisheries and ecosystems in the surrounding catchment.

Fishing

Fishing is a vital source of livelihood for local communities living along the Chambeshi River, with fish providing a primary source of animal protein and income in a region where there is not a strong culture of keeping livestock. The river supports a rich biodiversity of fish species, making it a crucial resource for sustenance and economic stability (Figure 15). The seasonal nature of fishing in this region, influenced by the annual flooding cycle, dictates the availability and abundance of fish. During the wet season, when the river swells, fish populations flourish, leading to a peak fishing period that sustains livelihoods throughout the year. However, the role of seasonal migrations of fishes within this largely intact river system needs to be better understood. This will contribute valuable information to the management of the fishery, thereby ensuring that fishing pressure is sustainable, particularly considering the rapidly growing human population.

[9] *Chundu ML. et al. 2024. Modelling land use/land cover changes using quad hybrid machine learning model in Bangweulu wetland and surrounding areas, Zambia. Environmental Challenges, Volume 14.*

Once captured, fish are either sun-dried or smoked until dry and transported to nearby markets (Figure 16). The largest local markets are in the urban areas of Mansa, Mbala, Kasama, Chinsali and Mpika. These supply a combined urban population of nearly 1 million people, which has grown by 37% since 2010 (Table 6). Across national borders, the Copperbelt region of the southern Democratic Republic of Congo (DRC) receives significant volumes of fish from the Bangweulu, traded through the border of Kasumbalesa. Markets here include Lubumbashi — the second-largest city in the DRC and home to over two million people.

The average annual economic contribution of only a small area of the Bangweulu Swamps fishery was over ZMW14 billion (USD1.4 million) in 2019[10]. Currently, the direct economic inflow generated by fish sales within the greater Chambeshi-Bangweulu Swamps fishery is likely to be an order of magnitude higher, not counting multiplier effects (personal comms. Huchzermeyer, C. 2024). However, the economic aspects of the ecosystem services yield need more research, and this information will ultimately improve understanding of the sustainability of this important fishery.

Figure 15. A fisherman's catch, containing an impressive biodiversity of fishes from several families, including Schilbeidae, Mormyridae, Alestidae, Clariidae and Cichlidae.

[10] *Ng'onga M. et al. 2019. The contribution of fisheries-based households to the local economy (Capital and Labour) and national fish yield: A case of Lake Bangweulu fishery, Zambia. Scientific African, Volume 5.*

Figure 16. Fish caught in the Chambeshi River are prepared for market by sun-drying or smoking.

There were 260 active fishers along the Chambeshi River, equating to a density of one fisher every ~3 km. This is less than comparable ecosystems, such as the Barotse floodplains. However, it is important to note that fishing activity is likely under-recorded on the Chambeshi River survey, particularly in the Bangweulu Swamps and Chambeshi Flats, where tall vegetation obscured visibility from the main channel. In addition, fishing activity would have been concentrated along the floodplain margins rather than the main channel at this time of year (personal comms. Huchzermeyer, C. 2024).

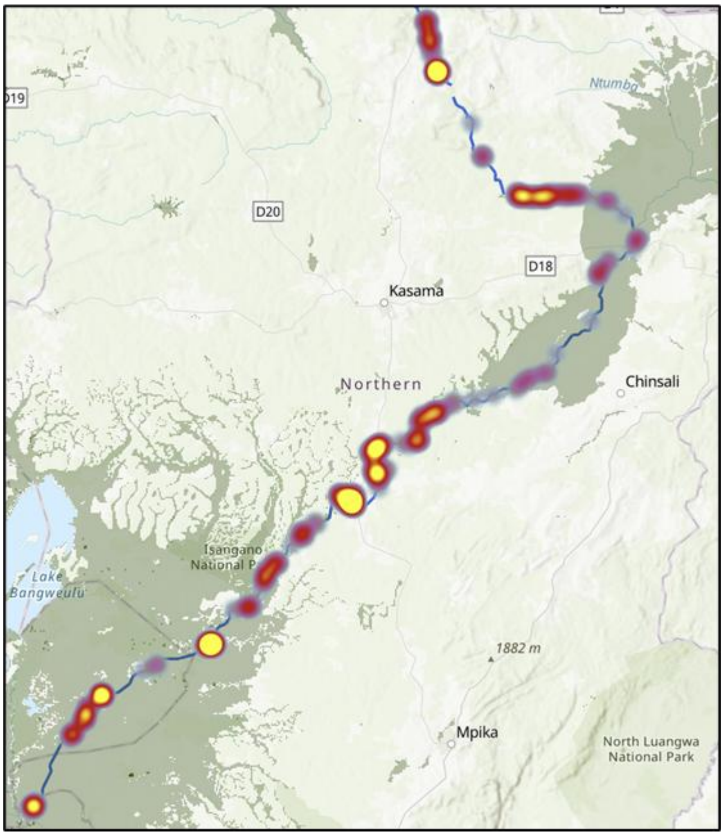

Figure 17. People fishing along the Chambeshi River transect.

Fishing Gear

Fishing gear is generally present within the riparian zone throughout the day — either deployed, in-use or along the banks of the river — even when people are not actively fishing. As a result, the count and distribution of fishing gear indicates the intensity of fishing pressure and allows for the identification of overfishing. By monitoring fishing gear, we can better understand the impact on fish populations and other wildlife, as well as the potential for gear loss, which can lead to ghost fishing and environmental degradation.

The distribution of fishing gear loosely followed that of fishing activity, with several obvious hotspots near the important fishing villages of Mwenyi, Chandamukulu, Fwama, Bwebe, Mwansa, Duta, Chandesi, Munyanga, Nsamba and Bwalya Mponda (Figure 18). In addition, fishing gear was continuous in some river stretches — particularly between Mwansa and Duta on the lower Chambeshi River and surrounding Bwalya Mponda in the Bangweulu Swamps. This indicates that fishers are active throughout these areas, despite not being present at the time of the survey. For example, fishing gear was abundant along a ~60 km stretch of river in the heart of the Bangweulu Swamps, where a commercial-scale fishery exports large quantities of fish for sale in surrounding markets.

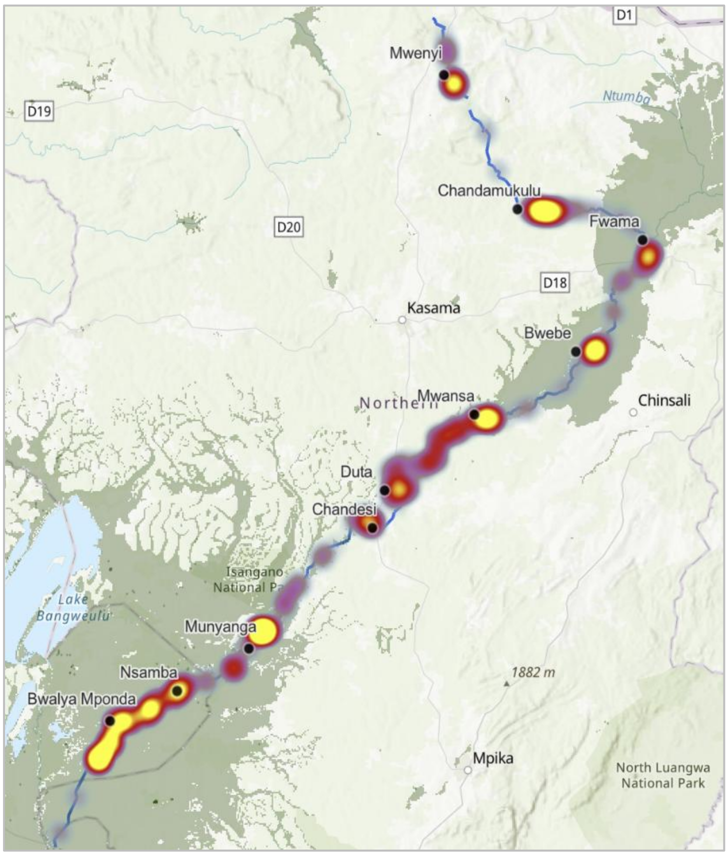

Figure 18. All fishing gear along the Chambeshi River transect.

Five types and 903 items of fishing gear were present along the Chambeshi River transect, whether in-use, deployed or idle (Table 7). These included gillnets (N=518), traps (N=153), lines (118), and fish weirs or other corral-like structures (N=46). Finally, 68 mosquito and shade-cloth nets were also counted, mostly in the Bangweulu Swamps.

Table 7. Summary of fishing gear used along the Chambeshi River.

Fishing Gear	Count
Gillnet	518
Trap	153
Line	118
Mosquito/shade-cloth net	68
Fish Weir	46
Grand Total	903

The diversity of fishing gear indicates that fish are targeted across all stages of their life cycle. In a floodplain 'boom and bust' environment, most of the fish population is <1 year old, as there is annual regeneration from a very small spawner stock. As a result, the size classes of fish available for harvest is often very small, and the fishing gears used reflects this.

Kusikila, also known as Kutumpula, is a technique whereby fish are driven into stationary surrounding gillnets by beating into the water with clubs or paddles from wading or canoeing fishermen. This practice was not recorded on the present survey; however, it has been documented within the wetlands in August–

November[11]. It is likely that the same static gillnets that were counted on the 2024 survey are used for Kusikila fishing later in the year.

Fish Traps and Fishing Weirs

Fish traps are traditional fishing instruments that are common in the upper reaches of the Chambeshi River and in the Bangweulu Swamps (Figure 19). In the wetlands, traps are constructed of mosquito nets as opposed to the traditional reed and wood traps used in the upper reaches of the river (Figure 20). This represents a potential source of pollution from insecticide-treated bed-nets and disregarded plastic material in the system.

Fish traps are usually built within weir structures of reeds and wood that alter the structure of the river margins or wetlands (Figure 20). This is done to improve fishing efficiency by i) damming the river to aide net and trap placement; and ii) corralling and concentrating migrating fish to improve catches. Generally, these traps and weirs work by targeting juvenile fish that are migrating to dry-season refuges with receding water levels. As a result, they are unlikely to be present in the same locations throughout the year.

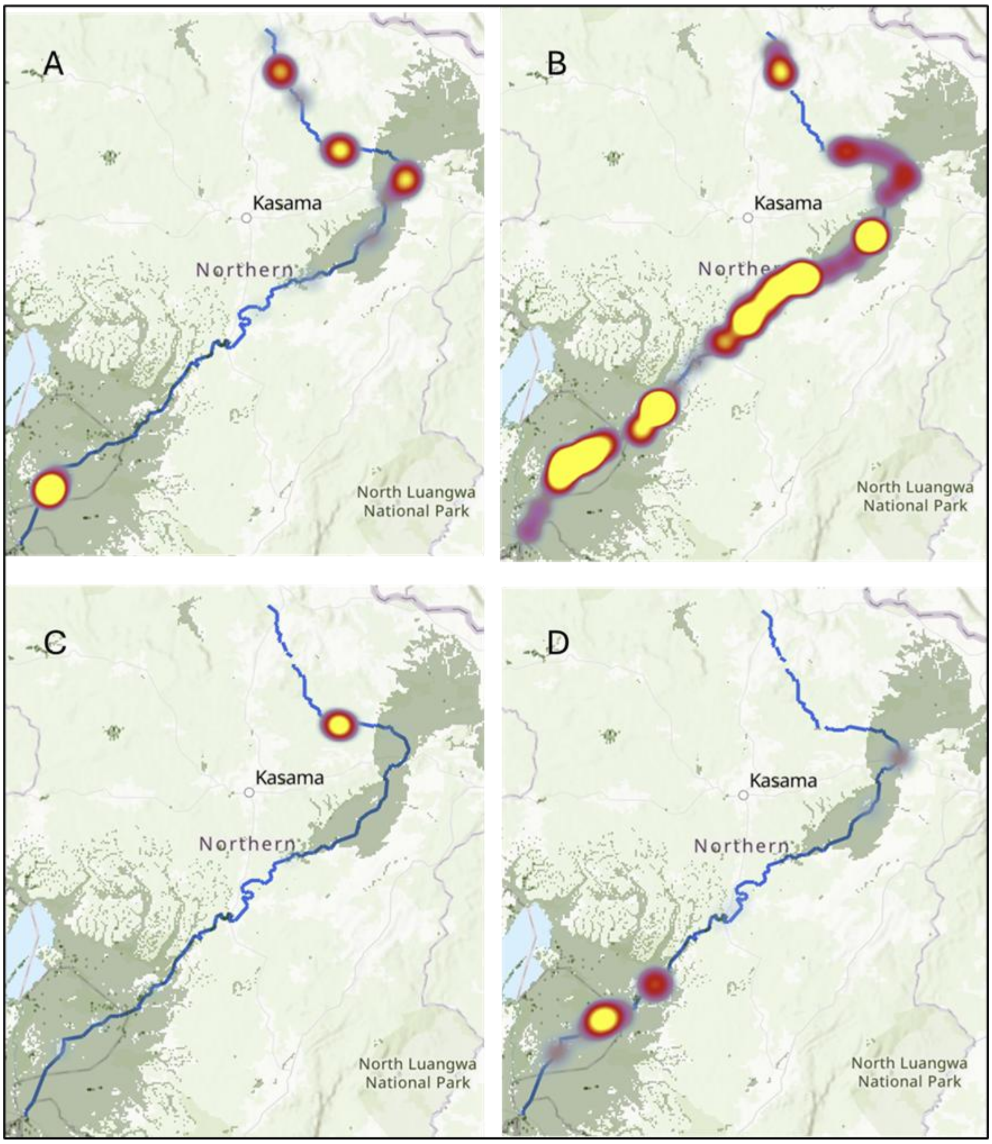

Figure 19. Fishing gear along the Chambeshi River transect. A = Fish traps; B = Gill Nets; C = Fish Weirs; D = Mosquito Nets.

[11] *Koldiong J. 2011. A brief review of the Bangweulu fishery complex. Report prepared for the Bangweulu Wetlandss Project.*

Figure 20. A mosquito net fish trap in the Bangweulu Swamps (top) and a fish weir in the Chambeshi Flats, with traditional fish traps nearby (bottom).

Gillnets

Gillnets are used to catch fish in tropical and sub-tropical freshwater ecosystems across Africa. They are cheap, accessible, and often favoured for their high catch-per-unit-effort and ability to target a range of fishes. In floodplain environments on the Chambeshi River, they are particularly effective for cichlids, catfishes and mormyrids — which are among the main targets of local fisheries. However, given their effectiveness, gillnets can pose several risks to the sustainability of fisheries, particularly when used at high levels and in conjunction with other fishing techniques.

If not managed correctly, the disposal of gillnets after their useful lifespan results in pollution or 'ghost nets' that indiscriminately kill fish and other biodiversity. Ghost fishing due to poor durability, high discard rate and very high efficiency are characteristic of monofilament gillnets, technically illegal in Zambia but ubiquitous in most waterbodies. In Bangweulu, the shift from multifilament nylon gillnets to monofilament took place during the 2010s.

Mosquito and Shade-cloth Nets
The use of mosquito and shade-cloth nets for fishing in Zambia is under-recorded and poorly documented in the literature[12]. This practice has proliferated with increased access to mosquito nets, particularly through initiatives aimed at reducing the prevalence of malaria in the region. These nets are commonly used as seine nets by creating a wide arc around a target area to entrap large quantities of fish at a time. This is the preferred method for targeting kasepa[13] — a term for several species of small fish, including the *Procatopodidae* (topminnows), *Pseudocrenilabrus* (dwarf cichlids) and *Smilogastrini* (cyprinid barbs), which are dried and sold in bulk.

Interestingly, mosquito nets are predominantly used in the Bangweulu Swamps, with very few in the upstream Chambeshi Flats (Figure 19). This is likely because the Bangweulu fishery is more commercial and is therefore better connected to supply chains for nets. Within the swamps, mosquito nets are strung across the river at nighttime to trap any fish moving through the channel. In the daytime, these nets are stored against the channel banks or fall to the riverbed as ghost nets (Figure 21).

Figure 21. Mosquito nets in the Bangweulu Swamps.

[12] *Short R et al. 2018. The use of mosquito nets in fisheries: A global perspective. PLoS ONE 13(1).*
[13] Kapenta is a similar term that usually describes the Lake Tanganyika sardine, *Limnothrissa miodon* and Lake Tanganyika sprat, *Stolothrissa tanganicae*, found in many large waterbodies.

The Bangweulu Swamps was the focus of a detailed fisheries assessment in 1996[14]. However, the growing human population, combined with a proliferation of illegal, synthetic nets, highlights the need for an updated fisheries assessment. There is evidence of declining catch-per-unit effort in the system, despite the increased uptake of more effective fishing techniques[15]. In addition, despite the different methodologies deployed to count fishing gear in the 1996 assessment, there appears to be a rise in the use of nets within the wetlands. However, this may be a seasonal bias, and further research is required to inform ongoing and adaptive fisheries management (Table 8).

Table 8. The proportion of fishing gear used in the Bangweulu Swamps in 1996 compared to 2024.

Technique	Proportion 1996 (%)	Proportion 2024 (%)
Gillnets (including kusikila)	49	62
Seine Nets	1	15
Weirs and Traps	50	17
Static lines	0	6
TOTAL	100	100

2.1 Infrastructure

Methods: Infrastructure

The type, quantity and distribution of infrastructure along a river offers insights about the level of development in the riparian zone. In addition, when combined with information about human activity, infrastructure can indicate the utilisation of resources. Importantly, permanent buildings such as houses were not counted in the observational survey. Rather, these are summarised in the Google Open Buildings Analysis in the Satellite Analyses Section below. Infrastructure, both in the river and along its banks, was categorized and recorded as follows:

- **Seasonal camps**: These were temporary structures made from thatch, fronds and wood that were constructed just above the high-water mark of the river.
- **Bridges**: Locations where structures were built across the river to aide travel.
- **Other**: Other infrastructure was noted, including cell-phone towers and gauging stations.

Results and Discussion: Human Activity

Outside of villages and towns, most infrastructure consisted of seasonal fishing camps. In total, there were 394 of these, most of which were located on small patches of dry land within the Chambeshi Flats and Bangweulu Swamps (Figure 22 and Figure 23).

[14] *Kolding J, Ticheler H. and Chanda B. 1996. Assessment of the Bangweulu Swamps fisheries. Final Report prepared for WWF Bangweulu Wetlandss Project, SNV/Netherlands Development Organisation, and Department of Fisheries, Zambia.*
[15] *Ng'onga M. et al. 2019. The contribution of fisheries-based households to the local economy (Capital and Labour) and national fish yield: A case of Lake Bangweulu fishery, Zambia. Scientific African, Volume 5.*

Figure 22. A seasonal fishing camp in the flooded Chambeshi Flats.

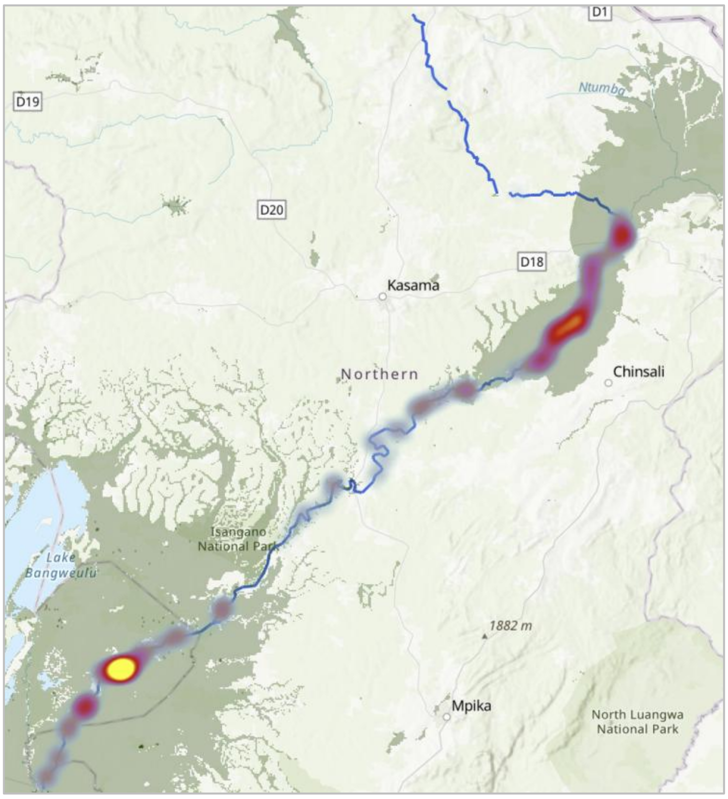

Figure 23. The distribution of seasonal fishing camps.

Seasonal fishing camps are used by local fishers to conduct fishing activities in the wet season. As a result, these serve as a proxy for fishing activity within the wetlands, indicating that most areas are accessible to fishers. Importantly, seasonal fishing camps do not indicate permanent settlement along the river — for more information in this regard, see the Google Open Buildings Analysis in the Satellite Analyses Section below.

There were 10 bridges along the transect, most of which were constructed from concrete (N=6), followed by wood (N=2) and metal (N=2). Small bridges were common in the upper reaches of the river, where the river is narrow and easy to bridge. These included two wooden pedestrian footbridges and three concrete bridges for single-lane traffic. Conversely, the bridges in the lower sections of the river were larger, including: i) a concrete bridge that was under construction in the Chambeshi Flats at the town of Fwama; ii) three large bridges where the M1 crosses the lower Chambeshi River; and iii) Tuta bridge, near the outlet of the Bangweulu Swamps (Figure 25).

Figure 24. Bridges on the Chambeshi River transect.

Figure 25. Bridges along the Chambeshi River transect: A) The Fwama bridge under construction; B) a small bridge in the upper reaches of the river; C) Tuta bridge, in the lower Bangweulu Swamps; and D) one of the three M1 highway bridges on the lower Chambeshi River.

There were no visible water abstractions along the river, probably because of the high-water level. Moreover, many farmers in the area lack access to pumps and fuel that are required to run water abstractions. This contrasts with some rivers in the region, including much of the Zambezi, where water abstractions are common. The lack of water abstractions suggests that most crops along the Chambeshi River are rainfed or irrigated by hand.

Bridges and water abstraction have no obvious effect on the hydrology of the Chambeshi River. Moreover, there is no major dam, weir or channel obstruction, making this one of the world's few free-flowing rivers. Combined with the good water quality along much of the river (see the Water Quality Section below), these attributes cement the Chambeshi River as an important example of a healthy river that supports biodiversity and provides a range of ecosystem benefits to surrounding communities.

2.2 Agriculture

Methods: Agriculture

All agricultural activity along the river was recorded, including the scale of the activity and the side of the river on which it was taking place. When recording livestock, animal numbers were estimated. For crops, the distance along the riverbank was estimated and farms were categorised as commercial-scale or subsistence-scale based on the size of the plots.

Results and Discussion: Agriculture

All farms along the transect were subsistence-scale and none had visible farm machinery or any other indicators of commercial activity. However, opportunistic interviews with farmers indicate that many have access to commercial-grade seeds, fertilizers and pesticides. This indicates improved agricultural productivity in the region, despite limited change in the extent of crop cover since 1992 (refer to LULC

Change Analysis below).

Most crops that were visible along the Chambeshi River were near the source in Senga Hills (Figure 26). Here, farmers have cleared much of the miombo woodlands to grow maize, beans and cassava. Moreover, sugarcane is grown in wetland areas. As a result, ~25% of the land that is visible from within 100 m of the edge of the upper Chambeshi River is heavily cropped, and most is deforested (Figure 27).

Figure 26. Crop cover along the Chambeshi River.

There is evidence that many of the farms in this area have existed since at least 1992 (see LULC Change Analysis below). Crop-cover observations from the river are validated by a satellite analysis of cropping, which indicates that the highest probability of cropping in the region occurs near the upper Chambeshi River, between Senga Hills and the Mibizi Mountains in Tanzania (Figure 28).

Figure 27. The source of the Chambeshi River in Senga Hills, surrounded by cropland.

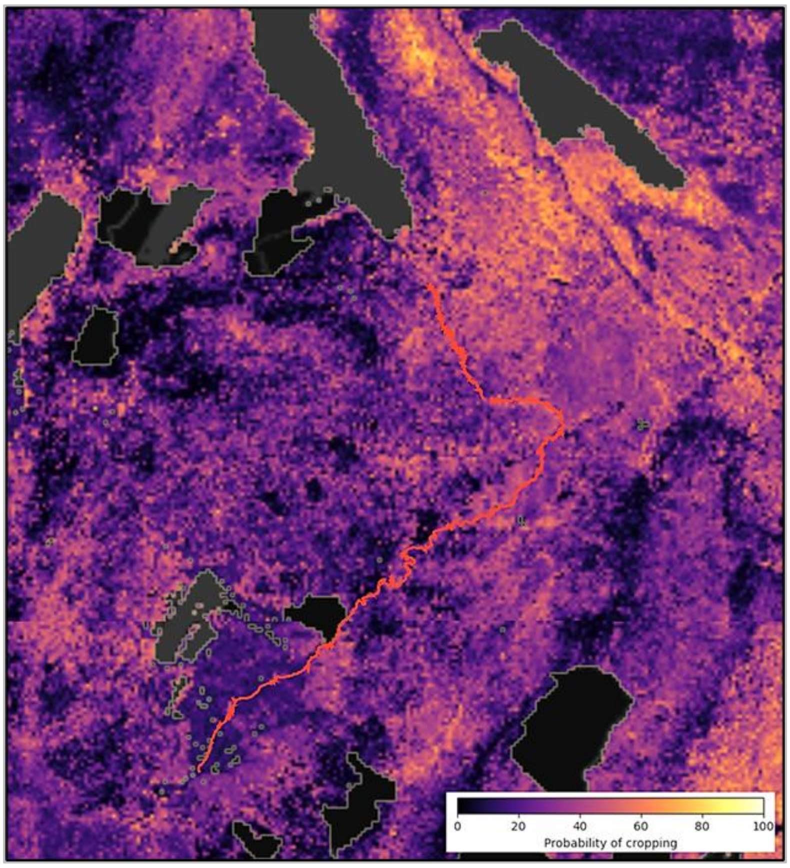

Figure 28. Probability of cropping around the Chambeshi River and associated wetlands[16]. Note the high probability in the upland areas surrounding the source of the river, particularly to the Northeast.

[16] *Geoscience Australia and CSIRO Data61. 2019. Digital Earth Africa. Available at: https://maps.digitalearth.africa/.*

Anecdotal discussions with farmers indicate that the upper Chambeshi River becomes slightly eutrophic in drought times, when fertilizer and pesticide pollution from surrounding farms is concentrated. To address this, ongoing water quality monitoring on the upper Chambeshi River is advised. This should culminate in a catchment management plan that explores the potential for agroforestry, among other climate-resilient and river-wise farming methods. This has the potential to encourage reforestation in the area, thereby restoring vital ecosystem services that have been lost because of reduced linkages between the land and the river. Moreover, farmers may be encouraged to inter-plant their crops with trees, minimise their use of pesticides and fertilizers, and increase the size of the buffer zones between their crops and the river.

Figure 29. Pesticide mix is commonly applied to crops along the upper Chambeshi River.

Maize is the most common crop along the Chambeshi River (45.6% of crop cover), followed by beans (12.5%) and bananas (10.7%) (Table 9). In addition, mixed crops represent 13.1% of crop cover along the river. These usually consist of beans, sunflowers and cassava that are grown in combination. Moreover, rice is a common crop in the Bangweulu Swamps; however, it is generally indistinguishable from native wetland grasses at distance or by remote satellite sensing.

Table 9. Summary of agriculture along the Chambeshi River.

Type of Crop	Distance Along River (m)
Maize	27,922
Beans	7,680
Bananas	6,530
Mixed Staple Crops	8,037
Mangos	3,606
Cassava	2,595
Sugarcane	1,750
Vegetables	1,300
Rice	930
Groundnuts	330
Sorghum	265
Sunflower	220
Papaya	50
TOTAL	61,215

Crop Production in the Bangweulu and Chambeshi Flats

The Bangweulu Swamps and Chambeshi Flats are suitable sites for crop production as they have moist, fertile soil that has accumulated over thousands of years of flood cycles. In the wet-season, agriculture is limited to areas surrounding islands or along the floodplain margins (Figure 30). Conversely, during low rainfall periods, communities expand crop production into the wetlands. Dry season crop production represents the main source of income and food security when fisheries are unproductive. Moreover, in times of drought, these wetlands offer some of the only arable land, making them a vital lifeline for fisher-farmer livelihoods in the region.

The Bangweulu and Chambeshi Wetlands are vital areas of carbon storage, clean water, floodwater regulation and nutrient cycling. As a result, they support food security and social development in the region. However, it is important to note that these services only exist if these wetlands are utilised sustainably. This involves, *inter alia*: i) ensuring efficient use of water resources and protecting the water sources for these wetlands; ii) limiting the use of fertilizers and pesticides near these wetlands; and iii) limiting the conversion and development of these wetlands[17].

Under climate change conditions, including increased rainfall variability, rising temperatures, and extreme flood and drought cycles, the Bangweulu and Chambeshi Wetlands will become increasingly important buffers of climate impacts for surrounding communities. This is highlighted by the 2024 drought in Zambia, which has resulted in the failure of 50% of maize crops and affected the food and water security of over nine million people[18]. Whilst the impacts of the drought have been less severe in the Northern and Luapula Provinces, the Western Province has encouraged farmers to crop within wetlands, with the aim of improving the short-term food security of those affected by the drought[19].

Wetland cropping has the potential to improve the immediate food security of vulnerable peoples. However, it is important to consider the long-term impacts of wetland conversion on these very communities. For example, clearing of wetland vegetation for agriculture reduces the capacity of the

[17] Scientific and Technical Review Panel (STRP) of the RAMSAR Convention on Wetlands. 2019–2021. Briefing Note 13: Wetlands and agriculture: impacts of farming practices and pathways to sustainability.

[18] United Nations Zambia. 2024. Zambia: Drought Response Appeal May 2024 - December 2024. Available at: www.zambia.un.org.

[19] Zambian Ministry of Community Development and Social Services. 2024. Press Release: Emergency Wetlands Cropping Programme Lauded in Western Province. Available at: www.mcdss.gov.zm.

system to regulate water flow, thereby enhancing the impacts of subsequent flood cycles[20]. Moreover, an emergency drought response may become a long-term livelihood adjustment, thereby encouraging the permanent conversion of wetlands for agriculture. As a result, a long-term wetland management plan should be developed to encourage the sustainable use of the Bangweulu Swamps and Chambeshi Wetlands that will ensure the provision of vital regulating services for years to come.

Figure 30. Islands like Matongo in the Bangweulu Swamps (top) and termite mounds in the Chambeshi Flats (bottom) offer some of the only arable land within the floodplain in the wet season. Note the rice crop nearing maturity and crop-lines that continue to the edge of the channel in the top picture.

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[20] *Ramsar Convention on Wetlands. 2018. Global Wetland Outlook: State of the World's Wetlands and their Services to People. Gland, Switzerland: Ramsar Convention Secretariat.*

2.3 Wetland-Associated Birds

Methods: Wetland-Associated Birds

Long-term monitoring of biodiversity can provide important insights into river health, eco-tourism opportunities and potential for human-wildlife conflict. Birds in particular serve as reliable indicators of disturbance and ecosystem health, often reflecting changes in habitat availability[21,22]. To this end, continuous monitoring of wetland-associated birds and other wildlife over time allows for detection of threats to riverine ecosystems. In addition, the identification of important nesting sites and foraging grounds informs proactive and effective conservation management.

Results and Discussion: Wetland-Associated Birds

Wetland-associated birds
A total of 3,133 wetland-associated birds and raptors, belonging to 71 species, were counted along the Chambeshi River transect (Table 10). The most common were the herons, bitterns and egrets (Ardeidae), which represented 1,699 (54%) of the total wetland bird abundance. In addition, pratincoles (N=302), ducks and geese (Anatidae) (N=220) and kingfishers (N=215) were common, although their distributions along the transect were different in response to varying habitat availability. There were no lapwings along the transect, and only two small wading birds (plovers, greenshanks, stilts) were recorded, likely because of the high-water level and lack of exposed mudbanks or sandbanks, which are often their preferred riverine habitat. A full count of wetland birds is available in Appendix 1.

Table 10. Total bird counts along the Chambeshi River transect.

Guild	Count
Ardeidae	1,699
Pratincoles	302
Anatidae	220
Kingfishers	215
Diving birds	163
Bee-eaters	157
Widowbirds	106
Raptors	80
Storks	66
Rallidae and jacanas	58
Gulls and Terns	30
Coucals	25
Ibises	7
Waders	2
Hamerkop	2
African finfoot	1
Lapwings and thick-knees	0
TOTAL	**3,133**

[21] *Fraixedas S, Lindén A, Piha M, Cabeza M. et al. 2020. A state-of-the-art review on birds as indicators of biodiversity: Advances, challenges, and future directions. Ecological Indicators, 18.*
[22] *Mugatha SM, Ogutu JO, Piepho HP. et al. 2024. Bird species richness and diversity responses to land use change in the Lake Victoria Basin, Kenya. Sci Rep 14, 1711.*

The Chambeshi Flats and Bangweulu Swamps offer extensive habitat that supports a large and diverse population of wetland birds (Figure 31). Birdlife was particularly concentrated within the Chambeshi Flats (8.45 birds/km), whereas the Bangweulu Swamps had a lower density of birds (4.91 birds/km). When the migratory collared pratincoles are removed from the analysis, the density of birds in the Bangweulu Swamps drops to just 3 birds/km — less than half that of the Chambeshi Flats. Unsurprisingly, wetland bird abundance was lowest in the stretches between major wetlands, with a density of just over 1 bird/km.

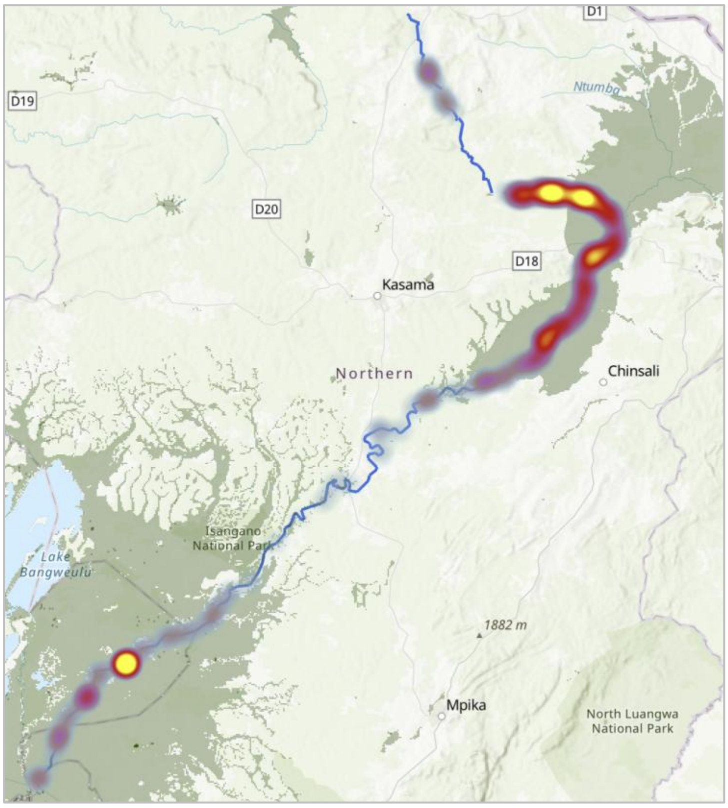

Figure 31. Wetland-associated birds along the Chambeshi River.

The Ardeidae (herons, bitterns and egrets) and kingfishers — all of which are largely piscivorous — were common in the Chambeshi Flats (Figure 32). This may indicate a pattern of bird abundance that is linked to seasonal migration of fishes. In the wet season, most small fish are in the shallow floodplain margins, which offer: i) warmer water; ii) food from terrestrial inputs of insects and organic matter; and iii) relative safety from predation by larger fishes. When floodwaters recede, these fish move towards the channel edges or are trapped in shallow lakes within the wetlands, making them accessible to hunting birds, particularly herons and kingfishers. As a result, these birds likely time their visit to the wetlands with the last rains of the season. This pattern is supported by evidence of similar fish and bird movements in other wetlands in the region, including the Barotse and Okavango[23].

[23] *Ketlhatlogile M et al. 2009. Fish, Floods, and Ecosystem Engineers: Aquatic Conservation in the Okavango Delta, Botswana, BioScience. 59 (1): 53–64.*

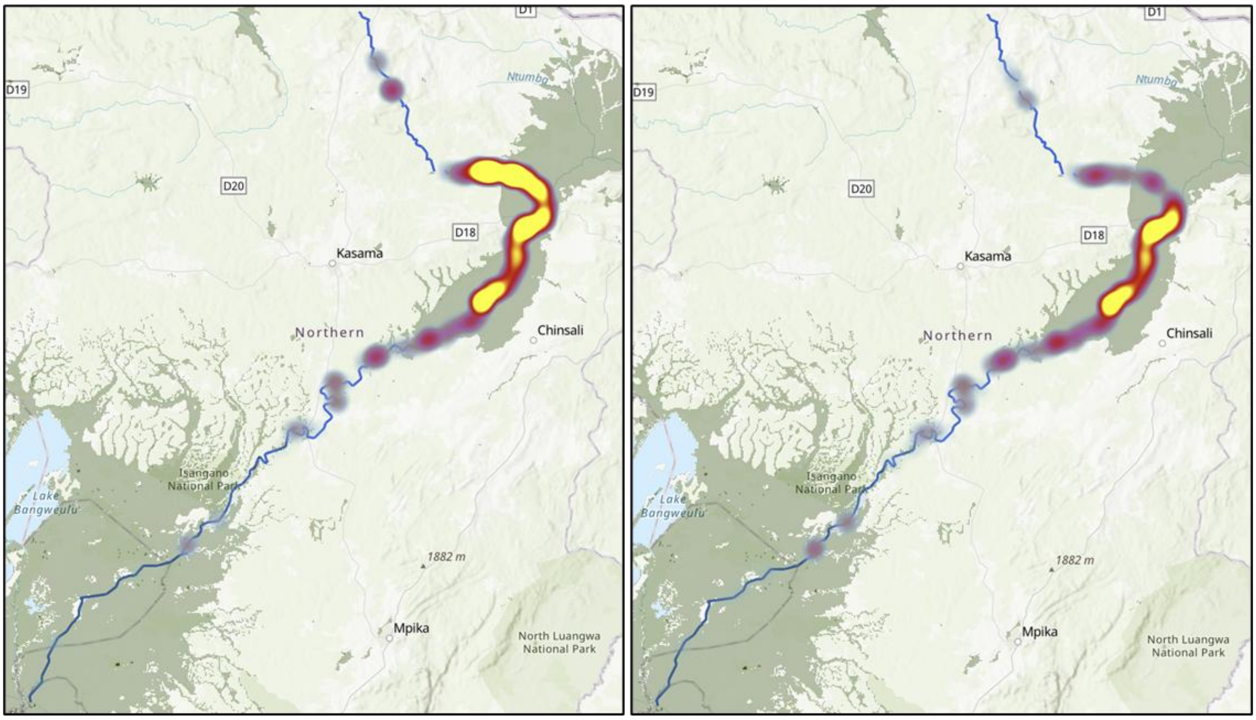

Figure 32. Ardeidae (left) and kingfishers (right) along the Chambeshi River transect.

Given that the Chambeshi Flats are nearer to the source of the Chambeshi River, they likely drain first, leading to late wet-season fish migration into the main channel that cascades downstream with receding water levels, culminating with the dry-season drainage of the Bangweulu Swamps. In this way, the hydrology, biodiversity and fisheries of the Chambeshi Flats and Bangweulu Swamps are intricately linked via the Chambeshi River. This should be studied further by examining the fisheries and avian linkages between these wetlands in relation to the timing of seasonal flood cycles, including: i) collaring herons and egrets to determine if they are resident or migratory within the system; and ii) assessing the spatial abundance of fishes within the wetlands across seasons.

Collared pratincoles were absent along most of the transect, apart from a large flock of over 300 birds which was encountered within the Bangweulu Swamps (Figure 33). These birds were roosting on the dredging tailings around Bwalya Mponda, within the wetlands. Collared pratincoles are opportunistic, migratory nomads and their use of the dredging tailings may be a recent colonisation of the new land within the swamps.

There are up to 400 bird species within the Bangweulu Swamps that were not recorded on this survey — primarily because of timing and the route taken by the survey. This includes ~10% of the global wattled crane (*Grus carunculata*) population and the southernmost population of shoebills (*Balaeniceps rex*)[24,25]. The ongoing work of Community Resource Boards (CRBs) and the Department of National Parks and Wildlife (DNPW), in partnership with African Parks, has made significant progress towards the conservation and study of these populations, particularly within Game Management Areas (GMAs) in the wetlands.

[24] *African Parks. 2022. Available at: www.africanparks.org*

[25] *Beilfuss R et al. 2003. Population and distribution of Wattled Cranes, Shoebills, and other large waterbirds in the Bangweulu Swamps, Zambia.*

Figure 33. Collared pratincoles

2.4 Non-avian wildlife

Large, non-avian wildlife was mostly absent along the Chambeshi River, with just one sitatunga (*Tragelaphus spekei*) and five hippos recorded along the 765 km transect (Table 11). The most common wildlife were water monitors (N=16). In addition, there were four groups of individual spotted-necked otters. Wildlife was randomly distributed along the transect, except for hippos which were located near the wetlands (Figure 34).

Table 11. Wildlife documented on the Chambeshi River transect.

Row Labels	Count
Water monitor	16
Hippopotamus	5
Spotted-necked otter	4
Waterbuck	1
Grand Total	**26**

Leopards, black lechwe, lions, sable, kudu, elephants, reedbuck, buffalo, impala, zebra, tsessebe and eland, among an array of other large wildlife, were abundant within the Chambeshi River basin in the early 20th century[26]. This is supported by anecdotal conversations with local community elders. However, within the last hundred years, widespread hunting and land-conversion to agriculture has limited most game to the Bangweulu GMA. This trend has been slowed by the Bangweulu Wetlands Project, which has facilitated partial recovery of the sitatunga and black lechwe population within the Bangweulu Swamps. Several translocations have bolstered genetic diversity of local wildlife populations — including zebra, impala, puku, waterbuck and buffalo.

[26] *Hughes JE. 1933. Eighteen Years on Lake Bangweulu.*

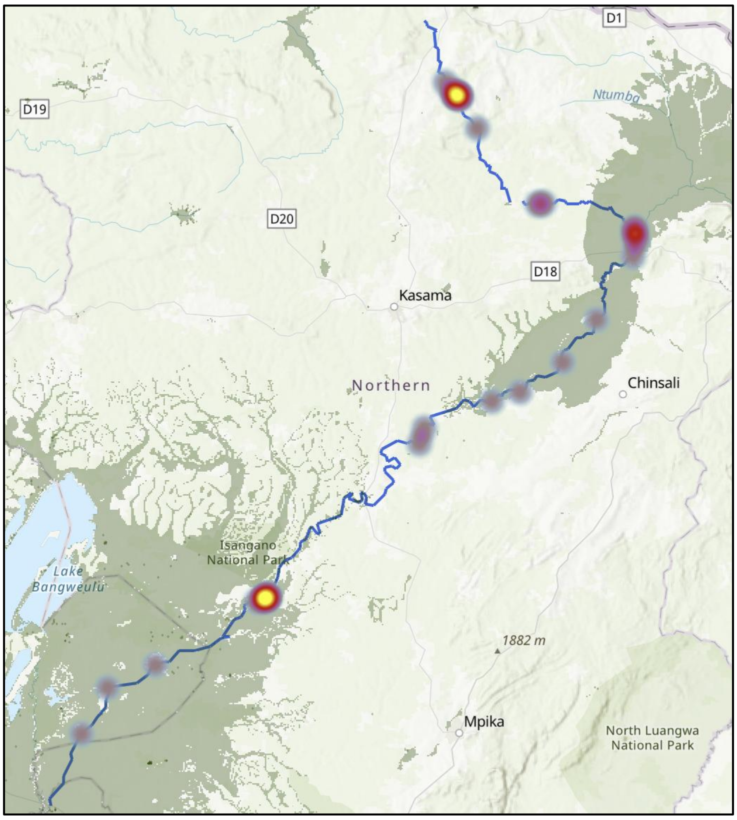

Figure 34. Distribution of wildlife along the Chambeshi River transect.

The extirpation of grazing animals within the Chambeshi Flats has resulted in the loss of nutrient cycling in the system. This has in turn likely reduced the productivity of the wetland, including the productivity of fisheries. As a result, wildlife densities should be restored through well-managed game reintroductions and community game areas or other effective conservation areas within the wetland. This will not only improve biodiversity but will likely enhance crop productivity and value chains from wildlife to local communities.

It is recommended that, in addition to current efforts in the Bangweulu Swamps, conservation measures are expanded to include the upper Chambeshi catchment. This is particularly relevant for the Chambeshi gorge and Chambeshi Flats, where there is potential for community management of extensive areas of rehabilitated wilderness. In addition, wildlife corridors between the Bangweulu Swamps and these upper reaches of the catchment may facilitate the migration of animals, including black lechwe, which were once abundant in the Chambeshi Flats [27].

[27] *Hughes JE. 1933. Eighteen Years on Lake Bangweulu.*

3. FIXED SITE MONITORING (EVERY 10KM)

Every 10 km, a fixed research site was conducted that included water quality analysis and an aerial drone survey. This amounted to a total of 71 research sites along the transect (Figure 35). When combined with continuous survey data, water quality and aerial surveys allow for the identification of land-use, development and pollution sources within the riparian zone.

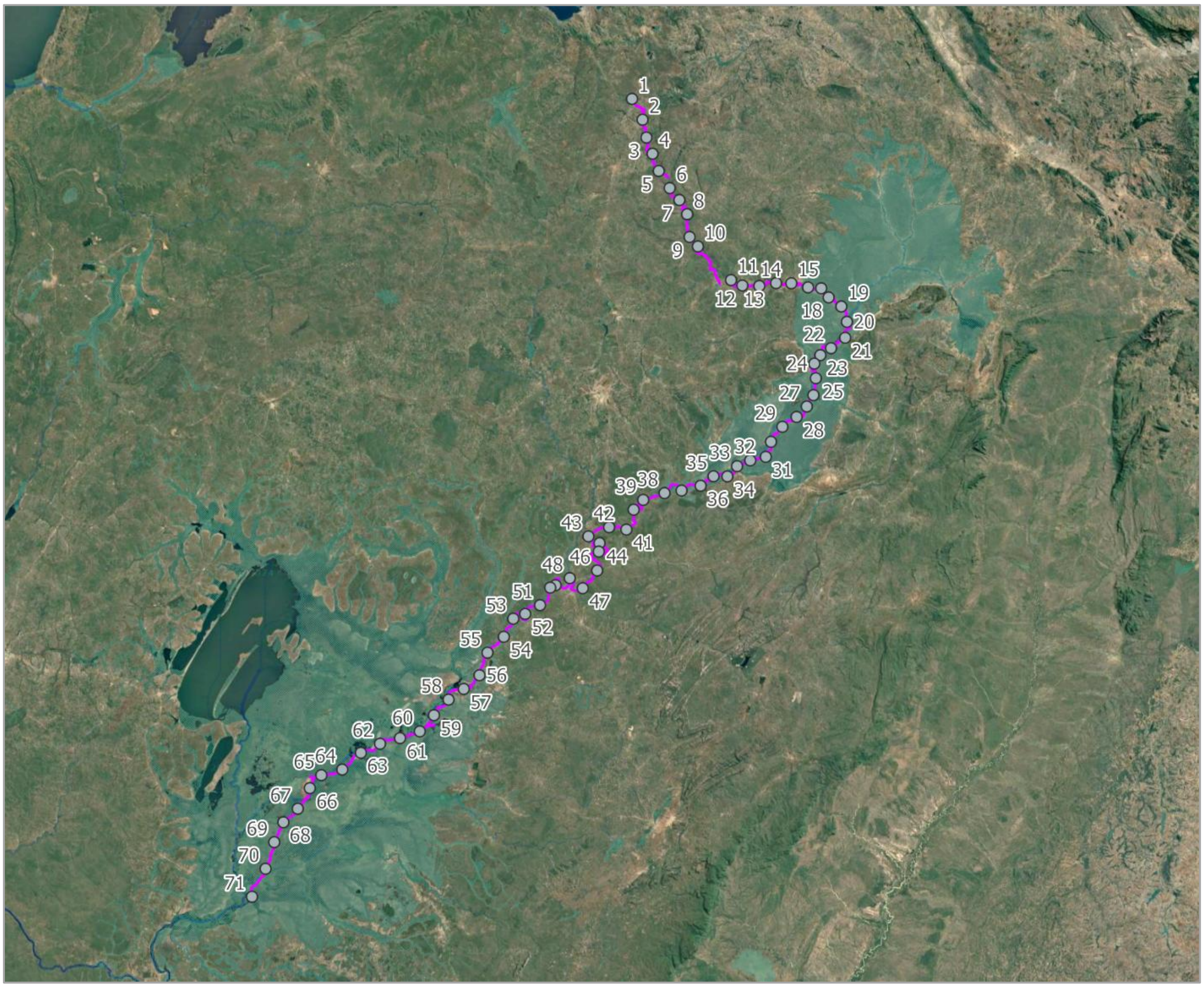

Figure 35. Fixed research sites were conducted every 10 km along the transect.

3.1 Fixed Point Aerial Photography

A series of 18 images were collected at each site; nine at 200 m elevation and nine at 100 m elevation. At each elevation, the first image was taken straight down. Then, four images (North, East, South, West) were taken at an angle of -20° to the horizon and four images at -45°. These aerial photographs provide a birds-eye view of the river along its course, thereby providing evidence against which future changes to the river and the surrounding floodplain vegetation can be compared. A collation of photographs taken from 200 m elevation is presented below — providing a visual reference along this unique river (Figure 36). The full database of aerial photography is available upon request.

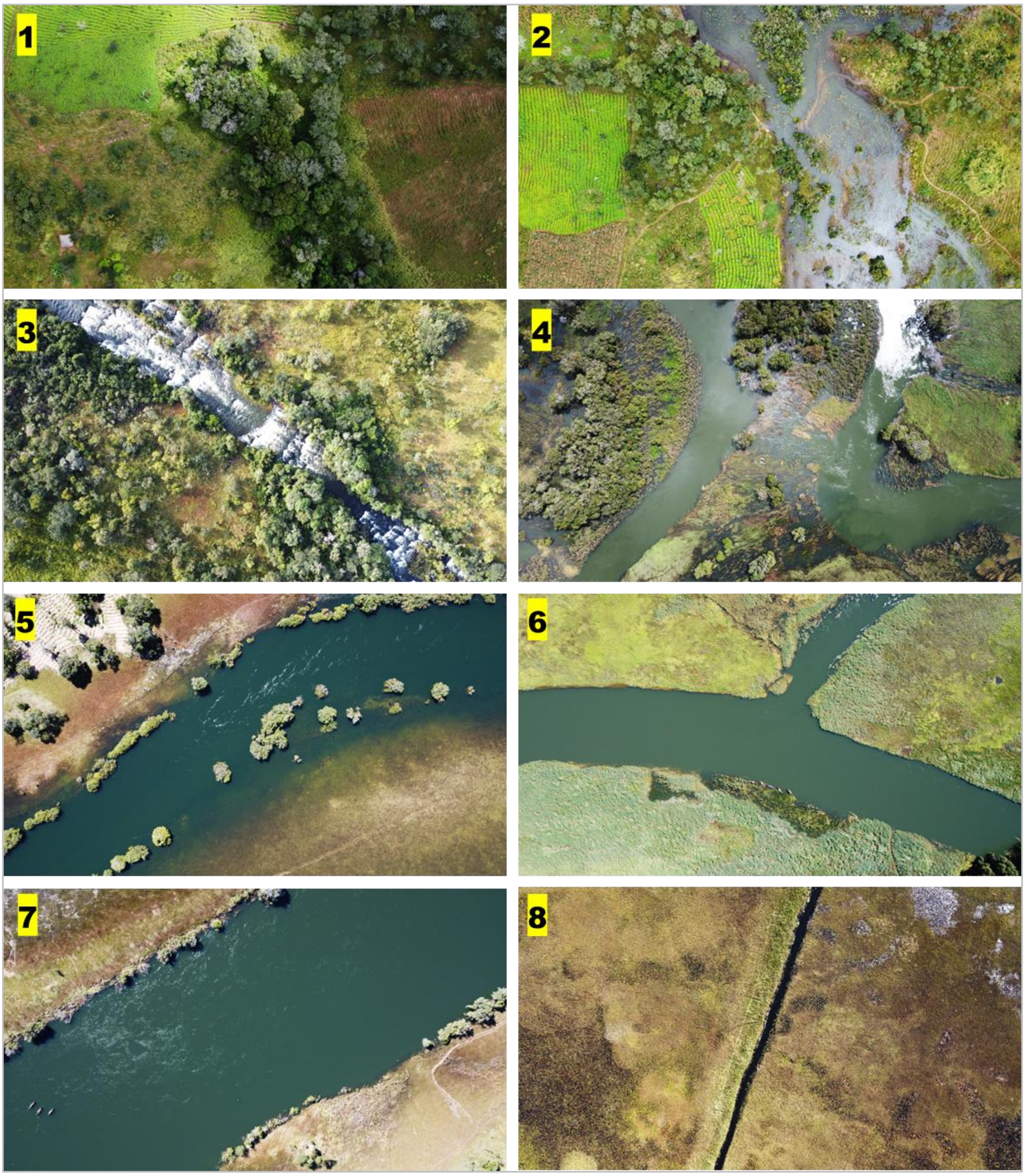

Figure 36. The Chambeshi River, from its source in the Senga Hills to the Bangweulu Swamps.

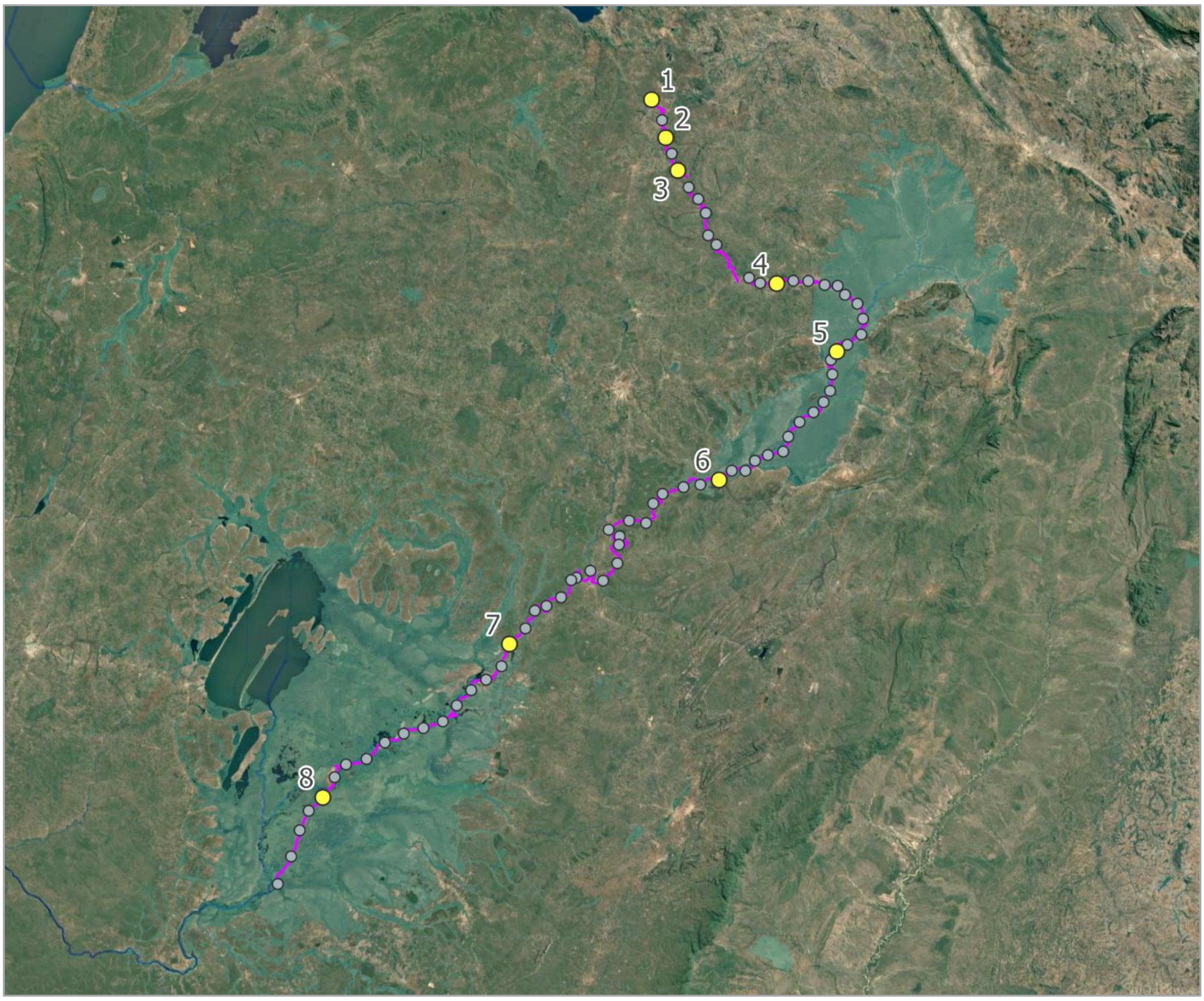

Figure 37. Locations of the subset of drone photographs presented in Figure 36.

3.2 Water Quality

Methods: Water Quality

An InSitu Aqua Troll 600 multi-parameter sonde was used to measure water quality along the Chambeshi River. In addition, one reading was recorded in the Luombe Tributary near the confluence with the Chambeshi River, upstream of the Bangweulu Swamps. The Aqua Troll 600 multi-parameter sonde measured pH, oxidation reduction potential (ORP), total dissolved solids (TDS), turbidity, dissolved oxygen (DO), conductivity, salinity, resistivity, water temperature and water density in the river water. The sonde was calibrated as per the manufacturer's instructions prior to conducting the survey and weekly during the survey.

Figure 38. An InSitu Aqua Troll 600 multi-parameter sonde in use on the upper Chambeshi River.

Results and Discussion: Water Quality

The water quality along the Chambeshi River transect was within the World Health Organization guidelines for potable water[28], indicating good water quality. However, there was spatial variability across the transect in all the measured water quality parameters (Figure 39). This is linked to: i) changes in the morphology of the Chambeshi River, ii) daily and diel fluctuations in cloud cover, rainfall and air temperatures that influence the physicochemical properties of the river water; iii) anthropogenic activities, particularly agriculture; and iv) water from incoming tributaries, notably the Luombe and Lulimala Rivers.

Importantly, the Chambeshi Flats/Luwala Wetlands complex plays an important role in regulating the water quality of the Chambeshi River. This wetland complex has dense *Phragmites* reeds, among other wetland grasses, that reduce the river's velocity, thereby allowing for settlement of suspended particles. This is most obvious in the gradual decline of turbidity within the wetland, from highs of almost 8 NTU at the inflow, to less than 1 NTU at the outflow. From the Luwala/Chambeshi Flats, turbidity remains low throughout the lower river, emphasising the importance of this dambo wetland complex in buffering the water quality of the Bangweulu Swamps.

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[28] *WHO. 2008. Guidelines for drinking-water quality. Volume 1. Geneva.*

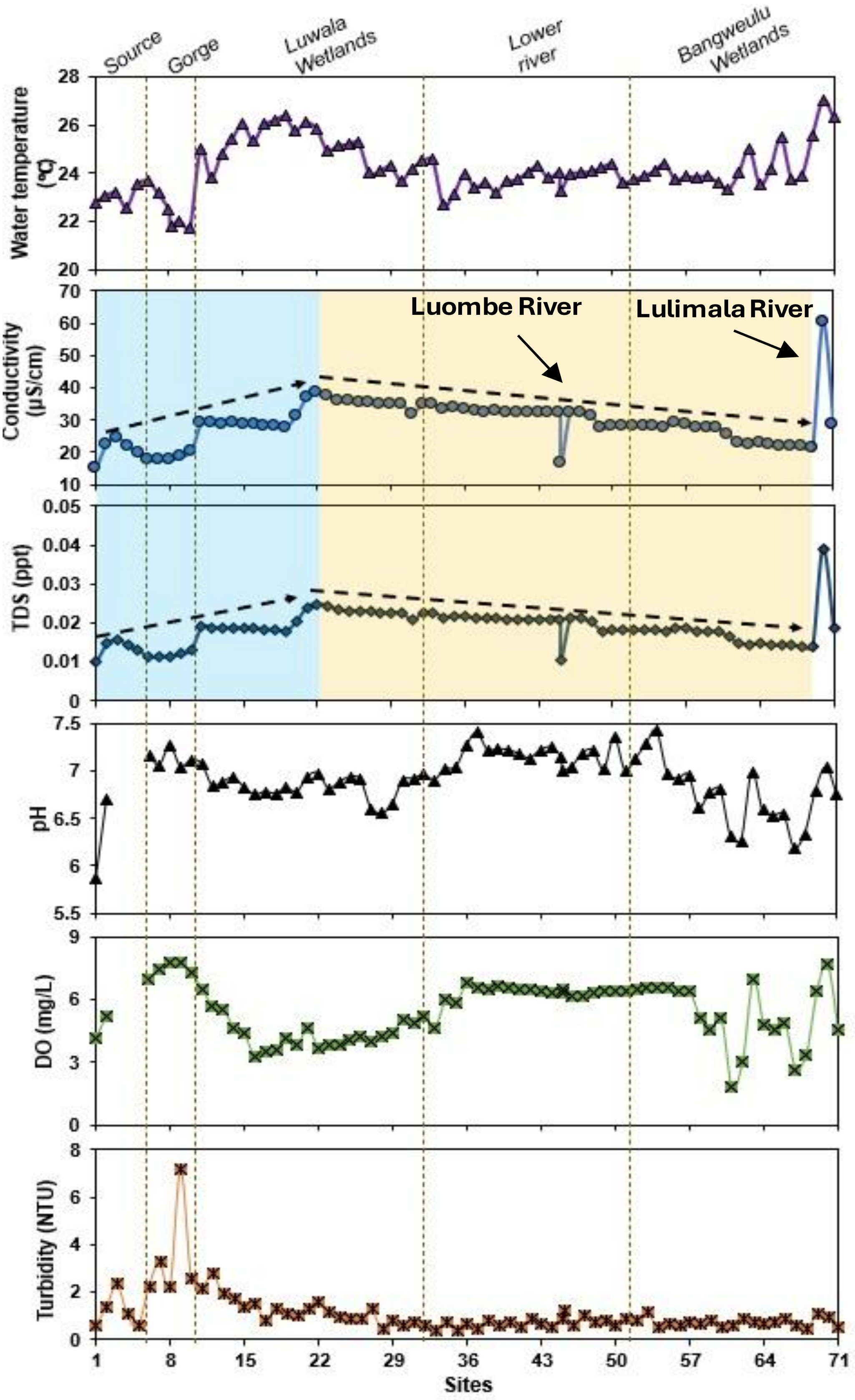

Figure 39. Spatial plots of water temperature, specific conductivity, total dissolved solids (TDS), pH, dissolved oxygen (DO) and turbidity measured along the different sections of the Chambeshi River.

Tributaries and Water Quality
The Chambeshi River is joined by the Luombe River at site 45, adding another 5–250 m^3/s to the total volume of the Chambeshi (Figure 40). The flow of the Luombe is highly variable, depending on seasonal rainfall in the upper catchment. In addition, the Luombe River flows through diverse landscapes with adjacent agricultural activities, potentially contributing sediments and nutrients to the Chambeshi River. This is visible in the discolouration of the Luombe — it is cloudy, with obvious stratification at the confluence. This may be caused by several factors, both natural and anthropogenic, and further water quality testing is advised to determine the drivers of this variation.

Figure 40. Luombe River (left) joining the Chambeshi River (right).

At Site 70 in the Bangweulu Swamps there was a 3-fold increase in total dissolved solids (TDS), conductivity and salinity — suggesting point-source pollution[29]. These parameters remained elevated for at least 10 km downstream, with mixing and dilution gradually occurring. Subsequent analysis of this anomaly revealed that the Lulimala River enters the Bangweulu Swamps at this site.

There is a manganese mine at the source of the Lulimala River, adjacent the Lavushi Manda National Park (Figure 41). This may be contributing heavy metals, including lead, and other pollutants to the river water, as is common in the surface water of manganese mine pits[30]. Importantly, heavy metals are carcinogenic and may pose a significant health risk to downstream communities who use the water for drinking, washing their clothes and bodies, and watering their crops. Considering this, it is suggested that water quality testing for heavy metals in the Lulimala River is conducted across seasons to validate this reading.

[29] *Yuwen Z et al. 2024. Predictions of heavy metal concentrations by physiochemical water quality parameters in coastal areas of Yangtze River estuary, Marine Pollution Bulletin, 199.*
[30] *Ewusi A. et al. 2022. Hydrogeochemical characteristics, sources and human health risk assessment of heavy metal dispersion in the mine pit water–surface water–groundwater system in the largest manganese mine in Ghana, Environmental Technology & Innovation, Volume 26.*

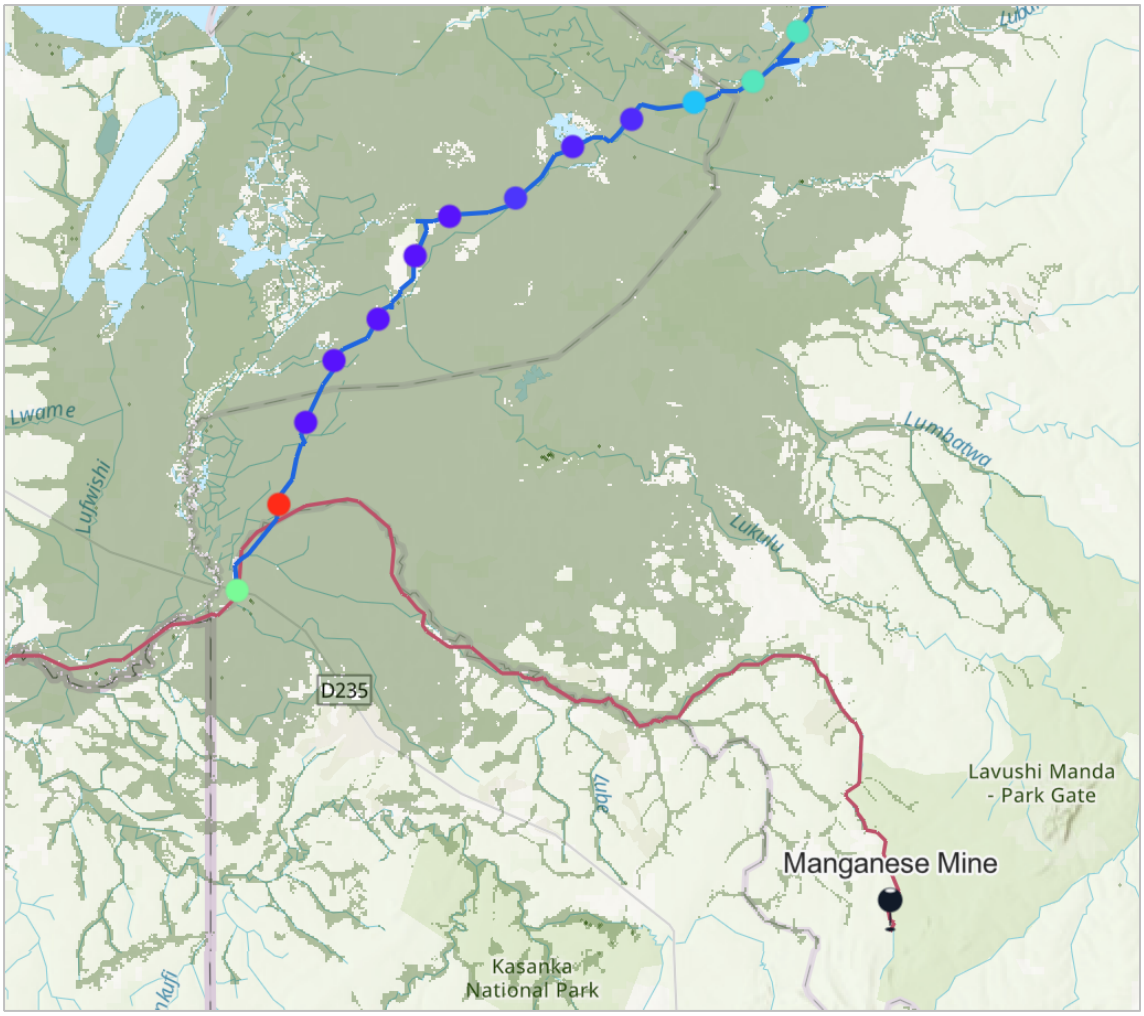

Figure 41. The Lulimala River is believed to contribute pollutants to the Bangweulu Swamps because of upstream mining activity. The red line indicates the path of the Lulimala River from its source near the Lavushi Manda National Park to the Bangweulu Swamps.

Water temperatures

The river water temperatures were lower in the source area and gorge section of the river due to cloud-cover near the source and faster flow in the gorge that prevented solar radiation from warming the river water (Figure 39). Moreover, the source is located at an elevation of ~1,650 m, compared to ~1,160 m in the Bangweulu Swamps.

Water temperatures were higher in the Chambeshi Flats and Bangweulu Swamps where flow is relatively slower and the water is shallower, leading to longer water residence times and prolonged exposure to solar radiation. In addition, it appears that the Luombe Tributary had slightly lower water temperature which can be attributed to multiple factors such as flow conditions (flow velocity and water depth) and/or forest and grassland cover along the Luombe tributary that may have provided shade.

Specific Conductivity and Total Dissolved Solids (TDS)

Specific conductivity and TDS are representative of the bulk of the conductive dissolved ions in the river water from mineral salts, organic matter and chemicals. Some of the dissolved ions in river water can be associated with pollutants. Expectedly, the conductivity and TDS showed similar spatial behaviour along the river (Figure 39). The conductivity and TDS increased in a stepwise manner within the first 22 sites, with notable peaks at sites 3 in the source area, and 11 and 22 in the Chambeshi Flats. This was followed by a slight downriver decrease in the conductivity and TDS until site 69, after which the conductivity and TDS suddenly spiked at site 70 towards the end of the survey.

The increase in the conductivity and TDS at the beginning of the survey can be linked to episodic delivery of dissolved ions from the local watershed/floodplains into the river by overland flow. The source area for the Chambeshi River is dominated by crop farming that utilizes fertilizers. These fertilizers and their ions can be mobilized and transferred into the river during rains or flooding through overland flow. It is noteworthy that the upper Chambeshi River received approximately 60 mm of rainfall 12 days before the start of the survey (Figure 42). The rainfall was high enough to cause flooding in the Chambeshi River and potential hydrologic connectivity between the river and sources of dissolved ions in the agriculture-dominated local watershed, resulting in the transfer of the dissolved ions into the river, reflected by the stepwise increase in the conductivity and TDS at the beginning of the survey. This influence of agricultural activities on the dissolved ions in the river is supported by the elevated pH in the river water at the beginning of the survey in the source and gorge sections (Figure 39).

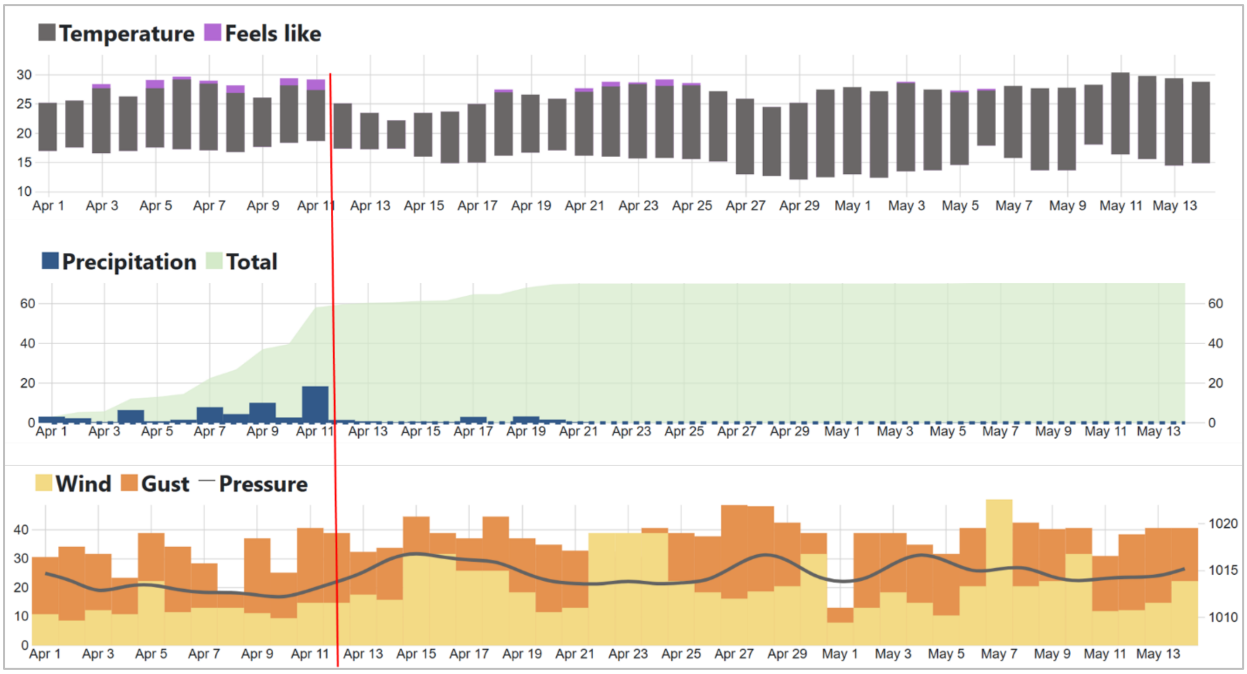

Figure 42. Historical (1st April – 13th May 2024) weather data for the Kasama weather station near the Chambeshi River[31]. The red line indicates the start date of the survey, on the 12th of April.

The slight downriver decrease in the conductivity and TDS between sites 23 and 69 could be due to slight dilution from more river water flowing downstream or limited connectivity of the river to floodplain derived solutes in this section of the river. The sudden spike in the conductivity and TDS observed at site 70 towards the end of the survey can be attributed to the contribution of water and associated pollutants from the Lulimala River, as is previously mentioned.

pH

The river water was mostly slightly acidic with pH fluctuating between 6 and 7 (Figure 39). The pH was lower at the source, Chambeshi Flats and Bangweulu Swamps, which is to be expected due to humic acid from decomposing wetland vegetation and peat. Biological processes such as aerobic respiration by aquatic plants and microbes can induce the observed slight decreases in the pH by releasing carbon dioxide which in turn increases carbonic acid in water (acidity).

DO and Turbidity

[31] *Visual Crossing Weather Data. 2024. Available at: www.visualcrossing.com*

The high, tumbling flow in the upper reaches of the river inevitably influenced the turbidity and dissolved oxygen, both of which were high at the first sites relative to downstream sections of the river. This pattern of high turbidity and dissolved oxygen continued into the gorge region of the river, where fast flow over rapids prevented the settlement of solids and ensured continued aeration. It is important to note that although turbidity was high in the early sections of the river because of flooding, peak turbidity only reached ~7 NTU. This level is higher than the WHO recommended standard of 5 NTU for drinking water but lower than what may be anticipated under flooding conditions. This suggests that although agriculture is common on the upper Chambeshi River, current land-use practices successfully limit runoff erosion. For example, the small, vegetated buffer-zones between croplands and most areas of the river reduces runoff velocity, thereby preventing sedimentation of the river (Figure 43). These buffer zones should be maintained and expanded by preventing overgrazing or cropping of the marginal vegetation along the river.

Figure 43. A vegetated buffer-zone between croplands and the upper Chambeshi River.

Water Quality Summary

Our findings offer an early analysis of the wet-season water quality of the Chambeshi River. The measured parameters indicate that the water quality of the river is of very high purity in the wet season. However, there is potential point-source pollution from mining activity at the source of the Lulimala River that should be further investigated. Moreover, the variable morphology, anthropogenic activities (particularly agriculture), weather conditions and biological processes should be further studied along the river in future hydro-chemical assessments. Finally, to better understand the controls of the Chambeshi River water chemistry, the connectivity between the Chambeshi River and watershed derived solutes from crop farming should be assessed in the dry season. This will allow for the detection of nutrient and fertilizer pollution from high-intensity farming practices in the upper Chambeshi River catchment.

4. FIXED SITE MONITORING (EVERY 50–75km)

Site monitoring consisted of collecting environmental DNA (eDNA) samples and conducting a benthic macroinvertebrate survey every 50–75 km along the transect. A total of 13 intensive monitoring sites were sampled, representative of all river sections and habitats (Figure 44).

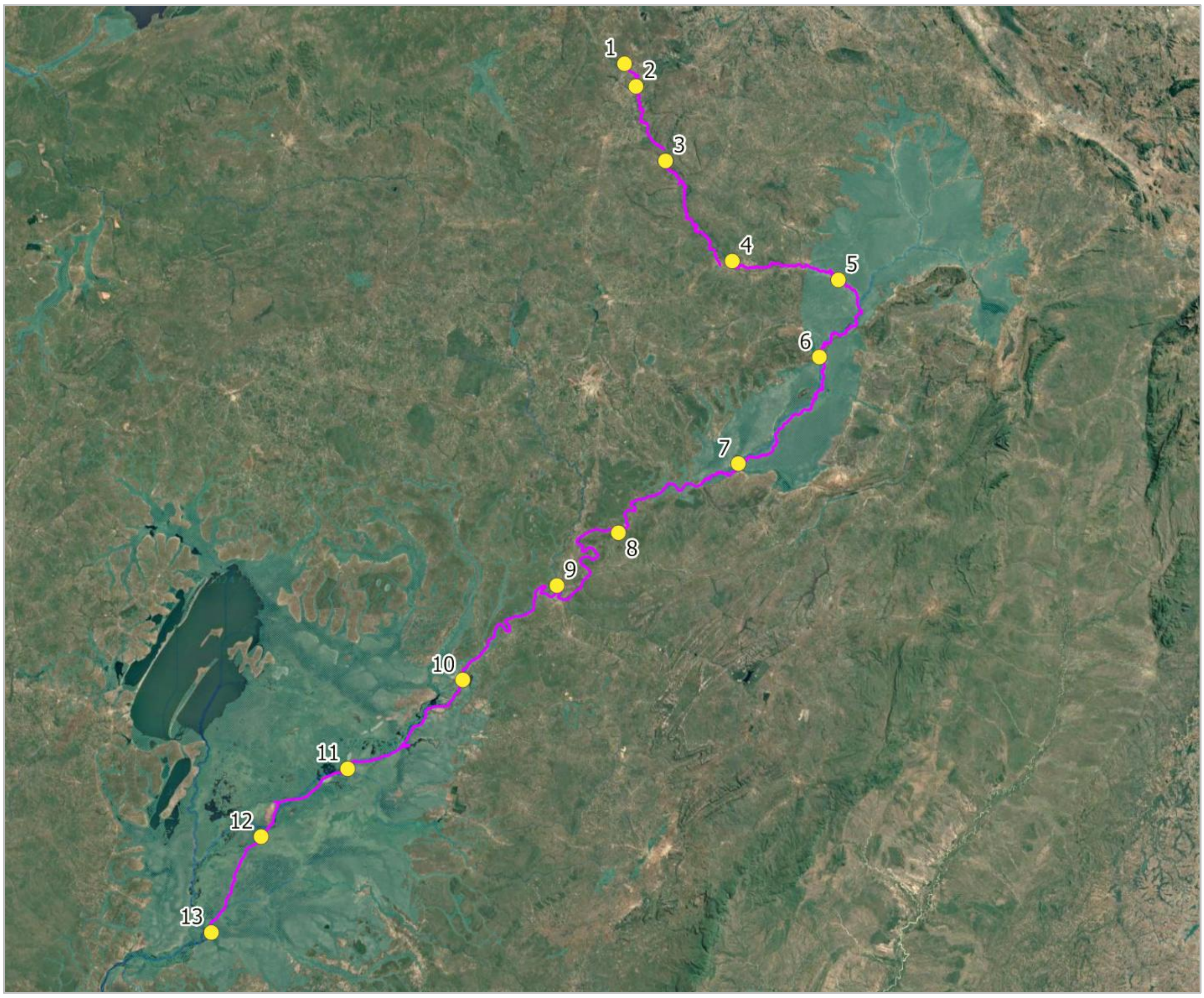

Figure 44. Intensive monitoring sites on the Chambeshi River transect.

4.1 Environmental DNA

Environmental DNA (eDNA) has emerged as a powerful tool for bioassessment and monitoring, offering a non-invasive, efficient, and highly sensitive method for detecting and cataloguing biodiversity in aquatic ecosystems. In African rivers, where traditional monitoring techniques can be hampered by logistical challenges, limited resources, and the vastness of remote regions, eDNA presents a promising alternative. By analysing trace genetic material shed by organisms into their environment, eDNA offers opportunities to assess species presence, monitor population trends, and detect invasive species or pathogens with unprecedented accuracy.

Methods: eDNA

Triplicate eDNA water samples were collected at four fixed monitoring sites, by filtering as much water as possible, up to one litre, through a 0.22 µm Sterivex™ filter with a sterile 50 ml piston syringe. Once no more water could be pushed through the Sterivex™, the filtration process was completed, and all excess water was removed from the filter by pushing air through. Next, 2 ml of ATL lysis buffer (Qiagen) was added to the Sterivex™ to preserve the DNA and start the extraction process. Finally, the ends were sealed with Helapet combi-caps and biofilm.

Samples were subsequently stored at room temperature for further processing. To avoid contamination, fresh surgical gloves were worn between each sampling iteration. Field blanks, to account for contamination, were done by filtering one litre of distilled water on two occasions. Once field work was concluded the samples were transported to a specialised laboratory at the Wild Bird Trust facilities in Maun, Botswana for DNA extraction.

DNA extraction was done at an ultra-clean, DNA free room using the DNeasy Blood and Tissue kit (Qiagen), for water samples, following a modified protocol[32,33,34]. Surfaces were sterilized with a combination of high intensity UV for 30 minutes prior to the extraction process, as well as frequent wiping with a 10% bleach solution. To account for contamination DNA extractions were carried out on negative controls in the lab using Ultra Clean DNA free water.

Results: eDNA

Following extraction, samples were sent to a specialised laboratory in Switzerland for sequencing and bioinformatics. This includes detecting the ichthyofaunal diversity of the Chambeshi River to the lowest-possible classification using eDNA metabarcoding. Following this, additional resolution will be obtained using species-specific primers or using multiple genetic markers from a local reference sequence database that is under development in partnership with the American Natural History Museum (ANHM).

It is important to note that many detected DNA sequences may remain unidentified or only assigned to higher taxonomic levels without local reference sequences against which to compare them. As a result, biodiversity surveys in the Zambian-Congo source rivers should prioritise the development of a genetic database of local ichthyofaunal diversity. This will reduce the cost and sampling effort of future biodiversity surveys in the region.

4.2 Aquatic Macroinvertebrates

The Zambian Invertebrate Scoring System (ZISS) is a standardized, rapid, field-based bioassessment tool assessing aquatic macroinvertebrate fauna at a family level to determine the health of perennial rivers in Zambia. The ZISS is based on the South African Scoring System (SASS) and, if repeated over time, can be used to assess the ecological state of a river.

The ZISS protocol scores the health of a site based on the sensitivity scores of each macroinvertebrate family recorded at the site. Generally, higher ZISS scores indicate heathier and more diverse aquatic habitats. Additional metrics for comparison include the total number of taxa recorded and the average score per taxon (ASPT). Given that much of the Chambeshi River is non-wadable, the ZISS protocol focuses exclusively on aquatic and marginal vegetation that can be safely sampled from the banks or from a boat.

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[32] *Czachur M.V., et al. 2022. Novel insights into marine fish biodiversity across a pronounced environmental gradient using replicated environmental DNA analyses. Environmental DNA 4, 181–190.*

[33] *Rossouw et al., in review. Where and when to sample: Investigating spatio-temporal variation of community assemblages in kelp forest systems with eDNA metabarcoding. npj biodiversity.*

[34] *Von der Heyden S et al. 2023. Environmental DNA biomonitoring in biodiversity hotspots: A case study of fishes of the Okavango Delta. Environmental DNA 5, 1720–1731. 4.*

Methods: ZISS

Benthic macroinvertebrate sampling was conducted at 11 sites along the river. These corresponded with the intensive research sites above, excluding sites 1 and 12, at which the river was either too small or difficult to sample using the ZISS method.

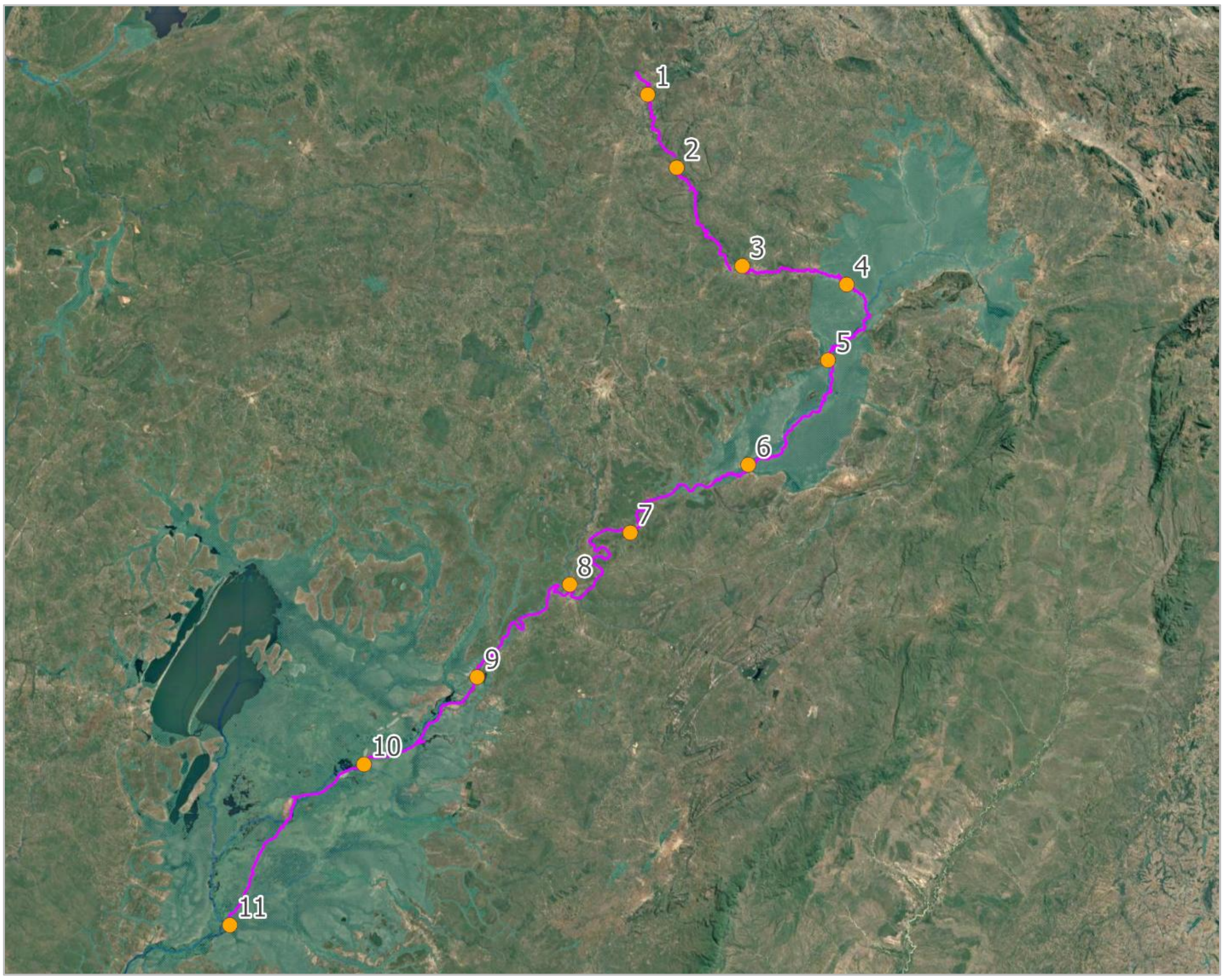

Figure 45. ZISS Sampling Sites

To conduct the ZISS assessments, an invertebrate net was used to sweep marginal and aquatic vegetation for a total of 2 minutes. The lack of gravel, sand and mud at sampling sites downstream of the Chambeshi Gorge meant that vegetation was the only biotype sampled reliably throughout the expedition. Following this collection period, 15 minutes were spent sorting and identifying each collection. The total number of taxa, the average score per taxon (ASPT) and the final ZISS score were then calculated and recorded. Representative samples of each family were retained in 95% ethanol and transported to the Botswana Wild Bird Trust office in Maun for identification verification.

Results and Discussion: ZISS

The mean ZISS score on the Chambeshi River was 32 (±11), with a mean average score per taxon (ASPT) of 4.5 (±1) (Table 12). Sites 6 and 9 had low ZISS Scores — both sites were at communal washing areas, where detergents are used to wash bodies, clothes and dishes in the river water. In addition, communities regularly launch their vessels and swim at these sites. These activities likely disturb the marginal and aquatic vegetation and cause localised deterioration of water quality that resulted in the low ZISS Scores. However, it is important to note that impacts are highly localised. At current levels, washing and bathing sites are unlikely to result in permanent or downstream deterioration of the aquatic environment.

Table 12. Summarised results of ZISS sampling on along the Chambeshi River.

ZISS Site	Latitude	Longitude	ZISS Score	No. of Taxa	ASPT
1	-9.18496	31.34637	38	7	5.4
2	-9.44379	31.45057	49	9	5.4
3	-9.79195	31.68592	37	8	4.6
4	-9.8575	32.06049	21	5	4.2
5	-10.1251	31.99359	31	6	5.2
6	-10.4946	31.70736	15	3	5.0
7	-10.7342	31.28422	42	8	5.3
8	-10.91722	31.06704	36	10	3.6
9	-11.22021	30.73362	14	4	3.5
10	-11.53890	30.32719	29	8	3.6
11	-12.09956	29.84849	37	9	4.1
AVERAGE			32	7	4.5
Standard Deviation			11	2	1

Ongoing monitoring of the Chambeshi River using the ZISS methodology will reveal fluctuations in invertebrate abundance and diversity that are linked to seasonality. In some cases, these fluctuations may represent areas of local pollution, particularly if assessments are conducted at communal washing sites. Moreover, although it was not included in this survey, ongoing monitoring of the Lulimala River using the ZISS methodology may capture deterioration of the aquatic environment that is linked to upstream human activity. This information will be particularly powerful if combined with regular heavy metal and water chemistry assessments.

5. OPPORTUNISTIC SAMPLING

5.1 River Discharge

River discharge — the volume of water flowing per unit of time — is vital for understanding river dynamics. In addition, key metrics such as river width, mean flow velocity, and maximum depth not only contribute to scientific understanding of river processes but also inform effective water resource management strategies in diverse environmental contexts.

Methods: Discharge

A SonTek RS5 Acoustic Doppler Current Profiler (ADCP) was used to measure river discharge. These included measurements of flow rates, depth, river profile and discharge. The ADCP was towed behind a canoe when conducting measurements. At each ADCP site, a minimum of two transects per site was run, or until the coefficient of variation between transect was < 0.05.

Given that the river was in flood at the time of the survey, the ADCP was only deployed at three sites. These were: i) in upper reaches of the river, ~40 km from the source; ii) above the Chambeshi Flats ; and iii) below the Chambeshi Flats , before the confluence with the Luombe River. In addition, an ADCP measurement was taken in the Luombe tributary to determine its contribution to the flow of the Chambeshi River above the Bangweulu Swamps. Sites that were considered suitable for ADCP sampling include those with: i) smooth laminar flow without bends or turns in the river; and ii) no obstructions or hazards including downed trees or current eddies.

A globally gauge-corrected monthly river flow and storage dataset[35] was used to complement the ADCP river discharge measurements for the Chambeshi River. This dataset benefits and builds upon others including the MERIT-Basins, the GLDAS VIC Land Surface Model, the GLDAS Noah Land Surface Model and the GLDAS Catchment Land Surface Mode. The global mapping process resulted in a final dataset of 1,001 gauges, and monthly average discharge for each gauge across the 1980–2009 period (360 time-steps) was calculated. The monthly ensemble average inflow was used as to generate corrected and uncorrected ensemble river discharge estimates across the 30-year period.

All discharge sites are presented below (Figure 46). Site descriptions are as follows: 1) ADCP Site 1, downstream of the Chambeshi source; 2) ADCP Site 2, above the Chambeshi Flats ; 3) below the Chambeshi-Kalungu confluence, within the Chambeshi Flats ; 4) below the Chambeshi Flats ; 5) ADCP Site 3, above the Chambeshi-Luombe confluence; 6) ADCP Site on the Luombe River; 7) below the Chambeshi-Luombe confluence; 8) Chambeshi River above the Bangweulu Swamps; 9) Luapula River draining the Bangweulu Swamps.

[35] *Collins EL et al. 2024. Global patterns in river water storage dependent on residence time. Nature Geoscience, pp.1-7.*

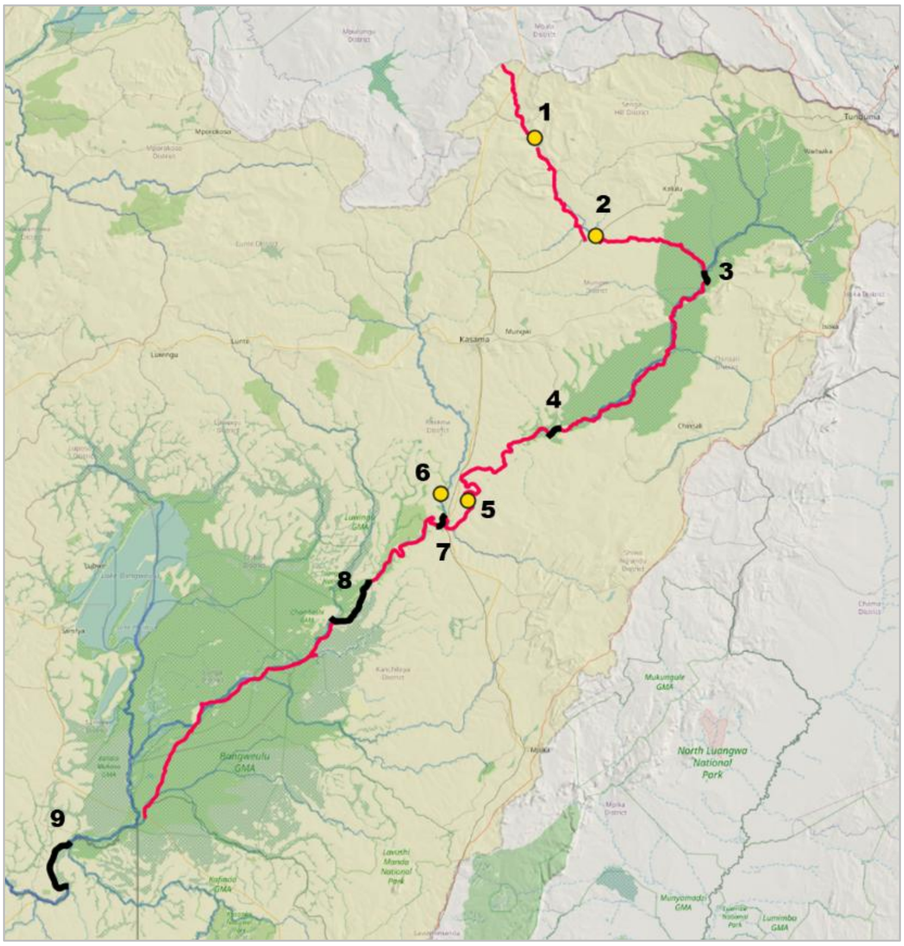

Figure 46. All hydrology sites. The yellow dots are where discharge was measured using both the ADCP and historical satellite data. The black lines are sections of the river for which only historical satellite data is available.

Results and Discussion: Discharge

The discharge of the Chambeshi River ~40 km from its source in Senga Hills was 26.5 m^3/s in April 2024 (Table 13). This is similar to the historical average monthly maximum of 29.0 m^3/s. In addition, within the dambo-like Chambeshi Flats, the flow of the river grows by 300–500% because of several tributaries — the largest of which is the Kalungu River. However, the wetlands extend towards the northeastern borders of the watershed, likely storing groundwater that sustains the flow of the Chambeshi River into the Bangweulu Swamps. This important hydrological linkage should further be investigated by: i) conducting dry-season discharge measurements; and ii) assessing the extent and flow of groundwater in the area.

Table 13. Discharge summary of the Chambeshi and Luombe Rivers at the ADCP measurement sites (More in Appendix 3).

ADCP Site	Date	Lat	Long	Q (m^3/s)	Historical Monthly Average Q (m^3/s)	Area (m^2)	Speed (m/s)	Max Depth (m)
1	17/04/2024	9.39957°S	31.43895°E	26.5	18.1	53.4	0.50	2.24
2	25/04/2024	9.79215°S	31.68601°E	104.3	88.3	124.7	0.84	5.18
3	03/05/2024	10.8515°S	31.16490°E	310.1	104.5	310.7	1.00	4.55
Luombe	11/05/2024	10.82714°S	31.05319°E	86.4	37.6	146.0	0.60	3.78

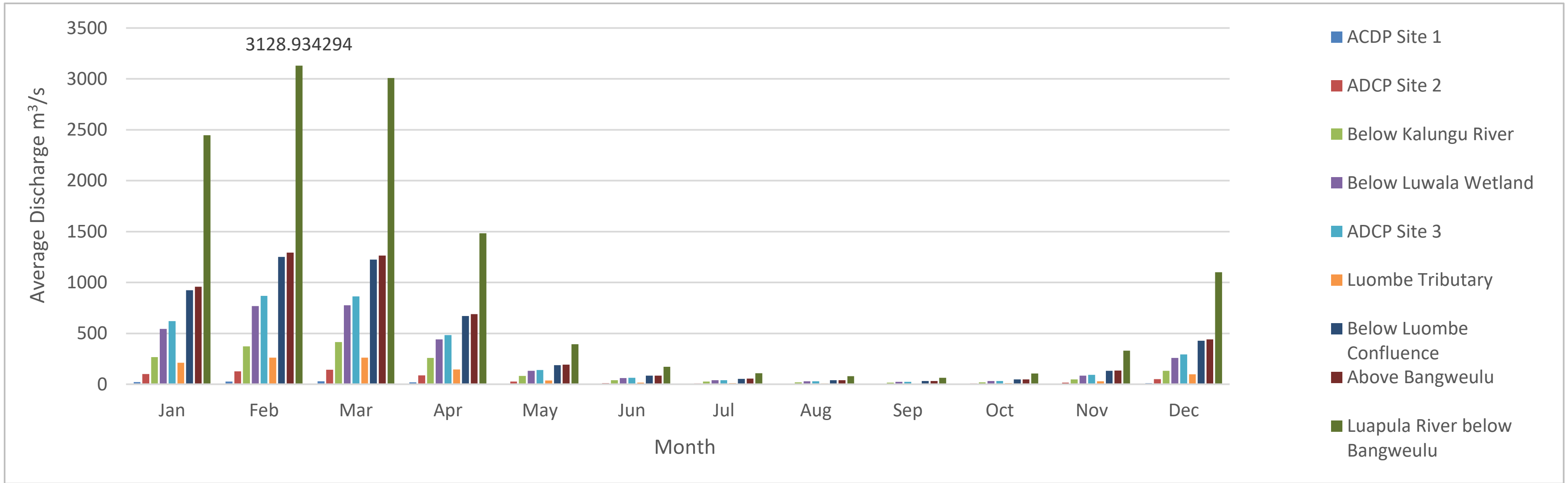

Figure 47. Historical monthly average discharge from 1980–2009[36] at the nine sites identified in Figure 46.

[36] *Collins EL et al. 2024. Global patterns in river water storage dependent on residence time. Nature Geoscience, pp.1-7.*

The Luombe River is the final major tributary that enters the Chambeshi River upstream of the Bangweulu Swamps, contributing ~25% of the flow of the Chambeshi River. In the dry season, this contribution drops to just ~18%, when the flow of the Chambeshi River into the Bangweulu Swamps is sustained primarily by the Chambeshi Flats. This highlights the importance of protecting and studying the Chambeshi Flats, which appear to be a significant source of dry season flow for the Chambeshi River, thereby acting as a buffer to seasonal variability of flows in the eastern Bangweulu Swamps.

The volume of water entering the Bangweulu Swamps from the Chambeshi River varies significantly between seasons (Figure 53). In the dry season, the river contributes as little as 30 m^3/s. Conversely, wet season flows can be almost 40X greater, particularly in February and March when discharge is ~1,300 m^3/s. Despite this variation, the proportional contribution of the Chambeshi River as a source of the Bangweulu Swamps is still high. In the dry season, the Chambeshi River inflow to the Bangweulu Swamps is equivalent to 50% of the total outflow via the Luapula River, which would seem to indicate that the Bangweulu Swamps and associated lakes have a reservoir effect.

Interestingly, the contribution of the Chambeshi River declines to less than 40% in the wet season, indicating that the Bangweulu system receives a greater proportion of its water from several other sources — the most obvious being localised rainfall. We speculate that the Chambeshi Flats act as a reservoir that is gradually depleted in the dry season, thereby sustaining the Bangweulu system. As a result, areas of the Bangweulu Swamps remain permanently inundated in the dry season, allowing for growth of papyrus and other foundational aquatic vegetation. To this end, the Chambeshi River is among the most important water sources for the Bangweulu Swamps, particularly in the dry season when the Chambeshi Flats serve as a buffer to reduced rainfall in the catchment.

5.2 Bat recorder deployments

Bat call recordings were obtained at several camp sites during the river expedition using a Wildlife Acoustics Song Meter SM4BAT-FS detector. To ensure peak activity was captured the recorders were set to begin recording 30 minutes before sunset and stop recording 30 minutes after sunrise. A total of 132 GB of recordings were made over the course of the transect. These will be stored for future cataloguing and analysis.

5.3 Fish Sampling

Methods: Fish Sampling

The Chambeshi River and associated wetlands were sampled for fish diversity by setting a fyke net overnight at suitable sites and dip-netting opportunistically. In addition, any fish from the crustacean trap were included in the sample. Once captured, fish were anaesthetized in clove oil, photographed, and preserved in 10% formalin for accession into the American Museum of Natural History. In addition, tissue samples were collected from two representatives per species and preserved in 99% ethanol. These subsets will be used to: i) conduct DNA analysis on specimens of interest; and ii) build an eDNA reference library to aide future detections.

Sampling was conducted at eight sites along the Chambeshi River (Figure 48). These were distributed mostly in the upper reaches of the river, including the Chambeshi Flats and the lower Chambeshi River. Limited fish sampling was conducted in the Bangweulu Swamps as these have been the focus of historical efforts in the basin[37].

[37] *Evans, D.W. 1978. Lake Bangweulu: a study of the complex and fishery. Msc.thesis, University of Toronto, Toronto.*

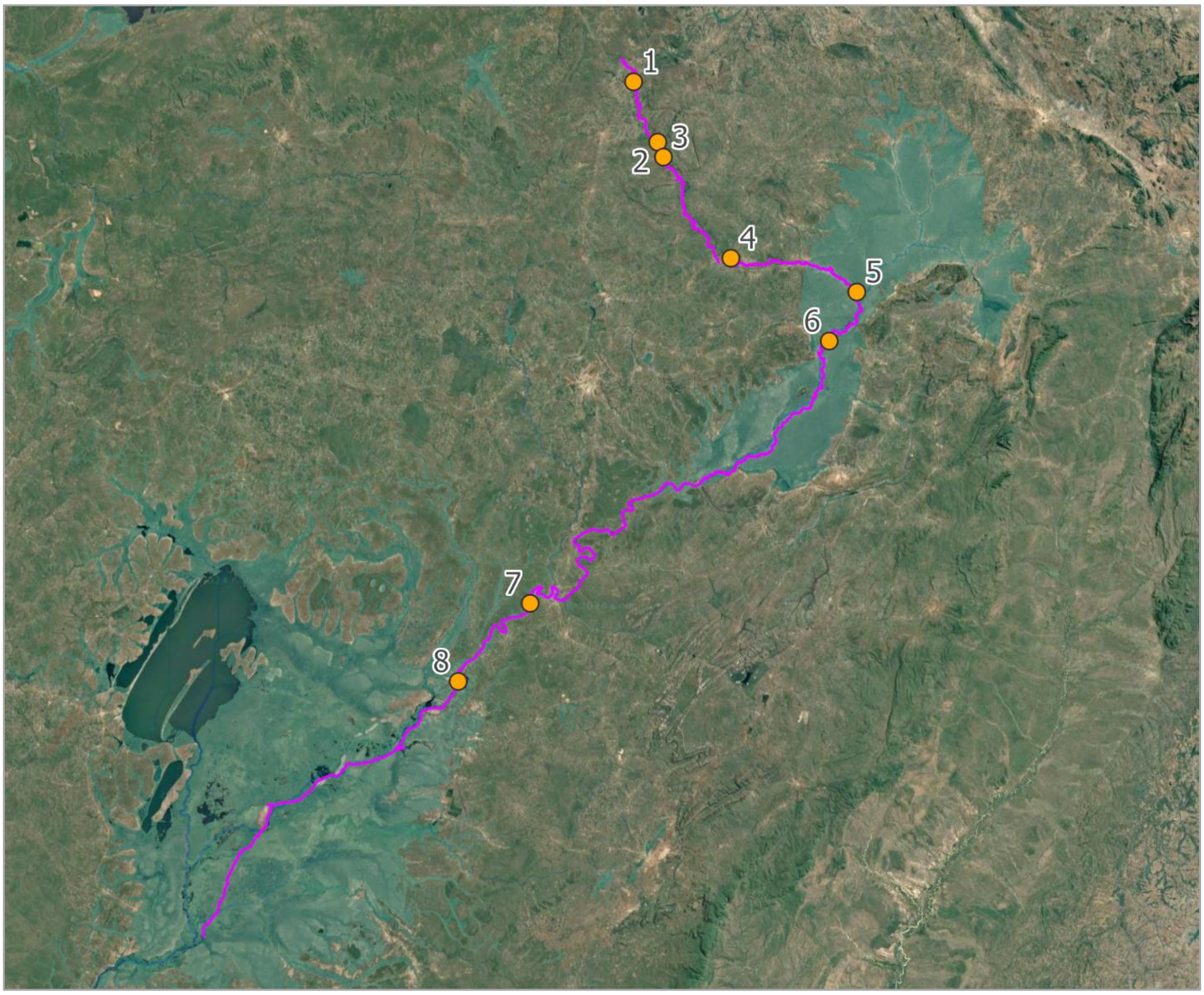

Figure 48. Fish Sampling Sites

Results and Discussion: Fish Sampling

Eighty-three species representing 13 taxonomic families have been recorded from the Bangweulu Swamps[38]. Given that there are no major biogeographical barriers for upstream fish movement between the Chambeshi Flats, Bangweulu Swamps and the lower Chambeshi River, it is likely that many of these species are consistent across the lower reaches of the river. However, the gorge area of the Chambeshi River has several large rapids that could influence differences in composition due to restricted upstream movement. In addition, the upstream habitats are different to those downriver (Table 1). As a result, it is possible that fish collected in these upper regions of the river are genetically distinct. Of particular interest are two species of Lacustricola (topminnows) that were collected in the upper reaches of the Chambeshi River (Figure 49).

[38] *Evans, D.W. 1978. Lake Bangweulu: a study of the complex and fishery. Msc.thesis, University of Toronto, Toronto.*

Figure 49. Two unknown species of Lacustricola that were detected on the upper reaches of the Chambeshi River, above the gorge area.

These two species contribute to an estimated 40 species that were detected on the Chambeshi River in the present survey (Appendix 4). Many of these individuals showed morphological variation to specimens documented elsewhere in the region, motivating the need for further taxonomic identification. Moreover, this sampling effort has returned one of the most extensive fish collections on the Chambeshi River to date, excluding previous efforts in the Bangweulu Swamps. As a result, the fishes in this collection contribute significantly to our knowledge of the diversity of the upper Congo tributaries.

Figure 50. Some of the fishes of the Chambeshi River that were detected in sampling efforts along the transect.

Of some concern is a fish disease, likely epizootic ulcerative syndrome (commonly known as red spot disease) that was noted on several Mormyridae (Figure 51). This disease is caused by the water mould *Aphanomyces invadans* and induces visible red sores on the bodies of fishes. It was first identified in the system in 2017 and there is concern over its potential to spread throughout the greater Congo Basin[39]. Moreover, local fishermen identified this disease as a major threat to their fishery and suggested that it is responsible in part for a decline in the abundance of large fishes in the wetlands over the last decade.

Figure 51. Epizootic ulcerative syndrome, commonly known as red spot disease, is believed to have caused the tissue damage on some of the fish specimens that were sampled in the Bangweulu and Chambeshi Flats. However, it is also possible that this is gillnet damage.

[39] *Huchzermeyer C. et al. 2017. First record of epizootic ulcerative syndrome from the Upper Congo catchment: An outbreak in the Bangweulu swamps, Zambia. Journal of Fish Diseases. 41.*

5.4 Invasive Crayfish Survey

Invasive crayfish (*Cherax* species, particularly *C. quadricarinatus*) are widespread within the Zambezi River, causing disruptions to ecosystems and fisheries. For example, within Lake Kariba, *C. quadricarinatus* scavenges on fish catches on static gillnets. This causes post-harvest fish losses in the region of 212 tonnes/year (which translates to roughly US$ 500,000)[40]. The Bangweulu Swamps offer an extensive habitat for *Cherax* species, with multiple entry points and high levels of human activity. Once within the wetlands, there are no real barriers to the downstream spread of these crayfish into the greater Congo River Basin. As a result, the potential spread of invasive crayfish into the Congo system via the Bangweulu Swamps should be closely monitored and prevented at all costs.

To assess the presence of invasive crayfish, a crustacean trap was baited with dry dog food and set overnight at several camp sites along the river transect. No invasive crayfish were collected on this expedition; however, this does not mean that *Cherax* species do not exist within the system. Ongoing monitoring for invasive crayfish is suggested, including regular discussions with local fishermen, who will likely be the first to detect these invasive species. Moreover, biocontrol measures should be considered, including limiting the movement of ballast water, sediments and aquatic vegetation between the Zambezi and Congo systems.

[40] *Chakandinakira AT et al. 2023. Socioeconomic impacts of Australian redclaw crayfish* Cherax quadricarinatus *in Lake Kariba. Biol Invasions 25, 2801–2812*

6. SATELLITE ANALYSES

6.1 CIFOR Analysis of Wetland Classes

Methods: CIFOR Analysis of Wetland Classes

The wetlands were classified using the Global Wetlands Map produced by the Sustainable Wetlands Adaptation and Mitigation Program (SWAMP https://www2.cifor.org/swamp/) and the Center for International Forestry Research (CIFOR). The Global Wetlands mapping uses a hydro-geomorphological model to estimate wetland areas. It relies on three biophysical indices linked to wetland and peat formation: i) long-term water supply exceeding atmospheric demand; ii) seasonally or annually waterlogged soils; and iii) geomorphological positioning that supports water retention41.

Results: CIFOR Analysis of Wetland Classes

The Bangweulu and Chambeshi Flats have a very similar composition of wetland classes. They consist mainly of floodplains, floodouts and marshes (Figure 52). Of these, marshes are the most common (43.2% combined across all classes) followed by floodplains (22.2%) and together these classes represent 65% of wetland extent within the basin. Within the total marsh cover, the 'general marshes' class of wetlands is common along river valleys, indicating that these are likely dambos — shallow, seasonally waterlogged, tropical and subtropical African wetlands[42].

Dambos are biodiversity hotspots that support various endemic and rare species, providing habitat for birds, insects, amphibians, and small mammals. They also sustain local communities by offering resources like grazing land, farming opportunities, medicinal plants, and water[43]. In addition to their ecological role, dambos help mitigate climate change by storing carbon in soil and vegetation and reduce flooding by absorbing excess rainwater, protecting downstream areas[44].

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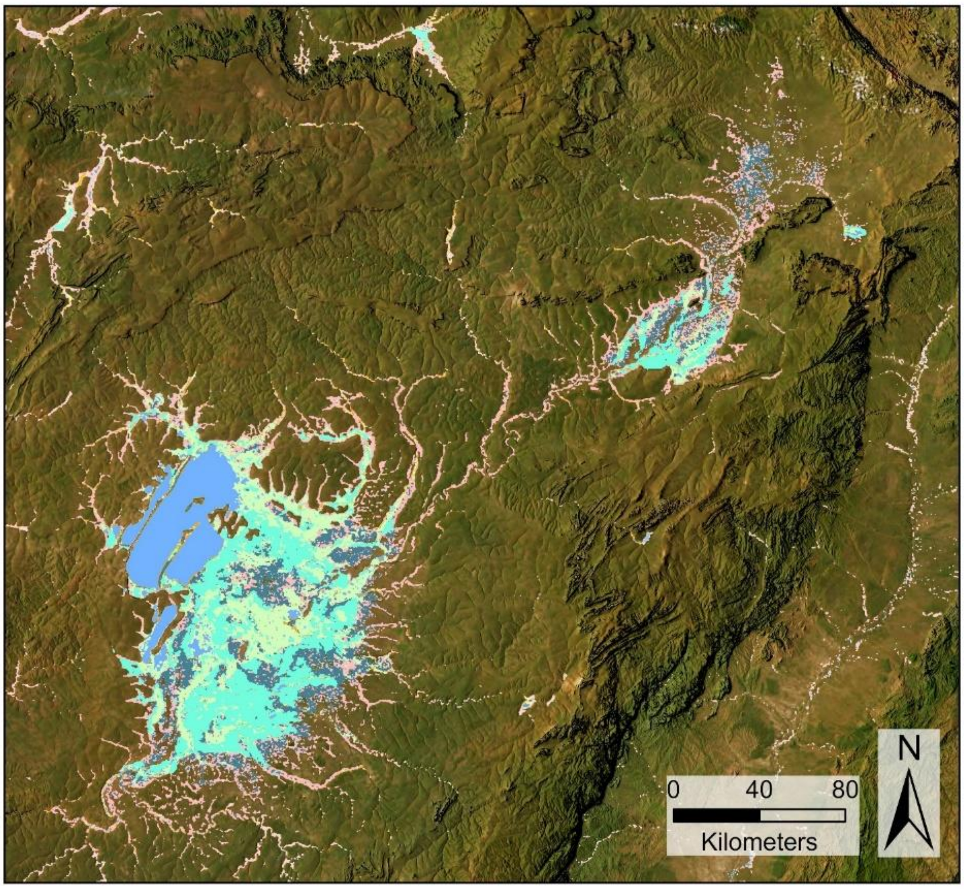
[41] *Gumbricht T et al. 2017. An expert system model for mapping tropical wetlands and peatlands reveals South America as the largest contributor.* Global Change Biology. *23(9):3581–3599.*
[42] *von der Heyden, CJ. 2004. The hydrology and hydrogeology of dambos: A review.* Progress in Physical Geography. *28(4):544–564.*
[43] *von der Heyden, CJ. 2004. The hydrology and hydrogeology of dambos: A review.* Progress in Physical Geography. *28(4):544–564.*
[44] *Boast, R. 1985. Dambos : a review.*



Legend	CIFOR Luwala and Bangweulu Wetland V2 classes	Area (km^2)
	Open Water	2,332
	Swamps	363
	Fens	0.09
	Riverine and lacustrine	0.83
	Floodouts	3,554
	Floodplains	4,070
	General Marshes	5,043
	Marshes in arid climate	53
	Marshes wet meadows	2,900
	Total Area	18,315

Figure 52. Wetlands within the Chambeshi River basin.

6.2 False Colour Satellite Analysis

Methods: CIFOR Analysis of Wetland Classes

Seasonal changes in water content in the wetlands were analysed using Sentinel-2 satellite imagery from ESA's Copernicus Open Access Hub[45]. The subsequent false-colour images for each season were generated by creating composites using the near-infrared (NIR), red, and green bands (Band 8, Band 4, Band 3, respectively). These bands were chosen because water absorbs NIR light, causing water bodies to appear dark, while wet soils and vegetation reflect more NIR light.

[45] *European Space Agency (ESA). Copernicus Open Access Hub. Available at: https://scihub.copernicus.eu/*

Results: CIFOR Analysis of Wetland Classes

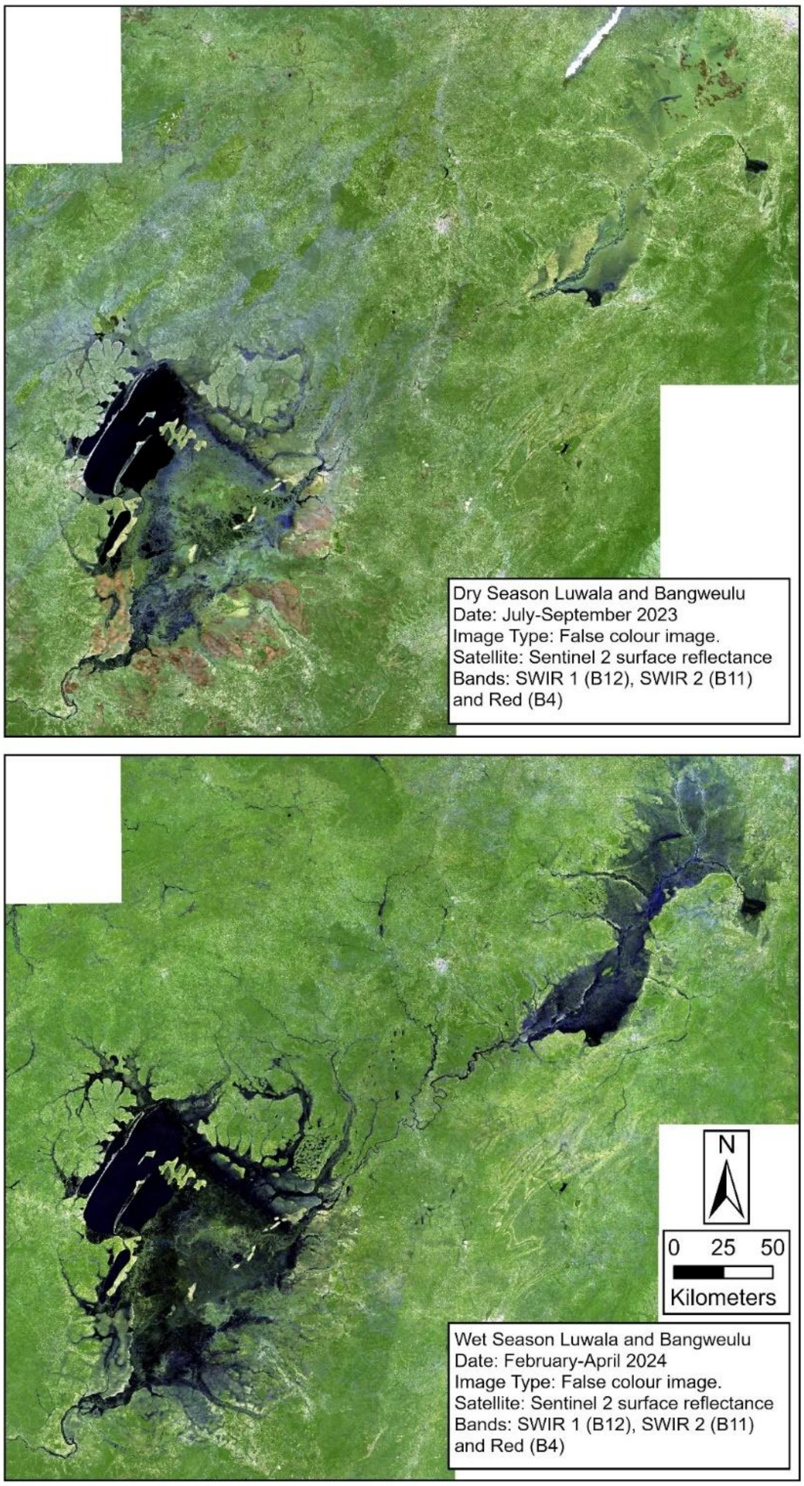


Figure 53. False colour images showing the difference in water content between the dry and wet seasons in the Bangweulu and Chambeshi Flats.

In the wet season, the Chambeshi Flats and Bangweulu Swamps are of comparable extent — particularly if one exludes the system of permanent lakes to the northeast of Bangweulu. However, in the dry season, the Chambeshi Flats diminish signficantly (Figure 53). This is finding aligns with the highly seasonal dsicharge of the Chambeshi River, as discussed in the hydrology section (see above). To this end, the Bangweulu Swamps can be considered a permenent freshwater marsh and lake system, whilst the

Chambeshi Flats are typical of a seasonal/intermittent freshwater marsh.

6.3 MODIS Fire RS Satellite Analysis

Methods: MODIS Fire RS Satellite Analysis

The 2000–2023 burn frequency of the Chambeshi Basin was extracted from the MCD64A1.061 MODIS Burned Area Monthly Global 500 m product[46]. A total of six burned area frequency categories were included in the analysis. It must be noted that, although this product does estimate burn area with accuracy, the size of burn areas must be greater than 500 m to be recorded. As a result, some smaller fires may not be identified by this product.

Results: MODIS Fire RS Satellite Analysis

Fire is common within the Chambeshi basin, with 7,002 km^2 (11%) of the basin burning every year and over 60% of the basin burning at least once every 4 years (Figure 54). Grasslands burn most frequently, with woodlands, shrublands and agricultural fields rarely burning (Table 14). However, the reported frequencies are likely underestimated due to the limitations of the MODIS Burned Area product, which cannot detect fires smaller than 500 m. This constraint may underestimate fire activity in densely populated areas where practices such as burning crop residues and slash-and-burn agriculture are common. Similarly, miombo woodlands, often burned annually in Zambia to stimulate caterpillar emergence, may also experience under-detection.

The Chambeshi Flats, which are a seasonally inundated marsh, burn on average every two years in the dry season. Conversely, the permanently inundated areas of the Bangweulu Swamps burn infrequently or not at all. Interestingly, the Chambeshi Flats commonly burn in June and July, whereas the low-lying areas of the basin burn in September and October (Figure 55). This is likely because water drains rapidly from the upper areas of the basin following the cessation of wet-season rainfall, thereby exposing the combustible fuel load earlier. Moreover, it is possible that local communities start many of these fires to prepare the landscape for crops and livestock. Generally, these fires only burn the aboveground vegetation — however, during prolonged droughts, the organic wetland soils may dry sufficiently to ignite and burn. Such fires — variously called groundfires, peat fires, or muck fires — have been observed in the Bangweulu Wetlands during dry years, where they lead to destruction of wetland vegetation and changes in organic matter storage[47].

The organic soils in wetlands represent enormous stocks of terrestrial carbon. Consequently, groundfires release substantial amounts of carbon to the atmosphere. It is estimated that peat fires may produce emissions 75% higher per hectare than fires consuming standing vegetation alone[48]. This is especially concerning given the projected increase in the frequency and intensity of droughts in Zambia under climate change conditions[49]. Wetland management plans should develop a fire management plan that includes long-term monitoring of monthly burns to determine their impact and detect changes in the local fire regime under climate change conditions. Additionally, this plan should involve better understanding the factors driving people to burn different areas and engaging communities in efforts to reduce fires in ecologically sensitive regions.

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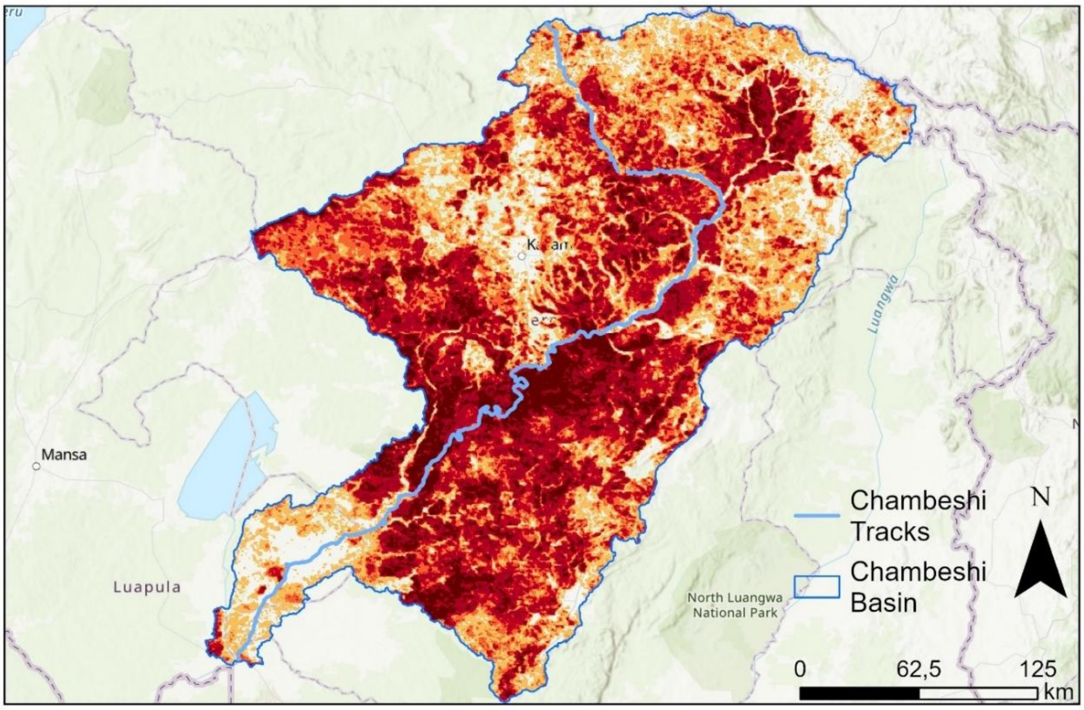
[46] *Giglio, L., C. Justice, L. Boschetti, D. Roy. MODIS/Terra+Aqua Burned Area Monthly L3 Global 500m SIN Grid V061. 2021, distributed by NASA EOSDIS Land Processes Distributed Active Archive Center.*

[47] *Watts, A.C., Schmidt, C.A., McLaughlin, D.L. & Kaplan, D.A. 2015. Hydrologic implications of smoldering fires in wetland landscapes. Freshwater Science. 34(4):1394–1405.*

[48] *Watts, A.C., Schmidt, C.A., McLaughlin, D.L. & Kaplan, D.A. 2015. Hydrologic implications of smoldering fires in wetland landscapes. Freshwater Science. 34(4):1394–1405.*

[49] *Kimirei, I.A., Mubaya, C.P. & Bere, T. 2022.* Ecological changes in the Zambezi River Basin.

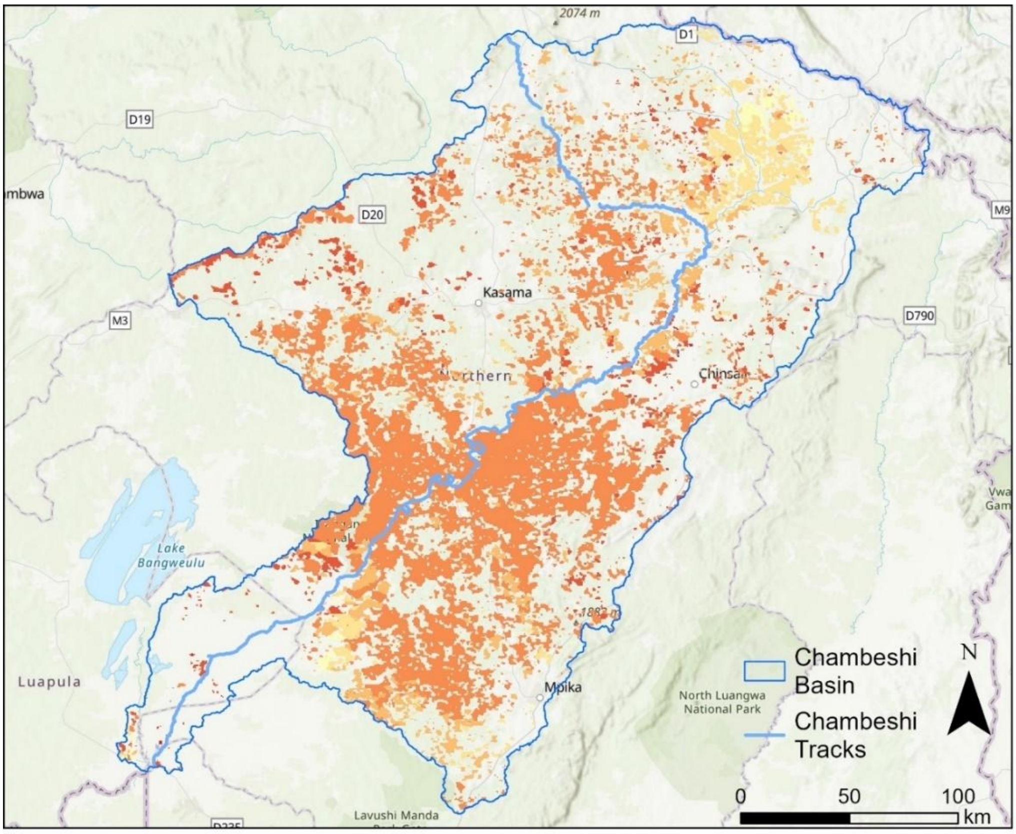


Legend	Burn Frequency (2000-2023)	Area (km²)	Proportion (%)
	No Burn	9,921	15%
	1-5 Burns	16,225	25%
	6-10 Burns	10,964	17%
	11-15 Burns	10,449	16%
	16-20 Burns	11,266	17%
	21-23 Burns	7,002	11%
	Total Area	65,955	-

Figure 54. Fire Frequency from 2000 to 2023 within the Chambeshi river basin.

Table 14. The percentage of land-cover burnt at different burn frequencies between 2000 – 2023. Note this is based on the vegetation LULC 2023 map of the Chambeshi Basin.

Burn Frequency (2000 – 2023)	Agriculture	Forest and Woodland	Grassland	Shrubland	Wetland	Settlement
No Burn	19%	11%	3%	17%	38%	98%
1 to 5	25%	23%	11%	26%	37%	1%
6 to 10	18%	18%	12%	15%	8%	1%
11 to 15	15%	18%	19%	14%	6%	0%
16 to 20	14%	18%	35%	18%	7%	0%
21 to 23	9%	12%	19%	11%	4%	0%
Total Area (km²)	13376.75	37803	3752.75	4504.75	6083	45.5



Legend		2023 Area (km²)	Burn Proportion (%)
	No Burn	44,310.50	-
	January	4.25	0.02%
	February	0.00	0.00%
	March	0.50	0.002%
	April	0.00	0.00%
	May	4.75	0.02%
	June	308.00	1.49%
	July	1,806.25	8.77%
	August	2,810.50	13.64%
	September	14,203.75	68.93%
	October	1,440.25	6.99%
	November	29.25	0.142%
	December	0.00	0.00%
	Total Burn Area	20,607.50	-

Figure 55. Burned area per month in 2023 in the Chambeshi river basin.

6.4 Land-Use and Land-Cover Change Analysis 1992-2020

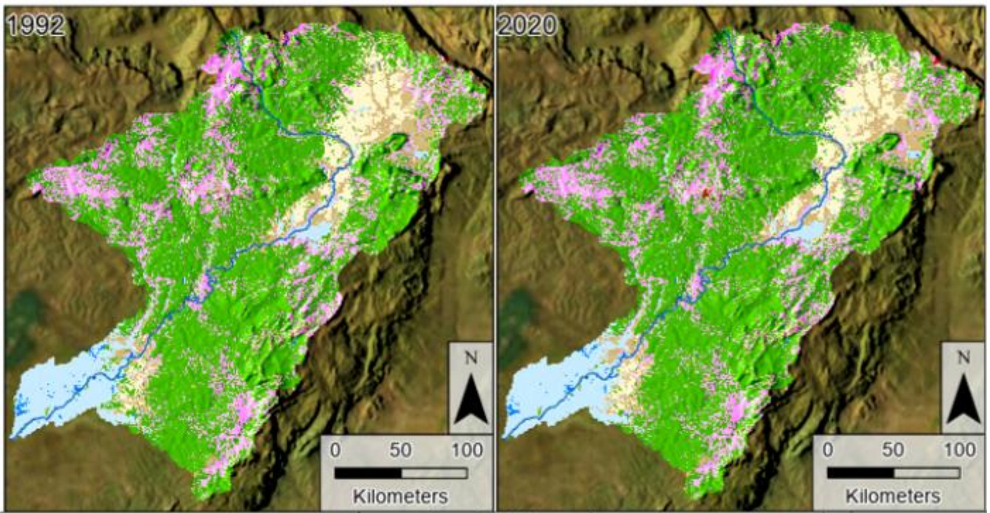
Methods: LULC change analysis

The land-use and land-cover (LULC) change analysis for the Chambeshi River Basin was conducted using 300 m resolution maps from the European Space Agency Climate Change Initiative. These maps, covering 1992 and 2020, were reclassified into broader categories based on user guidelines for change detection.

Vegetation Dynamics
The Chambeshi Basin is predominantly covered by forests and woodlands, which accounted for 58% of the area in 1992 and remained stable at 59% in 2020 (Figure 56). These ecosystems are primarily composed of Zambezian miombo woodlands, dominated by Brachystegia, Julbernardia, and Isoberlinia species. Grasslands, wetlands, and shrublands complement this natural vegetation, with wetlands fluctuating seasonally between 10–30% of the basin's coverage.

Cropland represented 21% of the basin's total area, largely concentrated in the northwestern regions such as the Senga Hills, the source of the Chambeshi River. This confirms the results of the observational survey, which indicated that the land surrounding the Chambeshi River source was heavily cropped (Figure 27).

Notably, some rice plantations within the Bangweulu Swamps were not captured in the analysis, as rice fields are visually indistinguishable from sedges and grasses. Consequently, the actual extent of agricultural land is likely higher than reported.



Legend LULC Class	Chambeshi Watershed 1992 (km²)	Chambeshi Watershed 2020 (km²)	Change (%)
Agriculture	12942	12756	-1,44%
Forest and Woodland	35870	35958	0,25%
Grassland	3446	3506	1,74%
Wetland	4797	4962	3,42%
Settlement	4	43	1083,33%
Shrubland	4375	4238	-3,14%
Bare/ sparse vegetation	0	0	-
Water	214	186	-13,13%
Total	61648	61648	

Figure 56. Land-use and land-cover change analysis for the Chambeshi basin between 1992–2020.

Human land-use cover
Agricultural land decreased slightly by 186 km² (-1.44%) between 1992 and 2020, but several factors complicate the interpretation of this change. First, the high rate of urbanization in the region suggests that the population of rural small-scale farmers may be more static, limiting significant expansion of agricultural areas. Second, the dominant agricultural practice in much of the basin is the shifting slash-and-burn (chitemene) system, characterized by long fallow periods. During these fallow cycles, forest regeneration

often occurs, resulting in dense woody vegetation that can give off a signal similar to increased forest cover. Additionally, elevated atmospheric CO^2 levels may promote the growth of woody vegetation over grass, further contributing to apparent forest density increases.

This complex interplay of factors may obscure the true extent of agricultural activity and highlights the limitations of remote sensing in capturing dynamic land-use systems such as chitemene. Despite this, agricultural activity remains a significant land-use type, with cropland largely concentrated in areas like the Senga Hills and parts of the Bangweulu Swamps.

For the swamp islands specifically, the population has also increased, rising from 24,000 in 2010 to 39,000 in 2022, reflecting an annual growth rate of 4.2%[50]. This growth, surpassing the national rural average of 3.4%, is likely attributed to limited access to reproductive healthcare and family planning services due to the remote setting, rather than migration.

The expansion of settlements and human activity within the Chambeshi Basin and surrounding areas highlights the escalating pressure on natural ecosystems, particularly wetlands. These trends emphasize the urgent need for a balanced approach to development that prioritizes sustainable land management and ecological conservation.

Discrepancy with Chundu et al. (2024)

Our LULC findings differ from those of Chundu et al. (2024)[51], who reported significant transformations within the Bangweulu Wetland System from 1990 to 2020: a 40% decrease in forest cover, a 30% reduction in grasslands, an 80% expansion in cropland, and a 50% growth in settlements. These discrepancies stem from differences in analytical scope and methodology. Chundu et al. focused exclusively on the Bangweulu Wetlands, utilizing five land-cover classes at 30 m resolution, while our study analyzed the entire Chambeshi Basin using eight land-cover classes at 300 m resolution.

This contrast underscores the need for comprehensive and harmonized LULC studies across the Chambeshi Basin. Moreover, accuracy of remote sensing can be improved by incorporating ground-truthed data and a consistent methodology, thereby providing a clearer understanding of land-use dynamics in this interconnected system.

Conclusion

The Chambeshi River Basin has experienced dynamic changes in land use and cover between 1992 and 2020, driven by both natural processes and growing human pressures. These changes have profound implications for the region's ecological health and socio-economic development.

To ensure sustainable development and conservation, there is a critical need for detailed, high-resolution land-use change analyses that encompass the entire Chambeshi River Basin. These studies must integrate ground-truthed data to capture localized dynamics and provide actionable insights for effective land management. Such comprehensive analyses will be instrumental in balancing human needs with the preservation of vital ecosystems, ensuring the long-term functionality of this interconnected basin.

[50] *Lunga District Integrated Development Plan*

[51] *Chundu ML. et al. 2024. Modelling land use/land cover changes using quad hybrid machine learning model in Bangweulu wetland and surrounding areas, Zambia. Environmental Challenges, Volume 14.*

6.5 Google Open Buildings Analysis

Methods: Google Open Buildings Analysis

The Google Open Buildings dataset[52], which provides building footprints derived from satellite imagery, was used to calculate the number and total area of buildings within a 4 km buffer zone around the: i) Chambeshi River; ii) Bangweulu Swamps; iii) Chambeshi Flats; and the iv) greater Chambeshi Basin, including downstream areas. Within these buffer zones, the total area and number of buildings were calculated. By highlighting human settlements and their proximity to these key ecological areas, the dataset aids in assessing human presence surrounding important waterbodies compared to that of the greater Chambeshi River Basin (Figure 57).

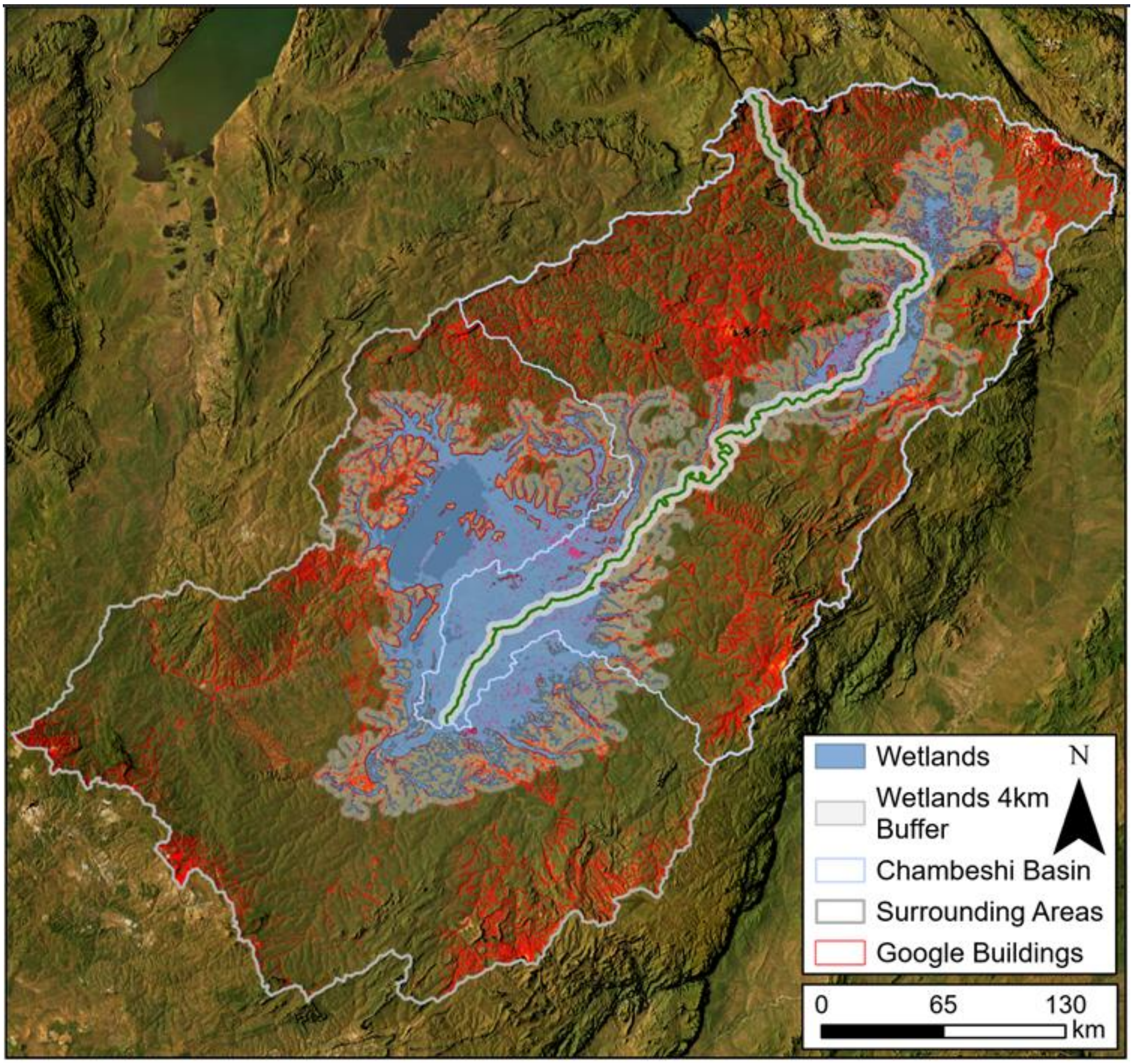
Results: Google Open Buildings Analysis

The greater Chambeshi River basin, including areas south of the Bangweulu Swamps, has a total building area of over 32 km^2 (Figure 58). Interestingly, this is lower than the settlement cover detected by the LULC change analysis above — suggesting that actual building area is between 32–43 km^2, depending on the data and model used. Many of these settlements are likely to be small homesteads constructed of clay or bricks and consisting of 2–3 buildings, with adjacent crops for subsistence production.

Along the Chambeshi River, there are ~30,177 buildlings, amounting to an average settlement density of 6.22 buildings/km. The Bangweulu and Chambeshi Flats have a comparable settlement density of 6.04 and 7.04 buildings/km, respectively. These values are moderate compared to some other river sections in Zambia. For example, the Zambian Lungwebungu River had an average settlement density of 3.01 buildings/km, whereas settlement density is as high as 16.93 buildings/km surrounding the Barotse floodplains.

Figure 57. A typical building along the Chambeshi River.

[52] *Sirko, W. et al. 2021. Continental-scale building detection from high resolution satellite imagery.*



	Buffer Area	Total no. of buildings	No. of buildings/km²	Total building area (km²)	Building area (%) within Buffer zone
Chambeshi River	4,855	30,177	6.22	0.0093	0.0002%
Bangweulu Wetlands	34,639	209,092	6.04	0.1132	0.0003%
Luwala Wetlands	11,555	81,900	7.09	0.0449	0.0004%
	Basin Area	Total no. of buildings	No. of buildings/km²	Total building area (km²)	Building area (%) within Basin
Chambeshi Basin and surrounding areas	13,2136	904,691	6.85	32.4174	0.0052%

Figure 58. Building analysis of the Chambeshi River Basin.

7. CONCLUSION AND RECOMMENDATIONS

The Chambeshi River is the most distant source of the Congo River, originating in the Senga Hills region of Zambia. The river is near-pristine, with no dams and limited infrastructure development. In addition, local communities along the river predominantly practice fisher-farmer livelihoods that rely heavily on the Chambeshi Flats and Bangweulu Swamps for ecosystem services including water filtration, soil fertility and fish nurseries.

Water quality along the river is generally excellent, with the exception the Lulimala River Mouth, where conductivity and salinity are 3X higher than immediately upstream. This is believed to be a result of pollution by manganese mining activity further up the Lulimala river adjacent to Lavushi Manda National Park. However, ongoing water quality monitoring is essential to reveal the source of this anomaly.

Agriculture around the source of the Chambeshi River is intense and expansive, leaving only small areas of intact forest remaining. Pesticides and fertilizers may cause a significant decline in water quality in the river in the dry season, however these were not detected as the river was in flood at the time of the survey. Similarly to the Lulimala River, water quality monitoring should be conducted on the upper Chambeshi River on an ongoing basis to determine the impacts of agriculture on river health.

Ongoing water quality monitoring is particularly important considering the importance of the Chambeshi River as a fish biodiversity hotspot. Despite limited sampling efforts, an estimated 40 species of fish were detected on this expedition, including two potentially novel *Lacustricola* species from the upper Chambeshi River. Ongoing taxonomic analysis, including analysis of eDNA samples collected along the transect, will reveal the complete ichthyofaunal biodiversity sampled on the river.

The Chambeshi River is a significant water source for the Bangweulu Swamps, contributing an estimated 40–50% of the flow, depending on the season. Most of this water originates in the dambo-like Chambeshi Flats. During the dry season, contributions from smaller tributaries become negligible, and the storage effect of the Bangweulu Wetlands becomes more pronounced. This highlights the crucial role of the Chambeshi Flats as a hydrological buffer for Bangweulu, and Bangweulu in turn for the rest of the Luapula system.

The Chambeshi-Bangweulu wetland complex does not simply 'lose' water through evapotranspiration, as some outdated perspectives suggest, but instead plays a key role in sustaining downstream flows. Localized rainfall over the wetland, combined with its storage capacity, makes Bangweulu a vital regulator of water availability in the Luapula basin. This finding further underscores the importance of sustainably managing the Chambeshi River and protecting the Bangweulu Wetlands — not only for the large population in the basin that depends on them for their livelihoods but also for their critical role in maintaining biodiversity and regional hydrological stability.

There is notable biodiversity along the Chambeshi River, with at least 71 species of wetland-associated birds detected in this survey. However, wildlife populations along the river were absent at the time of sampling, supporting evidence of a long-term population decline in the basin over the last century. For example, only five hippos were counted along the 765 km transect. However, it is important to acknowledge the limitations of the survey methods in detecting terrestrial wildlife and birds in expansive wetland areas, as survey methods are better suited for main river channels.

In light of this information, future recommendations for the sustainable management of the Chambeshi River and associated wetlands include:

1. **Conduct a Comprehensive Land-Use and Land-Cover (LULC) Change Analysis**
    - Carry out a high-resolution LULC analysis of the entire Chambeshi Basin.
    - Incorporate ground-truthed data to improve accuracy and reliability.
2. **Expand and Maintain Ongoing Water Quality Monitoring**
    - Establish fixed monitoring sites along the Chambeshi River, including the upper and lower sections and the Bangweulu Swamps.
    - Ensure dedicated monitoring of the Lulimala River to confirm early signs of pollution from mining activity.
3. **Promote Climate-Resilient and Nature-Positive Agriculture**
    - Given the extensive deforestation and cropping around the upper Chambeshi, explore agroforestry as a sustainable alternative.
    - Support similar farming methods that enhance soil health, biodiversity, and climate resilience.
4. **Enhance Utilization and Rewilding of the Chambeshi Flats**
    - Recognize the potential of the Chambeshi Flats, floodplains, and grasslands for sustainable livestock grazing.
    - Encourage community-led game ranching as a rewilding strategy that complements existing ecosystem services like fishing.
    - Restore carbon and nutrient cycling through wildlife reintroduction, enriching fisheries and boosting local economies through meat harvests, tourism, and Zambia's growing game ranching sector.
5. **Support Wildlife Restoration in the Bangweulu Game Management Area (GMA)**
    - Encourage the expansion of wildlife populations into former ranges, particularly in grassy wetland margins that are not used for agriculture and only seasonally for fishing.
    - Promote wildlife restoration as a means of adding economic and ecological value without compromising other ecosystem services.
    - Highlight the role of herbivores in nutrient cycling, which can further support fishery productivity.
6. **Conduct a Comprehensive Fish Biodiversity Survey and Develop an Ichthyofaunal Database**
    - Assess fish species richness and composition across different zones of the Chambeshi River and associated wetlands.
    - Use indices of relative importance to identify key species and their ecological roles.
    - Focus particularly on migratory fish species, as these are the most vulnerable to future hydrological developments or environmental changes.
    - Establish a long-term ichthyofaunal reference database of fish tissues to support accurate species identification, future ecological studies, and conservation planning.

8. APPENDICES

Appendix 1. Full bird list from the Chambeshi River

Row Labels	Sum of Count
Western cattle egret	653
Squacco heron	505
Collared pratincole	302
Reed cormorant	162
Little bee-eater	152
Little egret	143
Great egret	117
Malachite kingfisher	103
Yellow-billed duck	79
White-faced whistling duck	73
African marsh harrier	63
Intermediate egret	63
Striated heron	62
Intermediate egret	66
African openbill	59
Marsh widowbird	55
Red-collared widowbird	51
Spur-winged goose	46
African pygmy kingfisher	42
Purple heron	34
Black-crowned night heron	32
Grey-headed gull	30
Pied kingfisher	28
Lesser jacana	22
Black heron	20
Black crake	17
White-backed duck	17
Half-collared kingfisher	17
African jacana	15
Coppery-tailed coucal	14
Giant kingfisher	13
Bateleur	10
Striped kingfisher	8
Woolly-necked stork	7
Glossy ibis	7
Southern carmine bee-eater	5
African pygmy goose	5
Senegal coucal	5
Brown-hooded kingfisher	4
Black coucal	4
Dwarf bittern	4
Common moorhen	3
Little bittern	3
White browed coucal	2
Lizard buzzard	2
African fish eagle	2
Hamerkop	2
African harrier hawk	2
Common greenshank	2
African finfoot	1
African swamphen	1
White-breasted cormorant	1
Black sparrowhawk	1
Grey heron	1
Grand Total	**3,133**

Appendix 2. LULC Supplementary Table.

IPCC Classes considered for the change detection (with colour)	LCCS legend used in the CCI-LC maps	
	Code	Description
1. Agriculture	10, 11, 12	Rainfed cropland
	20	Irrigated cropland
	30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)
	40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (< 50%)
2. Forest	50	Tree cover, broadleaved, evergreen, closed to open (>15%)
	60, 61, 62	Tree cover, broadleaved, deciduous, closed to open (> 15%)
	70, 71, 72	Tree cover, needle leaved, evergreen, closed to open (> 15%)
	80, 81, 82	Tree cover, needle leaved, deciduous, closed to open (> 15%)
	90	Tree cover, mixed leaf type (broadleaved and needleleaved)
	100	Mosaic tree and shrub (>50%) / herbaceous cover (< 50%)
	160	Tree cover, flooded, fresh or brackish water
	170	Tree cover, flooded, saline water
3. Grassland	110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)
	130	Grassland
4. Wetland	180	Shrub or herbaceous cover, flooded, fresh-saline or brackish water
5. Settlement	190	Urban
6. Shrubland	120, 121, 122	Shrubland
7. Bare / sparse vegetation	140	Lichens and mosses
	150, 151, 152, 153	Sparse vegetation (tree, shrub, herbaceous cover)
	200, 201, 202	Bare Areas
8. Water	210	Water

Appendix 3. Monthly and annual discharge of the Chambeshi River at various points along its course. Locations are indicated in Figure 46.

Month	ACDP Site 1	ADCP Site 2	Below Kalungu River	Below Chambeshi Flats	ADCP Site 3	Luombe Tributary	Below Luombe Confluence	Above Bangweulu	Luapula River below Bangweulu
Jan	20.4	99.2	265.7	544.8	621.1	211.7	924.9	958.8	2,447.0
Feb	26.0	126.8	373.5	766.9	868.0	262.4	1,251.4	1,292.6	3,128.9
Mar	29.0	141.3	415.7	775.5	863.2	260.3	1,225.1	1,264.6	3,008.8
Apr	18.1	88.3	259.0	442.1	483.6	145.7	669.1	688.4	1,482.2
May	5.5	26.8	82.5	131.4	140.5	37.6	188.3	192.7	392.2
Jun	2.4	11.9	38.5	59.9	63.6	15.9	84.0	85.8	172.2
Jul	1.6	7.6	25.1	38.7	41.0	9.9	53.8	54.8	108.6
Aug	1.2	5.6	18.7	28.6	30.2	7.2	39.5	40.3	79.3
Sep	0.9	4.6	15.1	23.0	24.3	6.0	32.0	32.6	64.2
Oct	1.5	7.1	19.6	30.6	32.9	11.7	47.2	48.6	104.9
Nov	3.4	16.3	48.4	84.0	92.8	29.1	131.7	135.4	329.6
Dec	10.4	50.5	133.2	258.8	292.4	96.7	426.6	440.9	1,099.4
Annual average	**10.0**	**48.8**	**141.3**	**265.3**	**296.1**	**91.2**	**422.8**	**436.3**	**1,034.8**

Appendix 4. Details of fish collection on the Chambeshi River transect. Fish IDs validated by Carl Huchzermeyer, but further genetic analysis is underway at the American Museum of Natural History.

Site	Latitude	Longitude	Date (Start)	Date (End)	Site Description	Capture Method	Collectors	Species
1	-9.18476	31.34651	April 13, 2024	April 13, 2024	Upper Chambeshi River, source area	Dip Net	M. Dooley	Lacustricola sp.
1	-9.18476	31.34651	April 13, 2024	April 13, 2025	Upper Chambeshi River, source area	Dip Net	M. Dooley	Lacustricola sp.
1	-9.18476	31.34651	April 13, 2024	April 13, 2026	Upper Chambeshi River, source area	Dip Net	M. Dooley	Micralestes sardina
1	-9.18476	31.34651	April 13, 2024	April 13, 2027	Upper Chambeshi River, source area	Dip Net	M. Dooley	Tilapia sparmanii
1	-9.18476	31.34651	April 13, 2024	April 13, 2028	Upper Chambeshi River, source area	Dip Net	M. Dooley	Enteromius greenwoodi
2	-9.39232	31.43085	April 15 2024	April 15 2024	Upper Chambeshi River, above gorge	Dip Net	S. Mbewe	Enteromius kerstenii
2	-9.39232	31.43085	April 15 2024	April 15 2024	Upper Chambeshi River, above gorge	Dip Net	S. Mbewe	Opsaridum zambense
2	-9.39232	31.43085	April 15 2024	April 15 2024	Upper Chambeshi River, above gorge	Dip Net	S. Mbewe	Lasucstricola sp.
2	-9.39232	31.43085	April 15 2024	April 15 2024	Upper Chambeshi River, above gorge	Dip Net	S. Mbewe	Amphilius sp.
2	-9.39232	31.43085	April 17, 2024	April 17, 2024	Upper Chambeshi River, above gorge	Dip Net	M. Dooley, J. Van Der Westhuizen, S. Mbewe	Clariallabes platpyprosopos
2	-9.39232	31.43085	April 17, 2024	April 17, 2024	Upper Chambeshi River, above gorge	Dip Net	M. Dooley, J. Van Der Westhuizen, S. Mbewe	Micralestes sardina
2	-9.39232	31.43085	April 17, 2024	April 17, 2024	Upper Chambeshi River, above gorge	Dip Net	M. Dooley, J. Van Der Westhuizen, S. Mbewe	Opsaridum zambense
2	-9.39232	31.43085	April 17, 2024	April 17, 2024	Upper Chambeshi River, above gorge	Dip Net	M. Dooley, J. Van Der Westhuizen, S. Mbewe	Enteromius greenwoodi
2	-9.39232	31.43085	April 17, 2024	April 17, 2024	Upper Chambeshi River, above gorge	Dip Net	M. Dooley, J. Van Der Westhuizen, S. Mbewe	Lacustricola johnsoni
3	-9.44379	31.45057	April 18, 2024	April 19, 2024	Upper Chambeshi River, gorge area	Dip Net and Fyke Net	S. Mbewe	Clarias stappersii
3	-9.44379	31.45057	April 18, 2024	April 19, 2024	Upper Chambeshi River, gorge area	Dip Net and Fyke Net	S. Mbewe	Enteromius lineomaculatus
3	-9.44379	31.45057	April 18,	April 19,	Upper Chambeshi River, gorge area	Dip Net and Fyke Net	S. Mbewe	Labeo cylindricus

			2024	*2024*				
4	*-9.791775*	*31.68603611*	*April 24, 2024*	*April 24, 2024*	*Upper Chambeshi River, just above Luwala Wetland*	*Dip Net*	*M. Dooley, S. Mbewe*	*Nannocharax sp.*
4	*-9.791775*	*31.68603611*	*April 24, 2024*	*April 24, 2024*	*Upper Chambeshi River, just above Luwala Wetland*	*Dip Net*	*M. Dooley, S. Mbewe*	*Nannocharax sp.*
4	*-9.791775*	*31.68603611*	*April 24, 2024*	*April 24, 2024*	*Upper Chambeshi River, just above Luwala Wetland*	*Dip Net*	*M. Dooley, S. Mbewe*	*Lacustricola johnsoni*
4	*-9.791775*	*31.68603611*	*April 24, 2024*	*April 24, 2024*	*Upper Chambeshi River, just above Luwala Wetland*	*Dip Net*	*M. Dooley, S. Mbewe*	*Lacustricola sp.*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Pseudocrenilabus philander*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Tilapia sparmanii*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Enteromius eutaenia*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Enteromius multilineatus*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Enteromius greenwoodi*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Lacustricola johnstonii*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Rhabdalestes cf. maunensis*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Tilapia sparmanii*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Enteromius afrovernayi*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Enteromius barotsensis*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Enteromius sp.*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Pollimyrus castelnaui*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Synodontis nigromaculatus*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Schilbe intermedius*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Petrocephalus okavangensis*

5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Macusenius macrolepidotus*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Tilapia sparmanii*
5	*-9.90784*	*32.12515*	*April 26, 2024*	*April 27, 2024*	*Upper Luwala Wetland*	*Dip Net and Fyke Net*	*M. Dooley, S. Mbewe*	*Enteromius raduatus*
6	*-10.07636*	*32.02891*	*April 28, 2024*	*April 28, 2024*	*Middle Luwala Wetland*	*Local fishermen*	*M. Dooley, S. Mbewe*	*Marcusenius sp.*
6	*-10.07636*	*32.02891*	*April 28, 2024*	*April 28, 2024*	*Middle Luwala Wetland*	*Local fishermen*	*M. Dooley, S. Mbewe*	*Serranochromis cf. angusticeps*
6	*-10.07636*	*32.02891*	*April 28, 2024*	*April 28, 2024*	*Middle Luwala Wetland*	*Local fishermen*	*M. Dooley, S. Mbewe*	*Serranochromis jallae*
6	*-10.07636*	*32.02891*	*April 28, 2024*	*April 28, 2024*	*Middle Luwala Wetland*	*Local fishermen*	*M. Dooley, S. Mbewe*	*Ctenopoma multispine*
6	*-10.07636*	*32.02891*	*April 28, 2024*	*April 28, 2024*	*Middle Luwala Wetland*	*Local fishermen*	*M. Dooley, S. Mbewe*	*Sargochromis mellandi*
6	*-10.07636*	*32.02891*	*April 28, 2024*	*April 28, 2024*	*Middle Luwala Wetland*	*Local fishermen*	*M. Dooley, S. Mbewe*	*Pseudocrenilabrus sp.*
6	*-10.07636*	*32.02891*	*April 28, 2024*	*April 28, 2024*	*Middle Luwala Wetland*	*Local fishermen*	*M. Dooley, S. Mbewe*	*Tilapia sparmanii*
6	*-10.07636*	*32.02891*	*April 28, 2024*	*April 28, 2024*	*Middle Luwala Wetland*	*Local fishermen*	*M. Dooley, S. Mbewe*	*Coptodon rendalli*
6	*-10.07636*	*32.02891*	*April 28, 2024*	*April 28, 2024*	*Middle Luwala Wetland*	*Local fishermen*	*M. Dooley, S. Mbewe*	*Sargochromis mellandi*
6	*-10.07636*	*32.02891*	*April 28, 2024*	*April 28, 2024*	*Middle Luwala Wetland*	*Local fishermen*	*M. Dooley, S. Mbewe*	*Pseudocrenilabus philander*
6	*-10.07636*	*32.02891*	*April 28, 2024*	*April 28, 2024*	*Middle Luwala Wetland*	*Local fishermen*	*M. Dooley, S. Mbewe*	*Clarias ngamensis*
6	*-10.07636*	*32.02891*	*April 28, 2024*	*April 28, 2024*	*Middle Luwala Wetland*	*Local fishermen*	*M. Dooley, S. Mbewe*	*Clarias theodorae*
7	*-10.97584*	*30.98576*	*May 4, 2024*	*May 5, 2024*	*Lower Luwala Wetland*	*Local Fishermen and Fyke Net*	*M. Dooley, J. Van Der Westhuizen, S. Mbewe*	*Enteromius radiatus*
7	*-10.97584*	*30.98576*	*May 4, 2024*	*May 5, 2024*	*Lower Luwala Wetland*	*Local Fishermen and Fyke Net*	*M. Dooley, J. Van Der Westhuizen, S. Mbewe*	*Schilbe intermedius*
7	*-10.97584*	*30.98576*	*May 4, 2024*	*May 5, 2024*	*Lower Luwala Wetland*	*Local Fishermen and Fyke Net*	*M. Dooley, J. Van Der Westhuizen, S. Mbewe*	*Tilapia sparmanii*
7	*-10.97584*	*30.98576*	*May 4, 2024*	*May 5, 2024*	*Lower Luwala Wetland*	*Local Fishermen and Fyke Net*	*M. Dooley, J. Van Der Westhuizen, S. Mbewe*	*Petrocephalus sp.*
7	*-*	*30.98576*	*May 4,*	*May 5,*	*Lower Luwala Wetland*	*Local Fishermen and*	*M. Dooley, J. Van Der Westhuizen, S.*	*Marcusenius monteiri*

	10.97584		2024	2024		Fyke Net	Mbewe	
7	- 10.97584	30.98576	May 4, 2024	May 5, 2024	Lower Luwala Wetland	Local Fishermen and Fyke Net	M. Dooley, J. Van Der Westhuizen, S. Mbewe	*Chrysichthys mabusi*
7	- 10.97584	30.98576	May 4, 2024	May 5, 2024	Lower Luwala Wetland	Local Fishermen and Fyke Net	M. Dooley, J. Van Der Westhuizen, S. Mbewe	*Mormyrops anguilloides*
7	- 10.97584	30.98576	May 4, 2024	May 5, 2024	Lower Luwala Wetland	Local Fishermen and Fyke Net	M. Dooley, J. Van Der Westhuizen, S. Mbewe	*Sargochromis mellandi*
7	- 10.97584	30.98576	May 4, 2024	May 5, 2024	Lower Luwala Wetland	Local Fishermen and Fyke Net	M. Dooley, J. Van Der Westhuizen, S. Mbewe	*Tylochromis bangwelensis*
7	- 10.97584	30.98576	May 4, 2024	May 5, 2024	Lower Luwala Wetland	Local Fishermen and Fyke Net	M. Dooley, J. Van Der Westhuizen, S. Mbewe	*Hydrocynus vittatus*
7	- 10.97584	30.98576	May 4, 2024	May 5, 2024	Lower Luwala Wetland	Local Fishermen and Fyke Net	M. Dooley, J. Van Der Westhuizen, S. Mbewe	*Alestes macropthalmus*
8	- 11.24336	30.73475	May 6, 2024	May 6, 2024	Between Luwala and Bangweulu Wetlands	Local Fisherman	M. Dooley	*Distichodus maculatus*

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