

Flows of Water and Wildlife in KAZA

by

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EXECUTIVE SUMMARY

Understanding how water resource distribution might shift and how those shifts could affect wildlife can help frame how we approach wildlife conservation into the future. Wildlife conservation is important not only for ecosystem stability and health, but also for economic growth, as wildlife tourism is an important economic driver in many regions of the world. In conjunction with the World Wildlife Fund, we developed a project looking at these shifts in a region of Southern Africa.

The Kavango-Zambezi (KAZA) trans-frontier conservation area, an area spanning the countries of Angola, Namibia, Botswana, Zimbabwe and Zambia, contains the Okavango Delta and its associated basin. The Okavango Delta is the largest inland delta in the world and is an important region for southern African wildlife and biodiversity, and also a major source of regional tourism.

The headwaters of the basin and the majority of its water resources are located upstream in the Angolan highlands, which have historically remained undeveloped. Angola has recently expressed an interest in developing the rivers of the upstream basin to support the economic and health needs of Angola's growing population. Angola has seen rapid economic growth through the oil sector in the past few decades, following an end of war and unrest in the region. Development of the upstream basin of the Okavango offers diversification of the economy of Angola as a whole and economic opportunity for this impoverished region.

The downstream countries of Namibia and Botswana have more stable economies, greater per capita wealth, and benefit highly from wildlife tourism surrounding the Okavango Delta. Cooperation between these countries is vital for water resource planning that protects the economic, human health, and wildlife conservation interests of the three countries.

Our research asked how new infrastructure development might change downstream flows and flooding, and by extension, wildlife connectivity in this region. Our work was divided into three parts: hydrologic analysis, floodplain analysis, and wildlife movement analysis.

Our hydrological analysis modeled stream flow change on the Cuvango River, a major tributary of the Okavango located in Angola and a river with several planned dams under discussion. We modeled how changes in streamflow could impact riverine flooding on the same river further downstream, where the river flows along a major conservation area and feeds the Okavango delta. For wildlife movement analysis, we modeled potential movement based on various resistance factors, incorporating seasonal waterholes and modeled water changes resulting from infrastructure development.

We developed a water balance model to show how changes in upstream storage and water diversions would alter flows and flood extent at a key downstream location where the Okavango flattens out and spills into its characteristic and seasonal floodplain. We modeled existing and proposed development and infrastructure options to determine how development plans could alter the seasonal distribution of surface water in the Okavango River Basin. We developed our spreadsheet model loosely based on Soil and Water Assessment Tool (SWAT) hydrological model outputs generated by The Nature Conservancy (TNC).

We conducted floodplain analysis of a stretch of the Cuvango River downstream of the hydrological modeling study area. The stretch of stream is adjacent to the Bwabwata National Park, which is a major wildlife area in Namibia and which was utilized in this project as the principle study area for habitat connectivity modeling. The goal of the analysis was to develop some understanding of how new infrastructure could impact floodplain extent, and by extension, distribution of and access to surface water along the Cuvango-Okavango Rivers in and adjacent to the Bwabwata National Park.

For the wildlife movement, we focused on elephant movement in Bwabwata National Park in Namibia. To understand potentially important wildlife movement pathways in the study area, we created current maps for elephant movement under the wet season scenario based on resistance surfaces. The resistance surface modelling approach allowed us to analyze the potential impact of upstream water infrastructure on wildlife movement. Current maps were generated using Circuitscape desktop software in advanced mode to represent potential movement of elephants across the landscape. We found that water is an important factor influencing elephant movement, but riverine flooding changes had little impact.

Our analysis is a first step in helping inform the development and conservation planning in the region. This will provide information to the region's economic planners and natural resource managers to help them make development management decisions to adapt to changing hydrology and development demands and maintain wildlife habitat. Based on our results, we expect that infrastructure development on the Cuvango will have only a minor impact on wildlife. However, we recommend further study, especially incorporating climate change impact modeling, before any recommendations are given to decision makers in the region.

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1. Introduction

As increasing population and political and economic interests demand new water infrastructure development throughout the world, water resources that wildlife depend on will likely shift, influencing their behavior, and possibly their survival. Wildlife conservation is important not only for ecosystem stability and health, but also for economic growth, as wildlife tourism is an important economic driver in many regions of the world. Understanding how water resource distribution might shift and how those shifts could affect wildlife can help frame how we approach wildlife conservation into the future.

1.1 The Kavango-Zambezi (KAZA) Trans-Frontier Conservation Area

The Kavango-Zambezi (KAZA) trans-frontier conservation area, an area spanning the countries of Angola, Namibia, Botswana, Zimbabwe and Zambia, contains the Okavango Delta and its associated basin (Figure 1.1). The basin spans a hydrologically active area of 323,192 km² (OKACOM, 2019). The Okavango River, located within its eponymous basin, is the fourth largest river system in Southern Africa (Hughes et al., 2011). The river originates in the subtropical highlands of Angola, flows over 1,609 kilometers before reaching Namibia, and then terminates in Botswana where it drains into the Okavango Delta (Hughes et al., 2011). The delta itself is the largest inland delta in the world and is an important region for southern African wildlife, a major source of tourism in the region (Rothert, 1999). The river system is considered 'pristine' because of the relative lack of infrastructure that has been developed in the area. Angola, which contains the headwaters of the basin, which eventually flow into the delta, came out of a period of civil war in the early 2000's and is presently interested in economic growth opportunities, which include infrastructure development where there has historically been very little (World Bank, 2019). Economic growth in Angola since its time of civil war has been heavily based on oil, which has contributed to the concentration of wealth to elites, leaving widespread inequality in the country (Ovadia, 2013). Development of water resources in the Okavango region offers an opportunity for diversified economic growth that brings wealth to an otherwise impoverished region.

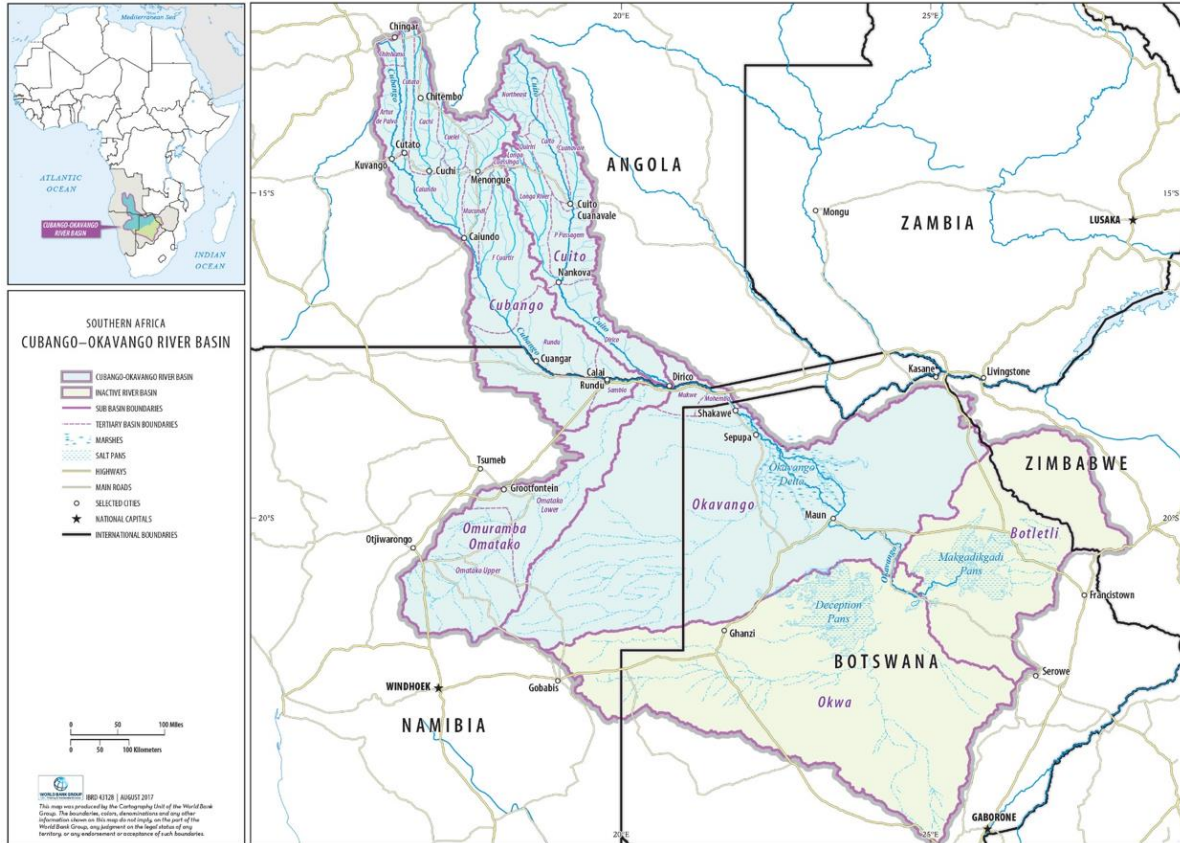


Figure 1.1. Map of the Cubango-Okavango River Basin (in blue), including the Okavango Delta, located in Botswana. The river basin is located in Angola, Namibia, and Botswana.

In order to prepare conservation and wildlife management strategies for these potential changes, it is vital to A:

1. develop an understanding of the nature and dynamics of the existing hydrological system and
2. identify the potential habitat availability in the region

and B:

1. identify how volumes and discharges of hydrologic flows may be expected to shift, which impacts water availability to people and wildlife, and
2. understand how wildlife movement is related to surface water distribution during the wet season, and how shifts in the spatial distribution of surface water could affect habitat availability and movement.

1.2 The Okavango Delta

Rich in both flora and fauna, the Okavango Delta is inundated with precipitation during the annual rainy season and attracts a healthy ecotourism industry (Andersson et al. 2006). However, the majority of the water resources contained in the rivers that eventually discharge into the delta are located in Angola (Andersson et al. 2006). The northern Okavango River Basin has historically avoided large-scale water resource development due to past civil wars in Angola (King et al. 2014). Today, the lack of historical development in the region provides an opportunity to meet the needs of people and ecological systems sustainably, by selecting infrastructure and management strategies that are sensitive to those drinking water, irrigation and power needs, in light of population and economic growth.

1.3 Objective

The goal of this master's project is to determine how shifts in surface water distribution related to infrastructure development could impact downstream water availability and wildlife habitat in the region. Our work will provide information to the region's economic planners and natural resource managers to help them make development management decisions to adapt to changing hydrology and development demands and maintain wildlife habitat.

To meet the goal of this master's project, we will assess the following questions:

1. How might hydrologic flows of the Cuvango River (which connects to the Okavango) change with new water infrastructure development projects?
2. How might changes in this hydrology impact floodplain extent and regional riverine flooding?
3. What does existing wildlife habitat connectivity look like, and how does surface water distribution during the wet season impact it?

The ultimate question of our project is the following:

How might **seasonal water distribution** influence **wildlife connectivity** and how might new **infrastructure** development change **surface water** distribution, and by extension, **wildlife connectivity** in this region?

The study is divided into three sections which work together and independently to help us answer this question (Figure 1.2).



Figure 1.2. Gaby Garcia analyzed changes in hydrology on the Cuvango River in Angola. Jannette Morris translated Gaby’s assessed changes into changes in seasonal flooding along the same stream in an area along an important wildlife zone in Namibia, downstream of Gaby’s hydrologic model area. Ga-on Lee then incorporated flooding scenarios into a habitat-connectivity analysis to model how changes in water distribution could impact wildlife movement.

2. Background

2.1 Water and Wildlife

Water availability, which is highly seasonal in the Okavango region, is a factor for the large mammal community (Western 1975). During the rainy seasons, as rainfall fills the small-scale holes, ephemeral water bodies emerge far from the river. This existence of water bodies can allow wildlife to forage in further reaches of the region than during the dry seasons. The existence of ephemeral water bodies is the most important factor for the distribution of wildlife in KAZA (Fryxell et al. 1988, Redfern et al. 2005).

Although there is a strong understanding of perennial water bodies in the KAZA region, little research has been done on seasonal changes to surface water and the existence and disappearance of ephemeral water bodies. Further, there is still little understanding of how these seasonal changes influence the availability of wildlife habitat and movement between water sources throughout the year. There has been research on the access to artificial surface water and the movement of elephants (Tshipa et al. 2017), or the elephant movement near the artificial water bodies (Shannon et al., 2009), but there has not been research incorporating ephemeral water bodies during the wet season into the wildlife movement. This understanding is crucial to determining how alterations to the existing hydrologic regime through climatic change, in the

form of precipitation and temperature changes, and infrastructure development, like new multi-purpose reservoirs and diversions for agricultural irrigation, could impact wildlife.

2.2 Economic Setting

The Okavango Basin spans Angola, Namibia, and Botswana. Of the three countries, Angola, emerging from decades of civil war and economic instability, has the largest economy and is growing the most rapidly. Although Namibia and Botswana have smaller economies, they have seen greater long-term economic stability and steady growth, and they have higher per capita wealth (OKACOM 2019).

A larger portion of the water resources provided by the Okavango Basin are found in Angola (Conley 1995), though for Namibia and Botswana, more so than Angola, the Okavango Basin supports a growing regional wildlife tourism industry (Rothert 1999). In Botswana, wildlife tourism is the second largest contributor to the country's GDP, behind diamond mining, and employs 40% of the population (Turpie et al. 2006).

Angola's economy is largely dependent on oil, which is a vulnerable resource, giving the country a strong incentive to diversify its economy to include utilizing its water resources (World Bank 2019). Although Angola has seen rapid economic growth, wealth accumulated from the oil sector remains concentrated among a small group of elites, further exacerbating existing inequality across the country (Ovadia 2013). Development of the upstream basin of the Okavango offers economic opportunity for this impoverished region.

Exports are the leading contributors to the economies of all three countries, making natural resources important for the region as a whole (OKACOM 2019).

2.3 Governing the Okavango

The Permanent Okavango River Basin Water Commission (OKACOM) was created by its member states in 1994 with the goal of balancing the conflicting needs of humans with the Okavango ecosystem (Folwell and Farquharson, 2006). In 2003, a protocol called the Southern African Development Community (SADC) Protocol on Shared Watercourses, signed and ratified by OKACOM member states, went into effect (King and Chonguica, 2016), reinforcing the legal framework for collaborative governance of the basin. A recent analysis of the existing legal framework found the framework around collaborative governance of the basin to be an important key to reducing the possibility of conflict between basin countries (Mogomotsi et al., 2020). It is beneficial that there is an existing advisory body with the goal of allowing the three basin countries to work together more effectively, considering both economic and ecosystem needs (Folwell and Farquharson, 2006).

In the last decade, OKACOM completed a Transboundary Diagnostic Analysis (TDA) to develop an understanding of what was already known about the basin and inform how to balance ecological and economic needs (OKACOM, 2011a). This analysis was then used to create a Strategic Action Programme (SAP) for governing the Okavango Basin. The goal of the SAP is to inform water resource decisions in member states' short-term and long-term development plans (King and Chonguica, 2016). Maintaining the river basin requires cooperation on the allocation of both the benefits and associated liabilities through joint management of the basin's water resources. The three basin states are facing imminent development upstream which could place increasing strain on the downstream Okavango River environment (King et al., 2014).

Several challenges will govern future water management and infrastructure development in the Okavango Basin. The river is subject to drastic changes in flow due to seasonal variation, evaporation, and absorption into the riverbed. Understanding water flows and how the transport and pulses of water and sediment impact ecosystems is important to water management when considering ecology (Brown et al., 2020).

Anthropogenic climate change associated with rising greenhouse gas emissions may impose change on the flow of rivers and tributaries in the basin, which will affect wildlife (Andersson et al., 2006). However, the change in climate is complex and uncertain, especially regarding precipitation. Thus, temperature and precipitation can be used as a proxy for climate change in our analysis. Therefore, system sensitivities and tipping points can be identified by assuming and testing the response to a varying degree of hydrological change.

2.4 Previous Hydrological Models

A number of hydrological models have been discussed in academic literature that model the Okavango River Basin's hydrological response to climatological variables and assess the impact of future development scenarios.

Below are descriptions of previous models used for similar studies in the region:

The Pitman Monthly Time-Step Model

The Pitman Model, first developed and described in the 70's (Pitman 1973), is a monthly time-step rainfall-runoff model widely used in Southern Africa. In Hughes et al. 2006, this model was modified and used to test the model predictions by modeling recent conditions in the Okavango River Basin and comparing them to existing data to assess the success of the model and potential for modeling future scenarios. Following their assessment, this version of the model was used to model various climate and development scenarios, as described in Andersson et al 2006.

How it worked: Storage areas were linked by functions representing hydrological processes and incorporated with a reservoir balance model into the SPATSIM water resources database and modelling package from the Institute of Water Resources, Rhodes University (Hughes et al., 2002).

Distributed GIS-based Hydrological Model

Developed in Alemaw and Chaoka, 2003, this model was a distributed physically based (conceptual) hydrologic model developed for Southern Africa. The purpose of the model was to assess the impact of human intervention or climate change on basin hydrology and water resources. Estimates expected monthly soil moisture, actual evapotranspiration, and runoff.

How it worked: It had a grid cell size of 30 by 30 min resolution and used consideration of surface and subsurface processes. In the subsurface zone, water balance components like actual soil moisture, evapotranspiration, and runoff were computed using a modified version of the Thornwaite and Mather soil moisture accounting technique (Thornwaite and Mather, 1957). In the surface zone, abstractions of overland runoff and interception were accounted for by using the SCS curve number method (SCZ 1985). The model created 3 high resolution datasets of actual soil moisture, evapotranspiration, and runoff.

A Grid-Based Approach to Water Scarcity Estimates for Eastern and Southern Africa

This model used by J. R. Meigh, A. A. McKenzie and K. J. Sene in 1999 applied a combined grid-based and catchment approach to a large regional area encompassing eastern and southern Africa. The model was used to estimate surface water flows, groundwater “yields”, and water demands in grids, predict how well available water supply could meet predicted demand, and assess water scarcity under current conditions and future scenarios.

How it worked: Flows for individual grid squares were estimated by a rainfall-runoff model. Prediction of water scarcity in eastern and southern Africa was based on current conditions and a simulation of population change, increased living standards, and Global Climate Model (GCM) climatic change impacts. For some locations, water demands could be determined with available data, whereas in areas where data was not available, submodels were used to determine water demands.

Daily disaggregation of simulated monthly flows using different rainfall datasets

This model, developed by Slaughter et al. 2015, and used by Hughes and Slaughter, 2015, was a daily rainfall-based disaggregation method (disaggregated from and compared with a monthly rainfall runoff model, like the Pitman Model). It’s purpose was to assess the impact of human intervention or climate change on basin hydrology and water resources. It was developed for Southern Africa to compare two methods and test daily disaggregation. Being able to simulate

daily flows is helpful for understanding water quality and possibly for other water management analyses, like floodplain inundation.

How it worked: It estimated expected monthly soil moisture, actual evapotranspiration, and runoff. It used daily rainfall data to extrapolate/separate simulated monthly flows into daily flows. A combined modeling approach using the pitman monthly timestep model and disaggregated flows with daily rainfall data.

Learning about previous models utilized in the area helped inform us on what type of studies have already been conducted and what types of considerations others found important in conducting their work. Many of the studies above used much more complex models than were within the capacity of this master's project, but the ideas and methods behind them were still useful.

The study conducted for this master's project used monthly time scales, similar to several of the models above. In using a monthly timescale, some aspects of discharge are lost, such as peak flows and rapid high discharge events. However, since this timescale is commonly used in the region, this study can be comparable to others.

A common challenge for modeling in this region is data limitations. Many models focused on monthly flow and had limited daily rainfall data to work with. The scale of the models also varied.

Factors considered in the above studies that were not considered in this study could lend ideas for future work, especially in thinking about incorporating climate change modeling.

3. Methods

3.1. Hydrological analysis

3.1.1. SWAT Model Description

For our hydrology analysis, we performed hydro-economic modeling of existing and proposed development and infrastructure options to determine how development plans could alter the seasonal distribution of surface water in the Okavango River Basin. We developed our spreadsheet model loosely based on Soil and Water Assessment Tool (SWAT) hydrological model outputs generated by The Nature Conservancy (TNC). SWAT is a physical watershed scale model that was initially developed to predict impacts of land management practices on water yields with varying land use and management conditions over time (Begou et al., 2016). It is a customizable time-step simulation model intended for large and complex watersheds such as

the Okavango. It was originally developed by researchers from the U.S. Department of Agriculture (USDA) in the mid-1990s, and the model has undergone frequent review and revision since it was first developed. As a result, the model is extremely well-documented and has been the subject of over 1000 peer-reviewed journal articles that describe applications and model enhancements. The model relies on governing equations to control water movement through surface, subsurface and lateral flow in each subbasin. For a more detailed description of SWAT, see the Soil and Water Assessment Tool input/output version 2012 (Neitsch et al., 2005).

The hydrologic cycle simulated by the SWAT model is based on the following water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

where, SW_t is the final soil water content (mm H₂O), SW_0 is the initial soil water content on day i (mm H₂O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H₂O), Q_{surf} is the amount of surface runoff on day i (mm H₂O), E_a is the amount of evapotranspiration on day i (mm H₂O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H₂O) and Q_{gw} is the amount of return flow on day i (mm H₂O) (Neitsch et al., 2005).

To calibrate the SWAT Model, TNC spatial processes hydrologist Tracy Baker partitioned the Okavango Basin into sub-basins, which were further divided into hydrologic response units (HRUs), each of which have unique soil, slope, and land management combinations. HRUs are the smallest spatial unit inputs for the model that are necessary for simulating water balance and water quality processes within SWAT, and enable the model to reflect differences in evapotranspiration for various crops and soils (Begou et al., 2016). Baker then calibrated the model based on specific Okavango flow gage data accounting for temperature and precipitation to simulate runoff based on historical accuracy. Runoff was calculated separately for each HRU and routed to obtain the total runoff for the watershed in order to increase accuracy.

A limitation of using the SWAT model at a monthly time-step is that only daily or smaller time steps will allow us to capture flood peaks. This could potentially affect our flood extent analysis because the flood-plain extent in the Okavango River Basin could depend more on short term flood pulses rather than monthly flow. Because TNC calibrated the SWAT model on a monthly time step, we accepted this limitation.

Another limitation is that the use of the raw inputs from SWAT at the HRU level as inputs into a hydrological flow balance is subject to error, and most critically means that losses

or recharge to and from groundwater, and river evaporation are ignored. This can be overcome with calibration to discharge data, however, it is important to note that we did not calibrate our model to discharge data. Incorporation of this type of calibration would be advisable in the future, but is dependent of discharge data availability.

3.1.2 Model Input Data and Databases

SWAT Model Inputs

TNC included the following data inputs to ensure the successful setup of our SWAT model:

Elevation Data: Elevation data is typically obtained from a digital elevation model (DEM), which provides topographic attributes of the watershed such as area, drainage slopes, flow direction, and flow accumulation. This allows for accurate watershed delineation.

Land Cover Data: Different land cover types will impact the flow of water through our watershed and will also produce differing runoff amounts.

Soil Data: Different soil types will influence water infiltration and thus runoff potential in the watershed.

Climate Data: Daily temperatures and the amounts and timing of precipitation are crucial for watershed processes such as crop growth and runoff.

Discharge Data: Used for model calibration and validation purposes.

Table 3.1 details the data sources and spatial and temporal resolutions, if available, for all SWAT data inputs.

Data	Spatial Resolution	Temporal Resolution	Source
DEM (Shuttle Radar Topography Mission)	90 meters	-	http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1
Land Cover (2006; 12 class)	30 meters	-	The Nature Conservancy
Soils (Food and Agriculture Organization of the United Nations)	90 meters	-	http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faunesco-soil-map-of-the-world/en/
Weather (Precipitation and Temperature; Climate Forecast System Reanalysis)	0.5 degrees	Daily	https://globalweather.tamu.edu/
Discharge	-	Monthly	MSIOA Pitman Model baseline discharge (Citation for this work is Hughes, Denis A., et al. "Regional calibration of the Pitman model for the Okavango River." Journal of Hydrology 331.1-2 (2006): 30-42.)

Table 3.1. Input Data Sources for SWAT Model.

Calibration and Validation of SWAT Model

SWAT model outputs will only be as accurate as their input data and governing equations. Therefore, model calibration is necessary to verify results. SWAT model calibration was performed by the Nature Conservancy (TNC) to better parameterize the model to a given set of observed data, therefore reducing the prediction uncertainty. The SWAT model outputs were calibrated by TNC for every month in the years from 1995-2003 by comparing them to monthly discharge data generated by the World Bank's Multi-Sector Investment Opportunities Analysis (MSIOA) until the model's simulated runoff results were acceptable as per the model performance measures.

Model validation was performed by running the SWAT model using parameters that were determined during the calibration process, and comparing the predictions to observed data not used in the calibration. SWAT model validation was also performed by TNC by comparing model results to an independent data set of outflow. 2004-2012 were considered validation years.

Discussion of SWAT Model Results

SWAT model outputs included areas of all subbasins (km²), net monthly runoff amounts leaving each subbasin and contributing to streamflow (mm/month), and monthly evapotranspiration amounts from each subbasin during simulation (mm/month). Special attention was paid to the distribution of flows across wet years and dry years.

3.1.3 Geospatial Data

Sub-Basins

TNC provided us with a polygon shapefile featuring sub-basin delineations of the Okavango watershed in ArcGIS Pro. There were a total of 182 sub-basins in the shapefile located in Angola, Namibia, and Botswana.

River/Tributaries

TNC also provided us with a polyline shapefile of the Cubango River and its associated tributaries. There were a total of 182 polylines located in both Angola and Namibia.

Nodes

For the purposes of this analysis, nodes were assigned to each HRU in the watershed. Each location where surface water was demanded or made available for supply was marked by a node. This included agricultural abstractions, urban abstractions, and hydroelectric dams. TNC provided us with an Angolan development planning shapefile featuring a total of 42 existing and proposed nodes. This development planning shapefile was provided to TNC by Dr. John

Mendelson, a Namibian ecologist and founder of Research and Information Services of Namibia (RAISON). Dr. Mendelson was hired by TNC to perform field reconnaissance to map Angolan development locations. All nodes were coded based on TNC naming mechanisms; the name specifies the development category, the first number specifies the river or tributary, and the second number represents the node's order in the river. For instance, Dam1_1 refers to the first dam on the Cubango River (Cuvango), while Irr3_2 refers to the second irrigation abstraction on the Cuchi tributary. A schematic of all nodes featuring water abstraction or storage mapped to their location on the Cubango River or its tributaries is shown below in Figure 3.1.

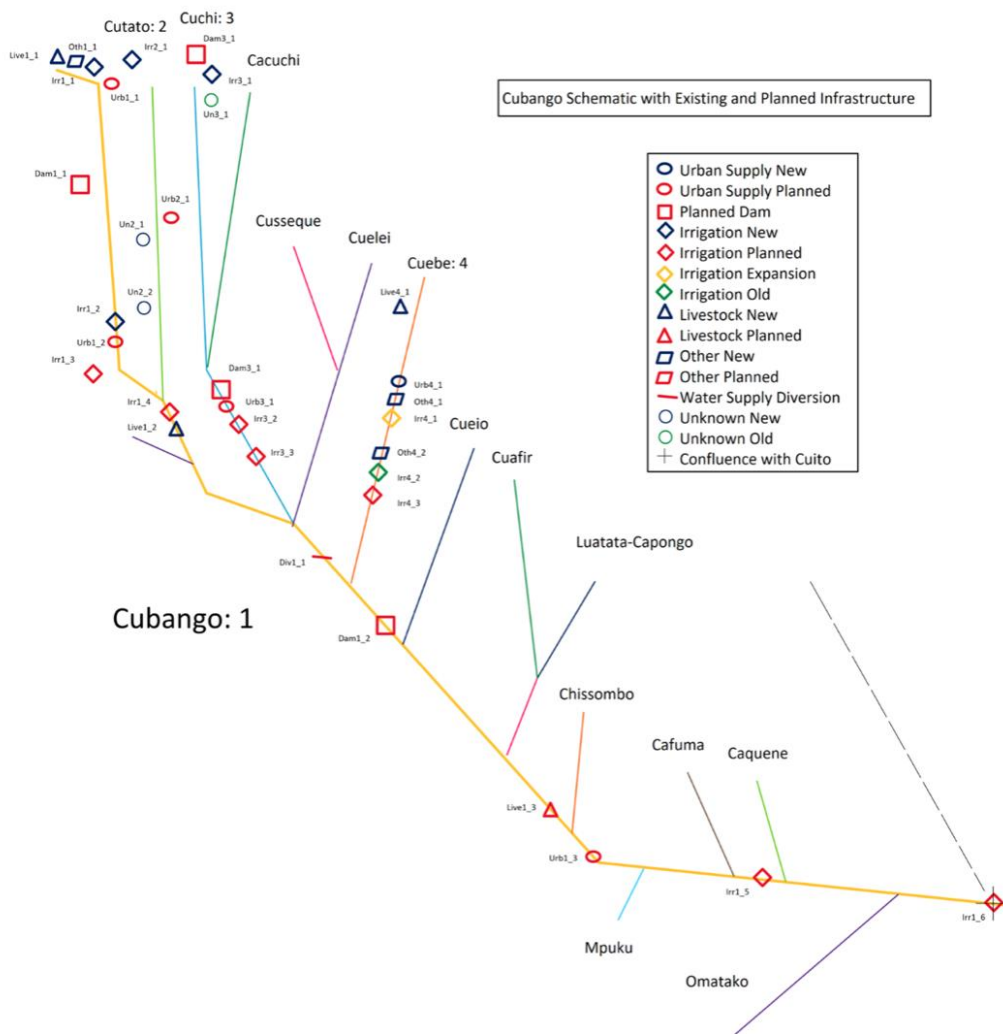


Figure 3.1. Schematic of Existing and Planned Development Infrastructure Nodes along the Cubango River and its tributaries.

The existence of all 42 nodes from the provided development planning shapefile were verified by cross-examining all Angolan government documents and World Bank documents provided to us by TNC, many of which were written in Portuguese. Google Translate was used

to translate information of interest into English. Special attention was paid to maps or tables depicting existing or planned irrigation or agriculture sites with provided water amounts. A major limitation of this method was that several of the nodes present in the provided development planning shapefile were not located in any of the provided documents; these nodes were assumed to not have projects, for the purposes of this analysis, due to lack of data on them. Nodes that were not located were still included in their respective HRU tabs in the spreadsheet model but assigned a theoretical and actual demand value of '0'.

Upon analysis, some of the existing and planned nodes were depicted on a 2012 map of irrigation sites on page 421 of the *Plano Geral de Utilização Integrada dos Recursos Hídricos (PGUIRH) da Bacia Hidrográfica do Cubango: Fase 0*, which is the full Angolan Cubango Basin Plan. The Angolan irrigation sites mapped were: Calai, Capico, Cuchi, Cuito Cuanavale, Cuvango, Dirico, Ebritex, Kahenge, Longa, Menongue, Missombo, M Pupa, and Tchicala Tcholohanga. This map is included in Appendix A.

A 2017 map of potential urban, agricultural, and dam developments in the Okavango Basin was located on page 115 of the Cubango-Okavango River Basin MSIOA Report: Volume 3. The Angolan urban abstractions mapped were Calai, Chingar, Chitembo, Cuchi, Cuito Cuanavale, Cuangar, Dirico, Menongue, Nankova, and Rundu. This map is included in Appendix A.

The most specific irrigated agriculture information was located for 11 of the 42 nodes from the development planning shapefile in Table 43 on pages 108 and 109 of the Cubango-Okavango River Basin MSIOA Report: Volume 3. This table was crucial for node selection as it included total annual water allocation amounts for each irrigation project in cubic mm/year, which were converted into mcm/month and then inputted as theoretical demands into the spreadsheet model. The simulated values fall under the MSIOA developed Irrigated Agriculture Scenario IRRIO2, which was created to “test the common notion that the development of irrigated agriculture within the Cubango-Okavango River Basin is the single biggest threat to the sustainability of the system as a whole, and particularly the Delta itself” (MSIOA Vol. 3. pp. 108, 2017). Therefore, this scenario included all of the irrigated agricultural areas allowed for in the Present Day Scenario in Table 3.3 in this report, plus an additional 203,890 hectares in Angola and an additional 15,611 hectares in Namibia.

Table 43 features columns for confirmed irrigation projects such as crop and water demand allocation, total annual water allocation, and total irrigation area in hectares. The Angolan irrigation projects listed were Chinguanja, Cuvango, Dirico, Ebritex, Longa, Lupire, Nankova, Menongue, Missombo, Mumba, Nankova, and Vissati. Again, nodes with water allocation amounts that could not be verified were assigned theoretical and actual demand values of '0'. Table 43 is included in Appendix A.

All existing or planned nodes found in our sources with total annual water allocation amounts and irrigation areas are listed in Table 3.2 below.

Node in System	Code	Type	Sub-basin	Source
Cuvango	Irr1_3	Planned Irrigation	30	MSIOA Volume 3 Table 43
Mumba	Irr1_4	Planned Irrigation	43	MSIOA Volume 3 Table 43
Vissati	Irr3_2	Planned Irrigation	38	MSIOA Volume 3 Table 43
Chinguanja	Irr3_3	Planned Irrigation	48	MSIOA Volume 3 Table 43
Longa	-	New Irrigation	51	MSIOA Volume 3 Table 43
Missombo	Irr4_1	Irrigation Expansion	45	MSIOA Volume 3 Table 43
Menongue	Urb4_1	New Urban Supply	36	MSIOA Volume 3 Table 43
Ebritex	Irr4_3	Planned Irrigation	59	MSIOA Volume 3 Table 43
Lupire	-	Planned Irrigation	39	MSIOA Volume 3 Table 43
Nankova	-	Planned Irrigation	81	MSIOA Volume 3 Table 43
Dirico	Irr1_6	Planned Irrigation	133	MSIOA Volume 3 Table 43

Table 3.2. Verified nodes selected as input for hydrological spreadsheet model.

Geospatial Analysis

Node locations were superimposed over sub-basins in ArcGIS Pro to delineate which nodes were geographically located in each sub-basin.

3.1.4. Spreadsheet Model Description

In order to accurately quantify our SWAT model output-downstream flows from each subbasin, a hydrology spreadsheet model was created in Excel to quantify the long-term water balance of the Okavango River Basin. This model is a hydrological routing application with a monthly time step. Flow routing equations were written to relate observed outflows at adjacent nodes in the basin. All equations are written for a time step of length t .

Reservoir Equation

$$Q_{i,t}^{\text{out}} = Q_{i-1,t}^{\text{up}} + Q_{i,t}^{\text{in}} - D_{i,t} - E_{i,t} - \Delta S_{i,t}$$

Where $Q_{i,t}^{\text{out}}$ = Total Downstream Flow from node i at time t ;

$Q_{i-1,t}^{\text{up}}$ = Total Downstream Flow from upstream node i at time t ;

$Q_{i,t}^{\text{in}}$ = Inflow from node i at time t ;

$D_{i,t}$ = Water Demand from node i at time t

$E_{i,t}$ = Total Evapotranspiration from node i at time t ;

$\Delta S_{i,t}$ = Change in Storage at node i at time t

This reservoir equation is visually depicted in the figure below.

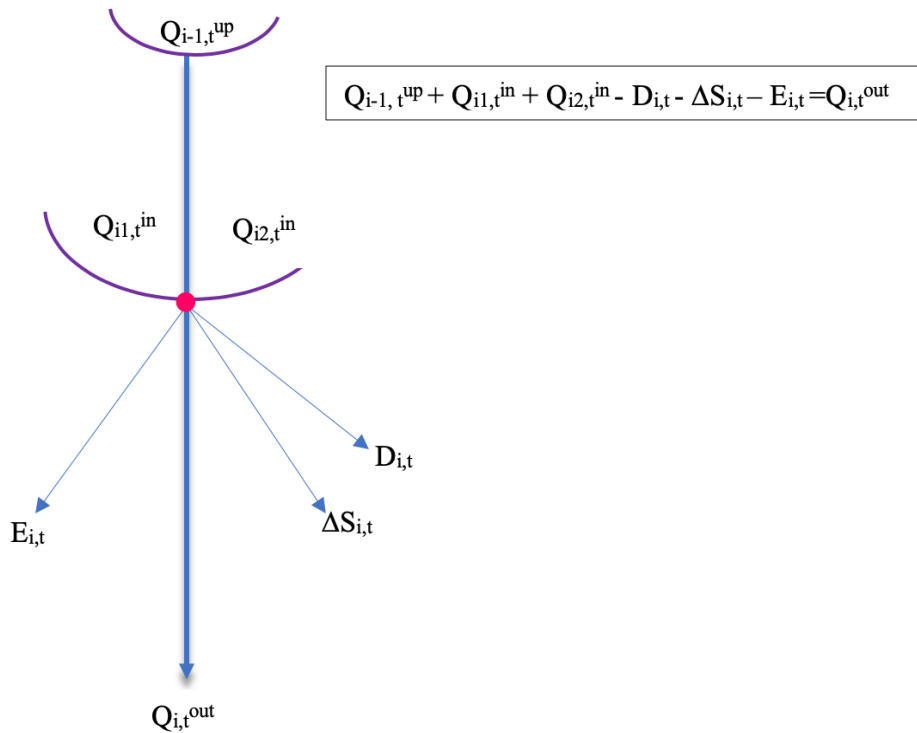


Figure 3.2. Schematic depicting hydrologic inputs for the Total Downstream Flow for node i at time t .

Change in Storage

$$\Delta S_{i,t} = S_{i,t} - S_{i,t-1}$$

Environmental Flow Equation

$$Q_{i,t}^{\text{out}} \geq 0.1 * [Q_{i-1,t}^{\text{up}} + Q_{i,t}^{\text{in}}]$$

The reservoir equation above forms the foundation for all node models used in this analysis. For flow at modeled river nodes without hydroelectric dams, there is no storage ($S_{i,t}$ and $S_{i,t-1}$ are set equal to zero) and the evaporation term $E_{s,t}$ is set equal to zero, such that the constraint in equation 1 simplifies to the following river node equation:

River Node Equation

$$Q_{i,t}^{\text{out}} = Q_{i-1,t}^{\text{up}} + Q_{i,t}^{\text{in}} - D_{i,t}$$

3.1.5. MSIOA Basin Development Scenarios

Overview

The MSIOA reports are based on scenario analyses, or internally consistent combinations of infrastructure investment projects that allow for “analysis of the cumulative impacts of different combinations of projects...and their respective values in terms of investments, benefits, and environmental impacts”(MSIOA Vol. 1. pp. 19, 2017). The scenarios are a compilation of irrigation, water supply, and hydropower projects, most of which were derived from the Angolan PGUIRH. The scenarios were developed to allow OKACOM Member States to provide a foundation for comparison and decision making, and guide their agreement process on “combinations of investments, management measures, policy, and/or technical interventions that enhance the productivity of the system within limits of acceptable hydrological change” (MSIOA Vol. 1. pp. 19, 2017).

The following table displays all ten Basin Development Scenarios along with their respective combinations of potential development and abstractions are displayed below in Table 3.3.

Scenario	Abstraction (Mm ³ /yr)				Irrigation (ha)				Irrigation (Mm ³ /yr)				Urban Water Supply (Mm ³ /yr)				HEP (MW)	Dams
	Tot.	A	B	N	Tot.	A	B	N	Tot.	A	B	N	Tot.	A	B	N	Tot.	A
Present Day (PV)	74	6	4	64	2,719	170	0	2,549	64	3	0	61	9	3	4	3	0	
Improved Livelihoods (IL)	94	22	5	68	2,719	170	0	2,549	64	3	0	61	30	19	5	6	0	
BDS1	139	22	5	112	2,719	170	0	2,549	64	3	0	61	75	19	5	51	0	
BDS2	698	506	6	186	66,720	55,060	0	11,660	604	491	0	114	94	15	6	73	40	Malobas
BDS3	698	506	6	186	66,720	55,060	0	11,660	604	491	0	114	94	15	6	73	105	Mucundi
BDS4	698	506	6	186	66,720	55,060	0	11,660	604	491	0	114	94	15	6	73	12	Cuito
BDS5	1,559	1,354	8	197	132,185	120,525	0	11,660	1,439	1,330	0	109	120	23	8	88	51	Malobas, Cuvango
BDS6	1,559	1,354	8	197	132,185	120,525	0	11,660	1,439	1,330	0	109	120	23	8	88	168	Malobas, Cuvango, Mucundi, Cuito
BDS7	2,542	2,264	8	270	222,261	204,060	0	18,201	2,422	2,240	0	182	120	23	8	88	51	Malobas, Cuvango
BDS8	3,557	3,279	8	270	302,701	284,500	0	18,201	3,437	3,256	0	182	120	23	8	88	51	Malobas, Cuvango
BDS9	1,301	1,076	28	197	100,660	87,500	2,000	11,160	1,102	974	20	109	199	102	8	88	168	Malobas, Cuvango, Mucundi, Cuito
BDS10 (CC)	1,301	1,076	28	197	100,660	87,500	2,000	11,160	1,102	974	20	109	199	102	8	88	168	Malobas, Cuvango, Mucundi, Cuito

Note*: A – Angola, B - Botswana, N – Namibia

Note**: The planning end-horizon was 2015-2040 for the economic modelling of NPV values and for the majority of the hydrological modelling apart from the hydrological modelling that incorporated higher levels of development and estimated impact of climate change (extended to year 2050).

Table 3.3. Overview of MSIOA Basin Development Scenarios

Selection of MSIOA Basin Development Scenarios

In order to accurately capture the range in variation of downstream flows in our watershed, we elected to model the MSIOA Basin Development Scenarios that would simulate

low development, medium development, and high development in the region. The following are the selected scenarios for the spreadsheet model:

- Present Day=Baseline Reference Point with only existing abstractions and no dams.
- BDS2=Malobas Dam and existing abstractions only
- BDS3=Mucundi Dam and existing abstractions only
- BDS4=Cuito Cuanavale Dam and existing abstractions only
- BDS6=All 4 dams and existing abstractions only
- BDS9=All 4 dams and all existing and proposed abstractions

The MSIOA present day (low development), BDS4 (medium development), and BDS9 (high development) development scenarios were utilized for the floodplain extent and wildlife connectivity analyses discussed later in this report.

3.2 Connecting Hydrologic Modeling to Surface Water Distribution and Wildlife Movement Potential

One of the challenging aspects of this project was translating the results of the hydrological modeling to an understanding of surface water distribution that can be used for wildlife habitat connectivity modeling. To do this, we conducted floodplain analysis of a stretch of the Cuvango River downstream of the hydrological modeling study area. The stretch of stream is adjacent to the Bwabwata National Park, which is a major wildlife area in Namibia and which was utilized in this project as the principle study area for habitat connectivity modeling. The goal of the analysis was to develop some understanding of how new infrastructure could impact floodplain extent, and by extension, distribution of and access to surface water along the Cuvango River in and adjacent to the Bwabwata National Park.

3.2.1 Creating a Basic Floodplain Model

To create a basic floodplain model, a 12-m resolution digital elevation model (TanDEM-x), which was provided to us free of charge, was used to delineate watershed downstream of hydrological model output and develop a stream network for analysis based on flow accumulation. To predict the shape of flood extent at different flood elevations, a simple model based on the topography given by the digital elevation model was developed. We utilized elevation thresholds to determine how water would be distributed across the landscape at a specified flooding elevation. It is important to note that the floodplain modeling is reliant on digital elevation model data and does not take into account factors such as groundwater seepage or dispersed precipitation.

The study area is very flat, and although 12-m resolution is very fine for digital elevation data, water level elevation changes predicted were minute enough that it was challenging to visually see changes in geospatial flooding and floodplain extent. To see more clear spatial

differences with different water elevation predictions, an interpolated version of the digital elevation data was used, created by developing a layer of centroids of each elevation pixel, which were then interpolated with the Inverse Weighted Distance tool in ArcPro to form a new elevation layer. The new elevation layer had raster cell sizes of 1m by 1m, as opposed to 12m by 12m raster layer, allowing for finer resolution analysis (Figure 3.2). It should be noted that this interpolated data could not be treated as precise data as the actual data is coarser.

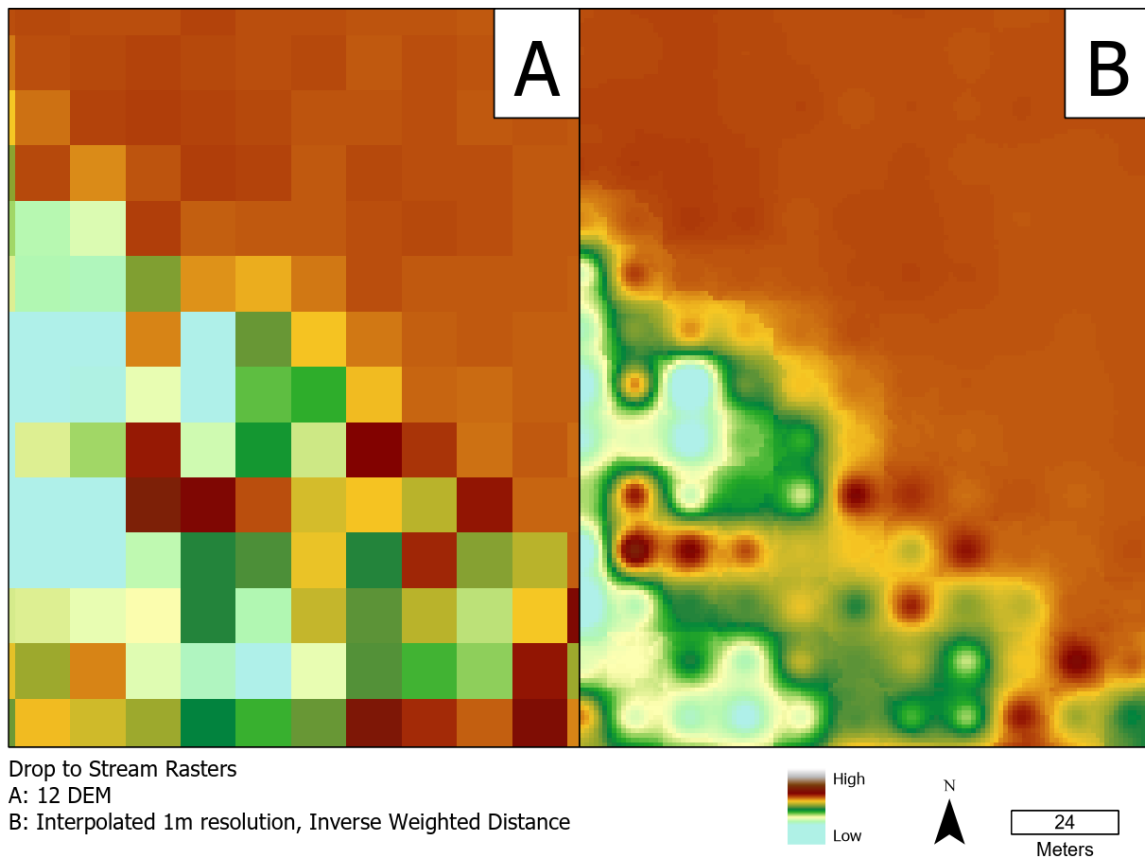


Figure 3.2. **A:** The original drop to stream raster created by the 12m resolution DEM. **B:** The drop to stream raster produced from interpolating the first raster to a 1m resolution using Inverse Weighted Distance

3.2.2. Connecting Streamflow to Flood Elevation and Extent

It is difficult to know what actual elevation of flooding can be expected from a certain level of streamflow. To predict flooding elevation based on discharge predictions, a statistical relationship was developed between water level and discharge measurements taken at the Mohembo stream gage by Botswana University (Figure 3.3) (University of Botswana).

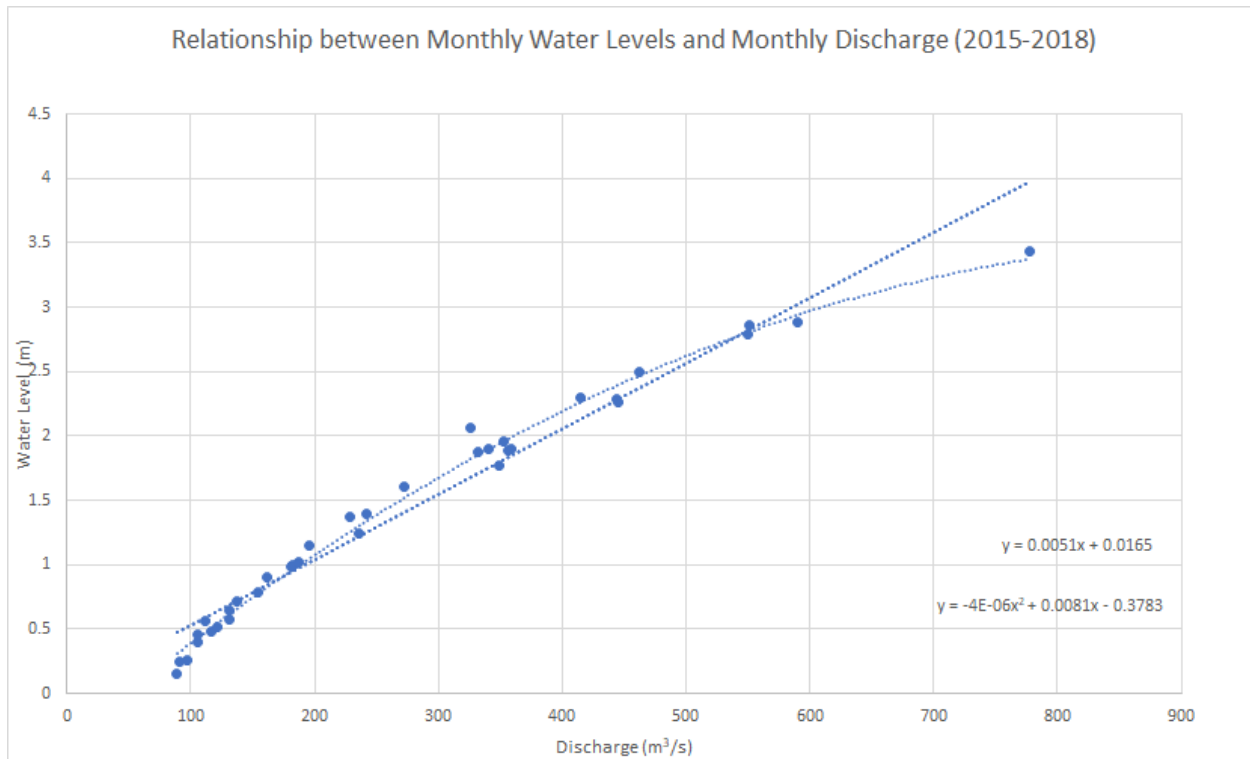
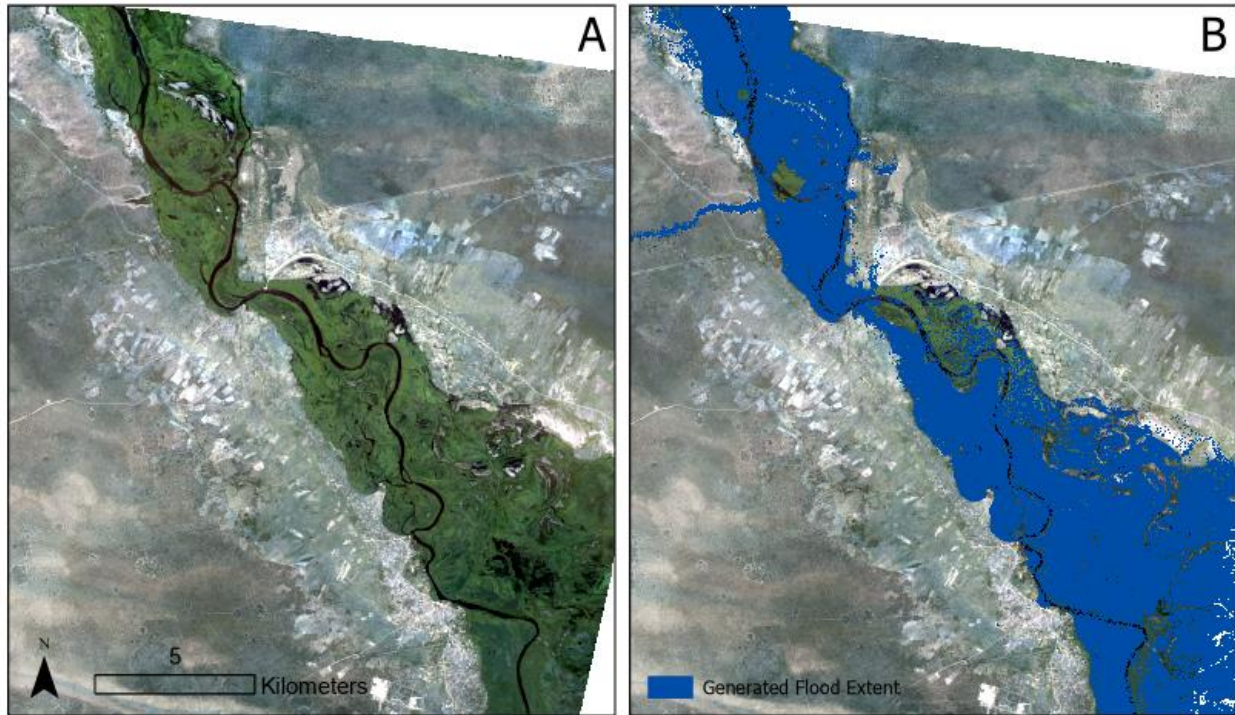


Figure 3.3. Water level and discharge data from the Mohembo gage station related with a linear and second order polynomial trend line

By statistically relating streamflow outputs generated from the hydrologic model in historical years with actual streamflow gaged by the University of Botswana, we could get an idea of how modeling outputs reflect actual expected streamflow in the study area.

Remote sensed images from the Planet database helped us guide our choices of water levels and flow rates (Planet Team 2017). Having extremes of wet and dry images gave us a visual cue to compare the extremes of the wet and dry seasons in the stretch of river we were studying.

Since March of 2016 show the highest streamflow level based on gaged streamflow by the University of Botswana, imagery from that month was used as a proxy for maximum flood extent. Imagery from drier wet seasons can then be used to represent alternative flood extent scenarios. Remotely sensed imagery was used to validate the flood extents developed using digital elevation data. (Figure 3.4).



Source: Planet Team (2017). Planet Application Program Interface: In Space for Life on Earth. San Francisco, CA. <https://api.planet.com>.

Figure 3.4. A: Remote sensed imagery mosaic for the month of March in 2016. Streamflow measurement by the University of Botswana, March 2016 was chosen as an example of maximum flooding along the Cuvango. **B:** Model generated flood extent raster image that best matches the remote sensed image.

3.2.3. Predicting Flood Elevations

Before flood elevations could be predicted, hydrological model discharge outputs needed to be adjusted to more realistic levels. The discharge outputs predicted by the hydrologic model did not account for any losses through things like evaporation or groundwater seepage. As a result, the discharge outputs are higher than they should be. To account for this, the discharge measurements that were predicted in a no-infrastructure development scenario were compared with the real discharge measurements taken at the Mohembo gaging station (Figure 3.5). Flood elevation predictions were then based on the adjusted discharge predictions, which were decreased to 30% so that they more closely followed real measurements.

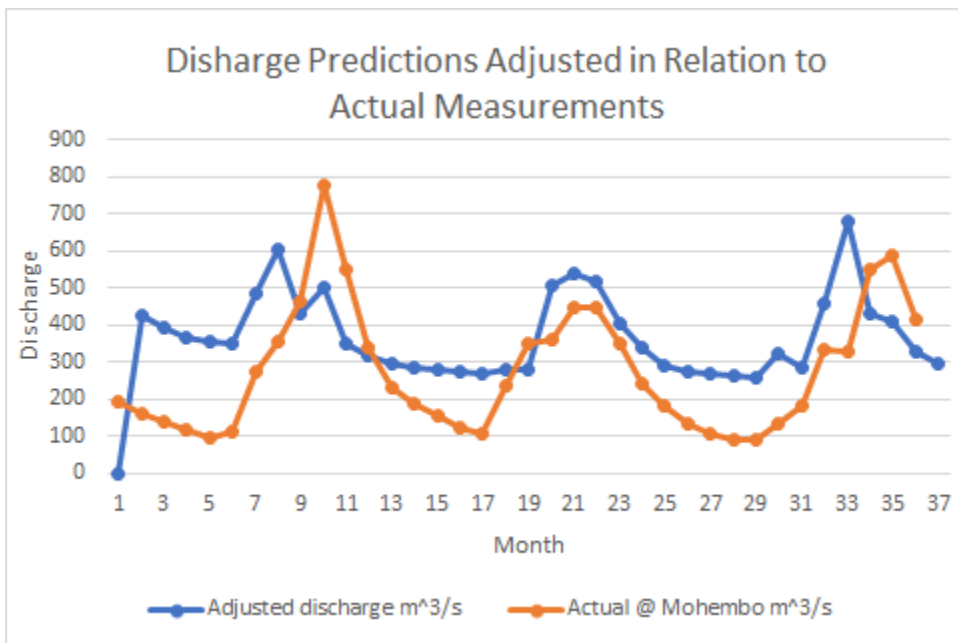
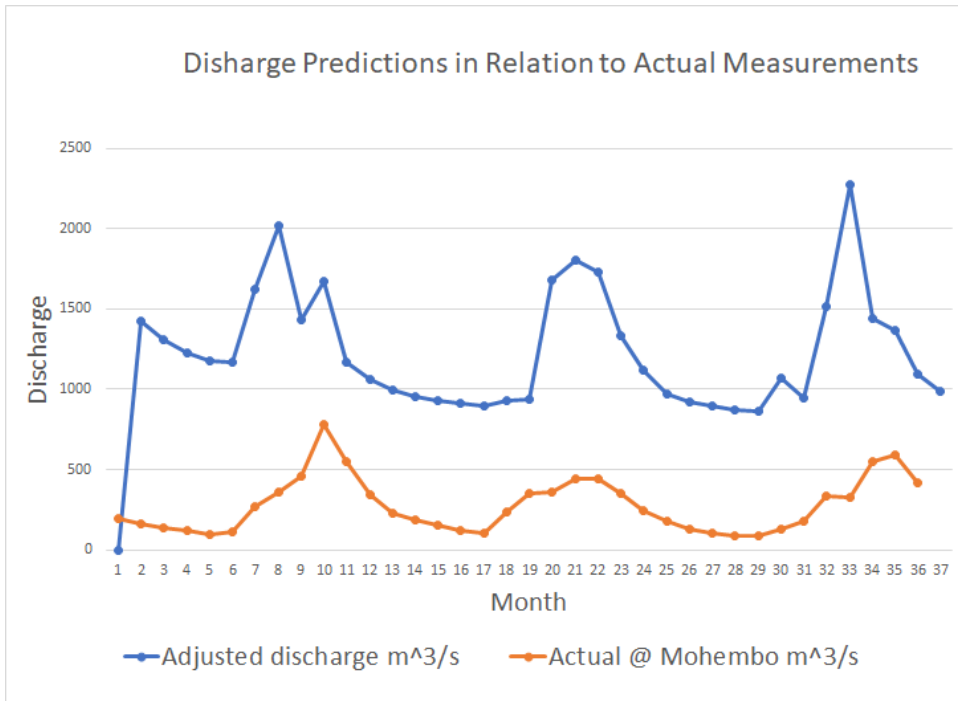


Figure 3.5. Top: Measured discharge and actual measurements for May 2016-June 2018; **Bottom:** Adjusted discharge and actual measurements for May 2016-June 2018. Discharge predictions developed from the hydrologic model were decreased by 30% so that the measurements more closely matched actual discharge measurements.

Two statistical relationships were developed between measured discharge and water elevation data, a linear and 2nd polynomial relationship. Each equation was used to develop flood elevation predictions based on the streamflow outputs generated by the hydrologic model.

Linear Equation: $y = .0051x + .0165$

2nd Order Polynomial Equation: $y = .000004x^2 + .0081x - .3783$

An excel sheet of adjusted generated outputs was used to predict water levels using each equation for the no-development scenario, development scenario #4, and development scenario #9. Outputs used for these predictions were those from subbasin 135, which is the subbasin directly upstream of Bwabwata National Park. The data adjustment was based on the Mohembo gage data, which is approximately 150 kilometers downstream of this location, making its reliability as a comparison tool uncertain.

While both line fitting approaches have limitations, the 2nd order polynomial line fit best matched the existing real data for the higher values (Figure 3.3). Flood levels were calculated for both equations and found that the values from the 2nd order polynomial line were more realistic and closer to actual measured water levels. Thus, the results from this equation were used to generate the predicted geospatial raster flood extent layers.

3.2.4 Limitations in Flood Extent Modeling

Hydrology: The flood extent model does not consider factors such as groundwater seepage or dispersed precipitation.

Elevation Data Resolution: Although the digital elevation data is high resolution (12m), it is still coarse enough to prevent fine incremental vertical changes to be detected. To get around this, we interpolated the digital elevation data, forcing it into a finer resolution. This allowed us to have a smoother elevation surface to work with and detect changes, given this artificial resampling.

Lack of ground truthing: Without traveling to the region it is difficult to know how accurate the DEM data used for this model is. Remote sensed imagery and ground imagery, such as Google Maps Street View, must be relied upon to validate the DEM.

3.2.5 A Qualitative Assessment of Flood Extent

It is important to note that the unreliability of the data used and limited availability of additional data led us to design this analysis as a qualitative assessment of the flood extents and the expected impact of the infrastructure scenarios analyzes, rather than a quantitative prediction of flood extent in each scenario. This analysis is useful for helping decision makers determine whether changes to the riverine floodplain extent is an important consideration when making infrastructure planning decisions.

3.3. Wildlife Movement Analysis

3.3.1. Overview

The seasonal difference of rainfall in Okavango delta impacts on wildlife in the region. During the dry season, elephants mostly remain around the floodplain area within 10km. During the wet season, elephants move far from the river about 30-50 km towards the ephemeral water (Loarie et al 2009). In this analysis, we focused on the wet season when the elephant movements are influenced by both perennial and ephemeral water.

To understand potentially important wildlife movement pathways in the study area, we created models of movement under the wet season scenario, focusing on elephants. Resistance-based movement modeling relies on estimating the physiological costs, or reduction in survival, or both, for an animal moving through a particular environment (Zeller et al., 2012). Since wildlife are likely to use the paths with low resistance values, resistance surface mapping is a commonly used geospatial tool to identify potential wildlife corridors.

The resistance surface modelling approach would allow us to analyze the potential impact of human development on wildlife movement. There are wildlife movement studies using GPS tracking but this result is limited to understanding the current movement, and cannot predict the change in movement after disturbance. Therefore, resistance surface modelling was chosen to understand the impact on the wildlife movement of the change of flows by potential dam construction.

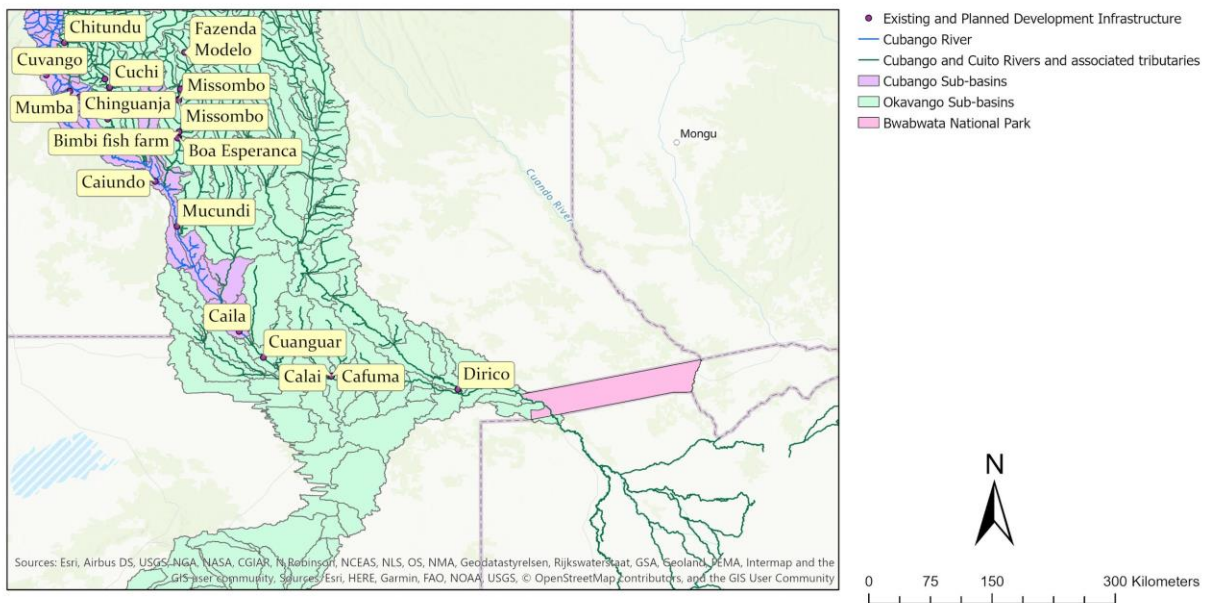
The wildlife movement is represented as an electrical current using Circuitscape (McRae, 2013). Circuit theory is based on the concept that each cell has a certain level of electrical flow. This flow represents the ease of the movement for wildlife. The current in each simulation flows from the source node to the ground node. The current is reduced against the resistance value of each pixel it passes by. Compared to the least cost path, this has the advantage of representing multiple paths with different widths instead of a single cell (McRae). Therefore, the wider the path, the more favorable for wildlife movement.

3.3.2. Study area and target species

To understand the effect of flow change after the dam construction in the Cubango river basin, we chose Bwabwata National Park in northeastern Namibia since it is the closest national park to the river basin where the infrastructure development is planned and also where WWF is tracking wildlife with GPS (Figure 3.6). Bwabwata National Park (17.95°S 22.54°E) was

established in 2007 with a total area of 6,274 km². The Park shares borders with Angola to the north and Botswana to the south. Located in the center of KAZA region, it is an important migration route for species like elephants, buffalo, zebra from Botswana into Angola and Zambia.

River Basin and Study Area



Source: The Nature Conservancy Hydrology data, WWF Bwabwata park boundary
 Projection: GCS WGS 1984
 Made by Ga-on Lee, Nicholas School of the Environment, Duke University on Mar 21, 2020

Figure 3.6. River Basin and Study Area.

For focal species, we chose savannah elephants (*Loxodonta africana*) based on the advice from WWF since they have high conservation values and elephants are under severe threat due to their conflict with poachers and villagers. Elephants move from permanent water to vegetation to sustain themselves during the dry season. During the wet season when the landscape is filled with small scale (1m-20m) water holes, their movement changes. The average walking distance is 10km a day. With enough resources, they move as little as 1.5km a day but when there is no resource, they can move up to 40km a day (Miller et al., 2016) and move in herds with 10 females and their calves (World Wildlife Fund, n.d.). They are found in open and closed savannah, grassland and arid desert (Animal Diversity Web, n.d.) avoid higher sloped areas (Sach et al., 2019). Since the landscape of the Bwabwata National Park was flat, the slope was not a big factor limiting elephant movement in this study.

3.3.3. Building the resistance surfaces

First, we integrated the floodplain and ephemeral water holes obtained from other teammates into WWF’s land cover data (Table 3.4). Due to limited water sources, wildlife movement is strongly linked to the distribution of surface water in the landscape. Ephemeral water bodies in Bwabwata National Park were identified at their fullest point during the wet season in 2018 with producer’s accuracy of 0.88 and user’s accuracy of 0.8593% for the water class (Schaffer-Smith et al., 2020). Google Earth Engine was used to classify waterholes from an entire year of 10-m Sentinel-2 imagery (coverage of Bwabwata every 75 days) and 10-m Sentinel-1 synthetic aperture radar (coverage every 14 days) (European Space Agency, 2018) Maximum and minimum extent river floodplains at 12-m dataset was generated from flow analysis described above.

Table 3.4. Information of water holes and floodplain dataset

Input variable	Data used	Resolution	Date	Source
Ephemeral water holes	Sentinel-1 SAR, Sentinel-2,	10m	February 13, 2020	Danica Schaffer-Smith
Floodplain extent	TanDEM	12m	February (monthly average), 2017	Jannette Morris, Gaby Garcia

Second, we selected three input variables for the resistance surface- land cover, canopy cover and human population density. In general, 2-4 environmental variables such as land cover, roads, DEM, slope, human development, percent canopy cover are often used (Zeller et al., 2012). In this analysis, slope was not considered since the landscape is pretty flat and slope around 10 degrees would not disturb elephant movement, according to the expert opinion (A.

Brennan, personal communication, 3/4/2020). We used a land cover dataset provided by WWF of 29 classes and updated it to include ephemeral water holes and river floodplains. In addition, percent canopy cover was used since elephants move in search of leaves- their main source of food. Also, because humans are a major disturbance to the elephant, larger human population areas were expected to deter elephant presence and movement.

After selecting input variables, we assigned resistance values to each input variable. To give 5 levels of resistance values to land cover types, I divided 29 classes into 5 categories (Table 3.5). In addition, since we do not know the actual resistance value of habitats across this landscape, we used two contrasting versions of land cover resistance - water with lowest resistance value vs water with higher resistance value (Table 3.6). This indicates the two cases when the water was the most preferred land cover type and when the water was less preferred land cover type than open or closed lands. We assumed bare land, where there is no vegetation, has the second highest of 4 and human development has the highest value of 5.

Table 3.5. 5 categories of land cover classes

Classification	Land cover type
water	Water 1,2,3, wetland floodplain, wetland seepage, wet bare
Open land	open grassland, open woodland, open-sparse bushland, sparse grasslands = bushland thicket
Closed land	closed canopy woodland, closed canopy forest, secondary and cleared forest
Bare land	non-wet bare, natural bare rock

Human Development	dryland cultivation, commercial cultivation, plantation, golf course, urban settlement, roads, mines, airstrips
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Table 3.6. Two versions of land cover resistance

category	low resistance on water	high resistance on water
water-related land cover classes	1	3
open land	2	1
close canopy	3	2
bare land	4	4
human development	5	5

For the human population variable, the Namibia population layer of 100m resolution was obtained from the World Population website(<https://www.worldpop.org/>). The human population was limited to the middle left side of the park where the tourists' lodges are concentrated. The data showed uneven distribution, thus we classified the data into 5 using natural jenks and assigned the highest resistance value of 5 to the most populated area and the 1 to the least populated area.

For the canopy percentage cover variables, 30m resolution forest canopy cover data from the year 2015 was downloaded from NASA Earth (Townshend, 2016). The data was not evenly distributed showing left-skewed distribution. Therefore, we used the natural jenks classification method and classified the data into five categories and gave the highest resistance value of 5 to the area with the lowest canopy cover percentage and the lowest resistance value of 1 to the highest canopy cover area.

Table 3.7. Information on input variables

Input variable	Data	Description	Resolution	Date	Source
Land cover	KAZA land cover	Land cover classification of 29 classes over the KAZA region	25m	2016	WWF ¹
Human population	Namibia population 2020	Estimated total number of people per grid-cell. The units are number of people per pixel with country totals adjusted to match the corresponding official United Nations population estimates that have been prepared by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2019	100m	2020-02-01	WorldPop ²

¹ Data was accessed by personal communication with Angela Brennan, WWF on July 17, 2019

² WorldPop (www.worldpop.org - School of Geography and Environmental Science, University of Southampton; Department of Geography and Geosciences, University of Louisville; Departement de Geographie, Universite de Namur) and Center for International Earth Science Information Network (CIESIN), Columbia University (2018). Global High Resolution Population Denominators Project - Funded by The Bill and Melinda Gates Foundation (OPP1134076). <https://dx.doi.org/10.5258/SOTON/WP00660>

		Revision of World Population Prospects).			
Canopy Cover	Global Forest Cover Change (GFCC) Tree Cover Multi-Year Global 30 m V003.	Percent of pixel area covered by tree cover derived from the GFCC Surface Reflectance product (GFCC30SR), which is based on enhanced Global Land Survey (GLS) datasets. The GLS datasets are composed of high-resolution Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images.	30m	2016	Townshend, J.

Subsequently, we computed a weighted sum of these three input variables (Table 3.7) to generate the resistance values across the landscape. Some assumptions were made for creating resistance values for input variables (Table 3.8). Land cover is assumed to have the biggest influence on elephant movement considering the availability of water and vegetation. Therefore, a weight of 0.5 was assigned to the land cover variable to make the resistance surface. Canopy cover and human population were assumed to have equal importance, and were therefore each weighted as 0.25. The final resolution of the resistance surface was 25m to match the most detailed resolution of the input layers resistance value ranging from 0 to 1.

Finally, we assigned the highest resistance value to the cells on the barriers such as roads and rivers to the elephant movement. There is one highway that traverses the park in the middle from east to west (Ministry of Environment and Tourism, 2013). Only the major Okavango River was considered since small tributaries are assumed to be shallow enough for elephants to move across. Roads do not totally prevent elephants from walking across (A. Brennan, personal communication, 3/4/2020; J. Poulsen, personal communication, 3/4/2020). Therefore, roads (30m width) and rivers (200m width) were given a higher resistance value of 0.8 compared to the other landscape considering that the value should still be higher than other landscapes.

Table 3.8. Assumptions used for building the resistance surfaces

Category	Assumptions
Land cover preference	Bare and developed lands are avoided when elephants move. Water, open, and closed land are preferred when elephants move.
	Open land is preferred to closed land when elephants move during the wet season
Barrier Influence (roads and rivers)	Roads and rivers prevent elephant movement to some extent. Only the major Okavango river was considered since small tributaries are assumed to be shallow enough for elephants to move across.

Weights	Land Cover has the highest influence over wildlife movement 0.5, and canopy cover and population have equal importance of 0.25.
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3.3.4. Connectivity modeling

Current maps were generated using Circuitscape desktop software (Mcrae et al., 2008) in advanced mode. To represent potential movement of elephants across the landscape, we used a wall-to-wall method. The wall-to-wall method of modelling permits the use of circuitscape without setting focal nodes. Instead, it assigns one side of the landscape as the starting node or “source” and the opposite side as the ending node or “ground” (e.g, north = source, south = ground) so that the current can flow without the setting an assumption on the locations of focal nodes. This is particularly useful in instances where the limited knowledge regarding wildlife population biology is available.

To run the wall-to-wall simulations, we created four patches, each 25m wide, covering each of the four sides of the landscape. We then ran Circuitscape four times, with one side as the source and the opposing side as the ground. The result showed the current flowing from north to south, south to north, east to west, and west to east. Lastly, calculated the sum of current from all four simulations using equal weights to generate the final current map.

3.3.5. Validated with the tracking data from WWF

To evaluate the outcome of our movement model, we conducted a visual comparison to the map tracking frequency of elephants detection between October 2010 and March 2012 in 2km * 2km grid GPS on 10 female elephants.

3.4. Dam construction scenario and impact on flow and wildlife

Scenario	Abstraction (Mm ³ /yr)				Irrigation (ha)				Irrigation (Mm ³ /yr)				Urban Water Supply (Mm ³ /yr)				HEP (MW)	Dams
	Tot.	A	B	N	Tot.	A	B	N	Tot.	A	B	N	Tot.	A	B	N	Tot.	A
Present Day (PV)	74	6	4	64	2,719	170	0	2,549	64	3	0	61	9	3	4	3	0	
Improved Livelihoods (IL)	94	22	5	68	2,719	170	0	2,549	64	3	0	61	30	19	5	6	0	
BDS1	139	22	5	112	2,719	170	0	2,549	64	3	0	61	75	19	5	51	0	
BDS2	698	506	6	186	66,720	55,060	0	11,660	604	491	0	114	94	15	6	73	40	Malobas
BDS3	698	506	6	186	66,720	55,060	0	11,660	604	491	0	114	94	15	6	73	105	Mucundi
BDS4	698	506	6	186	66,720	55,060	0	11,660	604	491	0	114	94	15	6	73	12	Cuito
BDS5	1,559	1,354	8	197	132,185	120,525	0	11,660	1,439	1,330	0	109	120	23	8	88	51	Malobas, Cuvango
BDS6	1,559	1,354	8	197	132,185	120,525	0	11,660	1,439	1,330	0	109	120	23	8	88	168	Malobas, Cuvango, Mucundi, Cuito
BDS7	2,542	2,264	8	270	222,261	204,060	0	18,201	2,422	2,240	0	182	120	23	8	88	51	Malobas, Cuvango
BDS8	3,557	3,279	8	270	302,701	284,500	0	18,201	3,437	3,256	0	182	120	23	8	88	51	Malobas, Cuvango
BDS9	1,301	1,076	28	197	100,660	87,500	2,000	11,160	1,102	974	20	109	199	102	8	88	168	Malobas, Cuvango, Mucundi, Cuito
BDS10 (CC)	1,301	1,076	28	197	100,660	87,500	2,000	11,160	1,102	974	20	109	199	102	8	88	168	Malobas, Cuvango, Mucundi, Cuito

Note*: A – Angola, B - Botswana, N – Namibia

Note**: The planning end-horizon was 2015-2040 for the economic modelling of NPV values and for the majority of the hydrological modelling apart from the hydrological modelling that incorporated higher levels of development and estimated impact of climate change (extended to year 2050).

Table 3.9. Overview of MSIOA Basin Development Scenarios.

Among 10 basin development scenarios, scenario 8 (BDS8) has the highest abstraction of water, 3,557 Mm³/yr). Our team chose three dam development scenarios based on the level of development - baseline , medium development (scenario 4), high development (scenario 9). Using the analysis of change in total downstream flow and flood extent after the water abstraction, the changes in resistance surface and conductance map for elephants were analyzed. The changes in flow are on the meter scale that the change in flood extent seems not significant. Based on the differences in flood extent, we generated current maps for each scenario. The three resulting current maps resulted for wet seasons by three scenarios.

4. Results and Discussion

4.1 Water Level Prediction

A sample of the water levels predicted using the equations developed by the relationship between real discharge and water level measurements from the Mohembo gaging station is shown in Table 4.1.

The water levels predicted by both the linear and 2nd order polynomial equations using discharge predictions from the hydrologic model's baseline scenario were generally higher than the water levels measured at the Mohembo station. This could be an artifact of some of the losses

that were difficult to accurately adjust for. It is challenging to use the Mohembo gaging station as a verification tool because of the distance downstream from the modeling location.

When there are water level changes between scenarios for the same given year and month, they tend to be on the .1 or .01m scale. The greatest change in water levels from the baseline scenario is seen in the highest development scenario, which is to be expected. A mid-development sometimes only shows change on the .001 or .0001m scale.

Flood extents generated based on water level predictions for the same year and month only varied on the pixel level across scenarios. This could be a result of too coarse digital elevation data, even though the data being used was interpolated to a 1-m scale. A qualitative judgement of the predictions indicates that infrastructure development seems to have little impact of stream flooding, unless the streams are highly developed.

Month	# Days	Scenario 9					Scenario 4					Baseline Scenario					MQ	MWL	SQ
		Q1	Q2	ADQ	LWL	PWL	Q1	Q2	ADQ	LWL	PWL	Q1	Q2	ADQ	LWL	PWL			
1	31	4507.16145	1682.781	504.8344	2.59	2.6914	4501.306	1680.595	504.1786	2.59	2.6888	4497.819	1679.293	503.7879	2.59	2.6872	349.009	1.765	354.9
2	28	4210.18523	1740.321	522.0964	2.68	2.7603	4352.7	1799.231	539.7694	2.77	2.8284	4365.616	1804.57	541.371	2.78	2.8345	359.129	1.901	559.6
3	31	4620.7814	1725.202	517.5606	2.66	2.7425	4627.162	1727.584	518.2753	2.66	2.7453	4632.738	1729.666	518.8999	2.66	2.7478	444.424	2.289	563.1
4	30	3537.58554	1364.809	409.4428	2.10	2.2676	3467.43	1337.743	401.3229	2.06	2.2282	3465.508	1337.001	401.1004	2.06	2.2271	445.707	2.26	505.2
5	31	2716.51443	1014.23	304.2691	1.57	1.7160	3004.142	1121.618	336.4855	1.73	1.8943	3006.629	1122.547	336.764	1.73	1.8958	352.242	1.955	413.4
6	30	2245.46074	866.3043	259.8913	1.34	1.4566	2520.565	972.4402	291.7321	1.50	1.6443	2513.112	969.5647	290.8694	1.50	1.6393	241.51	1.392	348.6
7	31	2148.1533	802.0286	240.6086	1.24	1.3391	2465.425	920.4842	276.1452	1.42	1.5535	2465.528	920.5227	276.1568	1.42	1.5535	181.815	1	294.1
8	31	1643.58292	613.6436	184.0931	0.96	0.9773	2392.786	893.3639	268.0092	1.38	1.5053	2392.963	893.4299	268.029	1.38	1.5054	131.166	0.65	250.5
9	30	2258.80327	871.4519	261.4356	1.35	1.4659	2267.596	874.844	262.4532	1.36	1.4720	2267.918	874.9683	262.4905	1.36	1.4723	105.122	0.453	211.1
10	31	2191.16556	818.0875	245.4263	1.27	1.3687	2307.495	861.5201	258.456	1.33	1.4480	2308.039	861.7231	258.5169	1.33	1.4484	90.865	0.25	166.7
11	30	2773.63783	1070.076	321.0229	1.65	1.8098	2776.385	1071.136	321.3409	1.66	1.8115	2782.22	1073.387	322.0162	1.66	1.8153	88.961	0.154	207.8
12	31	2422.15691	904.3298	271.2989	1.40	1.5248	2507.794	936.3031	280.8909	1.45	1.5813	2522.782	941.8991	282.5697	1.46	1.5911	131.16	0.57	123.3

Q1: Discharge predicted by spreadsheet model in million cubic meters per month

Q2: Discharge in meters cubed per second

ADQ: Discharge adjusted to 30% based on real discharge measurements

LWL: Linear Water Level Prediction (meters)

PWL: 2nd Polynomial Water Level Prediction (meters)

MQ: Measured discharge at Mohe mbo gaging station (meters cubed per second)

MWL: Measured Water Level at Mohe mbo gaging station (meters)

SQ: Streamflows from the SWAT model (meters cubed per second)

Scenario #9 (fully developed)

Scenario #4 (some new development)

Baseline Scenario (no new development)

Table 4.1. This table shows one year’s worth of discharge predictions (2017) from three of the scenarios used in the hydrologic model. The table shows water levels calculated for each month for each scenario based on the linear and 2nd order polynomial equations. Since this is a past year, we are able to compare it to real discharge and water level measurements.

4.2. Geospatial modelling on wildlife movement

Resistance surfaces

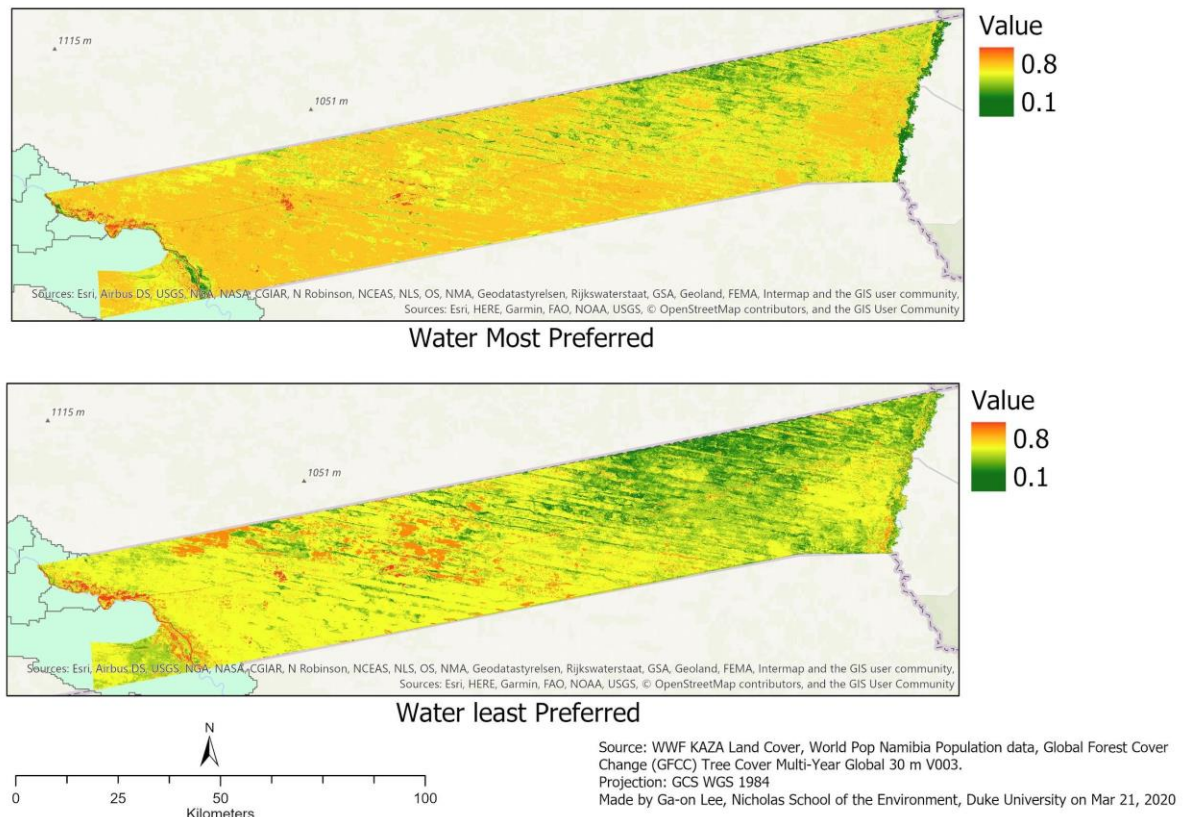


Figure 4.1. Resistance Surfaces

In Figure 4.1, the resistance surfaces were made for elephant movement. The map above is when the water was the most preferred land cover type and the map below is when the water was least preferred compared to open and close land. Both maps have resistance values ranging from 0.1 to 0.8. The higher value indicates higher efforts are required for the elephants' movement. The color stretches are represented in percent clip, removing the highest and lowest values.

For both versions, the red areas with high resistance values are located in the mid left area where the tourism establishments exist such as lodges with high human population. They both showed low resistance values on the open woodland/bushland thicket where the percent canopy was generally high. The resistance surface with water most preferred, has high resistance value near unfavorable land cover types such as non-wet bare or dryland cultivation and low resistance values near high canopy percentage area and along the wetland area near the Kwando river on the right side. In contrast, the resistance surface with water least preferred has high resistance near the Okavango river and low resistance value near open grassland.

Wall-to-wall method

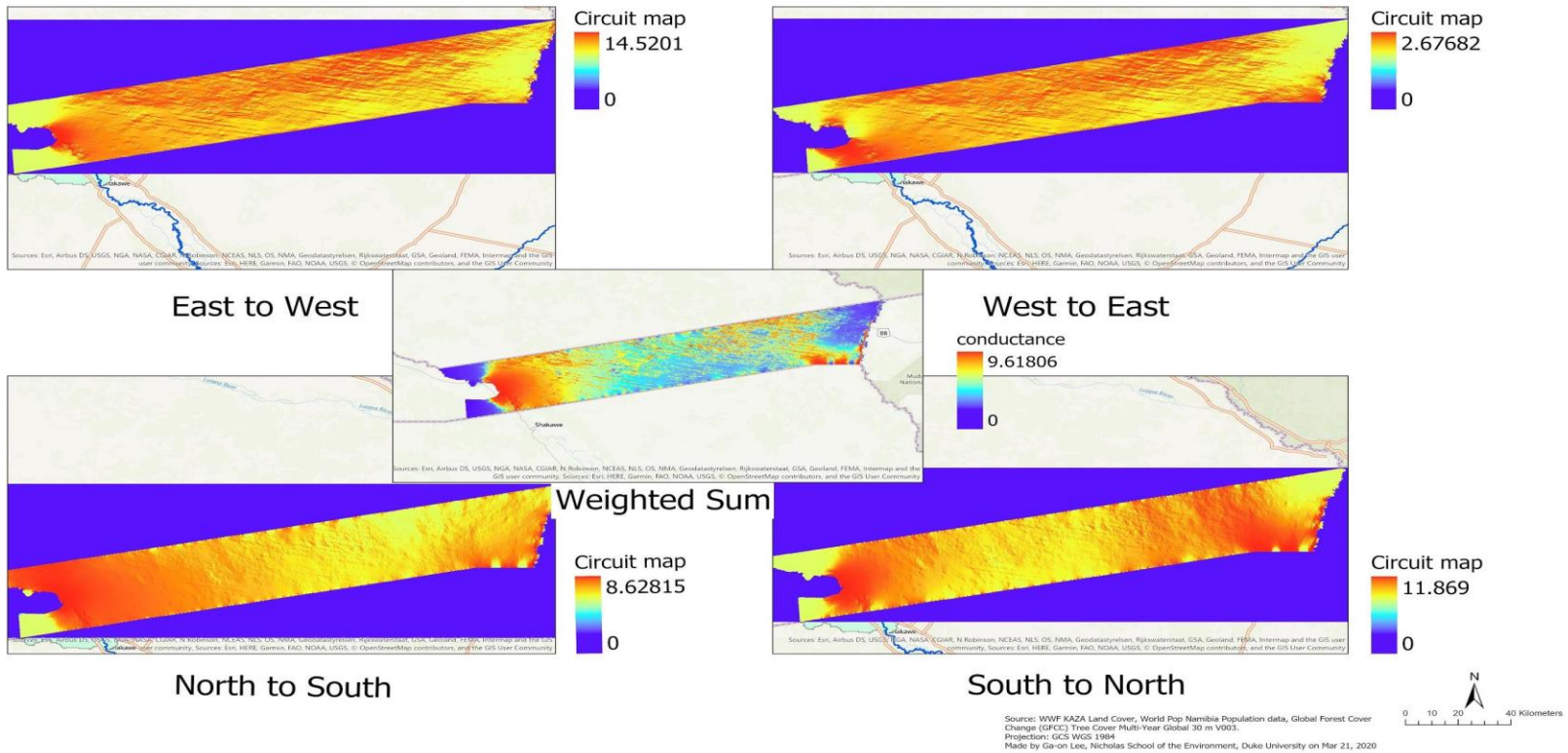


Figure 4.2. Wall-to-wall method

Figure 4.2 illustrates the wall-to-wall method which used four maps in the corner to create one current map in the middle. We can see that the current map of east to west direction has a high current value in the east side very narrowly compared to the current map with west to east direction. Also, the current map with north to south direction has very high conductance value on the upper left side compared to the current map with south to north direction.

Current maps

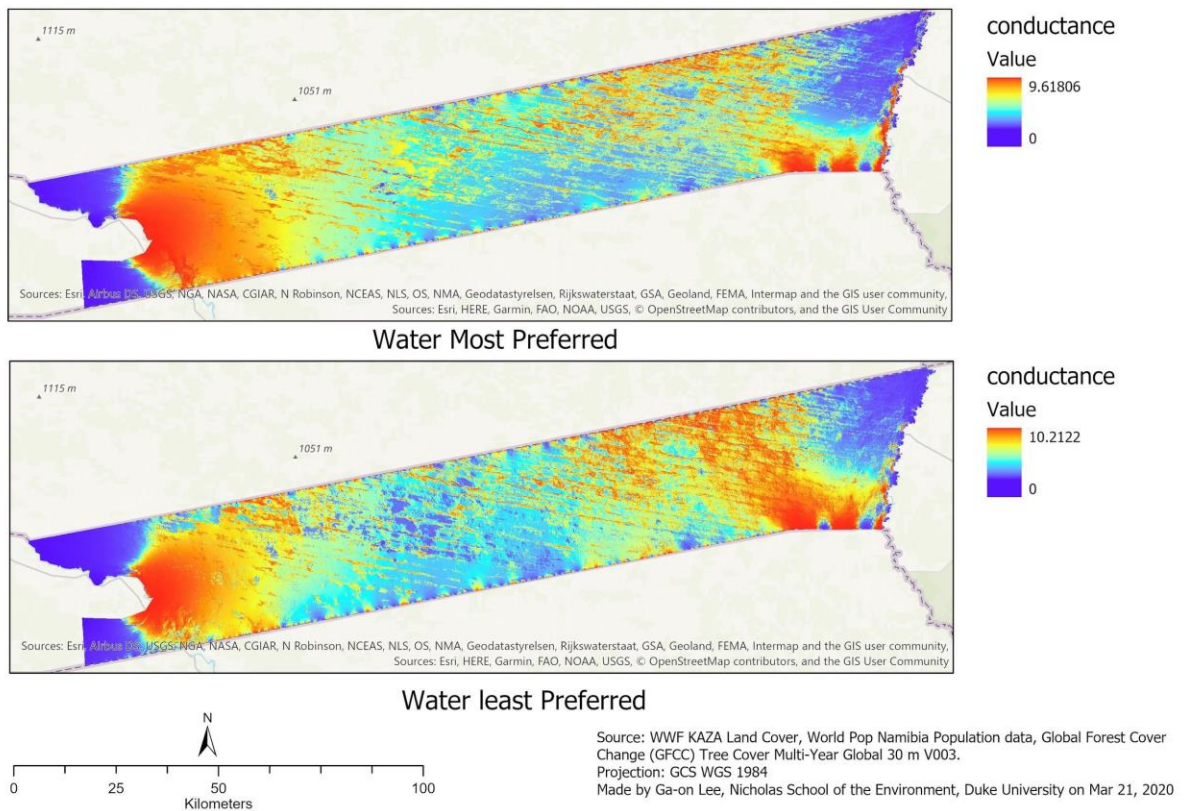


Figure 4.3. Current maps

In Figure 4.3, the map shows the high connectivity area in red and the low connectivity areas in blue. However, from both circuit maps, we could see that the areas on the middle left and the bottom right have the high current values. In addition, downward sloped stripes with high current value had high conductance value. This might be because this is where little creeks flow and vegetation could grow along the creeks. The stripe lines are a natural phenomenon of open woodland/bushland tickets where the canopy cover is higher than surrounding land cover type such as open sparsh bushland/open grassland. When the water was most preferred, high current is shown in the lower right side where there is water along the Kwando river. The red two circles on the bottom right are open grassland with high canopy cover.

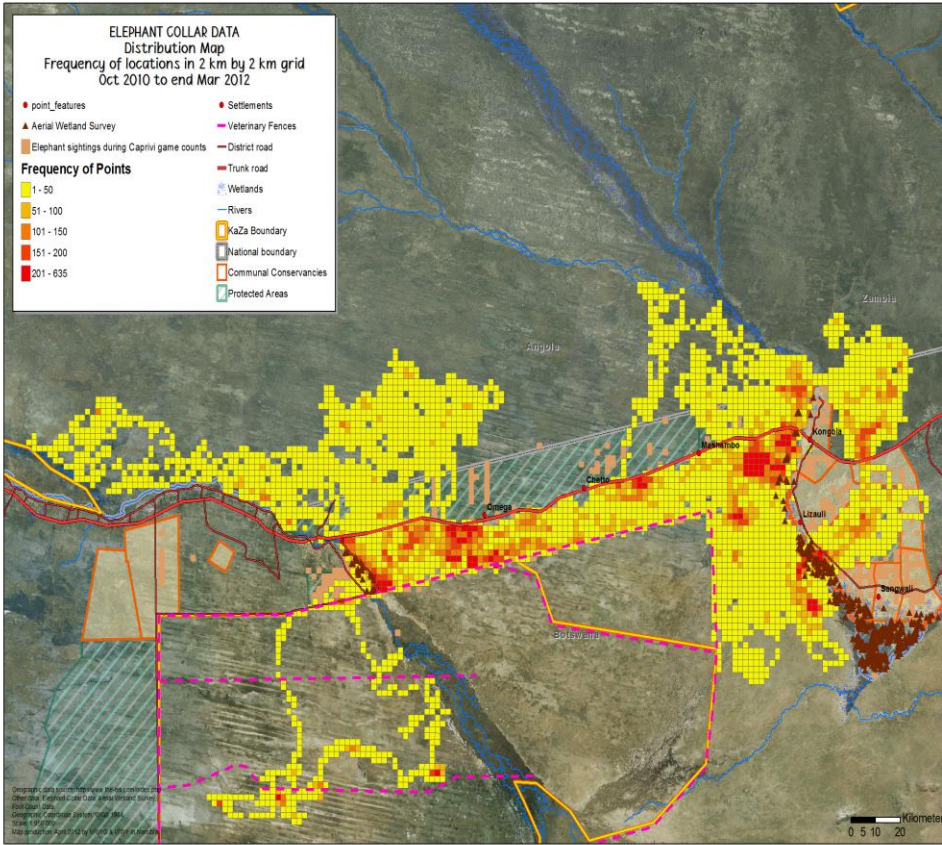


Figure 4.4. Elephant collar data distribution map (map courtesy of Angela Brennan, WWF).

When comparing the collar data map with water most preferred and water least preferred current maps, it showed more similarity with the water most preferred map showing high conductance near the Kwando river and low conductance in the low-middle area (Figure 4.3. and 4.4). Therefore, we used the water most preferred rank for the final scenario analysis.

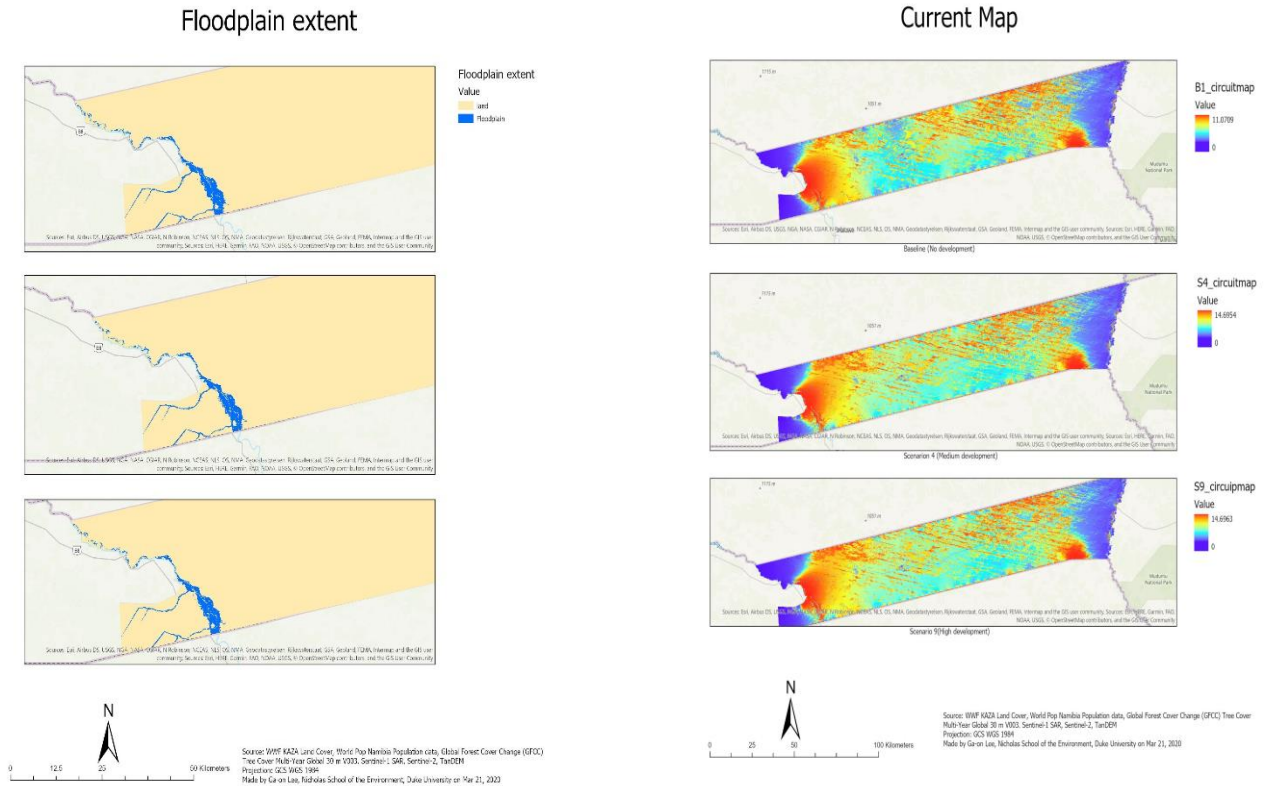


Figure 4.5. Flood extent and current map by development scenarios

Figure 4.5. Shows the floodplain extents by scenario - baseline, scenario 4, scenario 9 - and the current maps for each scenario. Since the predicted impact of dam construction on flood extent was not significant based on our modeling, the impact on wildlife movement was not significant either. Therefore, we might suggest that the dam development is not directly related to the elephant movement in Bwabwata National park.

However, when other factors such as climate change that would influence other surface water resources are considered, the result could change. Changes in temperature and precipitation patterns could influence how surface water is distributed across the landscape and the resulting impact of infrastructure to streamflow changes. This study did not consider the combined impacts of infrastructure development and climate change. Climate change modeling should be incorporated into future studies.

In addition, this research focused on the wet season to understand the impact of ephemeral water bodies on elephant movement. However, additional analysis on the dry season

could be conducted to understand the impact of the dam construction during the dry season. Also, as Kwando rivers are found to be the hot spot of elephant movement by our movement analysis, hydrological analysis on Kwando river could be done in the future.

The limitation of the research was that understanding of the landscape was only possible through Google Earth maps and remotely sensed images. Due to this lack of understanding of the landscape, our expectation of wildlife movement might be limited. For example, there are small scale tributaries in the Bwabwata National Park. We assumed that they are shallow enough for animals to move across easily. Field research on these tributaries would improve the resistance surface by providing knowledge of the traversability of these smaller streams.

Besides, even though we used the approach of making two versions of land cover preference, many assumptions were made in the process. For example, we assumed that all water-related land cover types such as water and wetland seepage have the same value for the elephants. However, it might not be true. This could be improved by in-depth research on wildlife behavior in the landscape. Another limitation of this model was that only a single weight is used. For further study, a wider range of weights could be incorporated with more variables such as soil quality.

Based on our analysis, we expect that infrastructure development on the Cuvango will have only a minor impact on wildlife. However, we recommend further study, especially incorporating climate change impact modeling, before any recommendations are given to decision makers in the region. This study is a first step to providing information and resources for decision making regarding water resource management in the Okavango River Basin.

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