AN INTEGRATED FRAMEWORK FOR HYDROLOGY-HYDRODYNAMIC MODELLING OF THE BAROTSE FLOODPLAINS, UPPER ZAMBEZI RIVER BASIN

By

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Declaration

This thesis contains no material which has been accepted for the award of any other degree in any university. To the best of the author's knowledge, it contains no material previously published except where due reference is made in the text or published by the author. The research described in this thesis has been carried out at Integrated Water Resources Management (IWRM) Centre-Geology department, School of Mines, University of Zambia, under the supervision of Dr. Kawawa E. Banda and Professor Henry M. Sichingabula.

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APPROVAL STATEMENT

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Abstract

In recent years the demand for improved assessments tools to help in understanding the wetland hydrological and hydrodynamic processes for the Barotse floodplains is ever increasing especially with the advent of climate change/variability. Despite several studies in the Upper Zambezi Basin, there was an absence of an integrated online (internal) framework for coupling hydrology and hydrodynamic model to be used to improve modelling of the Barotse floodplains. The objectives of this study were: (i) To investigate the mechanisms of groundwater-surface water interaction in the Barotse floodplains, (ii) To develop a rainfall-runoff hydrologic model for Upper Zambezi River basin focusing on modelling Barotse floodplain, (iii) To develop an integrated hydrologic-hydrodynamic online (internal) coupling modelling framework for Barotse floodplains and (iv) To test and evaluate the performance of an online one-way Barotse Coupled Hydrological-Hydrodynamic Model developed based on the framework in objective iii. The study used field data sets, models, remote sensing data, and secondary data to address the objectives at hand. Based on the study objectives, the study has shown that the interaction between groundwater and surface water does occur in the Barotse Floodplain as evidenced by hydro-chemical and isotopic results. Such kind of groundwater-surface water interaction in floodplain, among other factors play a role in the hydrological and hydrodynamic modelling of the Barotse floodplains system. This postulation is partly supported by the results of simulated flows generated by wflow hydrological model, for the upstream gauge stations the results were closely matched the observed flow as indicated by the evaluation statistics; Chavuma, nse =0.738; kge = 0.738; pbias = 2.561 and rsr = 0.511; Watopa, nse=0.684; kge = 0.816; pbias = 10.577 and rsr = 0.557; Lukulu, nse=0.736; kge = 0.795; pbias = 10.437 and rse = 0.509. However, despite that wflow model was able to simulate the upstream hydrology very well, wflow model statistical objective function results of the downstream Barotse Floodplain gauge station (at Senanga) were not as good as the upstream results as indicated by evaluation statistics: nse = 0.132; kge = 0.509; pbias = 37.740 and rse = 0.923. The observed inaccuracy in goodness of fit between observed and simulated at Senanga Gauge Station maybe attributed to model forcing data as well as to the fact the representation of both floodplain channels hydrodynamics and hydrological processes are necessary to correctly capture floodplain dynamics for groundwater dependent systems. This aspect also suggested that standalone hydrological models are not very suitable in modelling the flows of the of groundwater-surface water dependant tropical floodplains. To this effect, one-way online (internal) hydrologic-hydrodynamic coupling framework for Barotse Floodplain has been developed in this study. The coupled model output relatively performed better than a stand-alone hydrological results. The significant improvements in coupled model results were observed at the downstream gauge station at Senanga with noticeable improvement in nse which improved from 0.132 to 0.535, kge improved from 0.509 to 0.699 and pbias from 37.724 to 21.495 indicating reduced model over estimation. The water levels results output from the online Barotse hydrologic-hydrodynamic model coupling also relatively matched the observed water levels as demonstrated by the statistical goodness of fit objective functions results: Mongu, kge 0.792, rse 0.762, nse 0.55; Senanga; kge 0.6707, rsr 0.827, nse 0.503 and Lukulu, kge 0.630, RSR 0.644, nse 0.301. In addition to water levels comparisons, the simulated results of coupled mode inundation area were compared with MODIS MOD09A1 imagery. The statistical objective functions were nse 0.637, kge 0.731, rsr 0.502 and pbias 25.234. In general terms, the statistical results of the simulated and observed data sets (flow, water level and inundated area) of the on-line hydrological-hydrodynamic coupled model falls within what is deemed to be a good performing model indicating that the integrated framework for online coupling of hydrology-hydrodynamic models for the Barotse floodplain was a successful in coupling the two models used in this study.

Keywords: Barotse Floodplain; wetland; Hydrologic-hydrodynamic Model; Hydrochemistry.

Dedication

'To my daughter Mubanga Bwalya Chomba and posterity, may this work inspire you to reach for greater zeniths in all that you do for Humanity for the greater Glory of God'

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Glory be to God! ‘You are my God, and I give you thanks...complete the work that you began in me.’ Psalms 118:28., 138:8

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List of Abbreviations and Acronyms

ADCP	Acoustic Doppler Current Profilers
ASTER	Advanced Spaceborne Thermal Emission and Reflection
BMI	Basic Model Interface
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
ECMWF	European Centre for Medium-Range Weather Forecasts
GIS	Geographical Information System
GLOFRIM	GLObally applicable computational FRamework for Integrated hydrological–hydrodynamic Modelling
ITCZ	Inter-Tropical Convergence Zone
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
JICA	Japan International Cooperation Agency
LiDAR	Light Detection And Ranging
MWDSEP	Ministry of Water Development Sanitation and Environmental Protection
MODIS	The Moderate-resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
OLI-TIRS	Operational Land Imager Thermal Infrared Sensor
UNZA	University of Zambia
WARMA	Water Resources Management Authority
WWF	Worldwide Fund for Nature
UZB	Upper Zambezi Basin
ZMD	Zambia Meteorological Department

CHAPTER ONE: INTRODUCTION

1.1 Overview

This chapter presents the background to the study, statement of the problem, the aim, objectives of the study, research questions, the significance of the study, Conceptual Framework, and chapter summary.

1.2 Background

Floodplains play an important role in global hydrological and biogeochemical cycles. Many socioeconomic activities depend on water resources in floodplains, which are important components of many large river systems in Africa (Yamazaki *et al.,* 2012). In recent years the demand for assessments tools to help in understanding the hydrological and hydrodynamic processes for the Barotse floodplains is ever increasing especially with the advent of climate change/variability and expected upstream developments. Modeling floodplain processes is a topical issue in environmental studies. This interest has arguably grown largely due to the need to protect such aquatic ecological systems from the adverse effects of land use and climate change, which are linked to environmentally degenerative anthropogenic activities. Wetlands have developed around the globe in different climates, physiographic regions, and hydrologic settings resulting in a wide diversity of types. No two floodplain wetlands are exactly the same, for they differ in size, shape, biological characteristics, environmental conditions and human influences (Tiner, 2009). Globally, floodplains may be of greater value to society than any other wetlands. This is because of the critical role that interactions between floodplains and associated streams play in maintaining supplies of ecological services. While this is conceptually simple, the processes which define interactions (i.e., floodplain functions) in aquatic–terrestrial ecotones are exceedingly complex (Lockaby *et al*., 2008). A floodplain as a type of wetland is the land surface adjacent to a stream or river that is formed, in-part, by river processes and floods during discharge events that flow out of the channel and onto the surrounding land surface. In most rivers, floodplain inundation occurs when the discharge exceeds the capacity of the channel and flows overbank. However, in some settings, flood waters will leave the river via flow paths that laterally connect the river and floodplain and inundate the floodplain prior to filling the channel. Floodplains wetlands occur in nearly all tributary and main-stem river valleys (with the exception of channel heads) and can be found in alluvial and bedrock rivers, though they are most common in alluvial rivers (Meitzen, 2018).

Hydrology is the primary driving force in floodplain wetland dynamics. Even though plant species and soil characteristics are generally used to identify wetlands, the dominant feature is the presence of excess water either on or beneath the land surface. The amount of water available in a floodplain wetland area at different times and the way the water moves in and out of the area are defined by the hydrology of the area and the hydraulics of flow, respectively. When the existing hydrologic regime is altered, the nature and functions of wetlands are also altered. Changes in hydrologic variables are the leading causes of wetland degradation or destruction (Wheeler *et al.*, 2009). Although the Upper Zambezi River Landscape still has a significant number of pristine wetlands such as the Barotse Flood Plains. It is increasingly experiencing immense pressure from climate change/variability and human activities (agriculture and settlement, exploitation by local communities and planned development activities).

The potential threats of a varying and changing climate and its impact on hydrological variables such as precipitation, stream flow, soil moisture, groundwater recharge, and evapo-transpiration (Nijssen *et al.*, 2001; Zhang, 2005; Zhang *et al.*, 2007) will likely increase more pressure on the Barotse wetland. Climate variability and change is expected to hit sub-Saharan Africa harder than many other parts of the world IPCC 2007). The Zambezi Basin is already experiencing drastic climate variability. In recent years the annual rainfall in the region decreased considerably, which in turn affects the annual flow levels of the Zambezi. Temperatures are predicted to rise by 5°C for some regions in the Basin, thus increasing evaporation even further. Hence, climate change may pose substantial risk to Africa's hydrology and its water resources and the Barotse wetland is not an exception (IPCC 2007). The most obvious and immediate effects of climate variability and change on hydrology involve changes in hydrologic patterns (the nature and variability of wet and dry seasons and the number and severity of extreme events) (Nijssen *et al.*, 2001; Zhang, 2005). Thus, the hydrology-hydrodynamic processes of wetlands need be understood in detail in order to understand the spatio-temporal dynamics of wetland. Given the fact that, water is naturally variable across the Earth and its variability in terms of presence and absence, timing, duration, frequency, extent, depth, and chemical properties makes each wetland such as Barotse floodplain unique. An understanding of wetland hydrological and hydrodynamic processes and the role it plays in shaping the wetland in space and time, is essential when managing it (Environment Canterbury, 2000).

1.3 Problem Statement

Floodplain ecosystems are adapted to the prevailing wetland hydrological and hydraulic processes. Their form and maintenance are governed to a large extent, by the hydrological and hydraulic processes that occur within them, and their interactions with the catchment in which they are located (McCartney *et al.,* 2011). The Zambezi River Basin (ZRB) hosts several wetlands of local and international importance such as the Barotse Floodplains. However, despite a number of studies in the Upper Zambezi (Winsemius, 2006; Meier et al., 2011; Matos, 2014; Kling *et al*., 2014; Kabika, 2017, Zimba *et al.,* 2018; McCartney *et al.,* 2018; Nyambe *et al*., 2018; Makungu, 2019) there is no existence of an integrated framework for coupling hydrology and hydrodynamic model to be used as the basis for developing coupled hydrology-hydrodynamic model for Barotse floodplain. This kind of framework is crucial as a tool in improving the hydrological and hydrodynamic modelling of the floodplains. Moreover, it can be a basis for assessing the impacts of present and future changes in the upstream basin and the floodplain itself, on water availability, predictability of low flows and floods and possible threats to the ecosystem and the unique socio-economical system supported by it. The thesis of this study is that that although standalone hydrological and hydrodynamic models play a significant role in in assessing Barotse floodplain dynamics, integrated modelling of both hydrology and hydrodynamic is necessary in closing the gap between hydrology and hydrodynamics in floodplain assessment especially for groundwater dependant tropical systems.

1.4 Aim

The aim of this study was to develop an integrated framework for hydrological and hydrodynamic modelling that contributes to closing the gap between hydrology and hydrodynamics for Barotse Floodplain assessments.

1.5 Objectives

The objectives of this study were fourfold.

1. To investigate the mechanisms of groundwater-surface water interaction in the Barotse floodplains.
2. To develop a rainfall-runoff hydrologic model for Upper Zambezi River basin focusing on modelling Barotse floodplain.
3. To develop an integrated hydrologic-hydrodynamic online (internal) coupling modelling framework for Barotse floodplains.

4. To test and evaluate the performance of one-way coupled Hydrological-Hydrodynamic Model based on the framework in objective 3.

1.6 Research questions

The key research questions are:

1. What is the nature of groundwater-surface interactions of the Barotse Floodplain?
2. What are the uncertainties in using hydrological model to model the Barotse Floodplain?
3. How can an integrated hydrologic-hydrodynamic modelling online (internal) coupling framework for assessing the groundwater-surface water dependent floodplain be developed.
4. What is the performance of Barotse Coupled Hydrological-Hydrodynamic model?

1.7 Significance of the Study

This study has generated a framework that is critical and a pre-requisite in understanding wetland-floodplain environments and can be used in determining their vulnerability to human or natural induced change. Such information is required for sustainable management of the Barotse Floodplain. The finding of this study is assertive in closing the gap between hydrology and hydrodynamic assessment for the Barotse Floodplain. Improved assessment of the floodplain is important in developing approaches for sustainable management of the floodplain for the benefit of people and nature.

1.8 Conceptual Framework

Conceptual framework is a visual or written product, one that explains, either graphically or in narrative form, the main factors, concepts, ideas, assumptions, variables, and the presumed relationships among them, through which research would be understood (Miles and Huberman 1994). The main processes that are directly or indirectly involved in floodplain dynamics and key processes in hydrological assessments of floodplains are shown graphically in Figure 1. The nature of these interactions and processes affects the assessment of spatial-temporal dynamics of the wetland hydrology.

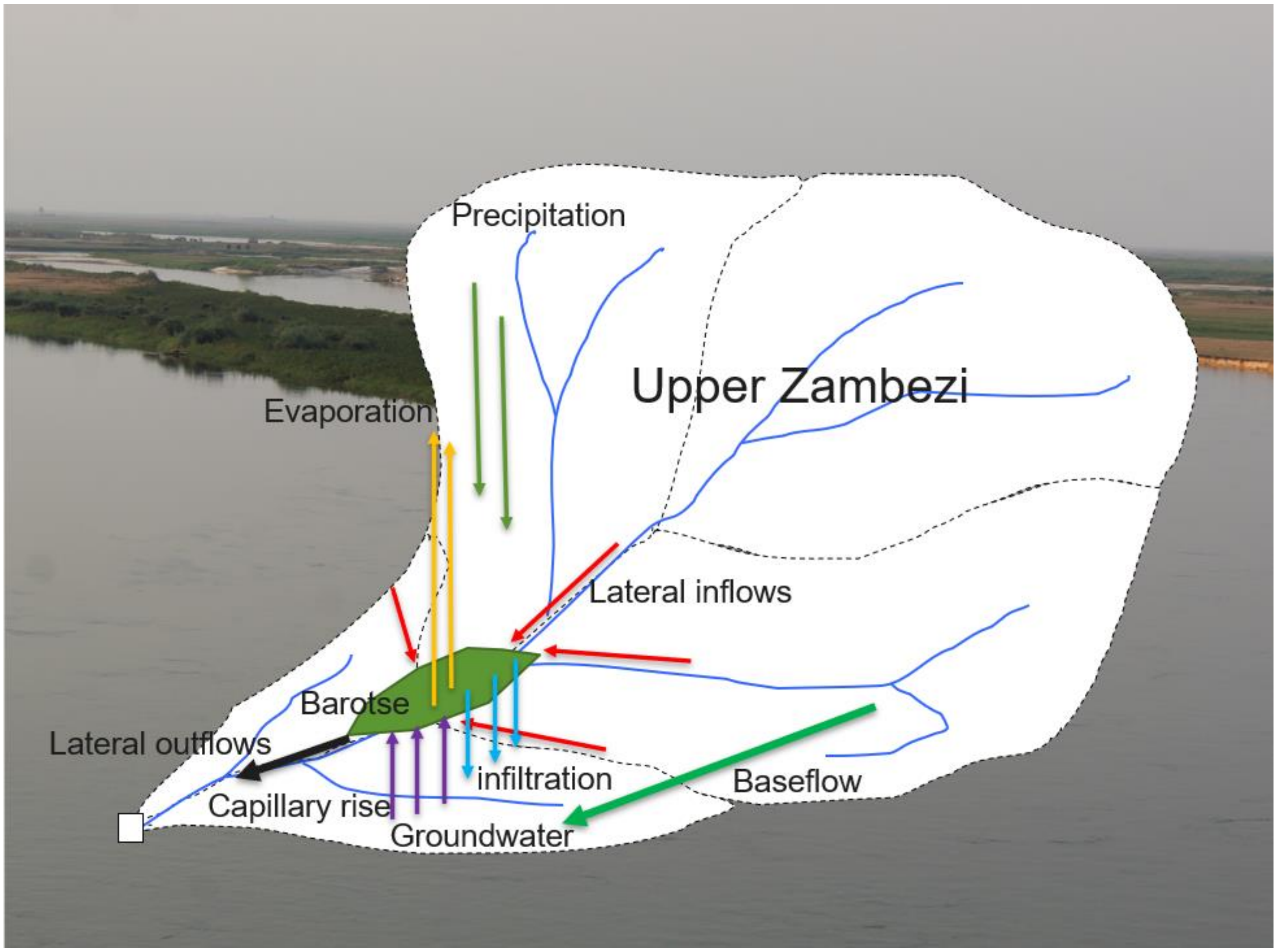


Figure 1: Basic conceptual understanding of wetland Hydrology in the Barotse Floodplain. (Source: Author of this study).

1.9 Ethical considerations

Consideration of ethics is fundamental to all research. According to Bassey (1995), research should be carried out within an ethic of respect for persons, respect for knowledge, and environment. Before going into field work, the researcher had submitted the thesis proposal to The University of Zambia for ethical clearance. Thus, the researcher obtained an ethical clearance letter from the University of Zambia to introduce the subject and the researcher (Appendix F). The ethical guidelines that were adhered to were as follows:

i. Respect for hosting communities that will be visited. The researcher will keep in mind a good relationship with people he will meet. During data collection local communities, a central principal of ethics, that is, informed consent was adhered to. The researcher will have informed key stakeholders about the purpose of research, why it was being undertaken and the institution which was overseeing it.

ii. Respect for knowledge and quality of geographical knowledge. In order to safeguard research against accusation of untruthfulness, the researcher has kept systematic and careful records in the project archive such that it would even be possible to work backwards through the archive of research from the research conclusion to the raw data and thereby be able to verify the conclusion.

1.10 Thesis Outline

Chapter 1 provides a background of the study, outlines the problem statement, aim, objectives, research question, significance of study, conceptual framework, and ethical considerations. Chapter 2 gives a review of literature with regard to key wetland drivers, hydrological and hydraulic models used in wetland assessments, groundwater-surface water interactions in wetlands, wetland modelling in the Upper Zambezi, application of Remote Sensing in wetland Studies and concludes with a summary of the literature reviewed. Chapter 3 presents the study area with regard to topography and drainage, main aquifers, soils, geomorphology, geology, vegetation and land use and climate. Chapter 4 provides the methodology starting with philosophical views behind this study, research design, data collection and analysis methods. Chapter 5 presents the results based on the objectives of the study. Chapter 6 discusses the results presented in Chapter 5. Chapter 7 gives the conclusions and recommendations. The thesis report ends with reference section and appendices.

CHAPTER TWO: LITERATURE REVIEW

2.1 Overview

This section presents literature reviews. It first reviews the drivers that determine the location and characteristics of wetlands and wetland Hydrology. It will further look at scholarly research work on hydrology and hydraulic modelling of wetlands globally, Africa and in Upper Zambezi, Zambia, and Channel-Floodplain Interactions. The section will close with a summary of key research gaps from reviewed literature that this study endeavour to address.

2.2 Key Wetland Drivers

Wetland hydrology is the study of storage and distribution of water into and out of a wetland (Ishida *et al*., 2006; Mekiso, 2011; Hayashi and Rosenberry 2013; Xiaolong *et al*., 2014). The definitions of wetlands vary. However, generally all definitions recognise that over time, wetlands have formed where water has accumulated at or close to the ground surface for periods enough to form wetland characteristics (National Wetlands Working Group, 1988; Cowardin *et al*., 1972). Thus, water creates and defines wetlands and distinguishes them from dry-land ecosystems, affecting every physical, chemical and biological process in wetlands and, in doing so, shaping their ecological character (Demissie, 1997). Wetlands themselves are commonly distinguished by three characteristics: the presence of water for all or part of the hydrologic cycle, unique soil conditions (hydric soils) and vegetation adapted to wet conditions, hydrophytes (Mitch and Gosselink 2000). Wetlands functions range from influencing both the quality and quantity of water, water storage, groundwater recharge and control of flooding and erosion and provide a habitat for a variety of fauna and flora, thus conserving the biodiversity, and are also used for tourism and recreation. (Gedan *et al.*, 2011; Ming *et al.*, 2007; Saunders and Kalff, 2001; Cole, 2006). According to Button and Tiner (2009), wetlands often occur as ecotones (transition zones) between dryland and a water body (e.g., along the margins of lakes, ponds, reservoirs, rivers, and streams or in channels of sluggish or intermittent streams and rivers. Low-lying lands in these locations may be frequently flooded during high-water periods. Many other wetlands however, form in areas not adjacent to a water body. These wetlands are found in isolated depressions on the land where water collects, on hill slopes where springs occur or groundwater seeps to the surface, in low areas with poorly drained soils (with seasonally high-water tables), and in areas where clayey soils, impervious rock, or other restrictions near the surface create a perched water table. Wetlands may also form in other altered landscapes such as mined lands (e.g., abandoned gravel pits). Thus, a wetland can be thought of as a wet land (that is land which is wet). But not all wet land results in a wetland. Because a wetland is found where the land is wet enough (i.e. saturated or flooded) for long enough to be unfavourable to most flora but are favourable to flora adapted to anaerobic soil conditions. As soil becomes increasingly wet, the water starts to fill the space; between the soil particles. When all the spaces are filled with water the soil is said to be saturated. In areas which are not wetlands, water drains away quickly, and the soil does not remain saturated. However, in wetlands the water persists or drains away very slowly, and the soil remains saturated or flooded for long periods (SANBI,2016). Climate and geomorphology are considered key wetland drivers that determine the location of wetlands across the landscape (Figure 2). They play an important role in determining characteristics of the wetland catchment and the characteristics of the wetland, such as its physical form, hydrology, water properties, biota and soils (Mitsch and Gosselink, 2000).

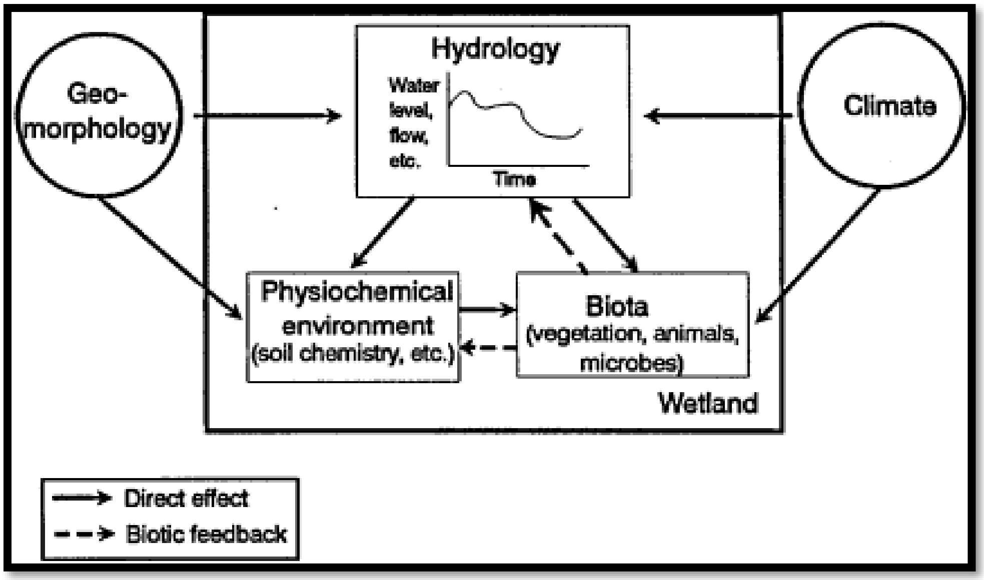


Figure 2. Key characteristics of all wetlands (hydrology, physico-chemical environment, and biota), key wetland drivers (geomorphology and climate) and the relationships between them as adapted from National Research Council by Victorian Department of Sustainability and Environment Papas, 2005).

2.2.1 Climate

Climate has an overriding influence on the distribution and abundance of wetlands and their biota globally. Generally, wetlands are more numerous in humid environments and become less common in drier climates (Semeniuk and Semeniuk, 1995). Climate also has a major influence on wetland hydrological regime (flooding, duration, extent, depth, seasonality, frequency, and variability). Hydrological variability in wetlands is closely associated with rainfall patterns. Over several years there may be periods that are wetter or drier than average which lead to longer-term changes in wetland filling frequency and duration of inundation. Diurnal and seasonal temperature fluctuations cause variations in daily and seasonal wetland water temperature. Temperature also affects hydrology through evaporation and transpiration (Papas, 2005).

2.2.2 Geomorphology

Geomorphic setting is a key factor that determines the water source of wetlands, the size and shape of wetlands, their location, their hydrology, physio-chemical properties of the water and soils (Figure 2) (Semeniuk and Semeniuk, 1995; Mitsch and Gosselink 2000). Moreover, physio-chemical environment such as soils are determined by geormorphic setting hosting the zone of biogeochemical activity where plants, animals, and microorganisms interact with the hydrologic cycle and other elemental cycles. A typical soil contains both mineral and organic materials as well as the adjacent water-filled and air-filled pore space. The physical and chemical properties of a soil may influence the processes that lead to wetland formation and function. The control is not one way; as biotic agents also greatly affect soil formation process. For instance, respiration by microbes that are mineralizing organic matter consumes oxygen in the saturated soil at a rate that is faster than the diffusion of oxygen back into the water held in pore spaces between soil particles. This creates anaerobic or anoxic (without oxygen) conditions in the soil (Button and Tiner, 2009).

2.3 Wetland Hydrology

Wetland hydrology is considered a key variable of wetland ecosystems, driving the development of wetland soils and leading to the development of the biotic communities (Mitsch and Gosselink, 2000). Hydrology controls the abiotic and biotic characteristics of wetlands (Figure 2). Abiotic characteristics such as soil colour, soil texture, and water quality depend on the distribution and movement of water, as do the abundance, diversity, and productivity of plants, vertebrates, invertebrates, and microbes. A wetland’s hydrology is determined by precipitation, evapotranspiration, and surface and groundwater inflows and outflows. Precipitation is controlled by climate; evapotranspiration is controlled by both climate and plant communities. Geomorphology and geology control inflows and outflows. Inundation frequency, duration and seasonality are components of wetland hydrology. Frequency of inundation refers to the average number of times a wetland is filled in each period. Duration is the length of time surface water is present and seasonality refers to the season in which inundation typically occurs (McKnight *et al.*, 1981; Mitsch and Gosselink, 2000).

Wetland hydrology is likely to be the single most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes. A wetland's hydrology both modifies and determines wetland characteristics (such as soil and biota) and, in turn, is affected by these characteristics, through a build-up of materials which leads to a change in wetland morphology (Tiner, 1999; Mitsch and Gosselink, 2000). Moreover, wetland hydrology influences the chemical and physical aspects of the wetland, which in turn, affect the biotic components. Hydrology affects the oxygen concentration in the soil, redox potential and availability of nutrients and toxicants. A longer duration of inundation will result in longer periods of anaerobic and/or reduced conditions that generally limit the plants that can survive. Consequently, wetlands with longer flooding durations generally have lower plant species richness than do less frequently flooded wetlands (McKnight *et al.,* 1981). Hydrology also affects the accumulation of organic matter. Longer hydro periods inhibit the breakdown of organic matter. Longer flooding periods will lead to the development of hydric soil properties and an accumulation of organic material (Tiner, 1999).

2.4 Hydrological and Hydraulic Modelling of Wetlands

In recent years the demand for an understanding the hydrological and hydraulic processes that govern floodplain wetlands is ever increasing especially with the advent of climate change-variability and its potential impact on water resources (Nijssen *et al.,* 2001; Zhang, 2005; Zhang *et al.,* 2007; Schumann *et al*., 2013). In the absence of adequate and continuous historical observations for most basins in Africa, advances in remote sensing and computing power and model coupling frameworks, have made models an increasingly attractive solution where spatial understanding of hydrology and hydraulics of wetlands is required (Hunter *et al.*, 2007). Thus, research on the hydrological dynamics of basins in Africa can benefit from these advances and coupling of hydrology and hydraulics to allow for physically more integrated assessments and to compensate for their respective shortcomings (Hoch *et al*., 2017a).

A distinctive approach to adequately calculate and represent physical processes within a basin is the application of a hydrological and hydraulic modelling. These models approximate the complex reality using a system concept. The overall intent of the hydrologic model system analysis is to study the system function and predict its output (Demissie *et al*., 1997), thus they are developed to understand different processes in the basin. Since the late 1950s many models have been developed to simulate the hydrologic and hydraulic processes occurring on basins. They are of many different types and are developed for different purposes (Demissie et al., 1997. Many have structural similarities due to the same underlying assumptions used in developing the models. Generally, models, focus on fulfilling two main objectives: i) to improve the understanding of the hydrological phenomena in the basins and how the changes generated in them affect the hydrological phenomena and, ii) the generation of synthetic sequences of hydrological data for the design of infrastructure or for its use in forecasting (Demissie *et al*., 1997).

On the basis of process description, the hydrological models can be classified in to three main categories. Lumped, distributed, and semi distributed models. Lumped models; parameters of lumped hydrologic models do not vary spatially within the basin and thus, basin response is evaluated only at the outlet, without explicitly accounting for the response of individual sub-basins (Demissie *et al*., 1997). Most of the time these models are not good for event scale hydrological processes. If the interest is primarily in the discharge prediction only, then these models can provide just as good simulations as complex physically based models. The other one is distributed models; parameters can easily vary in space at the desired resolution based on the preference of the user. Distributed modelling approach attempts to incorporate data concerning the spatial distribution of parameter variations together with computational algorithms to evaluate the influence of this distribution on simulated precipitation-runoff behaviour. Distributed models generally require large amount of data to adequately justify the use of distributed model especially in poorly gauged catchments (Demissie *et al*., 1997). However, the governing physical processes are modelled in detail, and if properly applied, they can provide the highest degree of accuracy. The last one is semi-distributed models. Parameters of semi-distributed (simplified distributed) models are partially allowed to vary in space by dividing the basin into several smaller sub-basins. The main advantage of these models is that their structure is more physically based than the structure of lumped models, and they are less demanding on input data than fully distributed models (Demissie *et al*., 1997).

2.5 Hydrological and Hydraulic Models

Ideally, a watershed hydrologic and hydraulic model capable of simulating wetland hydrology and hydraulics should include the ability to model rainfall, evapotranspiration, surface runoff, subsurface infiltration, groundwater flow, storage within the wetland, and flow through man-made drainage structures, as well as stream flow. The model should be capable of routing flows through wetland depressions in addition to routing overland flow, stream flow, and subsurface flow (Bengtson and Padmanabhan, 1999). Although a wide variety of existing hydrological and hydraulic models are available that are suitable for each of these individual tasks, few single models can do all these jobs.

Hence, the need for a coupled model simulation. Magungu (2019), argues that the choices of appropriate model are constrained by; 1) the purpose of the study; 2) the availability of data to run the model; 3) the hydrological processes captured in the model structure; 4) the time required to understand and become proficient at using a model. Based on these criteria, three hydrological models (WFLOW, SWAT, and PITMAN) and two hydraulic models (MIK SHE and LISFLOOD-FP) were reviewed in the present study.

2.5.1 Wflow_sbm Hydrological Model

Wflow is a rainfall-runoff grid physically based distributed model, part of the Deltares open streams project. It uses open-source global data such as DEM, surface water network, land cover, soil types and their parameters to simulate hydrological processes from climate data such as precipitation, temperature and radiation (Hassaballah, *et al.*, 2017; Deltares, 2019). Its physical basis and use of global data make it suitable for cases where field observed data is lacking (Deltares, 2019; Umuhuza 2020) and not adequate as is the case for the Upper Zambezi Catchment. The model was programmed in Python using the PCRaster Python extension (Deltares, 2019). The model consists of a set of python programs run on a command line to perform hydrological simulations over grid cells of static PCRaster maps (Vertessy and Elsenbeer, 1999; Roo, *et al*., 1996). Based on gridded topography, soil, land use and climate data, wflow_sbm calculates all hydrological fluxes at any given point in the model at a given time step. The movement of surface water across the landscape is determined by the reservoir and kinematic wave modules providing more accurate representation of river discharges. To route the water downstream, the model uses the same kinematic wave routine as the wflow_sbm model. The wflow_sbm model maximise the use of available spatial data by linking parameter values to soil or land use.

The distributed nature of the model implies that the model is run on each grid cell and that water flows from one grid cell to another either through the kinematic wave routine and/or through lateral groundwater flow (Deltares, 2019). Figure 3 shows water fluxes as modelled by wflow_sbm). In the soil model the focus is on the following fluxes: 1. Infiltration is calculated considering the soil infiltration capacity with use of the soil parameters. 2. Soil water accounting into the soil depth: saturated and unsaturated media 3. Transpiration and soil evaporation based on the soil water content and the vegetation canopy fraction. Among the water fluxes calculated in wflow there is the actual evapotranspiration for the land cover. The inputs used are raster maps of model inputs in combination with tabular parameters. The maps of parameters that don’t change over time are referred to as static maps while the maps of model inputs that change over time are prepared as map stacks per time step and are referred to as dynamic data (Deltares, 2019). The figure 4 below shows the stores and fluxes in the wflow model in terms of internal variable names.

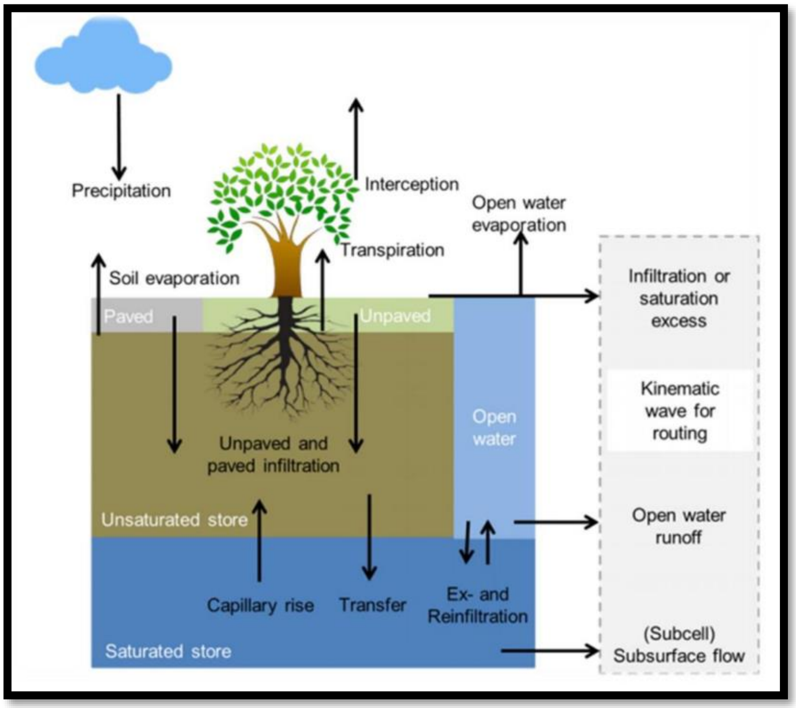


Figure 3.Water fluxes as modelled by wflow_sbm (Deltares, 2019).

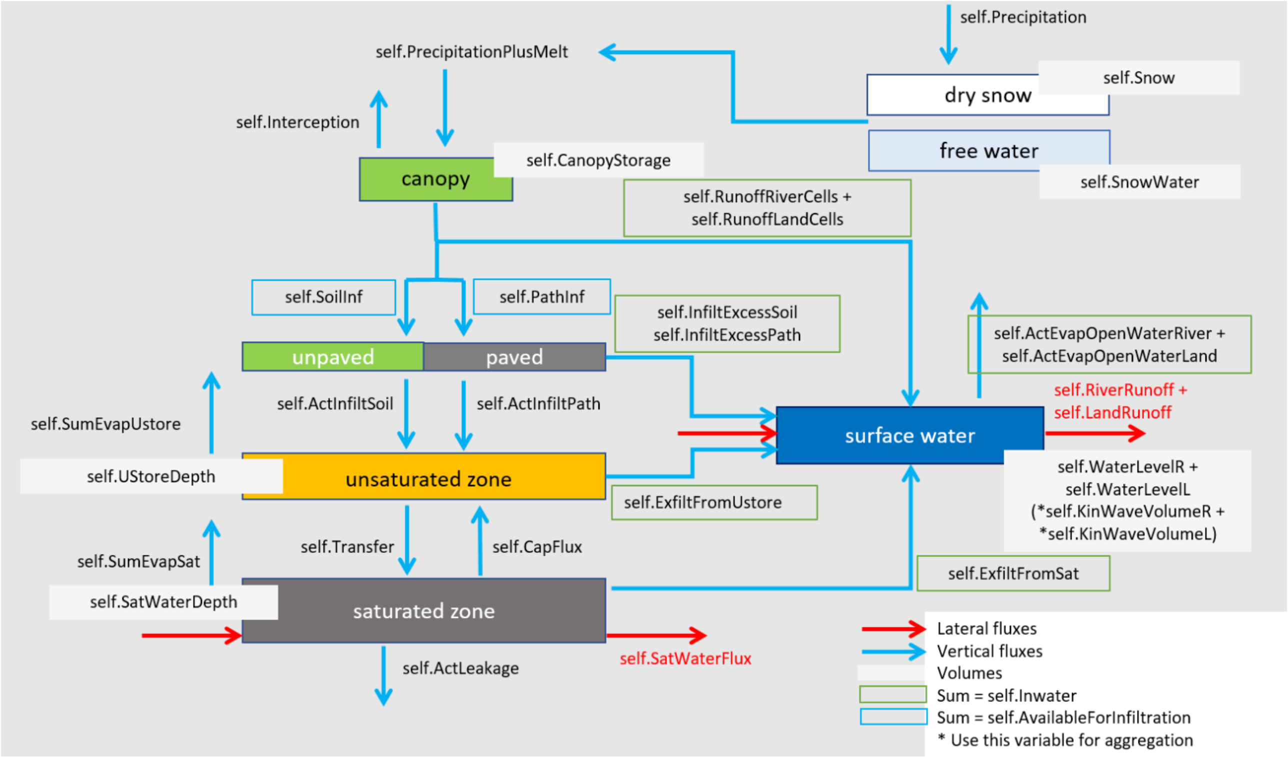


Figure 4.Stores and fluxes in wflow model in terms of internal variables (Deltares, 2019).

The wflow is exposed to the outside world via the industry standard Basic Model Interface (BMI) (https://csdms.colorado.edu/wiki/BMI_Description). Using this standard, the models have been successfully connected to other modelling suites such as D-Flow FM and D-Water Quality (DELWAQ) modules of the Delft3D FM Suite. As wflow uses the Python language as its basis, it has a transparent structure that can be adapted by modellers for their specific needs. This flexibility provides for easy integration with other models. Wflow_sbm has already been applied in various studies: Umuhuza, (2020) applied wflow_sbm model results for the estimation of potential irrigation capacity in the Rwandan part of Akagera catchment by comparing the simulated water availability to the estimated irrigation water demand under specific conditions; Azedeh (2015) modelled runoff of an Ethiopian catchment with wflow; Emaerton *et al*.,(2016) applied it in continental and global scale flood forecasting systems; Hassaballah *et al* (2017) investigated on the streamflow responses to land use land cover changes using satellite data and hydrological modelling in North Africa Dinder Blue Nile tributary; Lopep lopez *et al.,* (2016) investigated on improved hydrological modelling through assimilation of streamflow and downscaled satellite soil moisture observation.

2.5.2 SWAT hydrological model

The Soil and Water Assessment Tool (SWAT) model is a popular semi-distributed mechanistic watershed model that is used to evaluate the effects of land management and agriculture on water, sediment, and chemical fluxes across a wide range of watershed sizes, land uses, and physiographic provinces (Neitsch *et al*., 2005). The main purpose of the model is to predict the impacts of land management practices on water, sediments, and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over a long period of time (Neitsch *et al*., 2005; 2008; Makungu 2019). Wetlands are represented in two ways in SWAT: 1) as a reservoir on the main channel and; 2) located off-channel and receiving loadings only from the portion of the sub-basin where it is located (Martinez-Martinez *et al.,* 2014). Ndomba *et al*. (2010) applied the model to understand the hydrological characteristics of the Rugezi Wetland in Rwanda. Even though the SWAT model is a semi-distributed physical model, some wetland processes are not well captured in the model (Zhang *et al*., 2013; Rahman *et al*., 2016). As a result, some researchers Zhang *et al*., 2013; Rahman *et al.,* 2016) have modified the SWAT wetland module to improve its structure in their studies. For example, Zhang *et al*. (2013) modified the SWAT wetland component to simulate hydrological processes within the Zhalong Wetland in northeast China. The most recent wetland module of SWAT is SWATrw (Rahman *et al.,* 2016), in which the unidirectional hydrological interactions between wetlands and the river or aquifer have been modified, with a bidirectional approach to represent the interactions between riparian wetlands and the river (Makungu 2019). Additionally, Phiri *et al.,* (2021) proposed a novel pseudo-reservoir concept (PSRC) in the framework of the Soil and Water Assessment Tool (SWAT), to mimick and model the behaviour of an alluvial floodplain. Outflows from PSRC are predicated on a conceptual storage-outflow-stage relationship and decomposed into overflow and baseflow by considering floodplain hydrogeomorphic attributes and their dynamics in relation to critical bankful height.

2.5.3 Pitman hydrological model

Pitman (1973) developed the original version of the Pitman model for simulating runoff in both gauged and ungauged catchments in South Africa. The model primarily operates on a monthly time scale and its main inputs are rainfall and potential evapotranspiration. The model has undergone several modifications since its inception to improve its structure. The most recent modifications include the addition of surface–groundwater interactions (GW Pitman: Hughes, 2004), the inclusion of the model into a comprehensive uncertainty framework (Hughes *et al*., 2010), a wetland component (Hughes *et al.,* 2014) and a sub-model to disaggregate monthly flow values to daily discharge using daily rainfall data (Slaughter *et al*., 2015). The semi-distributed concept has been applied to the recent versions of the model in which a basin is divided into discrete areas (sub-basins), and these units are modelled independently. However, wetland hydrologic-hydraulic feedback processes are not captured in the Pitman wetland sub-model (Makungu 2019).

2.5.6. MIKE 21 hydraulic model

MIKE SHE model is commercial and an integrated hydrological modelling system for building and simulating surface water flow and groundwater flow. MIKE SHE can simulate the entire land phase of the hydrologic cycle and allows components to be used independently and customized to local needs. MIKE SHE emerged from Système Hydrologique Européen (SHE) as developed and extensively applied since 1977 onwards by a consortium of three European organizations: The Institute of Hydrology (the United Kingdom), SOGREAH (France) and DHI (Denmark) (DHI, 2004). However, the model can also be applied to floodplains, lakes and reservoirs (DHI, 2007). The model applies depth-averaged Saint-Venant equations and uses an implicit finite difference scheme to solve for continuity and momentum on each grid mesh covering the whole model domain (Karim *et al.,* 2012). The main model inputs include topography (DEM), boundary conditions (inflows and outflows), initial conditions, rainfall, evaporation, infiltration, bed roughness and other parameters such as eddy viscosity (DHI, 2004; 2007; Makungu 2019).

2.5.7 Lisflood-FP hydraulic model

Lisflood-FP is a two-dimensional (2D) non-commercial raster-based flood inundation hydraulic model designed for research purposes for simulating river flooding and floodplain inundation in data-scarce catchments by the University of Bristol. The model includes several numerical schemes (solvers) that simulate the propagation of flood waves along channels and across floodplains using simplifications of the shallow water equations. The choice of numerical scheme will depend on the characteristics of the system to be modelled, requirements on time of execution and the type of data available. The Lisflood-FP model inputs include upstream and downstream boundary conditions (discharge and water level), topography (DEM), river bathymetry (width and depth, bed elevation) and channel and floodplain roughness. In data-scarce areas where most of the river bathymetry data are not available (e.g. bankfull depths, bed elevation), the model estimates these variables using the hydraulic geometry equation. The simulated results consist of time series of channel and floodplain inundation extent, storage, and water depths in the wetland. The model is capable of simulating inundation for both small and large wetlands (1 000 to 100 000 km^2) at a high spatial-temporal resolution. A major advantage of LFP is its easy model creation which requires, for the simplest set-up, only ascii files describing the DEM, the channel width and bed level elevation, as well as the riverbank height. The computational grid is regular in all applications. A More model description and background information on Lisflood-FP can be found in, (Bates *et al.*, 2010; Bates *et al*., 2013). Additionally, Lisflood-FP has speed advantages for large domains as well as application in data scarce areas (Makungu, 2019, Bates and De Roo, 2000; Bates *et al*., 2010). Some of the Lisflood-FP model applications in Africa include to the Luangwa, Upper Zambezi, and the Usangu wetlands River basins (Makungu 2019), Lower Zambezi Delta (Schumann *et al*., 2013), the Inner Niger Delta (Zahera, 2011; Neal *et al.*, 2012).

2.6 Coupled Hydrologic and Hydraulic Models

According to Wang and Yang (2020) in order to protect ecologies and the environment in floodplains, analysis of changes in these water resources require a tool capable of modelling both small scale and large-scale basins. Hydrologic models are good at simulating rainfall-runoff processes on a large scale e.g., over several hundred km^2, while hydraulic models are more advantageous for applications on smaller scales. In order to take advantage of the unique capabilities of these two types of models, coupling them is a viable technique. Hydrologic models are employed to understand dynamic interactions between climate and land-surface hydrology (Singh and Woolhiser, 2002). Hydrologic models rely on the parameterisation of watershed properties and rainfall patterns and depths to produce a flood hydrograph of discharge at discrete time steps. These models have become widely used in flood forecasting, stream flow prediction, and to quantify effects of climate change, land use impacts or other spatially distributed properties. However, their limited routing methods do have some drawbacks in simulating flows in large watersheds (Abshire 2012; Wang and Yang 2020). Hydrologic and hydraulic modelling plays a crucial role in floodplain studies and there is much to gain in incorporating these modelling capabilities. Model coupling enables these coupled models to share fluxes at each time step as feedback is important and its accounted for. Hence, in order to compensate for the weaknesses of hydrologic and hydraulic modelling in flood modelling, it is becoming quite common to couple hydrologic and hydraulic models for floodplain simulation use (Hoch *et al*., 2019).

Coupling numerical models can be categorized into three categories: full coupling, internal (tight) coupling and external (loose) or coupling). Full coupling involves reformulating the governing equation for coupled models and solving it as a whole. While internal coupling involves solution of all model equations, and then iterative updating of shared model data using tool such as a coupling framework, which does not change model code (Haghizadeh, *et al.*, 2012; Abshire 2012). Such coupling uses information that would have major impacts on the coupled models and obviously can reduce the programming effort and computational costs. The simplest and most common approach is external coupling which performs simulations from each model. Modeled results from one or more models are used as the input to another model. Coupling tools are needed as interface in internal coupling, since hydrologic and hydraulic models are conceptually different standalone models. A variety of different model coupling frameworks are currently in use or under development in support of hydrologic and hydraulic model coupling such as GLOFRIM (GLObally applicable computational FRamework for Integrated hydrological–hydrodynamic Modelling;), ESMF (Earth System Modeling Framework), OASIS4 (part of PRISM), OpenMI (Open Modeling Interface) and CCA (Common Component Architecture) (Peckham, 2008; Peckham *et al*. 2013; Hoch *et al.*, 2017). These tools enable the user to create a coupled model whereby a hydrologic model is used to determine the conversion from rainfall to runoff for a number of sub-catchments. The resulting hydrographs are used as upper boundary conditions of a hydrodynamic model.

Thus, research on the hydrological dynamics of the Barotse Floodplain can benefit from these advances and coupling of hydrology and hydraulics in inundation models to allow for physically more integrated assessments and to compensate for their respective shortcomings (Hoch *et al*., 2017a). Currently for the Barotse floodplain, approaches to try and understand the wetland dynamic process are based on either a hydrologic or a hydrodynamic model and trend analysis of flooding using remotely sensing products (Michailovsky and Bauer-Gottwein, 2013; Zimba *et al*., 2018; Makungu,2019). However, as Hoch *et al*., (2017b) reasons, the resulting lack of interaction between hydrology and hydraulics, for instance, by employing groundwater infiltration on inundated floodplains, can hamper modelled inundation and discharge results where such interactions may potentially be important in this case in the Barotse floodplain.

Globally, with computation power increasing over the past decade, hydrologic–hydrodynamic coupling has already been applied in a number of studies (Lian *et al*., 2007; Biancamaria *et al*., 2009; Kim *et al*., 2012; Schumann *et al*., 2013; Hoch,2019). For example, by using GLOFRIM, Hoch *et al*., (2019) coupled the global hydrologic model PCR-GLOBWB with the hydrodynamic models CaMa-Flood and Lisflood-FP. Results show that replacing the kinematic wave approximation of the hydrologic model with the local inertia equation of CaMa-Flood greatly enhances accuracy of peak discharge simulations as expressed by an increase in the Nash–Sutcliffe efficiency (NSE) from 0.48 to 0.71. Flood maps obtained with LISFLOOD-FP improved representation of observed flood extent. It was concluded that model coupling can indeed be a viable way forward towards more integrated flood simulations. However, results also suggested that the accuracy of coupled models still largely depends on the model forcing (Hoch *et al.*, 2019). Lian *et al.*, (2007) linked the hydrologic model HSPF with the one-dimensional hydraulic model UNET in order to capture the complicated hydraulics of the Illinois River. They compared the linked model and HSPF alone to see how well the models reproduced historical flows. Their work found a decrease in error of simulated flood peaks as compared to observed peaks, and slight increases in efficiency of the coupled model in daily, monthly and annual flows, though this decreased with increasing time period. These studies show the possible improvements that can be realised through model coupling. Hoch *et al*., (2019) argues that since flooding inundation is driven by hydrologic or river routing and floodplain flow processes and are often simulated by different models, coupling these models may be a viable way to increase the integration of different physical drivers of simulated inundation estimates.

In Africa a number of studies have used coupled hydrologic and hydraulic coupling to understand flood inundation such as Komi *et al*., (2017) used a flood modelling approach to simulate flood extent in data scarce regions of Western Africa by using a hydrological model (Lisflood) and flood inundation model (Lisflood-FP). This was done in order to improve the provision of flood hazard information in the study area and across West Africa The methodology was based on a calibrated, distributed hydrological model for the whole basin to simulate the input discharges for a hydraulic model which was used to predict the flood extent for a 140 km reach of the Oti River thus, thy require both hydrological and hydraulic models to first simulate the peak flows or high water level and then simulate inundation of this peak to identify flood-prone areas. The outcomes of this study were anticipated to contribute towards an efficient flood risk management decision for Oti River basin.

Abdessamed and Abderrazak (2019), in their coupled modelling focused on the hydrologic modeling through the Hydrologic Engineering Center's Hydrologic Modeling System HEC HMS and the hydraulic modeling under the Hydrologic Engineering Center's River Analysis System with combination of Watershed Modeling System model and Geographic Information System. The aim of this study is to analyze the inundation behavior of Ain Sefra city during extreme flood events by considering concrete retaining walls existence built by local authorities and without it. The hydraulic modeling revealed that the existence of retaining walls resulted in decrease of flood zone area, and so much less lands are endangered by floods, so that damages of flood at the study area decrease clearly, but they still been insufficient for all return periods. The simulations also highlighted that the region most affected by the flood is the downtown area. Thus, they present paper presented an effective approach to estimate the peak discharge of flows developed from high rainfall events uniformly cover Ain Sefra watershed, and to predict and assess downstream flood hazard by the integration of hydrologic and hydraulic modeling and GIS.

Fleischmann *et al.*, (2017), in their study, they present the application of MGB-IPH large scale hydrologic and hydrodynamic model for the Upper Niger Basin, totaling 650,000 km2. The model coupled hydrological vertical balance and runoff generation with hydrodynamic flood wave propagation, by allowing infiltration from floodplains into soil column as well as representing backwater effects and floodplain storage throughout flat areas such as the Inland Delta. Model results show good predictions for calibrated daily discharge and validated water level and altimetry at stations both upstream and downstream of the delta (Nash-Sutcliffe Efficiency>0.7 for all stations), as well as for flooded areas within the delta region (ENS=0.5; r2=0.8), allowing a good representation of flooding dynamics basin wide and simulation of flooding behavior of both perennial (e.g., Niger main stem) and ephemeral rivers (e.g., Niger Red Flood tributaries in Sahel).

Coupling between hydrology and hydrodynamic processes indicates important feedback between floodplain and soil water storage that allows high evapotranspiration rates even after the flood passage around the inner delta area. Finally, such coupled hydrologic and hydrodynamic models prove to be an important tool for integrated evaluation of hydrological processes in such ungauged, large scale floodplain areas. Possible uses of the model involve the assessment of different scenarios of anthropic alteration, e.g., the effects of reservoirs implementation and climate and land use changes. Meanwhile, Fleischmann *et al*., (2018) in order to demonstrate benefits from coupling hydrologic and hydraulic models, the model was applied to the Upper Niger River basin encompassing the Niger Inner Delta, a vast semi-arid wetland in the Sahel Desert. Evaluation of model structure indicated that representation of both floodplain channels hydrodynamics (storage, bifurcations, lateral connections) and vertical hydrological processes (floodplain water infiltration into soil column; evapotranspiration from soil and vegetation and evaporation of open water) are necessary to correctly simulate flood wave attenuation and evapotranspiration along the basin. Two-way coupled models are necessary to better understand processes in large semi-arid wetlands. Finally, coupled hydrologic and hydrodynamic modelling proves to be an important tool for integrated evaluation of hydrological processes in such poorly gauged, large-scale basins. Subsequently, hydrological model coupled with Hydraulic Model of the floodplain provides improvements in floodplain model simulations and hence better information for floodplain management. Consequently, this would lead to improved decision-making and planning of adaptation and mitigation measures for sound floodplain wetland management plans and programmes especially with the advent of climate change and variability (Chomba *et al.*, 2021).

2.7 Groundwater-Surface Water Interactions in Wetlands

Globally, there has been many attempts to better understand the interaction mechanisms between groundwater and surface water in influencing the dynamics of wetland hydrology. Due to the complexity of process interactions in wetlands, quantifying a water balance through field observations alone is often impractical (House *et al*., 2015). Comprehensive wetland studies have instead relied on simulation of hydrological processes within fully integrated or coupled groundwater-surface-water models (Refsgaard, 1998; Crowe *et al*., 2004; Krause and Bronstert, 2005; Thompson *et al*., 2009; Frei *et al*., 2010). Understanding and modelling of hydrological processes in the wetland is further complicated by in-channel macrophyte growth and management, a compound geology, and subtle groundwater-surface water interactions (House *et al.,* 2015). Thus, models that can accurately represent wetland hydrological processes have enormous potential in the assessment of potential degradation to the ecological character of wetlands and their management (Acreman and Jose, 2000). In wetlands, the water balance can incorporate a significant measure of groundwater (Bravo *et al*., 2002; Krause and Bronstert, 2005). This can be time dependent, spatially heterogeneous, and influenced by topographical, geological, and climatic factors Hunt *et al*., 1999; Lowry *et al*., 2007; House *et al*., 2011; Sophocleous, 2002). The magnitude of the flux can exert strong controls upon the hydrological regime, nutrient status, and species composition (Wheeler *et al*., 2009; House *et al*., 2015).

Groundwater-Surface water interactions can strongly influence ecological productivity of wetlands. These interactions can have appreciable transient characteristics and can exert significant effects on the biology of a local stream-wetland system and on the dynamics of wetland hydrology and solute transport significantly. Therefore, it is important to incorporate the effect of processes such as surface-ground water interactions into wetland models and understand its consequences on attenuation, flood inundation and flood advancement, flood mitigation, groundwater exploitation, and biodiversity conservation, in a more integrated and sustainable manner (Schot and Winter, 2006; Kazezyelmaz-Alhana and Medina 2007). Quantification and understanding of this interaction is extremely important for determining of environmental river flows, identifying transportation of contaminants across the stream-aquifer boundary and managing in-stream ecology (Cook *et al*., 2003). Moreover, assessing groundwater–surface water interaction within a wetland may be required to accurately assess and manage the ecological habitat of the wetland (Hunta, 2006). Thus, the impacts of abstraction, sustained low river flows, climate change, or feedback from water management activities taking place within the catchment could result in significant adverse impacts, particularly where wetlands are underlain by permeable geology. The interactions between ground water and streams, lakes and wetlands are discussed by Winter *et al.,* (1998) in detail. Winter (1999) discussed the role of topography, geologic framework, water table level and climate on ground water interaction with streams and wetlands. The importance of surface-ground water interactions in wetlands on wetland functions are discussed in a study by Price and Wadington (2000). Restrepo *et al*., (1998) developed a computer package for MODFLOW to simulate the interaction of wetlands with aquifers. McHale *et al*., (2004) investigated stream wetland interactions by measuring nitrogen in stream and ground water at a riparian wetland site located in the Archer Creek watershed in the Adirondack Mountains of New York State.

McEwan *et al*., (2006) suggest that in semi-arid areas, surface water-groundwater interactions in wetlands are highly dynamic, are both temporally and spatially complex, and often extend beyond the surface water boundaries of the wetland. Surface water-groundwater interactions in wetlands are mostly controlled by factors such as differences in head between the wetland surface water and groundwater (which in turn are controlled by climate, catchment land use and river management), the local geomorphology of the wetland (in particular the texture and chemistry of the wetland bed and banks), and the wetland and groundwater flow geometry. Surface water-groundwater interactions in wetlands can be broadly classified into three flow regime types: (i) recharge - wetland loses surface water to the underlying aquifer; (ii) discharge - wetland gains water from the underlying aquifer; or (iii) flow through – wetland gains water from the groundwater in some locations and loses it in others. However, it is important to note that individual wetlands may temporally change from one type to another depending on how the surface water levels in the wetland and the underlying groundwater levels change over time in response to climate, and catchment and river management (McEwan *et al*.,2006).

Some studies (Verry and Boelter, 1978; Siegel, 1988) have emphasized that the important control on the hydrologic behaviour of wetlands is the interaction of surface water and groundwater intermediate or regional scale groundwater with smaller scale local groundwater flows. In wetlands which receive continuous groundwater discharge, such as in fens and swamps, water table position and surface hydrology are relatively uniform as groundwater sources buffer episodic precipitation events. Studies on wetlands isolated from large-scale groundwater discharge, as in many raised bogs and poor fens, suggest that water interacts primarily with the surface layer of peat, and water table fluctuations and the surface hydrology of these wetlands are influenced by the seasonality of local scale groundwater links and precipitation (Verry and Boelter, 1978; Taylor and Pierson, 1985). Consequently, wetlands connected to local aquifers may show a range of groundwater connections and contrasting seasonal patterns of surface saturation and water levels resulting in different runoff patterns and water balance (Devito *et al.,*1996)

Guggenmos *et al., (*2011a) utilised high resolution physical and chemical measurements to investigate the groundwater and surface water interactions of the small temperate Mangatarere Stream in New Zealand. The research focused on the use of chemical tracers to investigate surface water and groundwater interactions but supplementing these with physically based methods (that is water temperature and stage quantification). Results obtained from the Mangatarere catchment confirmed the temporal complexities of groundwater and surface water interaction and highlighted the benefits of multiple investigative approaches and the importance of high frequency hydro-chemical sampling and monitoring for hydrological processes understanding in catchments. By monitoring similarities and differences in tracer behaviour, one can gain insight into the relative importance of different catchment water sources and the potential interaction between chemically distinct groundwater and surface water bodies. Common approaches employed in the investigation of groundwater and surface water interaction include quantification of changes in water stage and discharge, water temperature, chemical tracers and/or hydrograph separation (Sophocleous, 2002).

Numerous studies suggest that similarities in water composition, total dissolved solids, nutrient concentrations and ion ratios between neighbouring groundwater and surface water bodies can also be used to infer potential surface water-aquifer interaction (Burden, 1982; Taylor *et al.,* 1989; Kumar *et al*., 2009). Groundwaters that provide base flow to surface water systems generally elevate surface water TDS and transfer their chemical signature (typically Na-Cl-NO3) to overlying fluvial systems (Taylor *et al.,* 1989; Rozemeijer and Broers, 2007). Furthermore, groundwater systems that receive a significant proportion of recharge from river systems have been found to display a relatively dilute Ca-HCO3 chemical signature typical of global freshwater river systems dominated by carbonate dissolution. The interaction of ground water and surface water in river valleys is affected by the interchange of local and regional ground-water flow systems with the rivers and by flooding and evapotranspiration. Larger rivers that flow in alluvial valleys, the interaction of ground water and surface water usually is more spatially diverse than it is for smaller streams. Ground water from regional flow systems discharges to the river as well as at various places across the flood plain. At some locations, such as at the valley wall and at the river, local and regional groundwater flow systems may discharge in proximity (Burden,1982; Berner and Berner, 1996; Guggenmos *et al*., 2011b).

Kazezyelmaz-Alhana and Medina (2007) explored the role of surface-ground water interactions on wetland sites to develop accurate wetland models. In this study, the effect of surface/ground water interactions on wetland hydrology was investigated for different wetland conditions, such as vegetation, slope of the land site, and lateral and vertical hydraulic conductivities by using the wetland model WETland Solute TrANsport Dynamics (WETSAND). It was observed that the effect of surface-ground water interaction on surface water depths were more dominant on wetland sites with high slopes and low vegetation. In another study, House *et al.,* (2015) used physically based, distributed model MIKE SHE to simulate hydrological processes at the CEH River Lambourn Observatory, Boxford, Berkshire, UK. Model calibration and validation was based upon comparisons of observed and simulated groundwater heads and channel stages over an equally split 20-month period. Model results were generally consistent with field observations and included short-term responses to events as well as longer-term seasonal trends. It was concluded that the hydrological processes in the wetland are dominated by the interaction between groundwater and surface water. Channel stage provides head boundaries for broad water levels across the wetland, whilst areas of groundwater upwelling control discrete head elevations. A relic surface drainage network confined flooding extents and routes seepage to the main channels. In-channel macrophyte growth and its management had an acute effect on water levels and the proportional contribution of groundwater and surface water.

Okruszko (2006) investigated on the groundwater-surface water interactions in the Biebrza Wetlands in north-eastern Poland. The most characteristic feature of the Biebrza River is flooding, which appears there almost every year. In the period 1999–2002, investigation of the flooding phenomena was carried out in order to understand the main processes involved in the inundation of the river valley and to combine them with characteristic vegetation patterns. The investigation used Landsat images, a hydrodynamic 1-D model of river and flood plain flow, and chemical analysis of flood waters. It was shown that river water was responsible for inundation of part of the valley only. Other parts of the valley were inundated by ground-water seepage. Inundation of the Biebrza wetlands resulted from the interaction of water coming from three different sources: flooded river water, exfiltrated groundwater as well as water coming from in situ snow melt. These observations were related to qualitative descriptions of water sources for some plant communities in the wetland. They further recommended that case of ecological studies aiming on conservation or restoration of habitat conditions of wetlands, there is a need for coupling regional ground water models with the hydrodynamical models for predicting the flood extent.

Li *et al.*, (2018) explore surface water-groundwater dynamics, interactions, and fluxes in a geographically complex river floodplain lake system in Poyang Lake, China. The floodplain system of Poyang Lake (China) has a large water storage capacity, where surface water -groundwater interactions play an important role in affecting its hydrological and ecological functioning for both the lake and wetland. Statistical analysis indicated that the wetland groundwater dynamics were mainly controlled by the river (R^2 = 0.93–0.98), rather than the isolated wetland (R^2 = 0.39–0.89), demonstrating that the river is a dominant factor in controlling adjacent floodplain groundwater levels. The combined effect of hydraulic gradient and geology of the floodplain determine the differences in the flux dynamic between the river, isolated wetlands, and groundwater interactions. In most cases, the river showed gaining conditions and occasionally losing conditions, with highly variable Darcy fluxes up to +0.4 and −0.2 m/day, respectively. The accumulated flux for the interactions between surface waters and groundwater exhibited distinctly seasonal variations. The seasonal flux rates for the surface water–groundwater interactions ranged from 7.5 to 48.2 m/day, whereas the flux rate for river–groundwater interactions was around four to seven times higher than that of the isolated wetland–groundwater interactions. They started that determining these interactions is critical for flood control and water resource management, as well as for understanding how the floodplain wetland may be potentially affected by the surrounding hydrological regime and how the wetland affects the local hydrology and ecosystem of the wetland. Generally, it is noted that groundwater dependent wetlands are unique in that baseflow is maintained by groundwater. As a result, even in the worst drought, the lower reaches of the wetland still have water in them. This is not to say that parts of the wetland don’t naturally dry-up seasonally, however the primary controlling factor of the ecosystem fauna and flora is its hydrology. This dependence means that maintaining aquifer levels above a certain minimum is essential to maintaining wetland health. (Environment Canterbury, 2000).

2.8. Wetland Modelling in the Upper Zambezi

Mohammed, (2015) study focused on hydraulic flood modelling to simulate flood inundation characteristics that would benefit provision of recession farming, canal management, and land use planning in the Barotse floodplain. This study was the first study in attempting to model the flood dynamics of Barotse floodplain. For this study the one-dimensional hydrodynamic model (HEC-RAS 4.1.), HEC-GeoRAS10 (GIS extension), ARC-GIS 10, and Google Earth were used. The inundation depth, velocity and extent map were developed using HEC-RAS flood model, HEC-GeoRAS and ARC-GIS were integrated to pre-process HEC-RAS inputs and post process the model outputs. Flood Modelling and mapping model results presented only covered part of Barotse floodplain, not the entire floodplain, but mainly in Mongu district. Besides the model simulation did not simulate the flooding over a period of many years to assess the inundation characteristics and the dynamics of flooding for the entire Barotse Floodplain.

Makungu (2019) conducted a research study which focused on improving the water resource assessments modelling of three data-scarce African river basins that contain large wetlands: the floodplains (Luangwa, Upper Zambezi, and the Usangu wetlands River basins). The general objective was achieved through a combined modelling approach that used a detailed high-resolution Lisflood-FP hydraulic model to inform the structure and parameters of the GW Pitman monthly hydrological model. The results from the Lisflood-FP were used to improve the understanding of the channel–wetland exchange dynamics and to establish the wetland parameters required in the GW Pitman model. While some wetland parameters were directly quantified from the Lisflood-FP model results, others, which are highly empirical, were estimated by manually calibrating the GW Pitman wetland sub-model. The study demonstrated that the wetland and channel physical characteristics, as well as the seasonal flow magnitude, largely influence the channel–wetland exchanges and wetland dynamics, but the study did not look at the channel-floodplain feedback processes and how these influence the wetland dynamics of the Barotse.

Zimba *et al.* (2018) assessed the inundation extent of the Barotse flood Plains based on the remote sensing approach. Inundation extent time series was used to test the inundation correlation with discharge and water level using Pearson r correlation. Based on the established correlation Mann–Kendall, was used to analyse trends in the inundation extent and discharge and water level time series from which inferences on the direction of the historical trend in inundation extent was made. The results revealed that there is observable inter-annual variability in inundation extent in the Barotse Floodplain with prominent differences demonstrated in both the flood ascending/peak and receding period. By correlation inference, the overall inundation extent trend in the floodplain was observed to be in a downward movement. However, this study thought it did make a mention of the factors that would have contributed to the observed downward trend; it did not holistically quantify the hydrological processes that would have contributed to the observable results. The study further did not address the spatio-temporal variability of Barotse wetland hydrology with respect to all features of hydrological regimes (timing, frequency, duration, water depth, inundation extent and variability in these all) with regard to discharge contributions from the upstream streams that have significant impact on the dynamism of Barotse flood Plains. And no hydrological modelling was applied in order to have an in-depth understanding of the hydrological processes of the that are connected to flood inundation in Barotse flood Plains. Golmohammadi *et al.* (2014) note that hydrological models are important as they can be used to acquire adequate understanding of the characteristics of water resources and can help to predict the impacts of natural and anthropogenic changes on water resources and also in quantifying the spatial dynamics of hydrological processes.

Meinhardt *et al*. (2017) researched on wetland in the Upper Zambezi River Basin, focused on the Luanginga River basin not the Barotse Flood Plains. The study quantified the potential impacts of climate change on annual floods and water resources in a large southern African watershed, the Luanginga River basin (33000 km^2), which is a tributary of the Upper Zambezi River ranging from the Angolan highlands to the Barotse floodplain. The catchment is characterized by an annual flow regime and extensive wetland areas, which are especially sensitive to changes in hydrological conditions. The climate change assessment undertaken in this research consisted of the application of the process-based distributed hydrological model J2000-(Flood) using a daily time step. The applied floodplain simulation extension was developed with the goal of simulating wetland inundation within the model. Overall, the model was able to accurately represent the annual flood regime of the system. The model results revealed a substantial decrease in runoff generation (39%), flood extent (35%), and groundwater recharge (32%) as being very likely. The decrease in water quantity was inferred to likely lead to damaging the wetland ecosystem and signified, increased risk to the people living in the region, many of whom depend upon this highly productive ecosystem for their livelihoods. Michailovsky and Bauer-Gottwein, (2014) in their study of operational reservoir inflow forecasting with radar altimetry of the Zambezi Basin built a simple floodplain model for Barotse floodplain but the model did not allow for determination of channel-floodplain feedback processes.

2.9 Application of Remote Sensing in Wetland Studies

The application of satellite based remote sensing techniques in floodplain assessments provides an important and expanded avenue for data collection on the dynamic state of wetland processes, especially for vast wetlands where ground-based methods are virtually impractical (Schumann *et al.*, 2007). With the advantage of area coverage (spatial resolution), regular revisit time (temporal resolution) and acquisition of data in a wide range of the electromagnetic spectrum (spectral resolution), the remote sensing approach is best suited for study of inundation dynamics as compared to conventional mapping methods (Ticehurst *et al*., 2014). A host of satellite sensors are currently generating enormous amounts of data at various resolutions that form the core for both historical and continued monitoring of inundation regimes and other landforms. For mapping of open water features with optical satellite imagery the use of indices is the most common practice (Baig *et al*., 2013). Various spectral based water features extraction indices have been developed and include the Normalised Difference Vegetation Index (NDVI) (Rouse et al., 1973), Normalised Difference Water Index (NDWI) (McFeeters, 1996), Modified Normalised Difference Water Index (MNDWI) (Xu, 2006), Automated Water Extraction Index (AWEI) (Feyisa et al., 2014), and the Desert Flood Index (DFI) developed by Baig *et al.* (2013).

The NDWI developed by McFeeters (1996) and the MNDWI by Xu (2006) are the most utilised water feature extraction indices (Baig *et al.*, 2013). NDWI and the MNDWI are focused on differentiating the water body from the non-water-body information by using pixel scales. Over the years remote sensing has been adopted for various hydrological and hydrodynamic assessments in the Barotse Floodplain such as Aduah and Phiri *et al* 2012; Mantey, 2012; Meire, 2012; Cai *et al.*, 2015; et al.2018; Banda *et al.*, 2023. For example, Zimba, *et al.*, 2018 used a remote sensing to an assess of the spatial and temporal trends in inundation extent, by applying MODIS satellite data to quantify the inundated area in each flood cycle from 2001 to 2013. Phiri, *et al*., (2012) used modelled data operating on MODIS to estimate evapotranspiration. Banda *et al*., (2023) investigated groundwater and surface water interactions using remote sensing. Among the vast spectrum of uses, remote sensing data has increasingly become an important source of information for hydrological-hydrodynamic modelling, water use planning, monitoring, and management at various levels of management such as field, catchment, and regional scale (Mu *et al*., 2007).

2.10 Summary

Much as we appreciate some several studies in the Upper Zambezi River Basin (Winsemius, 2006; Meier *et al.*, 2011; Matos, 2014; Kling *et al* 2014; Meinhardt *et al*., 2017; Kabika 2017; McCartney *et al.*, 2018; Nyambe *et al* 2018; Zimba *et al.*, 2018; Makungu, 2019 et cetera) there is no existence of an integrated online framework for coupling hydrology and hydrodynamic model to be used as the basis for developing coupled hydrology-hydrodynamic model for Barotse floodplain. Premised on the general portrait of the study results, this study endeavoured to develop an integrated hydrologic-hydrodynamic online modelling framework for the Barotse floodplains based on field investigations, models for hydrological-hydrodynamic modelling, daily discharge data, meteorological data, water samples, groundwater, water levels, satellite images, and Digital Elevation Models (DEM).

CHAPTER THREE: STUDY AREA

3.1 Overview

This section describes the study areas. It describes the physical, Population and socio-economic characteristics of the study area.

3.2 Location

The Barotse Floodplain is found within the Upper Zambezi Basin (UZB). The Upper Zambezi is the broad extent of the Zambezi River from the source 25 km southeast of Kalene Hill in Mwinilunga District, North-Western Zambia, through Angola and Barotse Floodplain to the Victoria Falls. The basin lies between latitudes 11°S and 19°S, and longitudes 18°E and 27°E, which covers part of western Zambia. While the Barotse Floodplain lies between 14°S and 17°S and longitudes 22°E and 24°E in Western Province of Zambia (Figure 5).

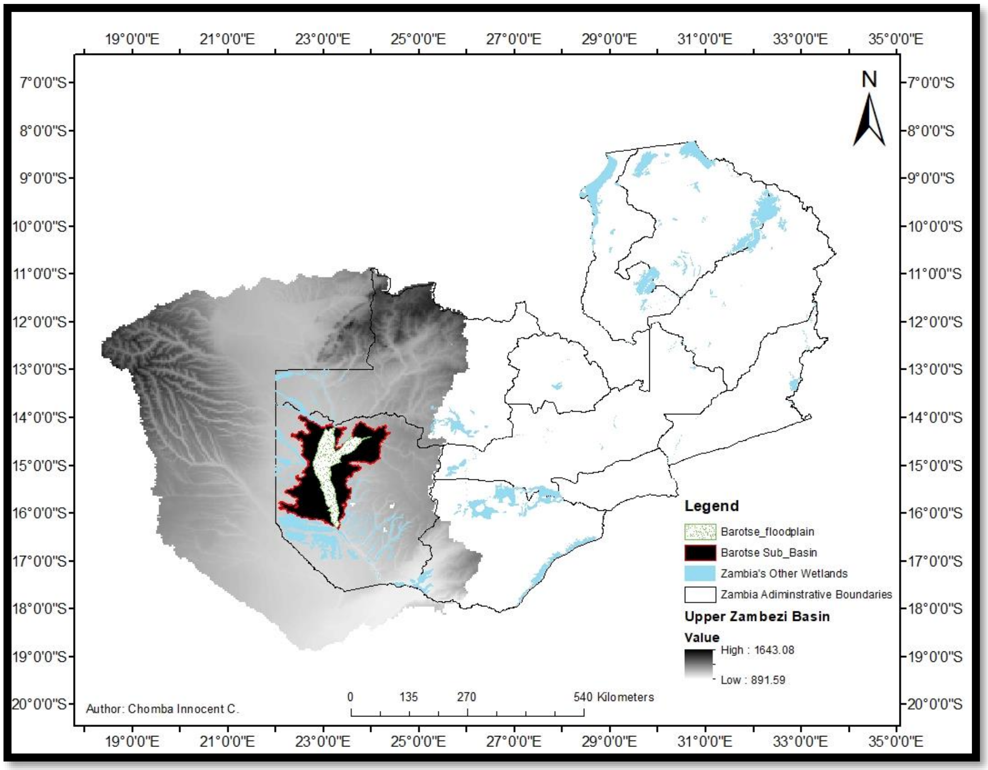


Figure 5.Location of Barotse Floodplains in the Upper Zambezi Basin-Wester Part of Zambia

Different studies have approximated the extent of the floodplain to be 5,500 Km^2; (Emerton, 2005); 7,200 Km^2 (Timbelake, 2000); 7,700 Km^2 (Hughes and Hughes, 1992). The floodplain generally has a complex of old and new channels, swamps, and pools as well as extensive grassy plains

(Mohammed, 2015). The wetland is a sanctuary to variety of biodiversity both flora and fauna (Timberlake, 1997; IUCN, 2003; Zimba, 2017). The study area was selected due to the fact that the project was funded under WWF Upper Zambezi Project. The Upper Zambezi is currently an unregulated river System and data scares basin thus offers potential for sustainable management. And it can benefit from Open access models, coupling techniques, and remotely sensed data sets for creating assessment tools to generate data for sustainable management.

3.3 Topography and Drainage

The land elevation over the study area ranges from 1192 metres above sea level in the north-eastern part to about 900 metres above sea level in the southern part. The topography and slope characteristics of the Upper Zambezi River basin are illustrated in Figure 6 (Makungu, 2019). The lower areas form part of the floodplain. The drainage pattern is dendritic with all major rivers/streams, which include the Lungwe Bungu, Luanginga and Kabompo, being tributaries of the Zambezi River. The Zambezi River and its tributaries account for the flooding in the Barotse Wetland (Timberlake, 1998; IUCN, 2003; Zimba, 2017).

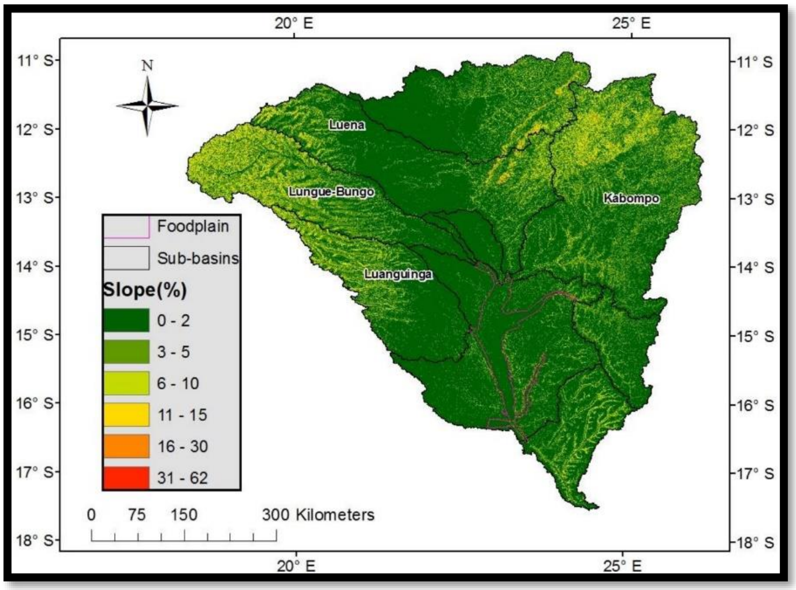


Figure 6.Sloe characteristics of the Upper Zambezi River Basin (Makungu, 2019).

3.4 Groundwater, Main Aquifers and Typical Yields

Groundwater constitutes one major source of water supply in many parts of the country. It also sustains flows for many perennial rivers, streams, and wetlands. The country's aquifers are classified into three main types, namely, (i) aquifers, where groundwater flow is mainly through fissures / channels / discontinuities, which are classified as either highly or locally productive; (ii) aquifers, where intergranular groundwater flow is dominant, which occur mainly in alluvial soils as is the case with most part of Western Province; and (iii) Low yielding aquifers with limited potential (Figure 7) (JICA-MEWD, 1995).

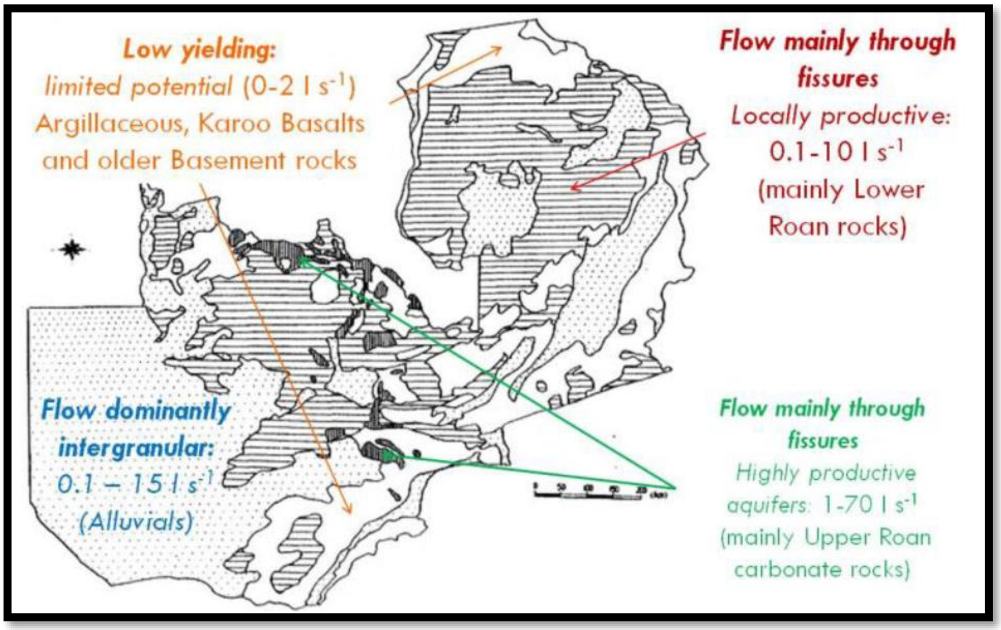


Figure 7. Map of Zambia showing three main types of aquifers in Zambia (JICA-MEWRD,1995).

3.5 Soils

FAO soil classifications associate Zambian Soil distribution to be related to topographic classification. There is a substantial variation in the soil characteristics within the basin (Figure 8). Black and grey fertile soils enriched by silts and humus, which resulted from the decomposition of vegetation and aquatic species, remain on top of the Kalahari sands when floods recede in the floodplain (Moore *et al*., 2008; Makungu 2019). The Barotse floodplains are dominated by Gleysols, which are commonly found in wetlands characterised by high groundwater levels. Aeronosols, which cover a large part of this basin, are unconsolidated soils with low clay content and a high degree of porosity. Ferralsols dominate the north-eastern parts including the Kabompo sub-basin and Kalene

Hills and they are deeply weathered, acidic, leached, and permeable soils with high iron content (JICA, 1995 Ashton *et al*., 2001; Muzumara, 2011; Makungu 2019).

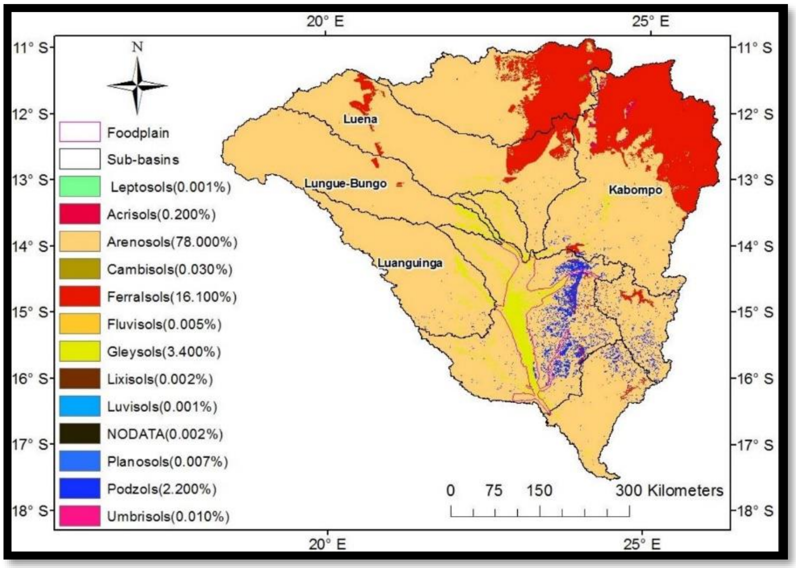


Figure 8.Distribution of different soils in the Upper Zambezi River Basin (Source: Hengl *et al.*, 2014).

3.6 Geomorphology

Western Province in general terms consists of an extensive sand-covered Pliocene plain whose recent geomorphological history has considerable bearing on the soil and vegetation of the area, and hence on land use. Most parts of Zambia are classified as Central African Plateau-with the elevation ranging from 600 to 1,850m above mean seal level. The highest parts of the plateau are in the northern direction and Northwest of Zambia. Elevation gradually reduces in the southwest/south to the Zambezi River. The plateau is gently undulating in all places. The Central African plateau is subdivided into two major subunits that are degraded plateau and aggraded plateau. The surface of degraded plateau shows the effect of erosion and is traversed by a network of rivers. The terrain of the plateau is dominated by high drainage density, swamps, lakes, flood plains and isolated hills (JICA, 1995; Muzumara 2011).

3.7 Geology

The whole of Western Province is presumably underlain by the Pre-Cambrian Basement Complex. The Luena, Luanguinga, and Lungue-Bungo River sub-basins are underlain predominantly by sandstones and conglomerates covered by the Kalahari sands, whereas the Kabompo sub-basin lies on the copper-rich sandstones, quartzite, arenites, and conglomerates (Ashton *et al.,* 2001). The Barotse floodplain lies on the Karoo basalts (about 150 m thick) overlain by moist and permeable Kalahari sands (Winsemius *et al*., 2006; Makungu, 2019). The Karroo beds are mainly clastic sediments, sandstones, mudstones, grits, and shales of continental origin and of very variable thickness (Muzumara, 2011; Craig *et al.*, 2010; Verboom and Brunt 1970). Basement rocks in the Zambezi River Basin are overlain by Kalahari Sands locally known as Barotse Sands. These deep poorly sorted and unconsolidated sand measuring up to 100 m in depth and covers most of the Barotse sub-basin. Generally, Barotse Sands are mainly water-sorted sands with very little clay and silt content (Drystal *et al*., 1972; Sichingabula, 2016).

3.8 Vegetation and land use

The Barotse Sub-basin is predominantly grassland with breaks of semi-evergreen forest, evergreen forest, deciduous forest and shrub land. Other land cover types include mosaic cropland, water bodies and regularly flooded vegetation which covers the Barotse Wetland. The evergreen and semi-evergreen forest is composed of swamp and riparian woodlands while the deciduous forest is of Kalahari and Munga Woodland. The major land uses are cropland and timber production (Fanshawe, 2010; Mukosha, 2014). There are a variety of underground trees or suffrutices some of which are confined to the wetland. They have a dwarf habit with the main woody stem underground. The underground growth nature is attributed to adaptation to the high-water table and anaerobic conditions on seasonally flooded plains. The above ground shoots are often destroyed by fire or frost. The trees spread by means of rhizomes (Timberlake, 2000; Zimba, 2017).

3.9 Climate

The climate is mild and sub-tropical, as most of the country lies on the Central Africa high plateau at an average altitude of 1200 meter above sea level. Monthly precipitation for Kabompo illustrates the rainfall pattern for the upper catchment of the Barotse wetland. Rainfall distribution in the study area coincides roughly with the agro-ecological zones of Zambia. Much of the discharge into the Barotse Wetland is from upstream in Angola and North-Western Zambia, which receives an average of above 1000 mm of rainfall. Rainfall over the study area is a result of the movements of the Inter-Tropical Convergence Zone (ITCZ) over Zambia between October and April of a hydrological year (IUCN, 2003; Fanshawe, 2010). High temperatures are experienced between October and April with maximum temperature of around 34 degrees Celsius and minimum temperature of about 12 degrees Celsius. The highest relative humidity is about 70 percent in the months November to March **(**Zimba, 2017).

3.10 Population and socio- economic characteristics

The Barotse Wetland hosts about 250,000 people with settlements concentrated along the levee of the Zambezi River and at the edge of the floodplain. The Zambezi River forms a critical lifeline in the wetland for both humans and wildlife. The population is largely involved in crop, wildlife, livestock, cultural and fisheries activities (Figure 9). The wetland is cited as the most agriculturally productive area in western Zambia. Flooding plays a crucial role in agriculture as the flood waters bring into the plains sediments that are rich in nutrients essential for crop production when the flood recedes (IUCN, 2003). Crops grown include maize, cassava, rice, sweet potatoes, and sugar cane. The population of cattle in the wetland is as much as the human population estimated at over 250,000 with the grassland in the wetlands providing grazing pasture for cattle. Fish consumption is five times higher than the national average. At the peak of the flood, fish traps and spears are used for fishing while gill nets and spears are used in the lagoons left behind by the falling flood. The wetland is also home to a rich cultural ceremony known as the Kuomboka which entails annual migration with the coming of the flood to the upland. It is an annual event whose hosting is dependent on the flood water levels (Timberlake, 2000; Zimba 2017).

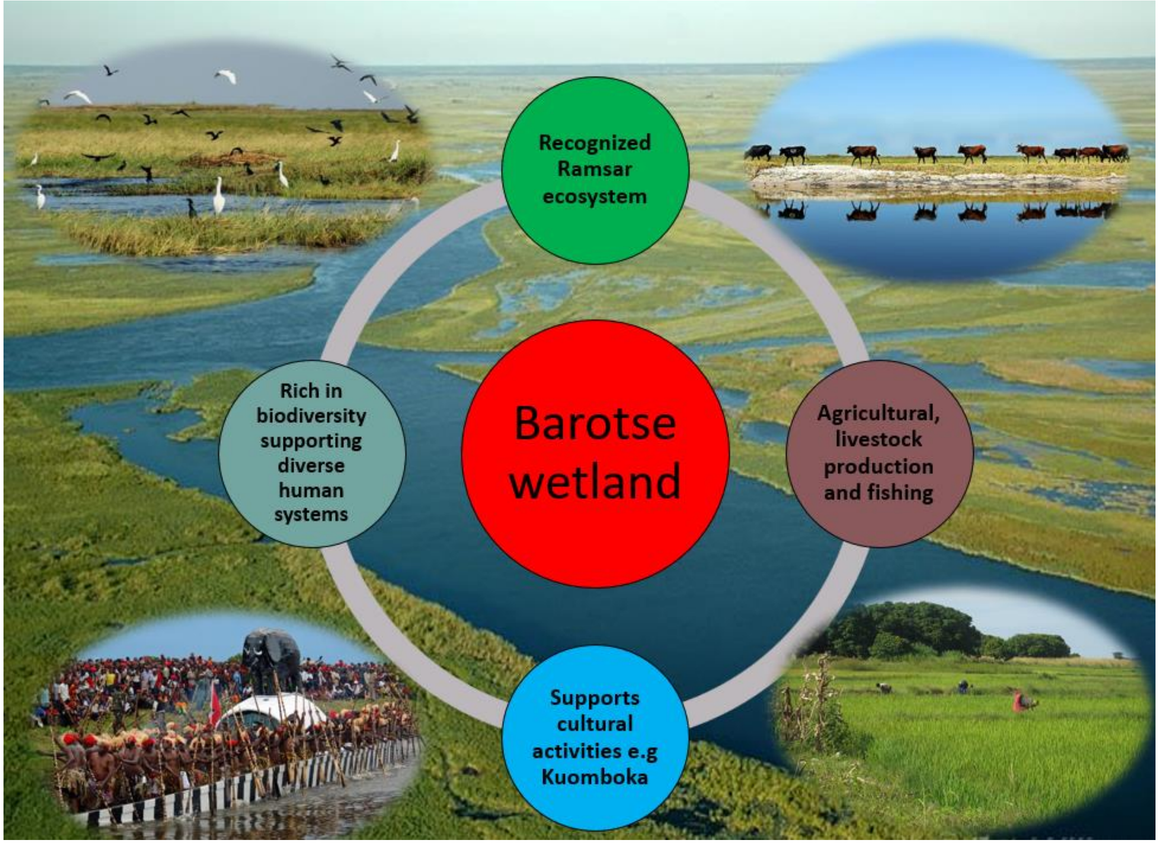


Figure 9.The socio-economic and environmental value of the Barotse Wetland (source: IUCN, 2003).

CHAPTER FOUR: METHODOLOGY

4.1 Overview

This section explains the philosophical basis of the study; methodological approaches; research design, sources of data, methods of data collection, analyses, and graphical methodological framework (Figure 16).

4.2 Philosophy of science behind this study

According to Guba, (1990), an important part of academic research process involves safeguarding that the methodology and methods used are consistent with the ontological and epistemological assumptions of a philosophy of science. The methodological framework of this study was guided by a research paradigm known as Empirical Analytic. It developed out of merging of 20th Century work on the logical foundations of mathematics with work on foundations of the physical sciences (Sheppard, 2001). The empirical dimension in Empirical analytic refers to the goal of inquiry which includes definition, prediction, control and scientific explanation of physical phenomena (Reeves, 1996). The analytic aspect of this paradigm reflects a belief in deterministic reality whereby parts can be separated from the whole, and cause and effect relationships among parts can be revealed (Reeves, 1996). Consequently, empirical analytic is a school of thought that promotes use of quantitative methods and techniques in understanding phenomena because it stems from a reliance on measuring variables and analysing relationships among them using appropriate mathematical models and/or statistical techniques. Methodologically, empirical analytic holds mathematical and statistical analysis in higher esteem.

The epistemological (philosophical study of how knowledge is acquired) assumptions of empirical analytic are diverse (Makumba, 2009). Firstly, Empirical analytic subscribes to determinism, empiricism, parsimony, generality, and rationalism. Determinism means that events for example, flood inundation and advancement, are caused by other circumstances such as rainfall, discharge, and wetland characteristics, and hence, understanding such causal links is necessary before arriving at conclusions in a quantitative study (Lotz-Sisitka *et al.*, 2012). Empiricism means collection of verifiable empirical evidence in support of claims and conclusions. Parsimony refers to the explanation of the phenomena in the most precise and straightforward way possible (Cohen *et al.*, 2000). Generality is the process of generalizing the observation of the phenomenon to the world at large (Reeves, 1996). Rationalism is a scientific principle that, knowledge should be based on clarity and objectivity of thought (Cohen *et al.*, 2000). This implies that in this study, the researcher isolated his bias from the phenomenon under study by bracketing any subjective notions to allow objectivity to influence the process of knowledge creation.

Ontologically (relating to nature of reality that emerges from a science and how it must be viewed) (Lotz-Sisitka *et al.*, 2012), knowledge that will be generated from this study will be real and independent of the researcher's subjective opinions. However, this does not mean the data will be rock solid and not challengeable by studies that may be done afterwards. This is based on the reasoning that hydrological processes are often stochastic and may undergo some variations with laps of time. The research is also generated factual data (actual existence of something that can be proven, as opposed to the supposition of something or a belief about something) unlike trans-factual data (reality that exists, but cannot be proven) (Reeves, 1996; Lotz-Sisitka *et al.*, 2012).

The rationale for using empirical analytic as a guiding philosophy of science in this study is that it supports a systematic and quantitative knowledge generation process and analysis which is essentially to enhance precision in the description of variables and the discernment of the relationship among them.

4.3 Research design

Case study research design was adopted in this study. Case study research design can be defined as an empirical research method used to investigate a phenomenon, focusing on the dynamics of the case, in this case the Barotse floodplains. The Zambezi River Basin has several wetlands. However, this study specifically focused on the dynamics of wetland hydrology of the Barotse Flood Plains as to provide detailed hydrological Processes of the wetland bearing in mind that all wetlands are unique. Case study method stipulates the use of specific techniques at each phase of research (Bassey, 1995).

4.4 Data Collection

Data collection methods included field investigations for collection of primary data for the selected study sites and desk research for secondary data. This section describes data and information collected such as; daily discharge data, meteorological data, water samples, groundwater levels and Digital Elevation Model (DEM).

4.4.1 Daily Discharge Data

The historical daily discharge data was collected from Water Resources Management Authority (WARMA) for the following stations in the Upper Zambezi Catchment (Figure 10); (Zambezi River at Chavuma (no.1-105); Kabompo River at Watopa (no.1-950; Zambezi River at Lukulu (no.2-030); Lungwe bungu River at Sakasumbi (no.2-020); Luanginga River at Kalabo (no.2-250); Zambezi River at Matongo (no.2-330) and Zambezi River at Senanga (no.2-400) from 1985 to 2020 hydrological years. This data was used for model calibration and validation.

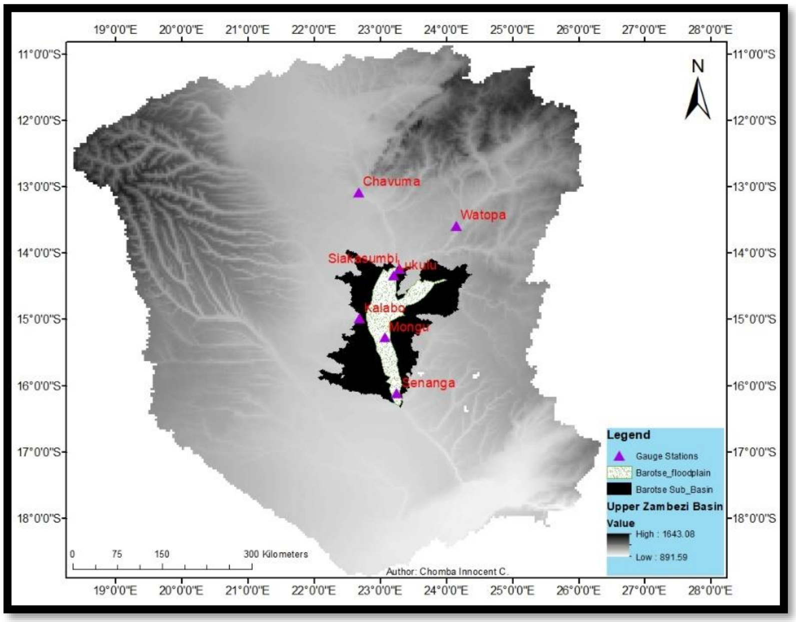


Figure 10. Location of gauge stations

4.4.2 Field discharge measurements

Field discharge measurement (Figure 11) were conducted at Zambezi River upstream; Kobompo River, Lungwe Bungu River; Zambezi at Lukulu Gauge station; Lunginga River; Zambezi River at Lubosi; Little Zambezi at Matongo gauge station, and Zambezi River at Senanga gauge station). The discharge measurement was conducted by using Acoustic Doppler Current Profilers (ADCP) to validate WARMA data. ADCPs calculate current speed and direction based on the measurement of the Doppler Effect. They have four ultrasound transducers that function both as transmitters and receivers. During a sound pulse is transmitted that reflects off particles in the water. Change in relative distance between the ADCP and the particles causes a Doppler shift, whereby the frequency of the sound waves change. When the reflected sound wave returns to the transducers, the frequency shift is measured and used to calculate the relative velocity between the ADCP and the particles in the water (RD Instruments 1996). A discharge measurement is based on the average of a minimum of ten transects from shore to shore. The discharge measurement was done in dry and wet season for two hydrological years as a means of verification for the discharge data provided by WARMA.

4.4.3 Meteorological Data

Meteorological data (rainfall and Temperature) was collected from Zambia Meteorological Department (ZMD) from the Meteorological Stations located in the Upper Zambezi Basin; Kabompo; Kalabo; Kaoma; Kasempa; Mongu; Senanga and Zambezi. This data was used for validating precipitation data from the fifth ECMWF ReAnalysis.

Figure 11. Field measurements of discharge at Matongo gauge stations

4.4.4 Global Datasets

The fifth ECMWF ReAnalysis (ERA5) was used to access data for precipitation, potential evapotranspiration data and temperature, while evaporation was computed using the Penman–Monteith equation. ERA5 was preferred, as the author had access to ERA5 datasets, and the data sufficed for the purpose of forcing the model. ERA5 is the fifth generation of European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate covering the period from January 1979 to present. ERA5 is produced by the Copernicus Climate Change Service (C3S) at ECMWF. ERA5 provides hourly estimates of a large number of atmospheric, land and oceanic climate variables. The data cover the Earth on a 30km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80km. ERA5 includes information about uncertainties for all variables at reduced spatial and temporal resolutions, accessed at https://www.ecmwf.int/en/forecasts/datasets.

The land cover map was from Global Land Cover Characterization database (GLCC) from United Sates Geological Survey and has a 1km resolution. MERIT Hydro was used for catchment delineation and The Digital Elevation Model (DEM) acquisition (to extract basin characteristics; drainage network basin slope, channels, sub-basins). As well as Lake Hydro was used for lakes data.

4.4.5 Groundwater Level Data

Groundwater Solinst Model 3001 dataloggers were installed in Lukulu, Mongu and Senanga for continuous measurements of groundwater levels (Figure 12). The recording of water levels was important for future validation of coupled model data. Solinst dataloggers are high quality groundwater monitoring groundwater dataloggers that automatically and continuously records fluctuations in water level on at a time interval. Water level data logs are stored in the datalogger's memory and can be downloaded using software app on the computer. These loggers are self-contained water level datalogger, using infra-red data transfer powered by a 10year lithium battery, offering the flexibility of installing by use of a Direct Read Cable, wireline, or Kevlar cord (Solinst Manual, 2020).

Figure 12. Field measurements of groundwater levels (a) Senanga (b) Lukulu

4.4.6 Satellite Images

Sentinel 2 images were accessed from COPERNICUS/S2 via; https://scihub.copernicus.eu/dhus/#/home.

4.4.7 Infiltration measurements

The field infiltration (Figure 13) experiments were conducted to measure soil infiltration rates in Barotse floodplains in Lukulu, Mongu and Senanga from 23rd to 28 May 2021. The infiltration rates was important as input into the coupled model. A double ring Infiltrometer was used for this purpose. This data was important for inputting into hydrological model.


(a) **(b)**

Figure 13. Field measurements of rate of infiltration at (a) Lukulu (b) Senanga

4.4.8 Water Samples

Water Samples were collected on different locations (Figure 14) in the Barotse floodplains from various surface and groundwater features including the Zambezi River, streams, springs, water pools (dambos), handpumps, shallow wells, and rainwater based on the accessibility of the places in both dry and wet season.

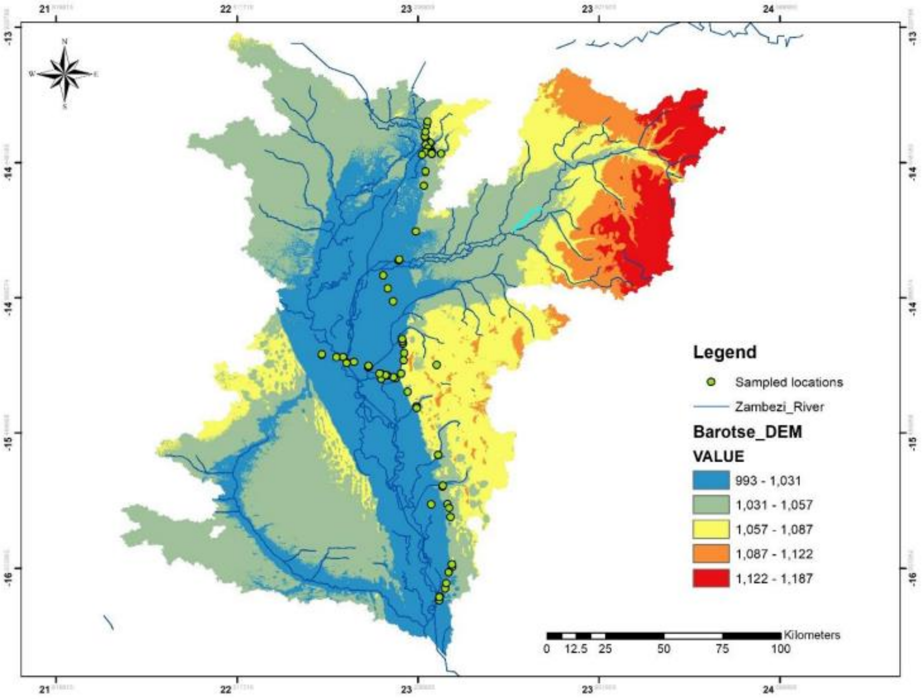


Figure 14. Location of water sampling points on the Barotse Floodplains.

4.6 Data analysis

This section will outline the method of data analysis per objectives of the study.

4.6.1 Objective 1: To investigate the mechanisms of groundwater-surface water interaction in the Barotse floodplains.

In addressing the first objective on the mechanism of groundwater-surface water interaction, four (4) analysis were made; NDVI and SAVI analysis and Isotopic analysis.

4.6.1.2 NDVI and SAVI Analysis

In identifying areas of groundwater discharge, remote sensing analysis was used. An online cloud computing platform, Google Earth Engine (GEE), was used to retrieve Sentinel 2 Top of Atmosphere imagery between 2019 and 2020. GEE combines a multi-petabyte catalogue of satellite imagery and geospatial datasets making it available to detect changes, map trends, and quantify differences on Earth's surface. Sentinel 2, with a spatial resolution of 10 m, is part of the European Commission’s Copernicus Programme and was launched in 2015. It was preferred in this study because of its high resolution and because its spectral sensitivity captures changes in vegetation state. Two vegetation spectral indices, Normalised Difference Vegetative Index (NDVI) and Soil Adjusted Vegetation Index (SAVI) were applied on the imagery. Both indices have a scale of -1 to +1; positive values indicate healthy conditions (green vegetation), and negative values indicate poor conditions. SAVI also accounts for soil condition which increases its saturation rate compared to NDVI.

4.6.1.3 Isotopic Analysis

δD and δ^{18}O were measured using a Liquid Water Isotope Analyzer with measurement accuracies of 1.0 and 2.0 ‰, respectively, at the University of Western Cape, South Africa, Department of Earth Science. The measurement results were expressed as the difference of thousands of Vienna Standard Mean Ocean Water (VSMOW) [δ (‰)];

Equation 1 $$\delta(‰) = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 1000$$

Where, R is the ratio of ^{2}H/^{1}H or ^{18}O/^{16}O for a sample or the standard.

4.6.1.4 Hierarchical Cluster Analysis (HCA)

To investigate the influence of groundwater-surface water interaction on the floodplain water quality, a multi-variate statistical approach, Hierarchical Cluster Analysis (HCA) was adopted. HCA is a data classification technique that classifies groundwater samples or physicochemical indices into independent clusters, enabling an understanding of the influencing factors of groundwater chemistry (Wu *et al*., 2020). In this study, HCA was computed using the Ward linkage rule using R statistical package, by Euclidean distance as the distance measure or similarity measure between different clusters. HCA is a widely accepted statistical method used to determine connectivity of cases using each group's measured characteristics (Wu *et al*., 2014; Yang *et al*., 2015). Several studies have used HCA to identify groundwater-surface water facies and processes with successes (such as Guggenmos *et al*., 2011b; Modie *et al*., 2022).

4.6.2 Objective 2: To develop a rainfall-runoff hydrologic model for Upper Zambezi River basin focusing on modelling Barotse floodplain.

wflow_sbm hydrologic model (Deltares, 2019) source code was used to develop the Hydrological Model for the Upper Zambezi.

4.6.2.1 Hydrological Calculation: wflow_sbm Model

The Hydrological Model for the Basin was set up using the wflow_sbm hydrological code at 2.15 arcmin spatial resolution (approximately 4 km × 4 km at the Equator). The setup was done as programmed in python using the PCRaster Python extension as documented in wflow manual (Deltares, 2019). The Digital Elevation Model (DEM) is the basic terrain data required to develop the model using wflow. DEM was downloaded from the open source USGS as represented. The mosaicked DEM (Figure 15) was then clipped for Upper Zambezi Basin. Once the mosaic operation was completed, the coordinate system was chosen. In case of the Upper Zambezi Basin, Projected Coordinates Systems UTM WGS1984 zone was used. This was followed by the creation of local drainage network file for the catchment using the DEM. This was followed by creation of the subarea/catchment maps of the basin by indicating outflow points (gauges) map and creation of landuse and soil maps and other maps: wflow_landuse.map, wflow_soil.map, wflow_river.map, wflow_subcatch.map. These were derived from Globcover for landcover (Olivier *et al.,* 2012), SoilGrids (Hengl *et al.,* 2017) for soil parameters, while MERIT Hydro; MERIT DEM for catchment delineation as well as Lake Hydro for lake data acquisition (Yamazaki *et al.,* 2017, available at http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/index.html) acquisition. The model was forced with the fifth ECMWF ReAnalysis (ERA5) (Copernicus Climate Change Service (C3S), 2017) for precipitation, potential evapotranspiration data and temperature and evaporation was computed using the Penman–Monteith equation. The wflow ini file attached in Appendix E defined the variable settings. The model was run was done in windows DOS and the simulated output variables were analysed using python 3. The Upper Zambezi Hydrological Model was set to run at daily time-steps from 2000 to 2018.

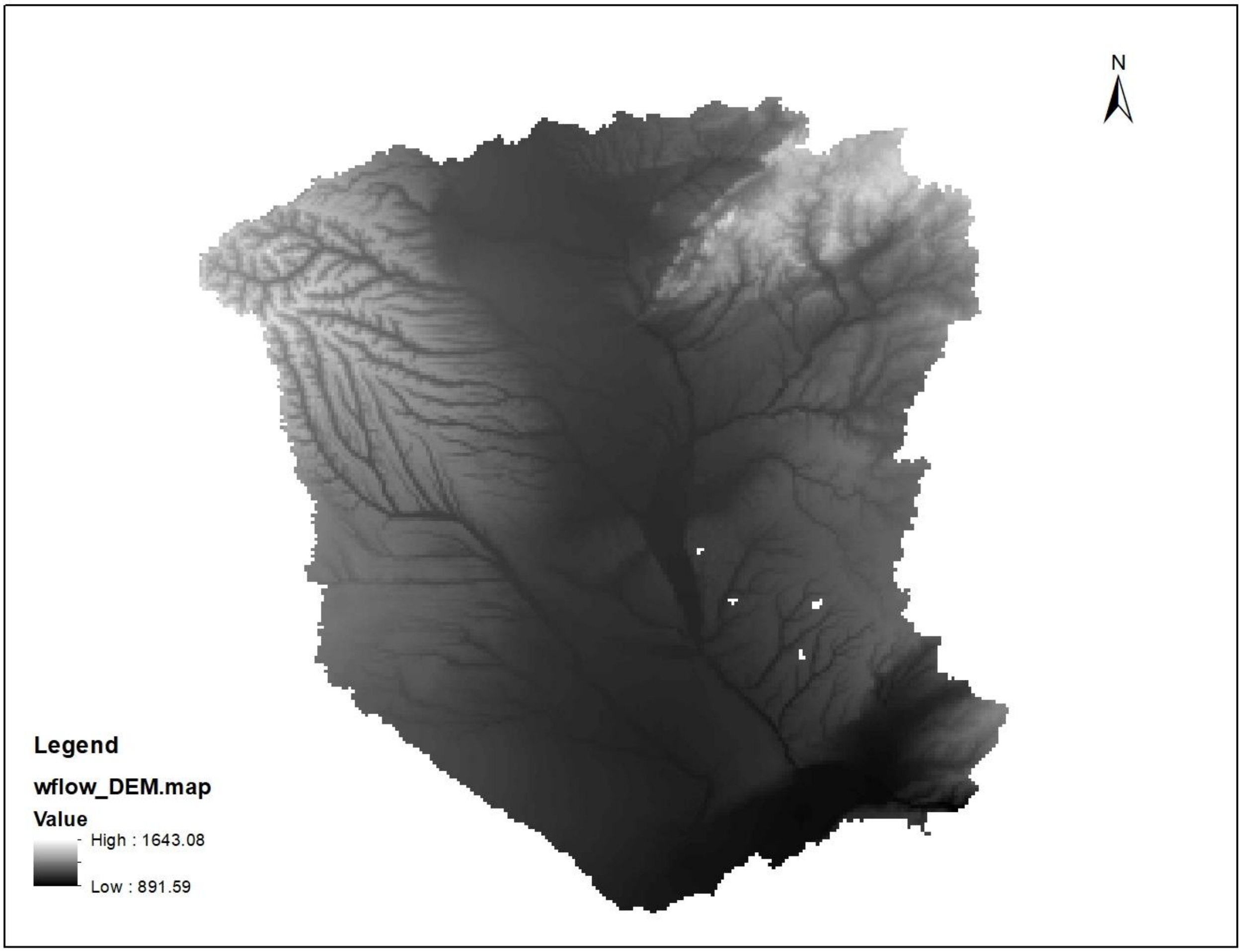


Figure 15. Mosaic DEM covering of the Upper Zambezi River Basin.

4.6.2.2 Wflow Model testing and performance estimation

Model calibration on the wflow model was done focusing on upstream gauge stations (Chavuma, Watopa and Lukulu) as are the major inflow into the barotse floodplains. Model calibration is the process of estimating model parameters by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions (Moriasi, 2007). Thus, the variability of the upstream hydrology was considered. WFLOW calibration was initiated with sensitivity test.

Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs (parameters). Parameter sensitivity was observed graphically. It is a necessary process in identify key parameters and parameter precision required for calibration (Ma *et al.,* 2000). The most sensitive parameters identified for use in the calibration of WFLOW model were; KsatVer (vertical saturated soil conductivity of various depth of soil surface); RootingDepth (controls the storage of the soil, the higher the rooting depth, the higher the storage of water and less the flow); SoilThickness (controls the storage of the soil module and affects the SoilWaterCapcity) and M (determines the decrease of vertical saturated conductivity with depth, range between 20 to 2000;) (Deltares, 2019).

In choosing few parameters for calibration, the researcher was conscious of the equifinality concept (Beven and Freer, 2001), that different combinations of values of the same parameters may produce an identical output signal. Hence, calibration was done both manually and automated using Monte Carlo simulations (Metropolis and Ulam, 1949). Monte Carlo is a technique that combines statistical concepts random sampling and the ability of computers to generate pseudo-random numbers and automating calculations. In this way generating random numbers of hydrological model parameters from a seed value and multiple system simulation, parameter values that generate a good representation of the system compared be achieved. The method then creates the largest possible number of simulations to explore the best fitting model (Morales *et al*., 2015).

Wflow model calibration focused on the following gauge stations Chavuma (no.1-105); Watopa (no.1-950); and Lukulu (no.2-030) and Senanga (no.2-400). Model calibration is the process of estimating model parameters by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions (Moriasi, 2007). All three stations were calibrated for a five-year period (2001-10-30 to 2006-09-30) and then validated using an independent three-year period (2006-10-30 to 2009-09-30) by comparing simulated and observed monthly flows. Model validation is the process of determining whether the model accurately represents the behaviour of the system. In most situations, this will involve confirmation that the model is predictive under the conditions of its intended use. This type of validation occurs by comparing model simulations to an independent experimental data set not used in calibration. (Aumann, 2007; Kerr and Goethel, 2014; Van der Merwe, *et al.,* 2018). Hydroeval v 0.0.3 (Hallouin, 2019) was used to calculate the goodness of fit. Four (4) objective goodness of goodness of fit statistical matrices were used; (Nash-Sutcliffe efficiency (NSE); Root Mean Square Error (RMSE); Percent Bias (pbias) and Kling-Gupta Efficiency

(KGE) were deployed to measure the goodness of fit of simulated streamflow time series against observed streamflow.

4.6.3 Objective 3: To develop an integrated online (internal) hydrologic-hydrodynamic modelling framework for the Barotse Floodplains.

Two models were used to set up a hydrologic-hydrodynamic modelling framework; Upper Zambezi wflow hydrological model developed in objective 2 and the Barotse hydrodynamic Model (Makungu, 2020) coupled using GLOFRIM v2.1 Hoch *et al*. (2020) coupling framework which offers a flexible and modular tool to couple hydrologic, routing, and hydrodynamic models. This enabled integration of physical processes of wflow and lisflood models. The setup Barotse Hydrodynamic model is not explained in this report as it has been explained and documented by Makungu (2020). The setting up of GLOFRIM was done within python 3 environment. This was done using conda environments commands that can be accessed at https://conda.io/docs/user-guide/tasks/manage-environments.html#creating-an-environment-from-an-environment-yml-file. Using python 3 environment, GLOFRIM environment called GLOFRIM Barotse was created and activated. Once the GLOFRIM Barotse environment was created, the GLOFRIM was installed by getting a copy of the source code from git repository at https://github.com/openearth/glofrim. Afterwards PC-RASTER 4.4.0 (Geographical Information System which consists of a set of computer tools for storing, manipulating, analyzing and retrieving geographic information) was also installed Therefore, using PCRaster 4.4.0, two models, (wflow Hydrological model and Barotse Lisflood-FP) coupling settings was defined in the GLOFRIM ini-file (initialization file) (Appendix D), the ini-file was then read by GLOFRIM to first initialize the model-specific configuration files and then initialized both models as a coupled entity. The coupling was done per grid basis. Once the two models were initialized, a loop was entered, starting at the start time, and terminating at the end time as specified in the python execution command wflow runs and feeds Lisflood_fp, on an hourly time step. During the loop, models were individually updated from the upstream end of the model cascade to the most downstream model. It was only then that the model was updated, the variables were exchanged (as defined in GLOFRIM ini-file) and retrieved from the providing model, then aligned the variables, and inserted into the receiving model. It is only after this, that the model time of the receiving model were forward and to be integrated until the model time of the providing model was reached and model end time was reached, and model execution was hence finalized.

4.6.4 Objective 4: To test and evaluate the performance of one-way Barotse Coupled Hydrological-Hydrodynamic Model developed based on the framework in objective 3

The test run of one-way Barotse Coupled Hydrological-Hydrodynamic Model was done using Windows Command Prompt (CMD) environment. For the model performance evaluation Four (4) goodness of fit statistical matrices were used; (Nash-Sutcliffe efficiency (NSE); Root Mean Square Error (RMSE); Percent Bias (pbias) and Kling-Gupta Efficiency (KGE) were deployed to measure the goodness of fit of simulated streamflow flow, water level and flood inundation extent with WARMA observed data monthly flow and water level for Lukuyu, Mongu and Senanga. While simulated flood inundation extent was compared with the calculated estimates of inundated area based on MODIS 09A1 imagery data for 2004 in the Barotse Floodplain, a study done by Zimba *et al*., (2018).

4.6.5 Goodness of fit Statistical Matrices

(a) Nash-Sutcliffe Efficiency (NSE)

NSE is a measure of how close the simulated discharges are to the observed relatively to how observed data are close to the mean observed discharges. It ranges from $-\infty$ to 1, with an NSE = 1 being a perfect match of modelled to the observed discharge, but this does not happen. An NSE above 0.5 is generally considered an indicator of a well performing model. (Ritter and Muñoz-Carpena, 2012). The model evaluation guidelines classify the values of NSE into categories of very good model for NSE > 0.75, good model for NSE between 0.65 and 0.75, a satisfactory model for NSE between 0.50 and 0.65 while NSE values less than 0.5 indicate an unsatisfactory model (D. N. Moriasi, *et al.*, 2007). NSE however, is known to present high sensitivity to peaks (Hrachowitz, *et al*., 2013). The expression of calculating NSE is presented in Equation 2.

Equation 2: Nash – Sutcliffe Efficiency.

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{obs,i} - Q_{simi}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs,i} - \bar{Q}_{obs}\right)^2}$$

Where:

n: the total number of river discharge samples

$Qobs,i$: The observed river discharge at time i,

$\bar{Q}obs$: The average of observed river discharge values.

$Qsim,i$: The simulated river discharge at time i

Here values at time 'i' are monthly values. Therefore, the observed values per month and the simulated values averaged per month.

(b) Root Mean Square Error (RMSE)

RMSE is a measure of the simulated discharges error in the calibration parameter units. It is given by the expression:

Equation 3: Root mean square error

$$RMSE = \sqrt{\frac{\sum_i^n \left(Q_{sim,i} - Q_{obs,i}\right)^2}{n}}$$

RMSE values fall in the range of 0 to ∞. A RMSE value equal to zero indicates a perfect match between observed and modelled discharge (Arnal, 2016). It takes into consideration the sample size. There is no standard of RMSE to indicate a good fit as it depends on the magnitude of the dataset but while comparing the parameters effects, the smaller the RMSE the better. It shows the errors in the units of the calibration parameter, in this case cubic meter. However, Singh et al. (2004) published a guideline to try and qualify what is considered a low RMSE based on the observations standard deviation known as RMSE-observations standard deviation ratio (RSR). RSR standardizes RMSE using the observations standard deviation by dividing RMSE by the Standard Deviation of Observed data.

(c) Percent Bias (PBIAS)

PBIAS quantifies the margin of error in percentage relative to the observed river discharge. Positive values indicate the modelled river flow under estimation while negative values indicate the modelled river flow over estimation (Hrachowitz, *et al.*, 2013). The smaller the PBIAS values the better the model. It is calculated with the expression in equation 4.

Equation 4: The percentage bias

$$PBIAS = \frac{\sum_i^n (Q_{obs,i} - Q_{simi})}{\sum_i^n Q_{obs,i}} \times 100$$

For the best fit PBIAS=0, |PBIAS| ≤ 10% is for a very good model, |PBIAS| between 10% and 15% indicates a good model, |PBIAS| between 15% and 25% indicates a satisfactory model and |PBIAS| ≥ 25% indicates an unsatisfactory model (Moriasi, *et al.*, 2007).

(d) Kling Gupta Efficiency (KGE)

The Kling Gupta Efficiency (KGE) also referred to as the improved NSE takes into consideration the Pearson coefficient of correlation, the standard deviation of the simulated and observed discharges as well as the relationship of the mean values of the simulated and observed river discharge. See Equation 5. KGE ranges between −∞ to 1.

Equation 5: The Kling-Gupta efficiency.

$$r = \frac{n(\sum Q_{simi} \times Q_{obsi}) - (\sum Q_{sim})(\sum Q_{obs})}{\sqrt{[n \sum {Q_{sim}}^2 - (\sum Q_{sim})^2] \times [n \sum {Q_{obs}}^2 - (\sum Q_{obs})^2]}}$$

Where:

Std.Qsim the standard deviation of the simulated discharges

Std.Qobs the standard deviation of the observed discharges

Avg.Qsiim the mean of the simulated discharges

Avg.Qobs the mean of the observed discharges

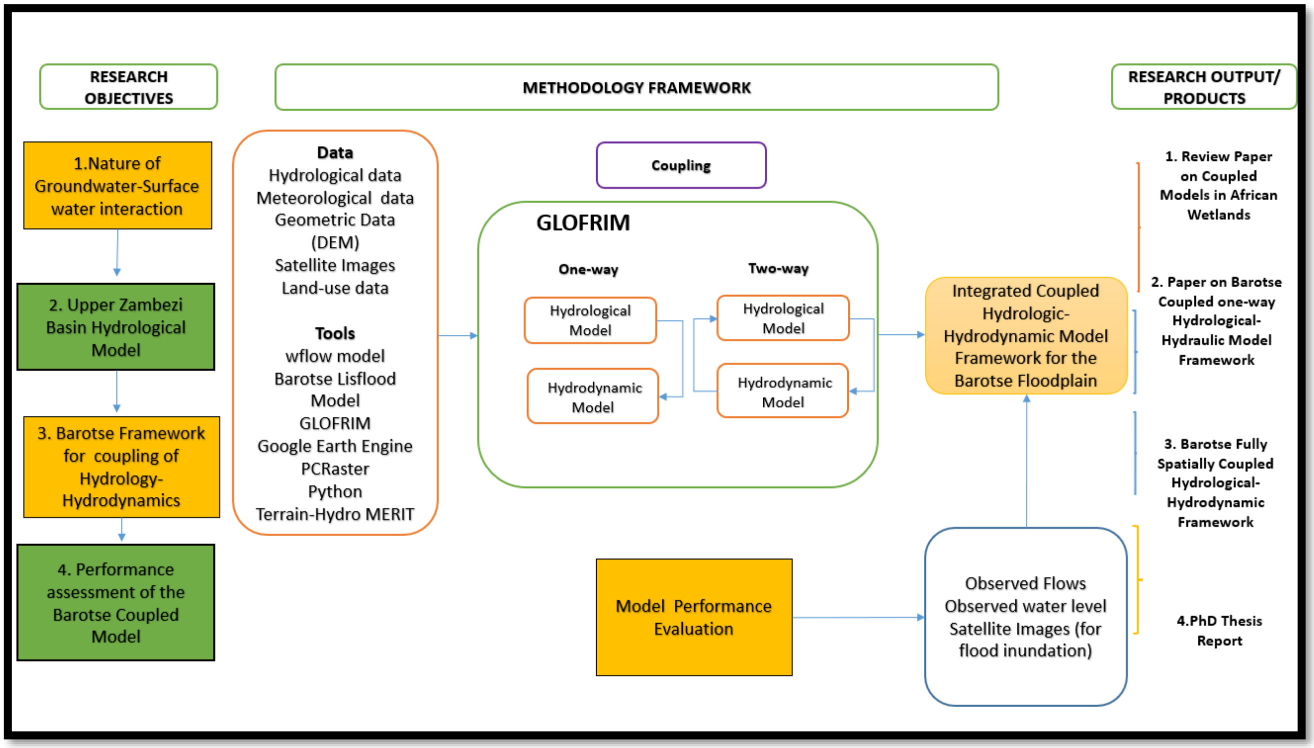


Figure 16. Methodological Framework applied in the study.

CHAPTER FIVE: PRESENTATION OF RESULTS

5.1 Overview

This chapter is about the presentation of the field findings of the research problem. The presentation of these field findings intends to address the research objectives and corresponding research questions:

5.2 Objective 1: Mechanisms of groundwater-surface water interaction in the Barotse floodplains

5.2.1 **Remote Sensing Analysis**

Remote sensing analysis produced median NDVI images for October 2019 and February 2020, dry and wet, respectively (Figure 17). In the dry season the NDVI, values ranged from - 0.3 to 0.7, whereas in the wet season the NDVI values ranged from - 0.2 to 0.8. The negative values represent water bodies and bare land while the positive values represent green vegetation from unhealthy to healthy vegetation. Subtracting the dry from the wet season values yields the NDVI difference image (Figure 18), which produces five classes using a natural Jenks break histogram classification (Table 1). Class 1 areas represent water bodies that were sustained in the dry season and areas that registered high soil moisture in the dry season. This class encompassed the Zambezi River, the riparian corridor and most parts of the wetland that remain waterlogged after the floods rescinded.

Table 1. Land classes derived from the NDVI Differences Map

Class	NDVI Values	Description
1	< 0	Water
2	0 – 0.1	Non-groundwater dependent ecosystems
3	0.1 – 0.2	Fast-drying vegetation
4	0.2 - 0.4	Slow-drying vegetation
5	> 0.4	Non-drying vegetation

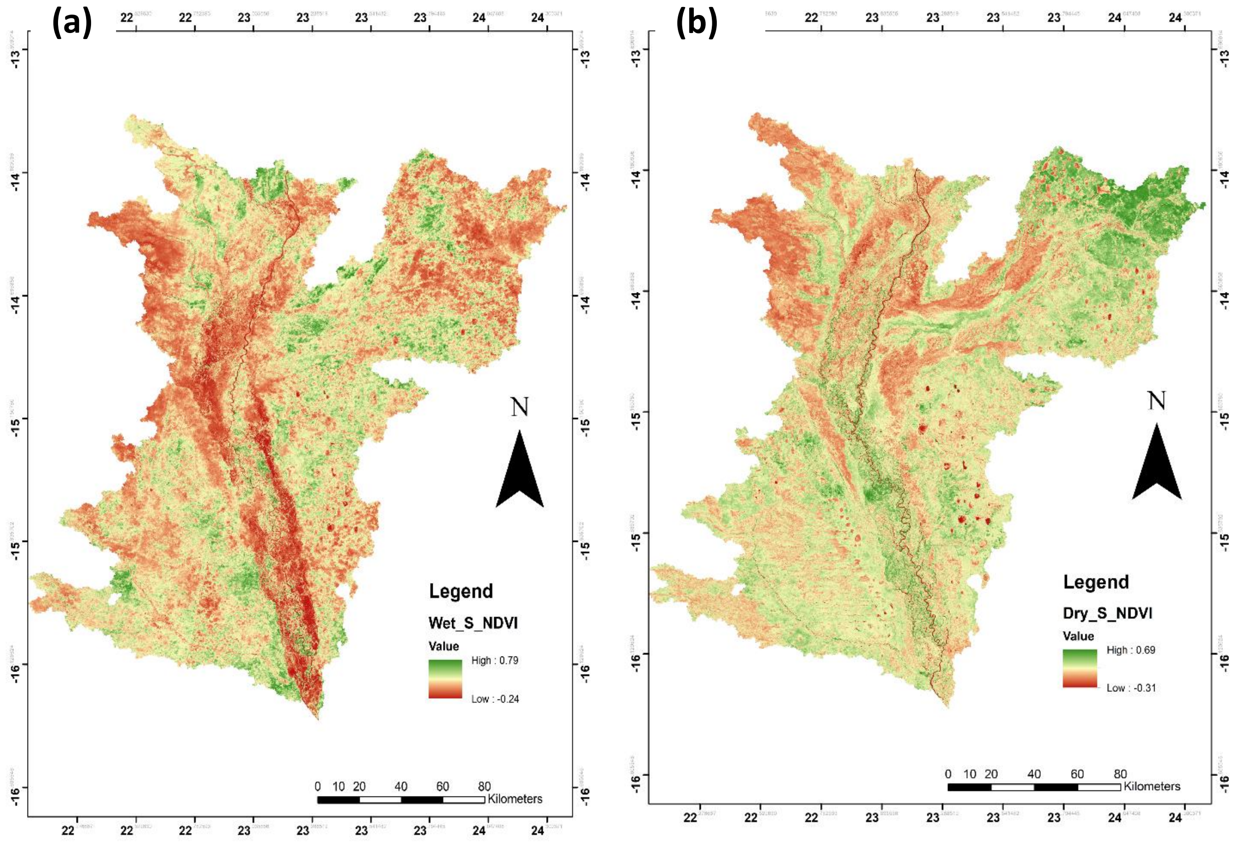


Figure 17. The NDVI over Barotse Catchment for the wet (a) season in February 2020 and (b) dry season in October 2019.

Class 2 areas had low NDVI values and did not show any changes across seasons. These were commonly settlements with sparse vegetation and bare soil. Class 3 areas had a sharp contrast from the dry season NDVI to the wet season NDVI. These areas were likely to have a deep-seated water table and were commonly associated with seasonal fields (locally called ‘Lizulu’), pastured areas and settlement areas within the floodplains. Class 4 areas were related to terrestrial vegetation with a diminishing access to water during the dry season with a relatively shallow groundwater table. These areas were within the wetland and some ephemeral streams. Class 5 areas was associated with a shallow water table. These areas were mostly found within the flood prone areas of the wetland that dried up in the dry season but retained high soil moisture. Classes 3, 4 and 5 are all likely groundwater water dependant vegetation with higher NDVI values indicative of a shallower groundwater level and vice versa. Figure 19 shows the relationship between depth to groundwater level (extracted from the Zambia Water Resources Management Database) and median NDVI values for the dry season in 2019. NDVI is thus a proxy, indicative of a shallow groundwater level when high (above 0.4) and tends to be lower with a deeper groundwater table (less than 0.1).

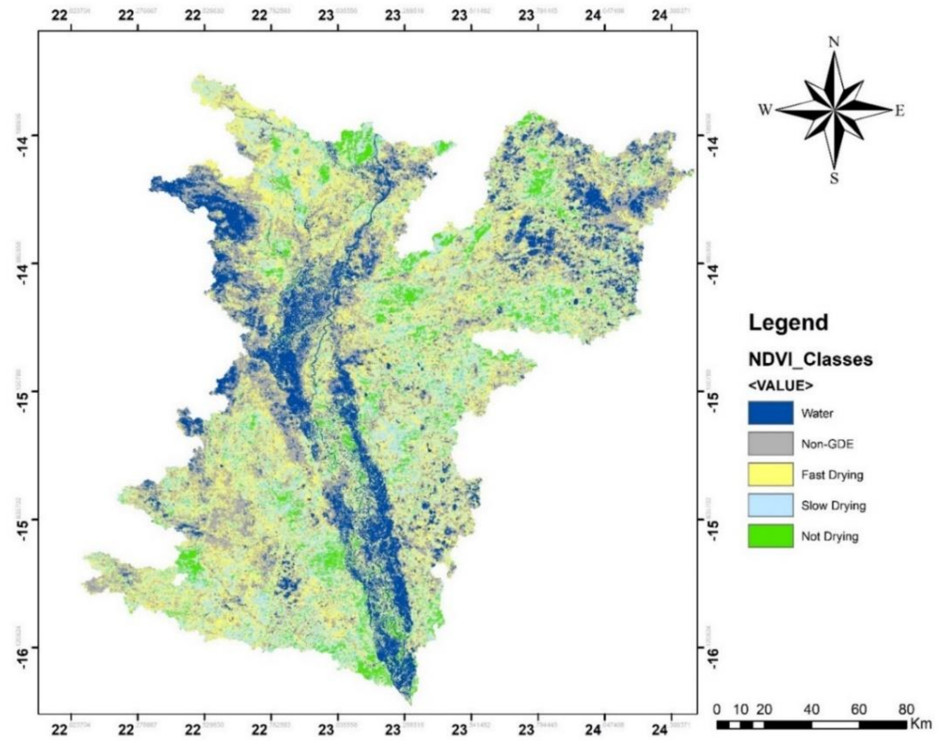


Figure 18. NDIVI difference map over the Barotse Catchment

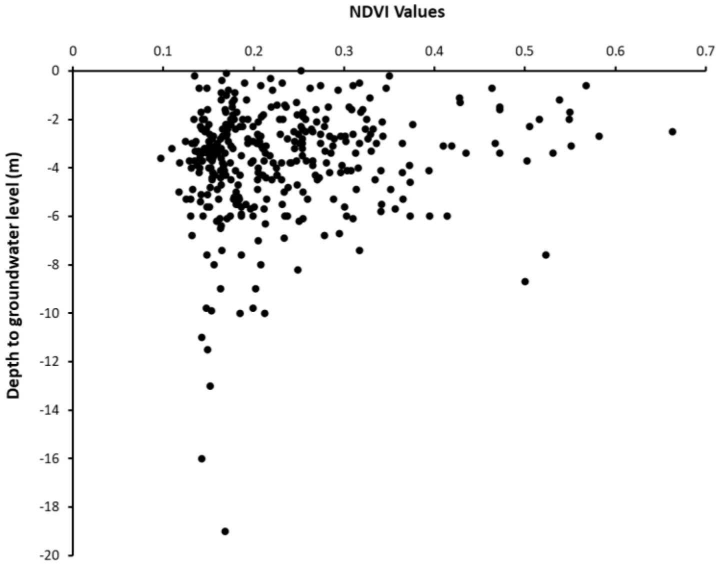


Figure 19. Relationship between depth to groundwater level (extracted from Zambia Water Resources Management Authority Database) and *NDVI* in the Barotse Basin.

5.2.2 **Major ion chemistry**

Table 2 provides a statistical summary of hydrochemical and stable isotopes analysis. Hydrochemical results showed increased mineralisation in the dry season compared to the wet season. Based on mean values in Table 2, surface water has an ionic trend of Ca > Na > Mg > K and Ca > K > Na > Mg, for the dry and wet season respectively. The major anions in both the dry and wet season were predominantly HCO_3^-. Groundwater had cations in the decreasing order of Ca > Na > K > Mg and Ca > K > Na > Mg, for the dry and wet season respectively. Similarly, the major anions had more bicarbonates (HCO_3^-) than sulphates (SO_4^{2-}) in both the dry and wet season. The piper diagram (Figure 20) showed that the surface and groundwater was predominately of Ca-Mg-HCO_3 facies. However, some of the groundwater samples during the dry season was also of Na-HCO_3 facies likely due ionic exchange reactions within the aquifer system.

Table 2. Statistical summary of surface water and groundwater hydro-chemical measurements and stable isotopes for the wet and dry seasons.

Wet Season	Groundwater (n =29)				Surface Water (n=13)			
Parameter	Min	Max	Mean	Std	Min	Max	Mean	Std
EC (μ/cm)	9	970	256	246	14	178	100	55
pH	5	9	7	1	6	9	8	1
Ca (mg/L)	1	201	36	53	0	23	18	5
Mg (mg/L)	1	54	5	10	0	14	6	4
Na (mg/L)	1	54	7	10	1	18	11	5
K (mg/L)	1	242	14	45	1	50	5	7
HCO_3 (mg/L)	0	234	41	58	1	50	25	15
Cl (mg/L)	0	0	0	0	0	0	0	0
SO_4 (mg/L)	1	152	23	43	1	28	278	8
dD (‰)	-53	63	-42	-53	-50	1	-31	20
d^{18}O (‰)	-8	14	-6	-8	-7	3	-4	4
Dry Season	Groundwater (n =32)				Surface Water (n=16)			
Parameter	Min	Max	Mean	Std	Min	Max	Mean	Std
EC (μ/cm)	2	1802	328	368	17	743	183	160
pH	5	10	7	1	7	10	8	1
Ca (mg/L)	1	357	43	74	1	72	20	16
Mg (mg/L)	1	19	4	4	1	16	8	3
Na (mg/L)	1	76	21	25	1	14	10	3
K (mg/L)	1	92	5	16	1	78	6	19
HCO_3 (mg/L)	3	141	53	43	8	67	33	13
Cl (mg/L)	0	0	0	0	0	0	0	0
SO_4 (mg/L)	1	462	25	82	1	24	6	7
dD (‰)	-53	-22	-44	6	-43	66	10	37
d^{18}O (‰)	-8	-3	-7	1	-7	14	3	7

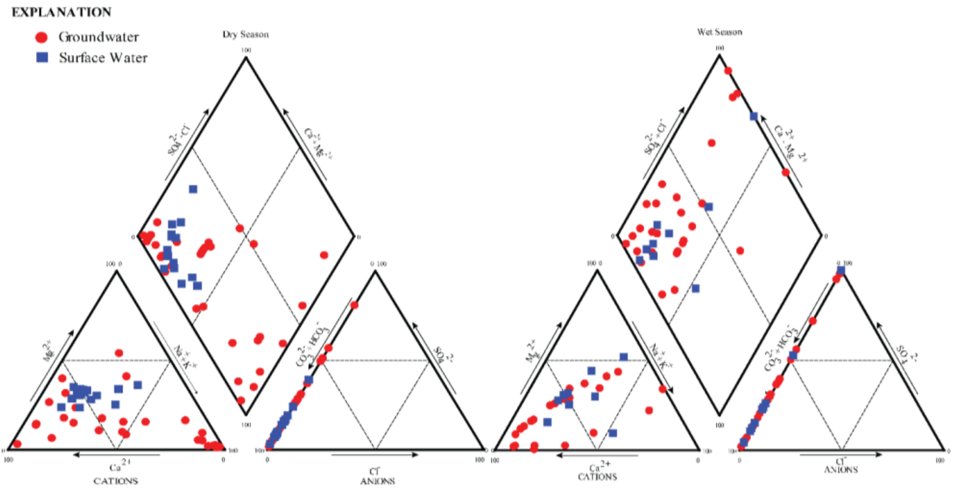


Figure 20. Piper diagram of surface and groundwater samples in the wet and dry season from in the Barotse Catchment.

5.2.3 Stable isotopes

δ^2H and δ^{18}O were used to visualise groundwater-surface water interactions in the Barotse Floodplain. The results are plotted relative to the local meteoric water line (LMWL) using data from Ndola town, which is the only dataset from Zambia in the International Atomic Energy Agency (IAEA) database. The equation for the local meteoric water line (LMWL) was $\delta^2H = 7.63\delta^{18}O + 9.14$ substantially compares to the global meteoric water line that is defined by the equation $\delta^2H = 8\delta^{18}O + 10$ (IAEA and WMO, 2006). Figure 21 shows the isotope composition from the dry and wet season, respectively. In the dry season, δ^{18}O values for surface water ranged from -42.9 ‰ to 65.6 ‰, and δ^2H values ranged from -6.7 ‰ to 14.20 ‰, as shown in Figure 8. In groundwater, δ^{18}O values ranged between -56.3 ‰ and -18.2 ‰, whereas δ^2H values range from -8.24 ‰ to -2.33 ‰ (Figure 21). In the wet season (Figure 8), all groundwater samples plotted in the depleted portion of the LMWL with δ^{18}O ranging from -50.5 ‰ to -24.9 ‰ and δ^2H ranging from -7.23 ‰ to -3.93 ‰ except one anomaly from the upstream, that plotted in the enriched zone of the LMWL. Surface water samples had δ^{18}O ranged between -57.4 ‰ to 1.4 ‰ and δ^2H ranged from -7.5 ‰ to 3.3 ‰ (Figure 21). In both the dry and wet season, groundwater was constant and limited to the depleted stable isotope signature (except for one dataset from the upstream region) compared to the surface water which was enriched in the dry season. It can be deduced that groundwater was recharged primarily from precipitation in the wet season and was not receiving isotopically enriched surface water in both seasons (except for an upstream localised area).

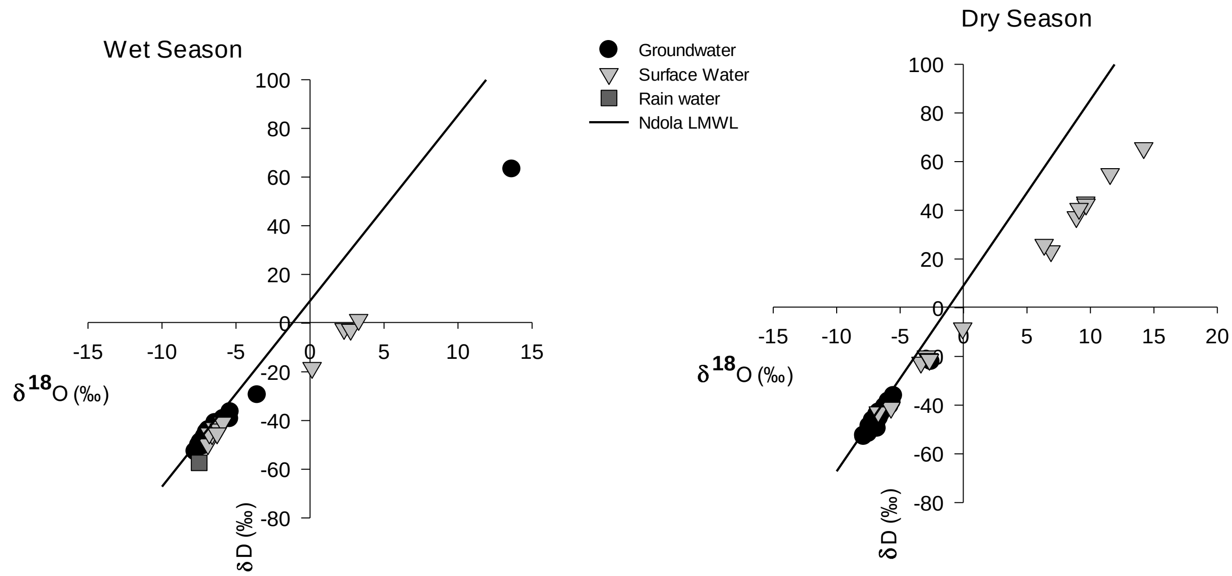


Figure 21. Stable isotopes signatures of surface and groundwater plotted with the Ndola Local meteoric line for the Barotse Floodplain.

5.3 Objective 2: Rainfall-runoff hydrologic model for Upper Zambezi River basin focusing on modelling Barotse floodplain.

5.3.1 Wflow Sensitivity Results

The analysis results on the wflow parameters with the sensitivity indices of P-value are as shown in Table 3. Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs (parameters). It is a necessary process in identify key parameters and parameter precision required for calibration (Ma *et al.,* 2000). In choosing few parameters for calibration, the study was conscious of the equifinality concept (Beven and Freer, 2001), that different combinations of values of the same parameters may produce an identical output signal.

Table 3. Parameter sensitivities for wflow hydrological model

Parameter	**Definition**	**Rank**	**Sensitivity Indices (P – value)**
KsatVer	vertical saturated soil conductivity of various depth of soil surface.	3	0.65
RootingDepth	controls the storage of the soil, the higher the rooting depth, the higher the storage of water and less the flow.	2	0.75
SoilThickness	controls the storage of the soil module and affects the SoilWaterCapcity.	1	0.78
M	determines the decrease of vertical saturated conductivity with depth.	4	0.55

5.3.2 Hydrological Model Performance Results

Four (4) goodness of fit of simulated streamflow time series against observed streamflow objective functions were used for assessment of goodness of fit; Nash-Sutcliffe efficiency (NSE); Root Mean Square Error (RMSE)- observations Standard Deviation Ratio (RSE); Percent Bias (pbias) and Kling-Gupta Efficiency (KGE). These objective function of goodness performance were applied on Chavuma,Watopa,Lukulu and Senanga Guage Stations. The calibration period was for five-year period (2001-10-30 to 2006-09-30) by comparing simulated and observed monthly flows. The results of the calibration were Chavuma, nse=0.738; kge = 0.738; pbias = 2.561 and RSR = 0.511; Watopa, nse=0.684; kge = 0.816; pbias = 10.577 and RSR = 0.557; Lukulu, nse=0.736; kge = 0.795; pbias = 10.437 and RSR = 0.509. Senanga, nse=0.132; kge = 0.509; pbias = 37.740 and RSR = 0.9233 (Table 4). Appendix A has the paper that was published based on the results been report in this thesis on the hydrological Model of the Upper Zambezi Basin.

Table 4. wflow model calibration objective function matrices results.

	Model Calibration Matrices			
Gauge Station	Kling-Gupta Efficiency (kge)	RMSE-observations standard deviation ratio (RSR)	Nash-Sutcliffe Efficiency (nse)	Percent Bias (pbias)
Chavuma	0.738	0.511	0.735	2.561
Watopa	0.816	0.557	0.684	10.577
Lukulu	0.795	0.509	0.736	10.437
Senanga	0.509	0.9233	0.132	37.724

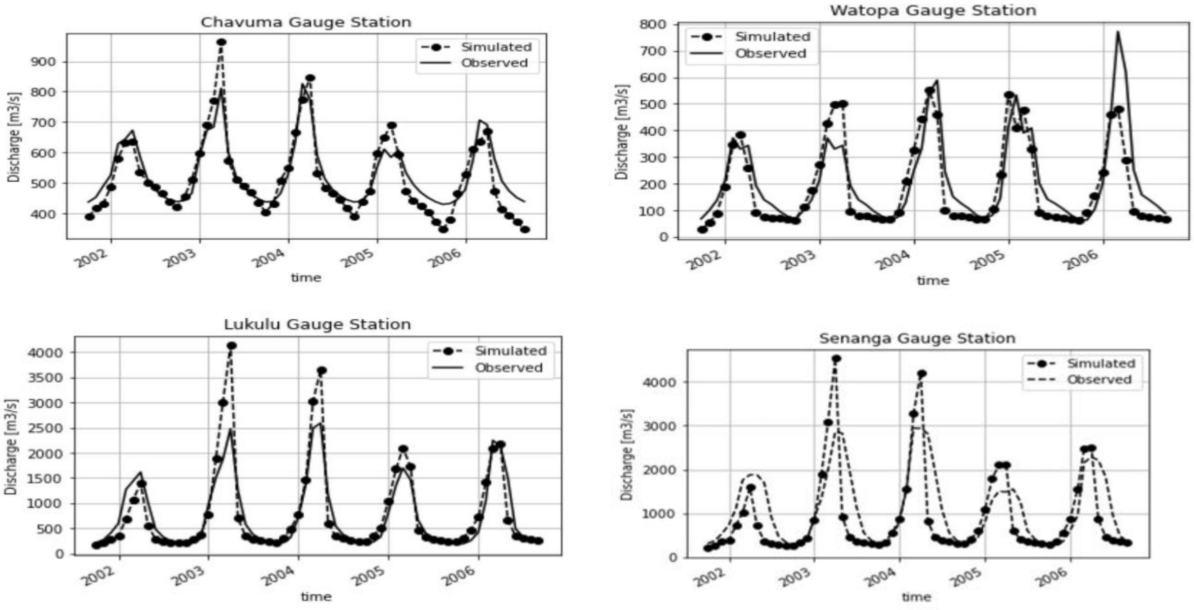


Figure 22. measured vs simulated discharge for the period October 2001 to September 2006.

5.3.3 **Hydrological Model Validation Results**

Using the same objective function matrices, the model validation was done using an independent three-year period data set (2006-10-30 to 2009-09-30) by comparing simulated and observed monthly flows. The validation results were Chavuma, nse=0.737; kge = 0.857; pbias = 4.559 and RSR = 0.501; Watopa, nse=0.661; kge = 0.622; pbias = 22.376 and RSR = 0.569; Lukulu, nse=0.705; kge = 0.853; pbias = 21.04 and RSR = 0.532. Senanga, nse=0.165; kge = 0.590; pbias = 34.787 and RSR = 0.569 (Table 5).

Table 5. wflow model validation objective functions matrices results

	Model Validation Matrices			
Gauge Station	Kling-Gupta Efficiency (kge)	RMSE-observations standard deviation ratio (RSR)	Nash-Sutcliffe Efficiency (nse)	Percent Bias (pbias)
Chavuma	0.857	0.501	0.737	4.559
Watopa	0.622	0.569	0.661	22.376
Lukulu	0.853	0.532	0.705	21.04
Senanga	0.590	0.569	0.165	34.787

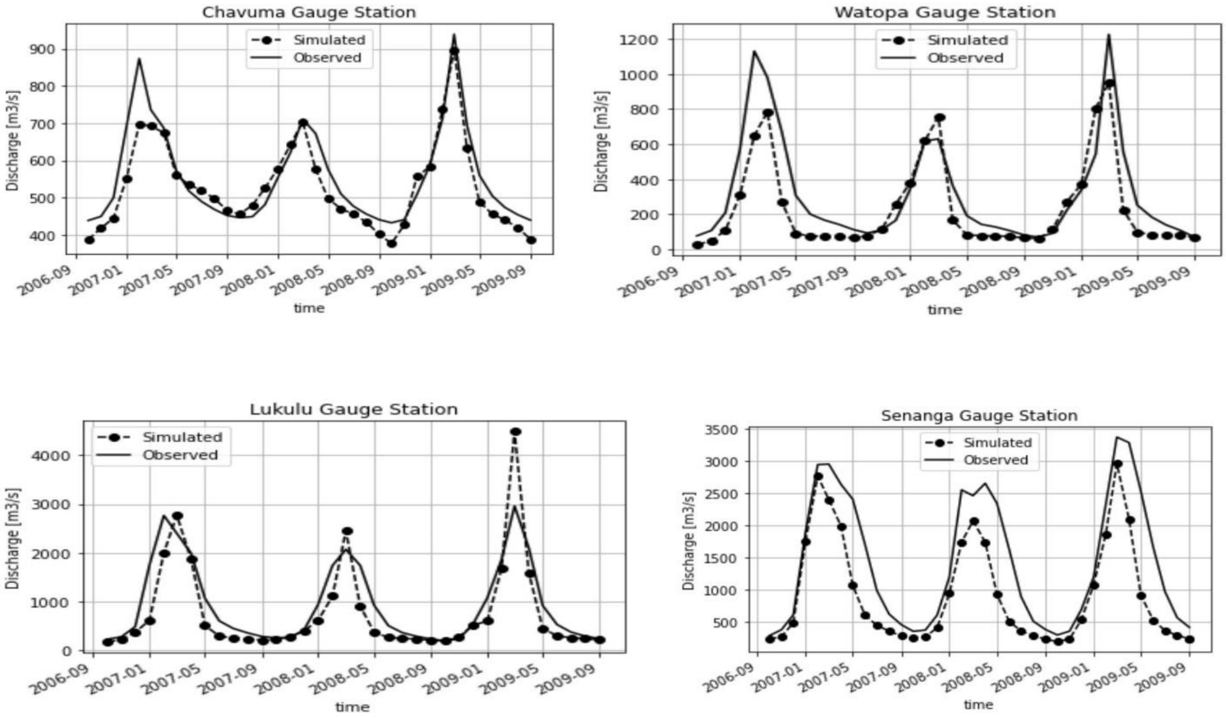


Figure 23. measured vs simulated results for the period October 2006 to September 2009.

5.4 Objective 3: An integrated hydrologic-hydrodynamic online (internal) model coupling framework for Barotse Floodplain

5.4.1 One-way online (internal) model coupling framework for Barotse Floodplain

The results of objective three (3) of developing an integrated hydrologic-hydrodynamic online (internal) model coupling framework for Barotse Floodplain is as indicated in figure 24. Two models used are Upper Zambezi wflow hydrological model developed in objective 2 and an existing Barotse Lisflood hydrodynamic Model (Makungu, 2019). These two models are integrated coupled using GLOFRIM v2.1. which enabled the integration of physical processes of wflow and lisflood models. The coupling settings is defined in the GLOFRIM ini-file (initialization file) Appendix (D). Once the ini-file is read by GLOFRIM it first initializes the model-specific configuration files and then initialized both models as a coupled entity. The coupling in this case is done per grid basis. Once the two models are initialized, a loop is entered, starting at the start time, and terminating at the end time as specified in the python execution command, wflow runs and feeds Lisflood_fp, on an hourly time step. During the loop, models are individually updated from the upstream end of the model cascade to the most downstream model. It is only then that the model is updated, the variables are exchanged (as defined in GLOFRIM ini-file) and retrieved from the providing model and inserted into the receiving model. It is only after this, model execution finalized. A complete python script for this framework is attached in Appendix B.

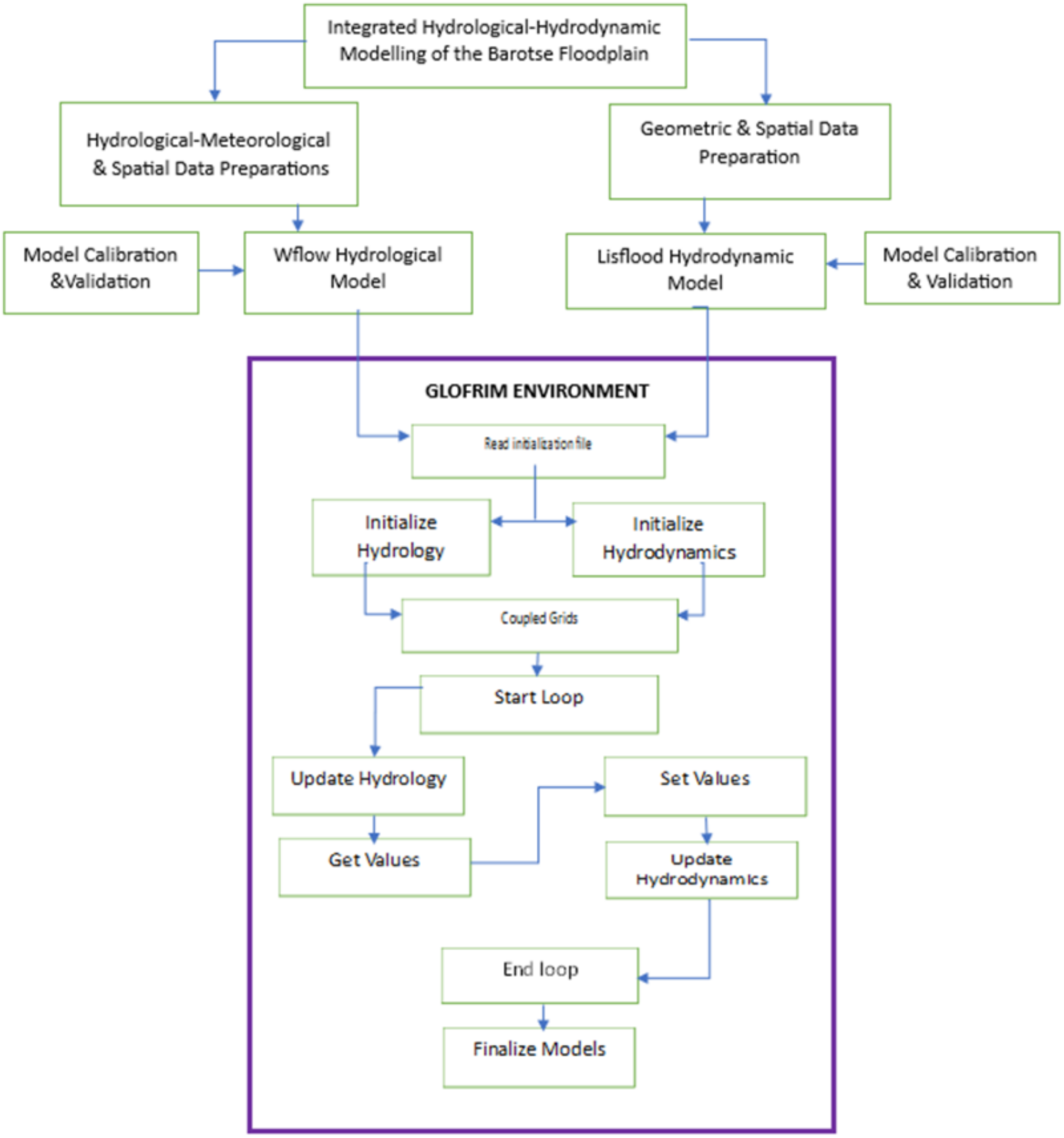


Figure 24. Integrated one-way online hydrologic-hydrodynamic modelling Framework for the Barotse Floodplain.

The hydrological model domain covered all Upper Zambezi Basin, while the lisflood covered the Barotse Floodplain catchment. Figure 25 shows the two model domains in terms of model extent and location of interactions wflow (inflow points and Lisflood boundary conditions) of the two hydrological and hydrodynamic models.

Figure 25. Model domains and location of interactions of wflow hydrological model and Lisflood hydrodynamic model.

5.5 **Objective 4. Testing and evaluating the performance of one-way Barotse Coupled Hydrological-Hydrodynamic Model**

5.5.1 **Barotse Coupled Hydrological-Hydrodynamic Model Testing**

The one-way online Barotse Coupled Hydrological-Hydrodynamic Model developed based on the framework in objective 3 was successful and run very well as indicated by some screen shorts taken on selected phases during the model run (Figure 26).

(a)

```
Microsoft Windows [Version 10.0.19044.2486]
(c) Microsoft Corporation. All rights reserved.

C:\git>conda activate barotse2

(barotse2) C:\git>dir
 Volume in drive C has no label.
 Volume Serial Number is 4205-5D12

 Directory of C:\git

09/02/2023  01:06 pm    <DIR>          .
09/02/2023  01:06 pm    <DIR>          ..
10/12/2022  09:39 am    <DIR>          barotse
31/10/2020  03:51 pm    <DIR>          glofrim
22/12/2022  08:21 am    <DIR>          Lisflood
31/10/2020  03:29 pm    <DIR>          wflow
               0 File(s)              0 bytes
               6 Dir(s)  47,273,742,336 bytes free

(barotse2) C:\git>cd barotse

(barotse2) C:\git\barotse>dir
 Volume in drive C has no label.
 Volume Serial Number is 4205 5D12

 Directory of C:\git\barotse

10/12/2022  09:39 am    <DIR>          .
10/12/2022  09:39 am    <DIR>          ..
19/10/2020  12:09 pm             2,861 .gitignore
03/02/2023  07:49 am    <DIR>          .idea
24/09/2020  09:17 pm    <DIR>          .ipynb_checkpoints
23/10/2020  01:05 pm               464 debug.log
06/07/2022  03:57 pm               653 environment.yml
31/10/2020  03:42 pm               419 env_glofrim.yml
06/07/2022  03:57 pm    <DIR>          example_models
22/12/2022  08:30 am    <DIR>          experiments
13/11/2021  11:09 am    <DIR>          gis
19/10/2020  12:09 pm             5,594 INSTALL.md
19/10/2020  12:09 pm               126 install wflow.bat
19/10/2020  12:09 pm            35,823 LICENSE
09/02/2023  08:59 am    <DIR>          lisflood
09/02/2023  01:05 pm    <DIR>          notebooks
19/10/2020  02:56 pm    <DIR>          png
19/10/2020  12:09 pm               821 README.md
07/02/2023  05:58 pm    <DIR>          results
25/01/2021  11:22 pm            42,896 run_montecarlo.bat
19/10/2020  02:56 pm    <DIR>          scripts
```

(b)

(c)

(d)

(e)

(f)

```
2003-09-27 00:00:00
2023-02-09 11:40:05,861 - wflow_sbm_inc_cap.ini - wf_DynamicFramework - INFO - saving maps
2023 02 09 11:40:05,860   GLOFRIM.WFL   INFO   updated model to datetime 2003 09 28 00:00
2023 02 09 11:40:05,860   GLOFRIM   INFO   setting WFL.RiverRunoff data to coupled LFP.SGCQin variable
2023 02 09 11:40:05,860   GLOFRIM   INFO   adding WFL.RunoffRiverCells data to coupled LFP.H variable
2023 02 09 11:40:15,584   GLOFRIM.LFP   INFO   updated model to datetime 2003 09 28 00:00:03 in 2729 iterations
2023-02-09 11:40:15,584 - GLOFRIM - WARNING - Model times out of sync: WFL: 2003-09-28 00:00:00; LFP: 2003-09-28 00:00:03.694215
2023-02-09 11:40:15,584 - GLOFRIM - WARNING - Model times out of sync: WFL: 2003-09-28 00:00:00; LFP: 2003-09-28 00:00:03.694215
2023-02-09 11:40:15,715 - GLOFRIM - WARNING - Model times out of sync: WFL: 2003-09-28 00:00:00; LFP: 2003-09-28 00:00:03.694215
2003-09-28 00:00:00
2023-02-09 11:40:16,226 - wflow_sbm_inc_cap.ini - wf_DynamicFramework - INFO - saving maps
2023 02 09 11:40:16,237   GLOFRIM.WFL   INFO   updated model to datetime 2003 09 29 00:00
2023 02 09 11:40:16,237   GLOFRIM   INFO   setting WFL.RiverRunoff data to coupled LFP.SGCQin variable
2023 02 09 11:40:16,247   GLOFRIM   INFO   adding WFL.RunoffRiverCells data to coupled LFP.H variable
2023 02 09 11:40:26,917   GLOFRIM.LFP   INFO   updated model to datetime 2003 09 29 00:00:17 in 2731 iterations
2023-02-09 11:40:26,917 - GLOFRIM - WARNING - Model times out of sync: WFL: 2003-09-29 00:00:00; LFP: 2003-09-29 00:00:17.927451
2023-02-09 11:40:26,917 - GLOFRIM - WARNING - Model times out of sync: WFL: 2003-09-29 00:00:00; LFP: 2003-09-29 00:00:17.927451
2023-02-09 11:40:26,948 - GLOFRIM - WARNING - Model times out of sync: WFL: 2003-09-29 00:00:00; LFP: 2003-09-29 00:00:17.927451
2003-09-29 00:00:00
2023-02-09 11:40:27,447 - wflow_sbm_inc_cap.ini - wf_DynamicFramework - INFO - saving maps
2023-02-09 11:40:53,663 - GLOFRIM.WFL - INFO - updated model to datetime 2003-09-30 00:00
2023 02 09 11:40:53,671   GLOFRIM   INFO   setting WFL.RiverRunoff data to coupled LFP.SGCQin variable
2023 02 09 11:40:53,673   GLOFRIM   INFO   adding WFL.RunoffRiverCells data to coupled LFP.H variable
2023 02 09 11:41:04,261   GLOFRIM.LFP   INFO   updated model to datetime 2003 09 30 00:00:03 in 2731 iterations
2023-02-09 11:41:04,261 - GLOFRIM - WARNING - Model times out of sync: WFL: 2003-09-30 00:00:00; LFP: 2003-09-30 00:00:03.231922
2023-02-09 11:41:04,261 - GLOFRIM - WARNING - Model times out of sync: WFL: 2003-09-30 00:00:00; LFP: 2003-09-30 00:00:03.231922
2023-02-09 11:41:04,277 - GLOFRIM - INFO - Setting up output structures
2023-02-09 11:41:38,599 - GLOFRIM - INFO - Merging outputs to Dataset
2023-02-09 11:41:39,115 - GLOFRIM - INFO - Writing outputs to C:\git\barotse\results\test_oneyear_1way_1D2D.nc
2023-02-09 11:42:50,419 - GLOFRIM - INFO - Closing model
2023 02 09 11:42:50,419   GLOFRIM   INFO   Finalize models bmi. Close loggers.
2023 02 09 11:42:50,427   GLOFRIM.WFL   INFO   Finalize bmi. Close logger.
2023 02 09 11:42:50,429   wflow_sbm_inc_cap.ini   wflow_sbm   INFO   Saving initial conditions...
2023 02 09 11:42:50,490   wflow sbm inc cap.ini   wf DynamicFramework   INFO   Saving summary maps to disk...
2023-02-09 11:42:50,754 - GLOFRIM.LFP - INFO - Finalize bmi. Close logger.
Finished.


Finish Date: 9/2/2023
Finish Time: 11:42:51


 Total computation time: 163.37 mins


(barotse2) C:\git\barotse\experiments>
```

Figure 26. Phase of one-way coupled Barotse hydrological-hydrodynamic model run: (a) activating Barotse model environment (b) initializing Barotse GLOFRIM environment (c) pulling wflow and reading its initialization file (d) pulling lisflood model (e) coupling the two models as one unit and initiating hydrology-hydrodynamic calculation (f) saving outputs and closing the model run successfully.

5.5.2 **Evaluating the performance of one-way Barotse Coupled Hydrological-Hydrodynamic Model**

5.5.2.1 Flows

The results of goodness of fit hydrography (Figure 27) of simulated streamflow from the coupled Hydrologic-hydrodynamic model against observed streamflow objective functions for Lukulu and Senanga Nash-Sutcliffe efficiency (NSE); Kling-Gupta Efficiency (KGE); Root Mean Square Error (RMSE)- observations Standard Deviation Ratio (RSE) and Percent Bias (pbias) were: Lukulu; nse 0.752, kge 0.876, RSR 0.563, ,pbias 8.254 and Senanga; nse 0.535,kge 0.699, RSR 0.9214, , pbias 21.495.

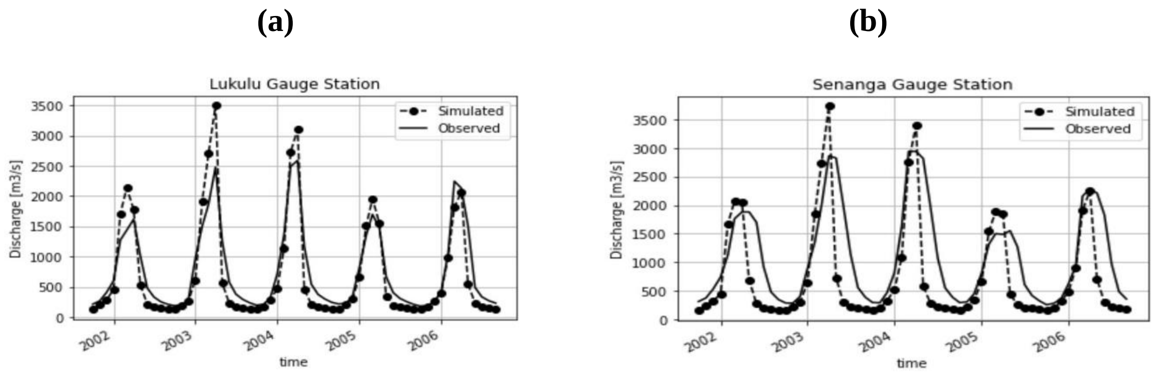


Figure 27. Hydrographs for observed vs simulated from Barotse Coupled model (a) Lukulu (b) Senanga for the period Oct 2006 to Sept 2009.

5.5.2.2 Water level

The monthly water levels results of the hydrologic-hydrodynamic modelling coupling framework for Barotse developed were compare with WARMA monthly observed results for Lukulu guage station, Mongu (Matongu gauge station) and Senanga Gauge station for statistical goodness of fit objective functions for Nash-Sutcliffe efficiency (nse), Kling-Gupta Efficiency (kge) and Root Mean Square Error (RMSE)- observations Standard Deviation Ratio (RSE): Mongu, kge 0.792, RSR 0.762, nse 0.55; Senanga; kge 0.6707, RSE 0.827, nse 0.503 and Lukulu, kge 0.630, RSR 0.644, nse 0.301. This is also shown graphically in Figure (28).

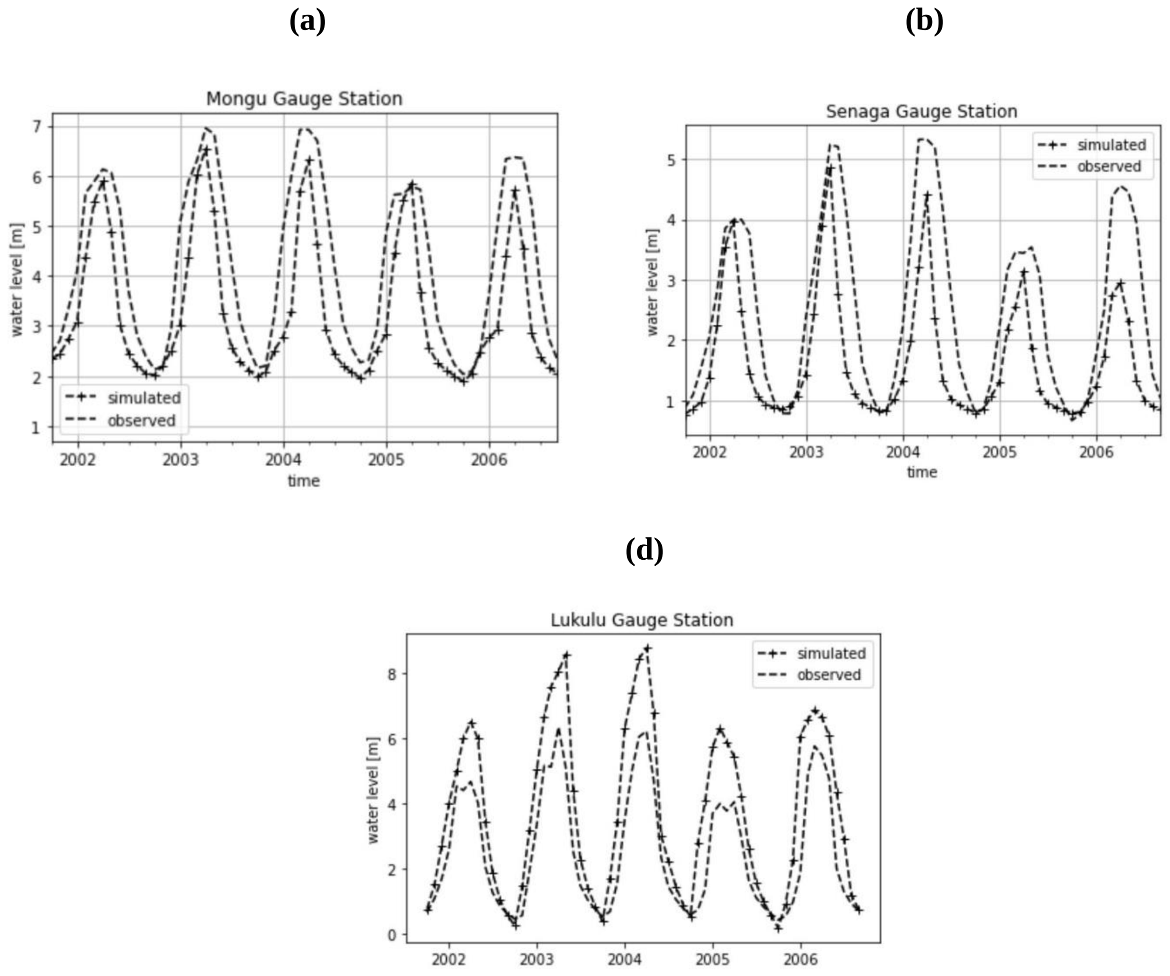


Figure 28. water level observed vs simulate results from coupled model (a) Mongu (b) Senanga(c) Lukulu gauge stations for the period October 2006 to September 2009.

5.5.2.3 Flood inundation Area

The simulated results of coupled mode inundation area were compared with Zimba *et al* (2019) study results that had used The Desert Flood Index (DFI) to detect Barotse Floodplain inundated area from MODIS MOD09A1 imagery. The statistical objective functions results based on days of 2004, day one as 1st January were nse 0.637, kge 0.731, RSR 0.502 and pbias 25.234. The graphical plotting of MODIS and simulated inundation area are as shown in (Figure 29).

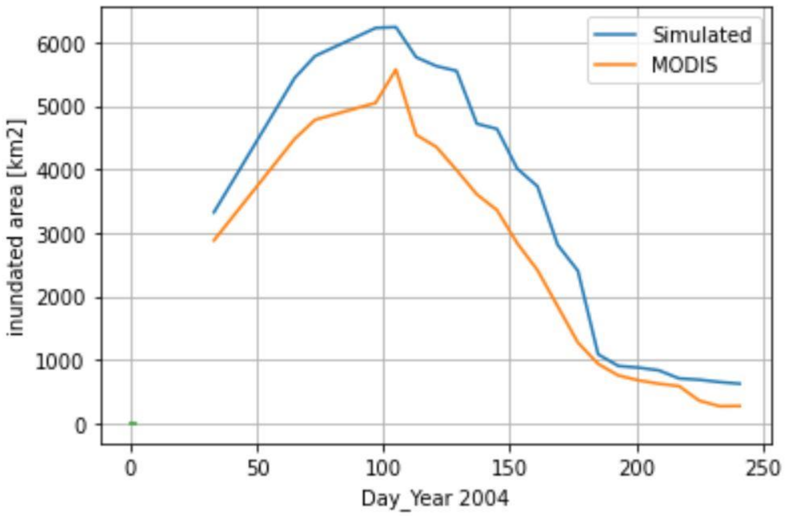


Figure 29. 2004 simulated inundated area vs calculated inundated area based on MODIS 09A1 imagery data by Zimba *et al*., 2018 for the Barotse Floodplain.

CHAPTER SIX

DISCUSSION OF RESEARCH FINDINGS

6.1 Overview

The previous chapter has presented the field findings of this research. This chapter discusses the research findings presented in the previous chapter. It provides a detailed analysis of the data gathered and presented based on the research objectives which were.

i. To investigate the mechanisms of groundwater-surface water interaction in the Barotse floodplains.
ii. To develop a rainfall-runoff hydrologic model for Upper Zambezi River basin focusing on modelling Barotse floodplain.
iii. To develop integrated hydrologic-hydrodynamic online (internal) coupling modelling framework for Barotse floodplains.
iv. To test and evaluate the performance of one-way Barotse Coupled Hydrological-Hydrodynamic Model developed based on the framework in objective 3.

6.2 Mechanisms of groundwater-surface water interaction in the Barotse floodplains

The results of the multivariate cluster analysis (Figure 30) show a dendrogram of five clusters (A, B, C, D, E) with a similarity of 66 % and above in both the wet and dry season. The multivariate analysis was based on 92 hydrochemical observations of physio-chemical variables (Ca, Mg, Na, K, HCO3, Cl, SO4, TDS). The five clusters are indicative of the potential groundwater-surface water interaction in both wet and dry seasons. The similarity in hydrochemistry between groundwater and surface water may be a result of interactions between them and observed hydrochemical signatures observed in the study area or atleast some hydrochemical signature observed. To examine this further, the study considered HCA clusters for the dry season data. Figure 31 shows a spatial distribution plot with three similarity groups based in HCA and the associated water quality facies (Ca-Mg-HCO3, Na-HCO3 and NaCl). The lower reaches of the floodplain sampled sites were typified with Ca-HCO3 water, low in major ions concentration and subsequent conductivity level. Moreover, based on the depth to groundwater and NDVI, this area has an NDVI > 0.4 thus near surface or shallow groundwater level (< 10 m bgl).

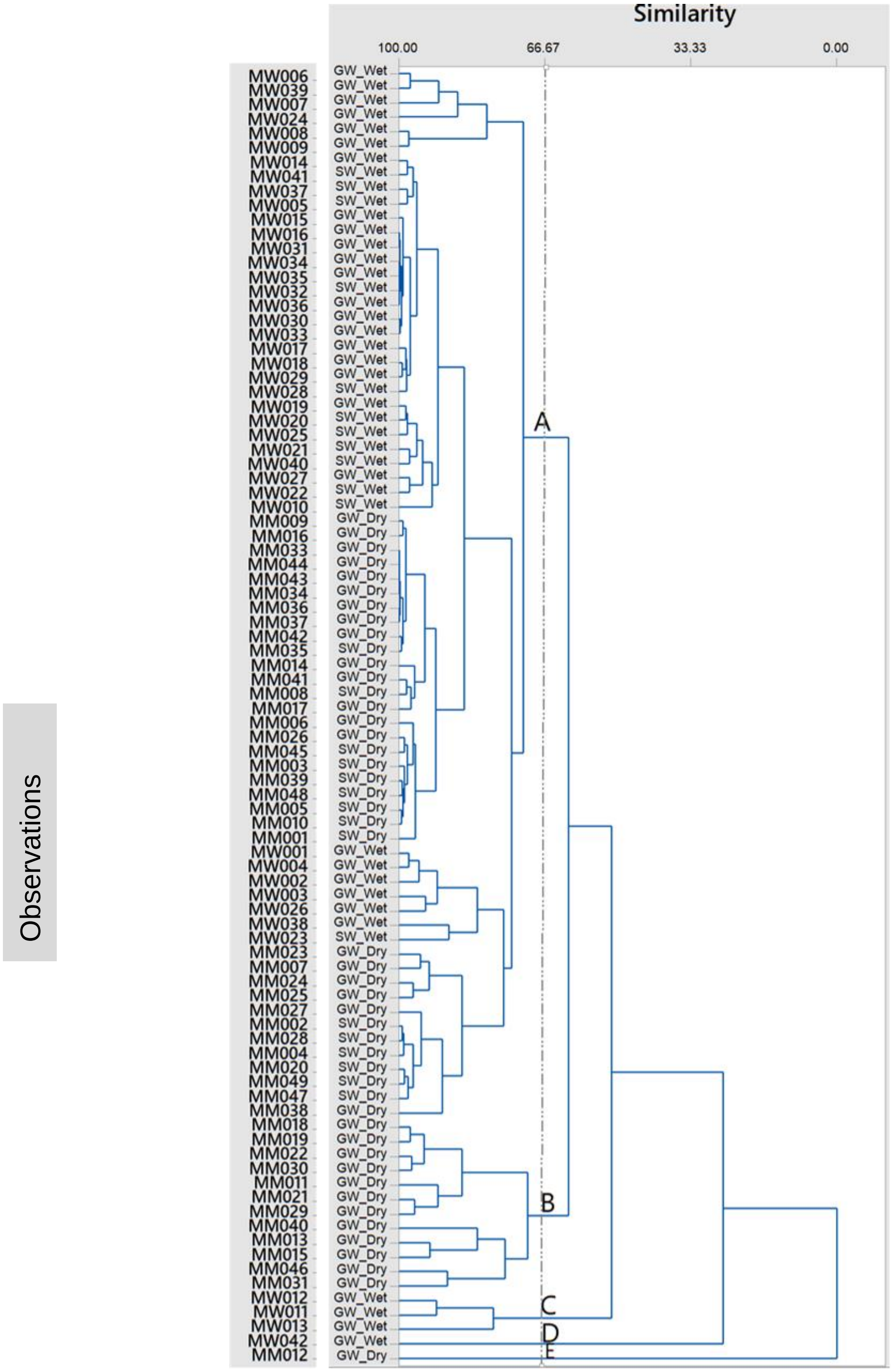
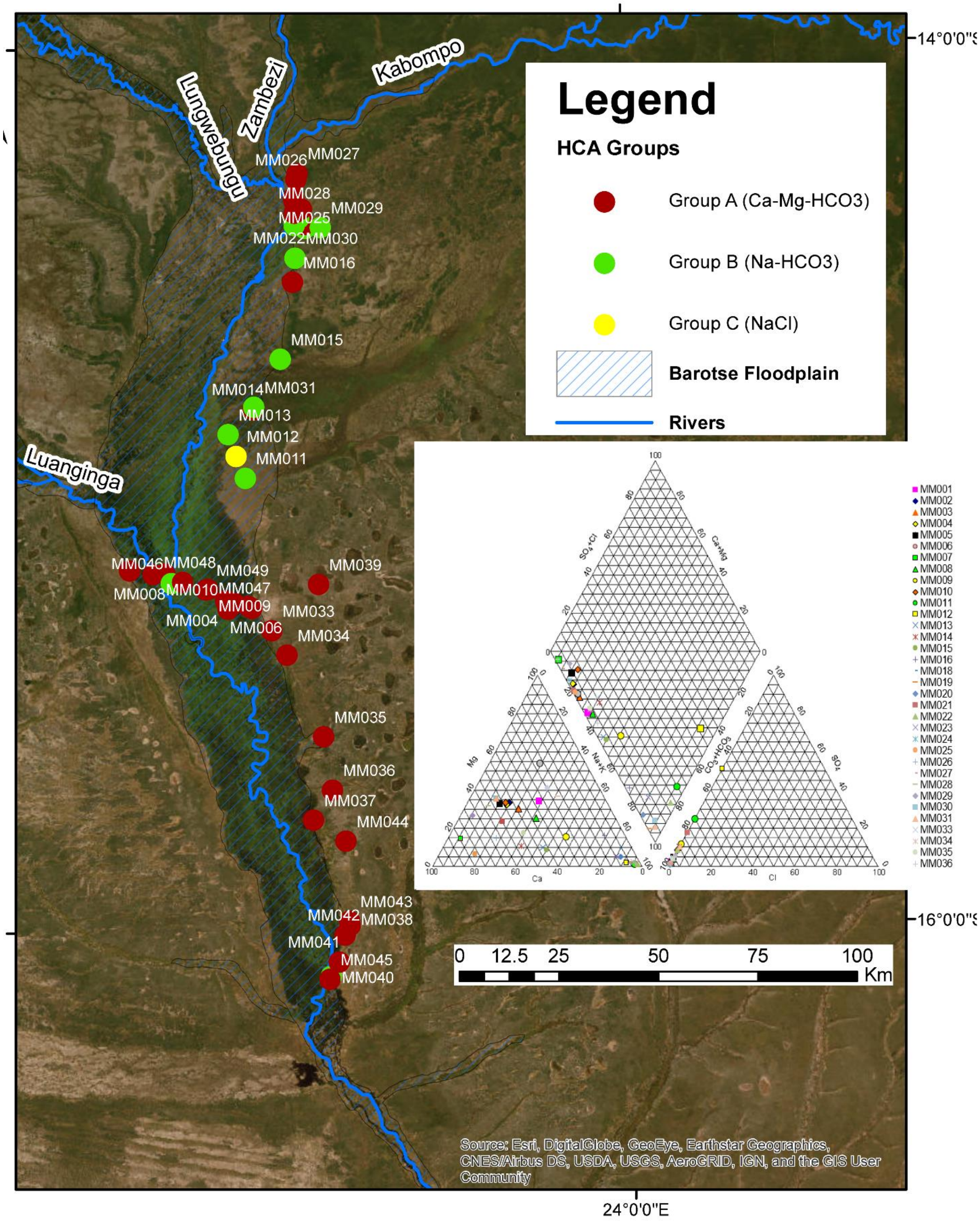


Figure 30. Dendrogram of surface and groundwater observations from the dry and wet season using the hydro-chemical analysis results from the Barotse Floodplain Catchment.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 31. Spatial distribution of groundwater and surface water sampled points for the dry season assigned to groups based on Hierarchical Cluster Analysis (HCA) and the related hydro-chemical facies in the piper diagram insert.

It can be deduced from the finding of the study that the shallow groundwater levels are located in alluvial sands that foster high connectivity between surface and groundwater. Based on the foregoing, it can be inferred that the observed Ca-HCO3 signature was due to river water seepage to the groundwater aquifer system. These results are similar to the study by Guggenmos *et al,* 2011, who investigated GW-SW interactions in the Wairarapa Valley with alluvial gravels that reflected a high proportion of Ca-HCO3, low Na, Cl in shallow groundwater due to recharging rivers within close proximity. Additionally, groundwater seems to be providing baseflow to the upper and middle reaches of the floodplain based on the hydro-chemical similarity assigned to Group B (Na-HCO3). This also supported by the findings of Mulema (2023) who argued that there can be many other factors that can increase river flow, but from the data collected in his study, baseflow was one of the main contributors to increased river flow downstream. The baseflow analysis from the study showed an upstream base flow contribution of 0.448 whereas the downstream contribution to the river flow was 0.482. it was further argued that the Barotse Floodplain has an average of 46.5% groundwater contribution to the surface runoff. Moreover, most of the existing boreholes in this region have a groundwater level of more than 10 m within a sandy-silt or silty-clay deposits. Compared to samples in Group A, Group B had higher mean values of all major ions, conductivity, higher Na relative to Ca. Stable isotopes, the δD and $\delta^{18}O$ suggests rainfall recharge which likely has been mineralised through water-rock interactions. It therefore can be deduced that the observed hydrochemistry of Group B was due to rainfall recharged groundwater into stream baseflow. Hiscock (2005) reported a similar transfer of chemical signature from rainfall-recharged groundwaters into stream base flow. Group C (Na-Cl) based on Figure 31, was weakly linked to Group A and B, and therefore confined to a groundwater system in a localised area. This study had to look at the nature of surface-groundwater interactions has it is often argued that a clear understanding of the interactions of surface and groundwater is essential in order to develop appropriate strategies for numerical models for successful simulations of complex aquatic systems in which such interactions do influence hydrological and hydrodynamic dynamics (Haque, *et al.,* 2021).

6.3 **Rainfall-runoff hydrologic model for Upper Zambezi River basin**

The simulated flows generated by wflow model for the upstream gauge stations were quite similar and closely matched the observed flow as indicated by the evaluation statistics; Chavuma, nse=0.738; kge = 0.738; pbias = 2.561 and RSR = 0.511; Watopa, nse=0.684; kge = 0.816; pbias = 10.577 and RSR = 0.557; Lukulu, nse=0.736; kge = 0.795; pbias = 10.437 and RSR = 0.509. Moreover, the results showed that the peak values and low values for both observed and simulated in similar ranges.

The decision to use the combination of these four (4) metrics was guided by the recommendation of (Ritter and Muñoz-CarSpena, 2013) to compensate weaknesses of some of the statistical objective indicators. As they argued that when a single indicator is used it may lead to incorrect verification of the model. Instead, a combination of graphical results, absolute value error statistics and normalized goodness-of-fit statistics is ideal. The range of objective goodness of fit matrices obtained in this study are similar to Barbosa *et al*. (2019) who also applied multiple model performance matrices for HEC-HMS hydrological model which had objective values for Uberaba River two (2) subbasin RSR 0.63, nse 0.63, Pbias 11.8 and Kge 0.76. It was argued that the obtained values from the goodness-of-fit tests indicate that there was good fit between the simulated and observed data for the period under consideration and hence it was a good performing model. According to Moradkhani, and Sorooshian (2008), the best performing model is the one which give results as close as possible to reality. In general, rainfall-runoff hydrological models are the standard tools used for investigating hydrological processes. Good performing models can be used for the modelling and understanding hydrological processes in river catchments. To this effect, good performing hydrological model helps in flood forecasting, provide input into hydrodynamic models, helps with proper water resource management, and can be incorporated in evaluating water quantity, water quality, erosion and sedimentation, nutrient and pesticide circulation, land use and climate change assessments (Devia *et al*., 2015). Hydrological scholars have often stated that a hydrological Model with the following matrices kge >= 0.5, Pbias <= +/- 25%, nse >= 0.65, rse >= 0.50 is generally considered to be a well performing model (Moriasi, *et al*., 2007; Ritter and Muñoz-Carpena, 2012; Moradkhani, and Sorooshian, 2008). However, despite that wflow model was able to simulate the upstream hydrology very well, wflow model statistical objective function results of the downstream Barotse Floodplain gauge station (at Senanga) were not as good as the upstream results as indicated by evaluation statistics: nse=0.132; kge = 0.509; pbias = 37.740 and rsr = 0.923. The observed slightly inaccuracy in goodness of fit between observed and simulated at Senanga gauge station which is at the downstream of the Barotse Floodplain maybe attributed to model forcing data and the Barotse floodplain effect in which the representation of both floodplain channels hydrodynamics (storage, bifurcation, lateral connections) and vertical hydrological processes are necessary to correctly capture floodplain dynamics especially for groundwater-surface water dependant systems. Thus, it can be postulated that standalone hydrological models are not very suitable in modelling the flows of the of groundwater-surface water dependant tropical floodplains and this necessitates the need for online (internal) coupled hydrological-hydrodynamic models to be able to integrate hydrology-hydrodynamic floodplain processes and possibly improve simulation results.

The other noticeable aspect of the hydrological model was pbias values which indicated that the hydrological model was slightly overestimating the flows in some years. This could be attributed to inaccuracies in global data sets used in the parametrization process. Scholars argue that lack of in-situ basin physical characteristics such as soils, geological, topographical and land cover to estimate model parameters affects the parameterization processes (Lehner *et al*., 2006; Rodriguez *et al*., 2006; Andreadis *et al*., 2013; Hengl *et al*., 2014). In most cases, as is the case for The Upper Zambezi Basin, these data are typically not available locally, and global datasets offer an alternative source for these types of data. For instance, this study used fifth generation (ERA5) of European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalyses of the global climate for forcing data which is not necessarily a good reproducer of absolute quantities of rainfall in comparison to absolute rainfall estimates from the local rainfall gauges. Nevertheless, for the purpose of this study, the ERA5 forcing data was sufficient. In Africa and in Zambia in particular, among some of the limitations for developing effective hydrological models is the lack of reliable and up to date in-situ data in many river basins. Fortunately, opportunities exist for using remotely sensed datasets. This has led to increased use of satellite and reanalysis precipitation datasets in hydrological modelling (Kleynhans *et al*., 2007]). Precipitation, for example, is one of the key drivers of watershed models. Currently there are many open-access precipitation datasets at different spatial and temporal resolutions over global or quasi-global scale (Poméon *et al*., 2017). Some commonly used open-access precipitation datasets in Africa include ERA5 precipitation products, CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data), TRMM (Tropical Rainfall Measuring Mission) and CFSR (Climate Forecast System Reanalysis) (Naumann *et al*, 2017) of which model development can benefit from.

6.4 An integrated online hydrologic-hydrodynamic modelling coupling framework

One-way online (internal) hydrologic-hydrodynamic coupling framework for Barotse Floodplain

An online (internal) hydrologic-hydrodynamic modelling coupling framework for Barotse Floodplain has been developed as presented in the results sections. Many scholars argue that use of online coupling of hydrological and hydrodynamic models for floodplain assessment is necessitated by increasing demand for an understanding the hydrological and hydraulic processes that govern floodplain wetlands especially with the advent of climate change-variability and its potential impact on water resources (Nijssen *et al*., 2001; Zhang, 2005; Zhang *et al*., 2007; Schumann *et al*., 2013). Moreover, in the absence of adequate and continuous historical observations for most basins in

Africa, advances in remote sensing and computing power and model coupling frameworks, have made models an increasingly attractive solution where spatial understanding of hydrology and hydraulics of wetlands is required (Hunter *et al.*, 2007). Thus, research on the hydrological dynamics of basins in Zambia can benefit from these advances and coupling of hydrology and hydraulics to allow for physically more integrated floodplain assessments (Hoch *et al.*, 2017a). Hydrologic and hydraulic modelling plays a crucial role in floodplain studies and there is much to gain in incorporating these modelling capabilities. Online model coupling enables coupled models to share fluxes at each time step as feedback is important and it's accounted for. Hence, in order to compensate for the weaknesses of hydrologic and hydraulic modelling in flood modelling, it is becoming quite common to couple hydrologic and hydraulic models for floodplain simulation use (Hoch *et al.*, 2019).

The framework setup in this study has been referred to as an online coupling framework as it enables the internal coupling of wflow hydrological model and lisflood hydrodynamic model. Online (internal) coupling involves solution of all model equations, and then iterative updating of shared model data using tool such as a coupling framework (GLOFRIM was applied in this study), which does not change model code (Haghizadeh, *et al.*, 2012; Abshire 2012). Such coupling enables the running of the models concurrently, uses information that have major impacts on feedback processes, can reduce the programming effort and computational costs as well provides the ability of plugging in different aspects of assessment and can supports the implementation of a fully spatially coupled hydrological-hydrodynamic models for floodplain assessments. This is unlike the common coupling approach, the offline or external coupling approach which performs simulations from each model individually. In this case, the modeled results from one or more models are used as the input to another model. Unlike the coupling framework used in this study, the applied GLOFRIM enables the user to run both models simultaneously whereby a hydrologic model is used to determine the conversion from rainfall to runoff for a number of sub-catchments. The resulting hydrographs are then routed as upper boundary conditions of a hydrodynamic model. Examples of offline coupling approach in Africa include studies done by Makungu and Hugues (2021) who used an external coupled modeling approach combining the Pitman Hydrological Model with Lisflood-FP to simulate the impacts of the Luangwa and Barotse floodplains on the downstream flow regimes of the Luangwa and Zambezi rivers in Zambia, Schumann *et al*. (2013) used a hydrological model to generate floodplain inflows and a hydraulic model to simulate the inundation extents in the lower Zambezi floodplain, whereas Komi *et al*. (2017) used the LISFLOOD hydrological model to simulate floodplain inflows and the Lisflood-FP hydraulic model to generate inundation extents in Oti River basin . However, this offline (external) coupling approach is a costly approach, requires more processing time and does not allow for the development of a fully coupled hydrological-hydrodynamic model.

Another important concern that may arise when coupling two or more models externally (offline) is the inconvenience and potential error during the transfer of input/output between the individual models (Wei *et al*., 2019). In this regard, automating the model by online (internal) coupling result in making a single modelling unit with capabilities of the constituent models, which would greatly help their quick implementation in various floodplain applications. Moreover, since the models run sequentially, river backwater effects are hardly represented in offline coupled approach (Li *et al*. 2014). Thus, online coupling framework is superior to external coupling approach. The developed online framework in this study for Barotse Floodplain can be adapted for the use of in other catchment area with tropical floodplains as it can form an important tool for sustainable management. It has to be re-stated that, this model framework developed in this study is one-way coupling without any feedback loop from hydrodynamic to hydrological. Nevertheless, this study act as the basis of developing a two way-coupling framework for the Barotse Floodplain (Figure 32) (a full python code for this framework is attached in appendix C). This is an online coupling that allows two-directional feedback between floodplain hydrodynamics and vertical hydrology, since runoff generation and channel/floodplain dynamics are treated as interdependent processes (Fleischmann *et al*., (2018).

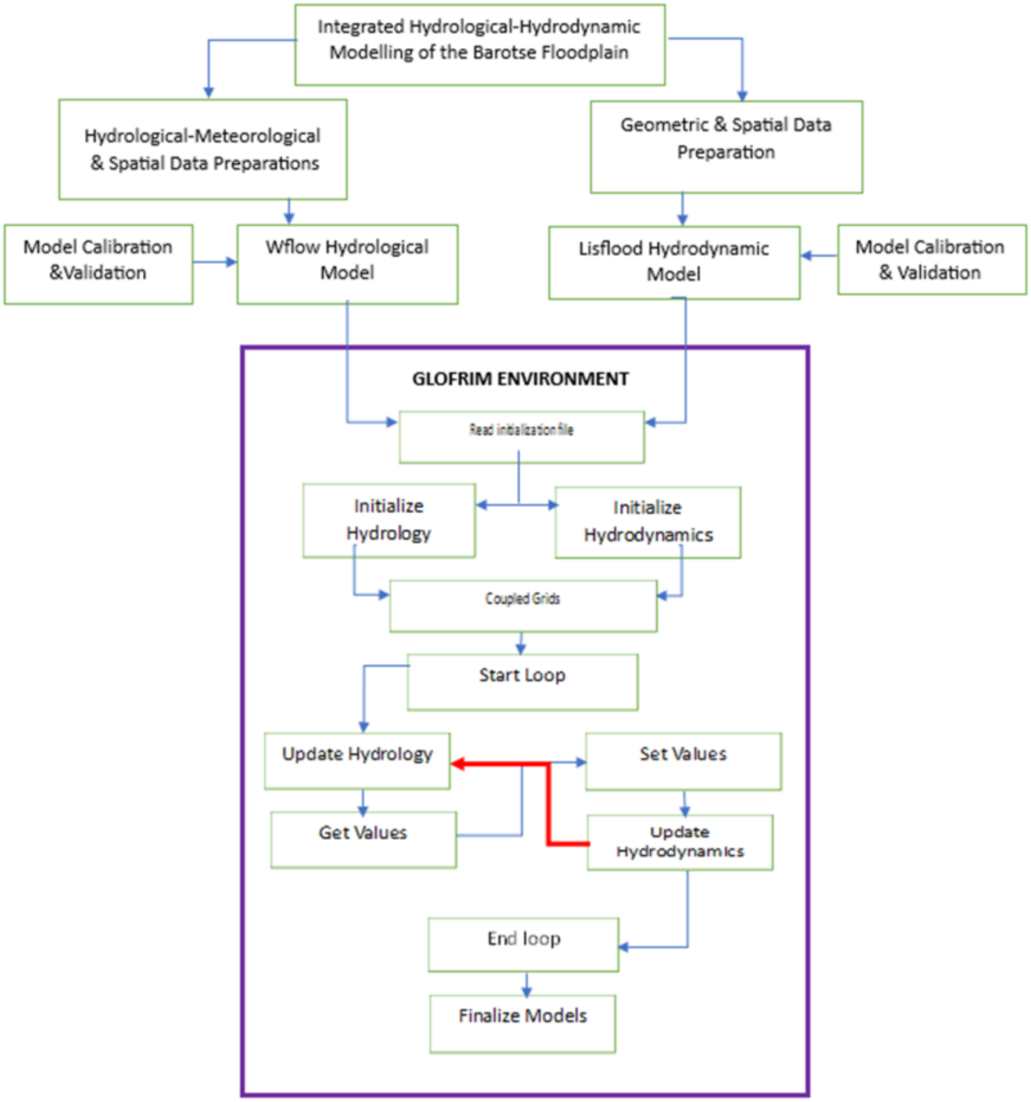


Figure 32. two-way online hydrology-hydrodynamic coupling model Framework for the Barotse Floodplain.

The development of a fully coupled online hydrology-hydrodynamic model will be a step further in closing the gap between hydrology and hydrodynamics in the Barotse floodplain assessment especially for groundwater dependent floodplain system. This is due to the fact that the feedback loop (indicated in the figure in red arrow) to the hydrology from hydrodynamic facilitates the coupled model to capture more feedback processes and has the potential of improving coupled model simulations. This is possibly because groundwater-surface water interactions that support groundwater dependent floodplain systems is a critical element in assessing such systems. With continuous advancement in model development technology, the framework can be used in future to develop a fully coupled model for the Barotse Floodplain. One such hydrodynamic model that is promising to have such capability is SFINCS (Super-Fast INundation of CoastS) which is poised to be an open access model; however, the model code is not yet open access, and the use of the code is thus restricted for now. A fully coupled model framework provides the capability of developing a coupled Hydrologic-hydrodynamic model that capture the floodplain-channel feedback mechanism, and thus has the potential of improving the modelling of floodplain process and dynamics. If applied to the Barotse floodplain, this study postulates that it could further lead to improvement in simulation assessment of the Barotse floodplain hydrology-hydrodynamic processes. However, it has to be noted that the use of these online coupling frameworks developed in this study is not a guarantee to better simulation as the output of the coupled model depend on the quality of data used to force the model, and the calibration of the hydrological and hydrodynamic model. Consequently, the framework should be applied with an understanding of possible model uncertainties for each model used. The model uncertainties could those associated with the model structure, model parameter values and model inputs.

6.5 **Evaluating the performance of one-way Barotse Coupled Hydrological-Hydrodynamic Model**

The one-way online Barotse Coupled Hydrological-Hydrodynamic Model was successful and run very well as indicated by output results in flow (discharge), water levels and flood inundation.

6.5.1 Flow

Based on the coupled model results, the coupled model flow output relatively performed better based on the objective functions results. There was an improvement in some objective functions in general as compared to the results from stand-alone wflow results especially for the downstream gauge station. For upstream Lukulu, the results were quite similar with results from wflow, the noticeable improvement was specifically in pbias which improved from 10.43 to 8.25 and nse which improved from 0.736 to 0.752 indicating reduced model over estimations and peak values. Significant improvements in coupled model results were observed at the downstream gauge station at Senanga with noticeable improvement in nse which improved from 0.132 to 0.535, kge improved from 0.509 to 0.699 and pbias from 37.724 to 21.495 indicating reduced model over estimation. The improvement in the simulation results especially for downstream is similar to study by Hoch *et al*., (2019) who coupled the global hydrologic model PCR-GLOBWB with the hydrodynamic models CaMa-Flood and Lisflood-FP. Results the coupling enhanced the accuracy of peak discharge simulations as expressed by an increase in the Nash–Sutcliffe efficiency (nse) from 0.48 to 0.71. and it was concluded that model coupling can indeed be a viable way forward towards more integrated wetland assessment. Bengtson and Padmanabhan (1999) argue that ideally, a watershed hydrologic and hydraulic model capable of simulating wetland hydrology and hydraulics should be capable of routing flows through wetland depressions in addition to routing overland flow, stream flow, and subsurface flow is ideal for wetland assessments. Consequently, in order to take advantage of the unique capabilities of hydrology and hydrodynamic models, coupling them is a viable technique. Hoch *et al*., (2017b) reasons, the resulting lack of interaction between hydrology and hydraulics in wetland assessments, can hamper modelled results especially where such interactions may potentially be important particularly for floodplains. Fleischmann *et al*., (2018) are of the view that online (internal) coupled hydrologic-hydrodynamic model is an important tool for integrated evaluation of hydrological processes in large scale floodplain areas as is the case with the Barotse Floodplain. Possible uses of the model involve the assessment of different scenarios of anthropic alteration, for example the effects of reservoirs implementation and climate and land use changes. Subsequently, hydrological model coupled with Hydraulic model of the floodplain provides improvements in floodplain model simulations and hence better information for floodplain management. This would lead to improved decision-making and planning of adaption and mitigation measures for sound floodplain wetland management plans and programmes especially with the advent of climate change and variability.

6.5.2 Water Levels

The water levels results output from the online Barotse hydrologic-hydrodynamic model coupling relatively matched the observed water levels from the three-gauge stations in the Barotse plains (Mongu (Matongo), Senanga gauge and Lukulu gauge stations). This was demonstrated by the statistical goodness of fit objective functions results: Mongu, kge 0.792, RSR 0.762, nse 0.55; Senanga; kge 0.6707, RSE 0.827, nse 0.503 and Lukulu, kge 0.630, RSR 0.644, nse 0.301. These objective functions were within the range that is usually considered a good performing model in the field of hydrological-hydrodynamic modelling as earlier discussed (Moriasi, et al., 2007; Ritter and Muñoz-Carpena, 2012; Moradkhani, and Sorooshian, 2008). The exception was water levels for Lukulu gauge station, which is at the upstream, the one-way coupled mode was overestimating the peak levels demonstrated by low nse value. This could be explained with regard to the fact that the upstream is an infiltration zone, and the one-way coupled model does not allow for feedback processes such as infiltration. However, the model was had a faire predication of the water levels for the three-gauge stations. These results are similar to the study by Fleischmann *et al*., (2017) who demonstrated that the application of MGB-IPH large scale one directional hydrologic and hydrodynamic model coupling for the Upper Niger Basin showed a fair prediction for levels and at gauge stations both upstream and downstream of the delta nse between 0.5 to 0.7 for all downstream stations). Fleischmann *et al.*, (2017) goes on to argue that a good simulation of water levels is critical in allowing a good representation of flooding dynamics basin wide and simulation of flooding behaviour of both perennial and ephemeral rivers systems. In this regard, coupled model have the potential of been applied in systematic, and integrated assessments of river water levels in providing essential data needed to evaluate seasonal and long-term dynamic changes over time, in developing floodplain groundwater-surface water interaction models and forecast trends, and to design flood monitoring, implementing management and protection programs in floodplains such as the Barotse Floodplain.

6.5.3 Flood Inundation

Base on the statistical objective function of the goodness of fit between simulated and calculated inundation based on MODIS MOD9A1 by Zimba *et al.*, (2018) (nse 0.637, kge 0.731, RSR 0.502 and pbia 25.234), The Barotse coupled model is relatively good performing coupled model. The model results are comparable to Zimba *et al*. (2019) with regard to the generally trend as well as the days with recorded peak inundations. For instance, peak period, for daily inundation extent, Zimba *et al*., estimated maximum and minimum inundation extent in the Barotse Floodplain at about 5572 km^2 in 2004 on Day 105 which similarly also corresponds with maximum simulated inundation at 6239.75km^2. This value is also within similar range as documented by other scholars on annually inundated peak area of 5500 km^2 for the main floodplain at peak flood (Beilfuss, 2012; Cai *et al*., 2015). For instance, Cai *et al*. (2015) estimated the maximum inundated area at about 5520 km^2. However, it must be noted that despite the similarities with other studies, the coupled model is overestimating the inundated area as indicated by positive higher pbias value. This could be due to a number of factors including input model data, the type of imagery used, and the methods used in each study. More importantly, the one-way online coupled model used in this study does not allow a two-way feedback interaction between hydrology and hydrodynamic. Consequently, processes like re-infiltration is not taken into consideration. Hoch *et al*., (2017b) reasons, that the resulting lack of feedback interaction between hydrology and hydraulics, for instance, by employing groundwater infiltration on inundated floodplains, can hamper coupled modelled inundation and discharge results where such interactions may potentially be important especially for groundwater dependant floodplain systems. It is thus postulated in this study that a fully coupled hydrology-hydrodynamic model can further lead to improvement in modelled results for the Barotse floodplain in terms of flow, water levels and inundation extent.

CHAPTER SEVEN: CONCLUSION AND RECOMMENDATIONS

7.1 Overview

The previous chapter discussed and analyzed the findings. This chapter has presented the conclusions and recommendations of the study.

7.2 Conclusion

The following are the conclusions of this study:

- The Normalised Difference Vegetation Index (NDVI) showed that downstream catchment of Barotse Floodplain was a groundwater diffuse discharge zone, whereas the upper catchment was a surface water infiltration zone.
- The water chemistry results showed a high concentration in calcium and the bicarbonate ion in both river and groundwater. The similarity in chemistry was indicative of connectivity between river and groundwater.
- The stable isotopes of both surface and groundwater plotted on the local meteoric water line indicating meteoric origin. Both river and groundwater were not enriched in the oxygen-18 and deuterium indicating high local infiltration from precipitation. Both river and groundwater were clustered in the depleted zone of the LMWL suggesting high mixing.
- The groundwater-surface water interaction in floodplain needs to be taken into consideration in hydrological and hydrodynamic modelling of groundwater dependant floodplains. This is due to the fact that the representation of both floodplain channels hydrodynamics and hydrological processes are necessary to correctly capture floodplain dynamics for groundwater-surface water dependant systems. Thus, standalone hydrological models are not very suitable in modelling the flows of groundwater-surface water dependant tropical floodplains.
- Continued improvement in tools for assessments of Barotse floodplain processes is key and necessary in providing improved information on floodplain hydrological and hydrodynamic processes to feed into sustainable floodplain management strategies for the purpose of conservation and sustainable provision of ecosystem services to the communities dependent on the Barotse floodplain.
- An integrated model framework for hydrology-hydrodynamic model coupling developed in this study for groundwater-surface water dependant floodplains has the potential of been used in implementing adaptive floodplain management strategies for water resources allocation,

environmental flow (eflows) assessments, flood control and forecasting, land use and climate change impact assessments for the benefit of people and nature.

7.3 **Recommendations**

Based on findings of this study, the following recommendations are made for water resources managers in both public and non-governmental agencies and researchers.

- Application of standalone models for floodplain assessment is insufficient in assessing the dynamics of groundwater-surface water dependent floodplain systems. Hence, two-way coupled model that captures river flows, wetland inundation, and groundwater re-infiltration is required to improve the assessment of floodplains for sustainable floodplain management in Zambia.
- There is need for the future studies to integrate models that incorporate groundwater modules in the framework.
- In order to improve prediction capabilities of the floodplain wetlands response under current and future alterations, there is need understand the implications of human activities on groundwater-surface water dynamics.
- There is need to improve on the maintance of the existing gauge station and increase on the gauge station for hydrological spatial data in Upper Zambezi Basin. A particular problem in relation to calibration and validation of hydrological-hydraulic is that in-situ spatial data are seldom available for calibration and validation models and where gauges exist, data are generally of poor quality due to lack of maintance leading to many outliers.
- There is a need for more studies to evaluate the use of global remote sensing products at long term gauging monitoring sites in Zambia’s River Basins. It is this kind of application of remotely based products and techniques that can be utilised to overcome challenges and limitations associated with validating hydrologic and hydraulic coupled models results in data scarce river basins in Zambia.

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Zimba, H., Banda, K., Chabala, A., Phiri, W., Selma, P., Meinhardt, M., & Nyambe, I. (2018) Assessment of trends in inundation extent in the Barotse Floodplain, upper Zambezi River Basin: A remote sensing approach. *Journal of Hydrology: Regional Studies*, 15, 149–170.

Appendix A: List of Published Papers and Conference Paper Presentations based on WASP Project.

(a) Published Papers

Chomba, I. C., Banda, K. E., Winsemius, H.C., Chomba, M. J., Mataa, M., Ngwenya, V., Sichingabula, H. M., Nyambe, I.A., Ellender, B., (2021). A Review of Coupled Hydrologic-Hydraulic Models for Floodplain Assessments in Africa: Opportunities and Challenges for Floodplain Wetland Management. *Hydrology* 2021, 8, 44. doi.org/10.3390/hydrology8010044

Chomba, I.C., Banda, K.E., Winsemius, Makungu, E., Sichingabula, H.M., Nyambe, I.A. (2022). Integrated Hydrologic-Hydrodynamic Inundation Modeling in a Groundwater Dependent Tropical Floodplain. *Journal of Human, Earth, and Future*,3(2). doi.org/10. 28991/HEF-2022-03-02-010

Banda, K., Mataa, M., Chomba, I. C., Chomba, M., Levy, J., and Nyambe, I. (2023). Investigating groundwater and surface water interactions using remote sensing, hydrochemistry, and stable isotopes in the Barotse Floodplain, Zambia, *Geology, Ecology, and Landscapes*. doi.org/10.1080/24749508.2023.2202450

Banda K, Ngwenya V, Mulema M, Chomba, I. C, Chomba, M., & Nyambe I (2023) Influence of water quality on benthic macroinvertebrates in a groundwater-dependent wetland. Frontiers in Water 5:1177724. doi: 10.3389/frwa.2023.1177724

(b) Conference Presentations

Chomba, I.C., Banda, K. E, Winsemius, H.C., Makungu, E., Hrachowitz, M., Sichingabula, H. M., Nyambe, I. A., Mata, M, (2020). *A regional coupled spatially distributed hydrologic-hydrodynamic model Framework for the Barotse Floodplain, Upper Zambezi***.** Paper Presented at **TU Delft & Deltares Science Research Exchange Symposium on 25th May 2020, Delft, Netherlands.**

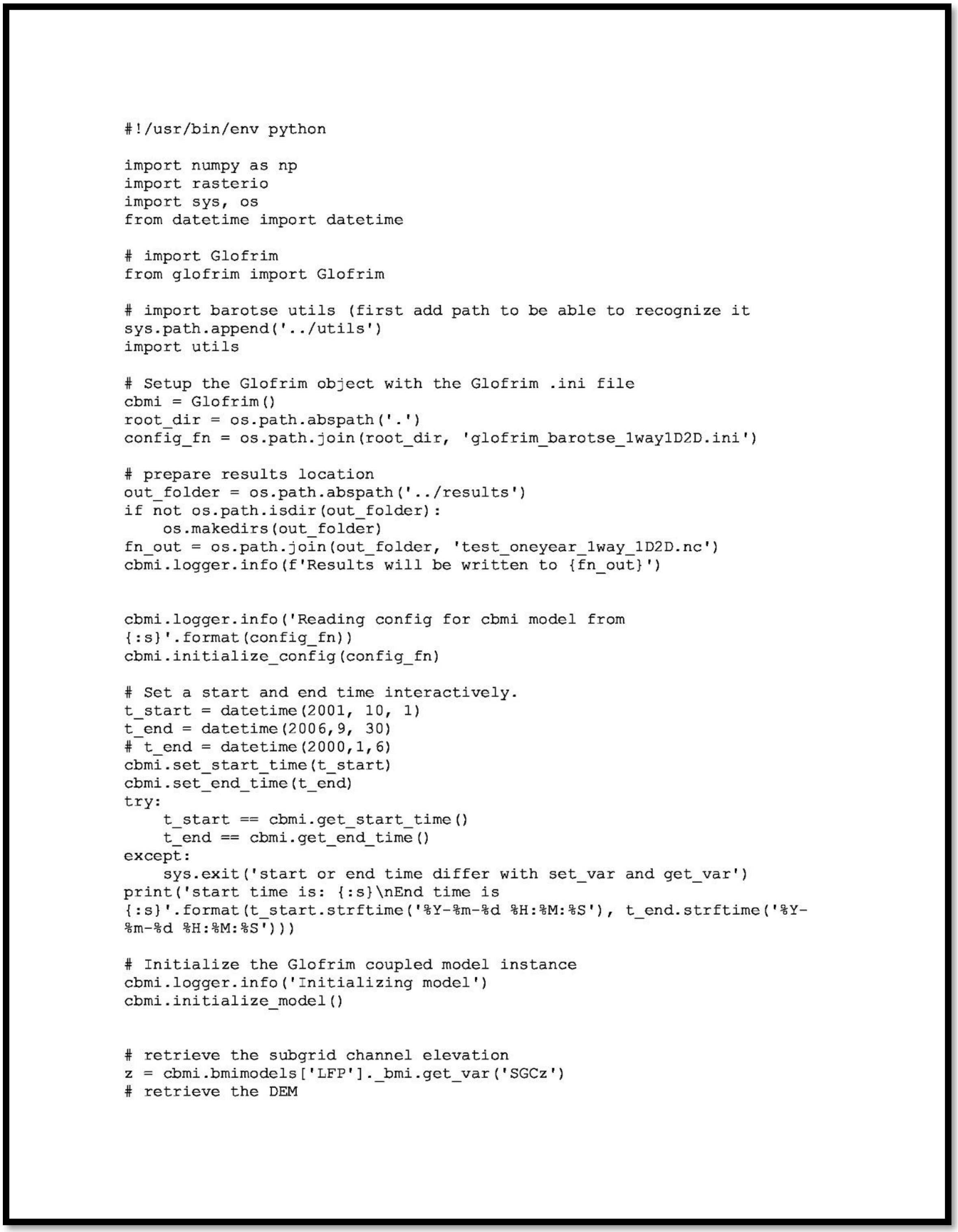
Chomba, I.C., Banda, K.E., Winsemius, Makungu, E., Sichingabula, H.M., Nyambe, I.A. (2020). *Spatially Distributed Hydrological Model for Upper Zambezi Basin***.** Paper presented at **the 22nd WaterNet/WAFSA/GWPSA Conference 20th -23rd October 2021.**

Chomba I. C., Banda K. E., Winsemius H.C., Hrachowitz M., Sichingabula. H. H., Nyambe I. A., Mata M and Chomba M. J., (2021). *A Review of Coupled Hydrologic-Hydraulic Models for Floodplain Assessments in Africa: Opportunities and Challenges for Floodplain Wetland*

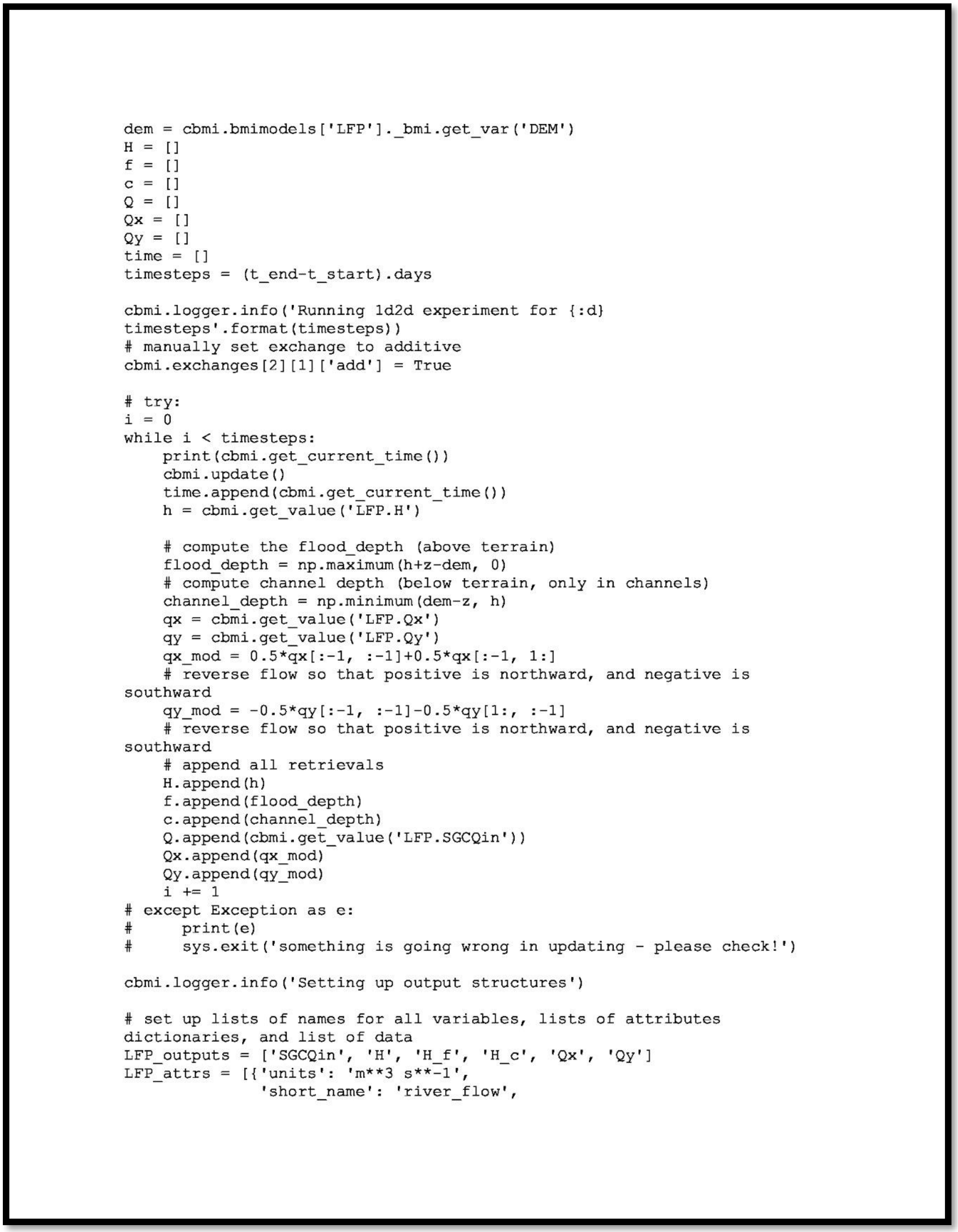
Management. Paper presented at **Water Security and Climate Change Conference 01-04, March 2021 Hanoi, Vietnam.**

Chomba I. C., Banda K. E., Winsemius H.C., Sichingabula. H. H., Nyambe I. A (2021). *An Integrated Framework for Hydrology-Hydrodynamics Modelling of The Barotse Floodplains, Upper Zambezi River Basin*. Paper presented at **European Geosciences Union (EGU) General Assembly 2021, 19TH - 30TH May 2021.**

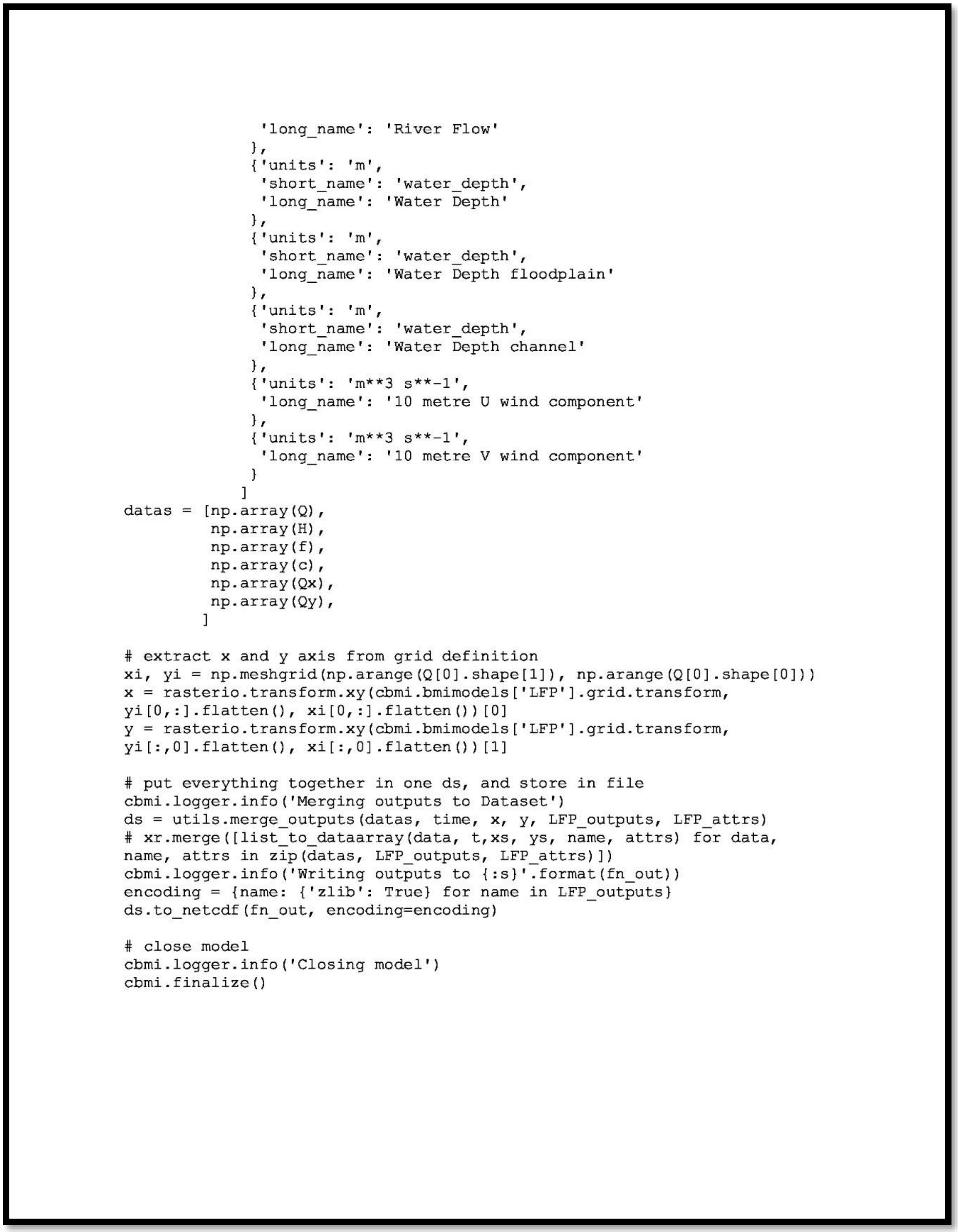
Appendix B: Python Script for one-way online hydrologic-hydrodynamic modelling framework for Barotse floodplains



```
#!/usr/bin/env python

import numpy as np
import rasterio
import sys, os
from datetime import datetime

# import Glofrim
from glofrim import Glofrim

# import barotse utils (first add path to be able to recognize it
sys.path.append('../utils')
import utils

# Setup the Glofrim object with the Glofrim .ini file
cbmi = Glofrim()
root_dir = os.path.abspath('.')
config_fn = os.path.join(root_dir, 'glofrim_barotse_1way1D2D.ini')

# prepare results location
out_folder = os.path.abspath('../results')
if not os.path.isdir(out_folder):
    os.makedirs(out_folder)
fn_out = os.path.join(out_folder, 'test_oneyear_1way_1D2D.nc')
cbmi.logger.info(f'Results will be written to {fn_out}')


cbmi.logger.info('Reading config for cbmi model from
{:s}'.format(config_fn))
cbmi.initialize_config(config_fn)

# Set a start and end time interactively.
t_start = datetime(2001, 10, 1)
t_end = datetime(2006,9, 30)
# t_end = datetime(2000,1,6)
cbmi.set_start_time(t_start)
cbmi.set_end_time(t_end)
try:
    t_start == cbmi.get_start_time()
    t_end == cbmi.get_end_time()
except:
    sys.exit('start or end time differ with set_var and get_var')
print('start time is: {:s}\nEnd time is
{:s}'.format(t_start.strftime('%Y-%m-%d %H:%M:%S'), t_end.strftime('%Y-
%m-%d %H:%M:%S')))

# Initialize the Glofrim coupled model instance
cbmi.logger.info('Initializing model')
cbmi.initialize_model()


# retrieve the subgrid channel elevation
z = cbmi.bmimodels['LFP']._bmi.get_var('SGCz')
# retrieve the DEM
```

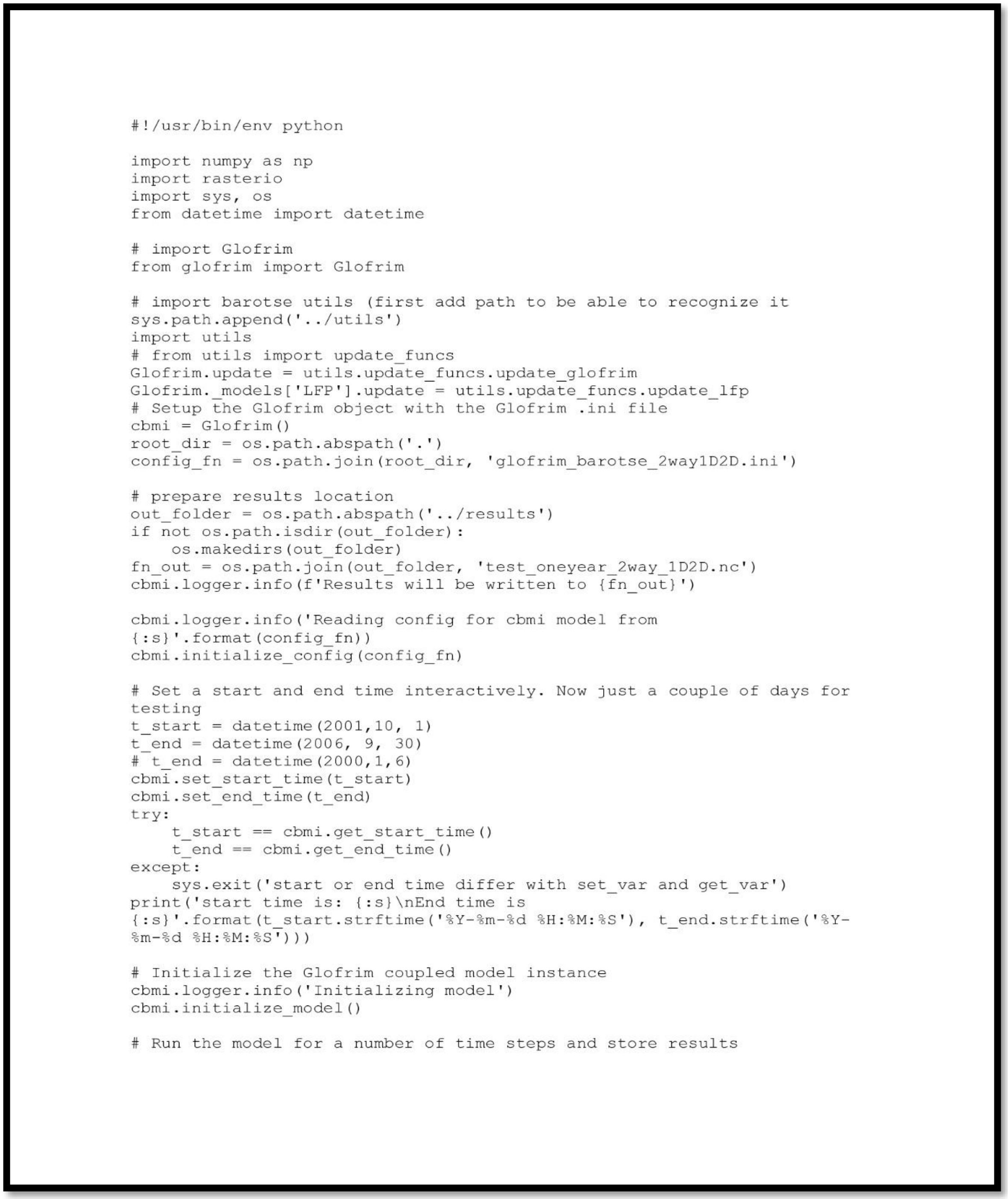


```
dem = cbmi.bmimodels['LFP']._bmi.get_var('DEM')
H = []
f = []
c = []
Q = []
Qx = []
Qy = []
time = []
timesteps = (t_end-t_start).days

cbmi.logger.info('Running 1d2d experiment for {:d}
timesteps'.format(timesteps))
# manually set exchange to additive
cbmi.exchanges[2][1]['add'] = True

# try:
i = 0
while i < timesteps:
    print(cbmi.get_current_time())
    cbmi.update()
    time.append(cbmi.get_current_time())
    h = cbmi.get_value('LFP.H')

    # compute the flood_depth (above terrain)
    flood_depth = np.maximum(h+z-dem, 0)
    # compute channel depth (below terrain, only in channels)
    channel_depth = np.minimum(dem-z, h)
    qx = cbmi.get_value('LFP.Qx')
    qy = cbmi.get_value('LFP.Qy')
    qx_mod = 0.5*qx[:-1, :-1]+0.5*qx[:-1, 1:]
    # reverse flow so that positive is northward, and negative is
southward
    qy_mod = -0.5*qy[:-1, :-1]-0.5*qy[1:, :-1]
    # reverse flow so that positive is northward, and negative is
southward
    # append all retrievals
    H.append(h)
    f.append(flood_depth)
    c.append(channel_depth)
    Q.append(cbmi.get_value('LFP.SGCQin'))
    Qx.append(qx_mod)
    Qy.append(qy_mod)
    i += 1
# except Exception as e:
#     print(e)
#     sys.exit('something is going wrong in updating - please check!')

cbmi.logger.info('Setting up output structures')

# set up lists of names for all variables, lists of attributes
dictionaries, and list of data
LFP_outputs = ['SGCQin', 'H', 'H_f', 'H_c', 'Qx', 'Qy']
LFP_attrs = [{'units': 'm**3 s**-1',
              'short_name': 'river_flow',
```

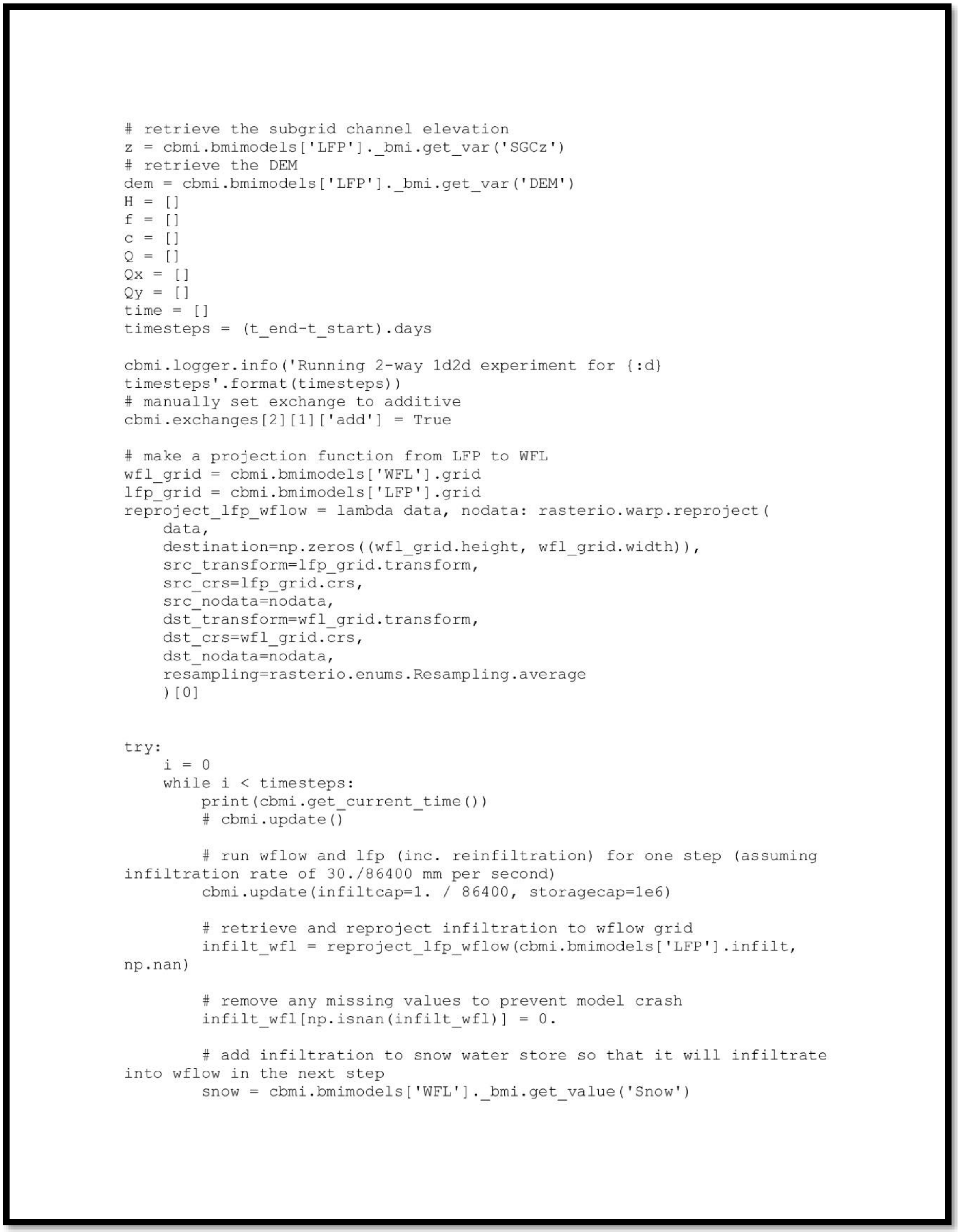


```
              'long_name': 'River Flow'
             },
             {'units': 'm',
              'short_name': 'water_depth',
              'long_name': 'Water Depth'
             },
             {'units': 'm',
              'short_name': 'water_depth',
              'long_name': 'Water Depth floodplain'
             },
             {'units': 'm',
              'short_name': 'water_depth',
              'long_name': 'Water Depth channel'
             },
             {'units': 'm**3 s**-1',
              'long_name': '10 metre U wind component'
             },
             {'units': 'm**3 s**-1',
              'long_name': '10 metre V wind component'
             }
            ]
datas = [np.array(Q),
         np.array(H),
         np.array(f),
         np.array(c),
         np.array(Qx),
         np.array(Qy),
        ]

# extract x and y axis from grid definition
xi, yi = np.meshgrid(np.arange(Q[0].shape[1]), np.arange(Q[0].shape[0]))
x = rasterio.transform.xy(cbmi.bmimodels['LFP'].grid.transform,
yi[0,:].flatten(), xi[0,:].flatten())[0]
y = rasterio.transform.xy(cbmi.bmimodels['LFP'].grid.transform,
yi[:,0].flatten(), xi[:,0].flatten())[1]

# put everything together in one ds, and store in file
cbmi.logger.info('Merging outputs to Dataset')
ds = utils.merge_outputs(datas, time, x, y, LFP_outputs, LFP_attrs)
# xr.merge([list_to_dataarray(data, t,xs, ys, name, attrs) for data,
name, attrs in zip(datas, LFP_outputs, LFP_attrs)])
cbmi.logger.info('Writing outputs to {:s}'.format(fn_out))
encoding = {name: {'zlib': True} for name in LFP_outputs}
ds.to_netcdf(fn_out, encoding=encoding)

# close model
cbmi.logger.info('Closing model')
cbmi.finalize()
```

AppendixC: Python Script for two-way online hydrologic-hydrodynamic modelling framework

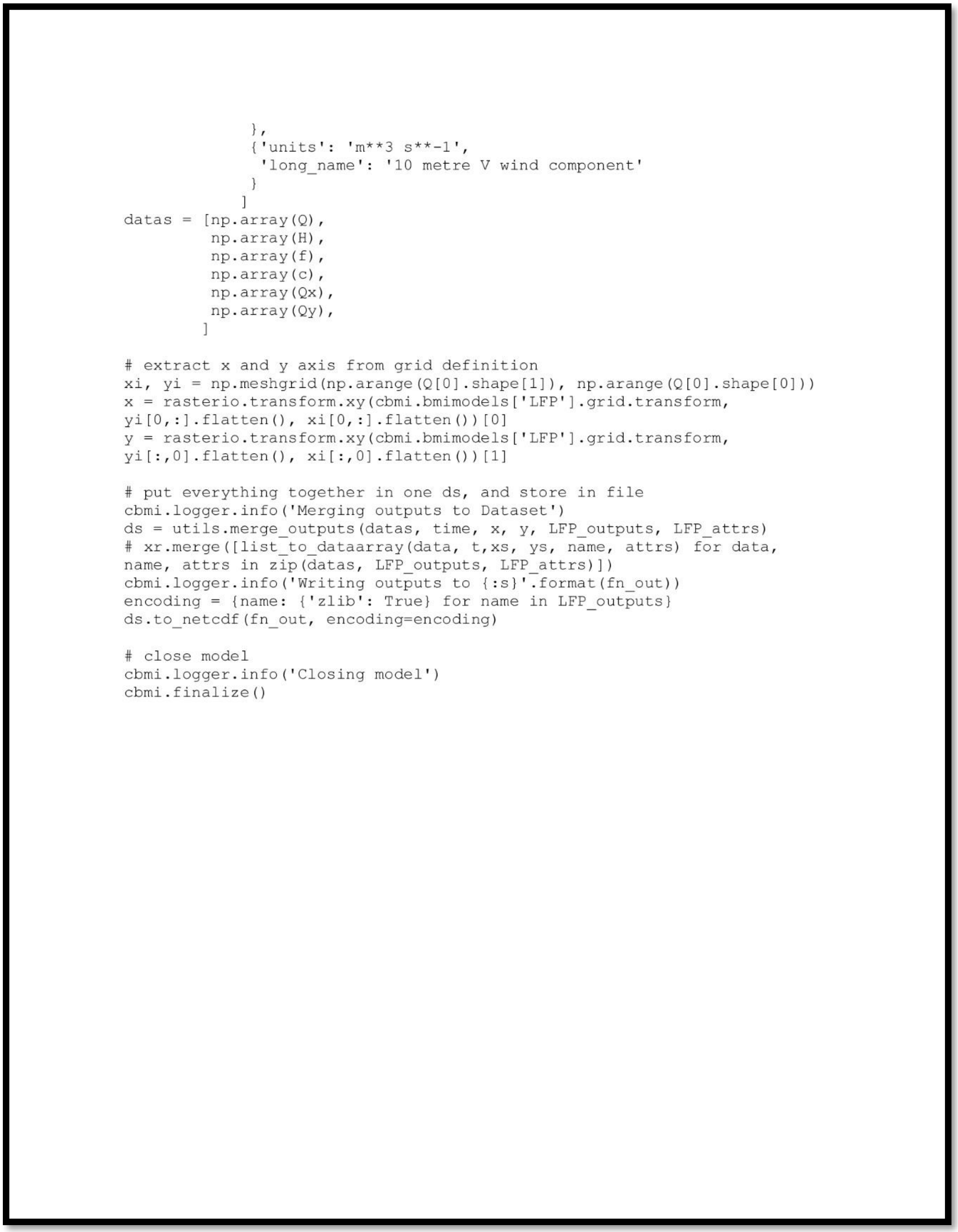


```
#!/usr/bin/env python

import numpy as np
import rasterio
import sys, os
from datetime import datetime

# import Glofrim
from glofrim import Glofrim

# import barotse utils (first add path to be able to recognize it
sys.path.append('../utils')
import utils
# from utils import update_funcs
Glofrim.update = utils.update_funcs.update_glofrim
Glofrim._models['LFP'].update = utils.update_funcs.update_lfp
# Setup the Glofrim object with the Glofrim .ini file
cbmi = Glofrim()
root_dir = os.path.abspath('.')
config_fn = os.path.join(root_dir, 'glofrim_barotse_2way1D2D.ini')

# prepare results location
out_folder = os.path.abspath('../results')
if not os.path.isdir(out_folder):
    os.makedirs(out_folder)
fn_out = os.path.join(out_folder, 'test_oneyear_2way_1D2D.nc')
cbmi.logger.info(f'Results will be written to {fn_out}')

cbmi.logger.info('Reading config for cbmi model from
{:s}'.format(config_fn))
cbmi.initialize_config(config_fn)

# Set a start and end time interactively. Now just a couple of days for
testing
t_start = datetime(2001,10, 1)
t_end = datetime(2006, 9, 30)
# t_end = datetime(2000,1,6)
cbmi.set_start_time(t_start)
cbmi.set_end_time(t_end)
try:
    t_start == cbmi.get_start_time()
    t_end == cbmi.get_end_time()
except:
    sys.exit('start or end time differ with set_var and get_var')
print('start time is: {:s}\nEnd time is
{:s}'.format(t_start.strftime('%Y-%m-%d %H:%M:%S'), t_end.strftime('%Y-
%m-%d %H:%M:%S')))

# Initialize the Glofrim coupled model instance
cbmi.logger.info('Initializing model')
cbmi.initialize_model()

# Run the model for a number of time steps and store results
```



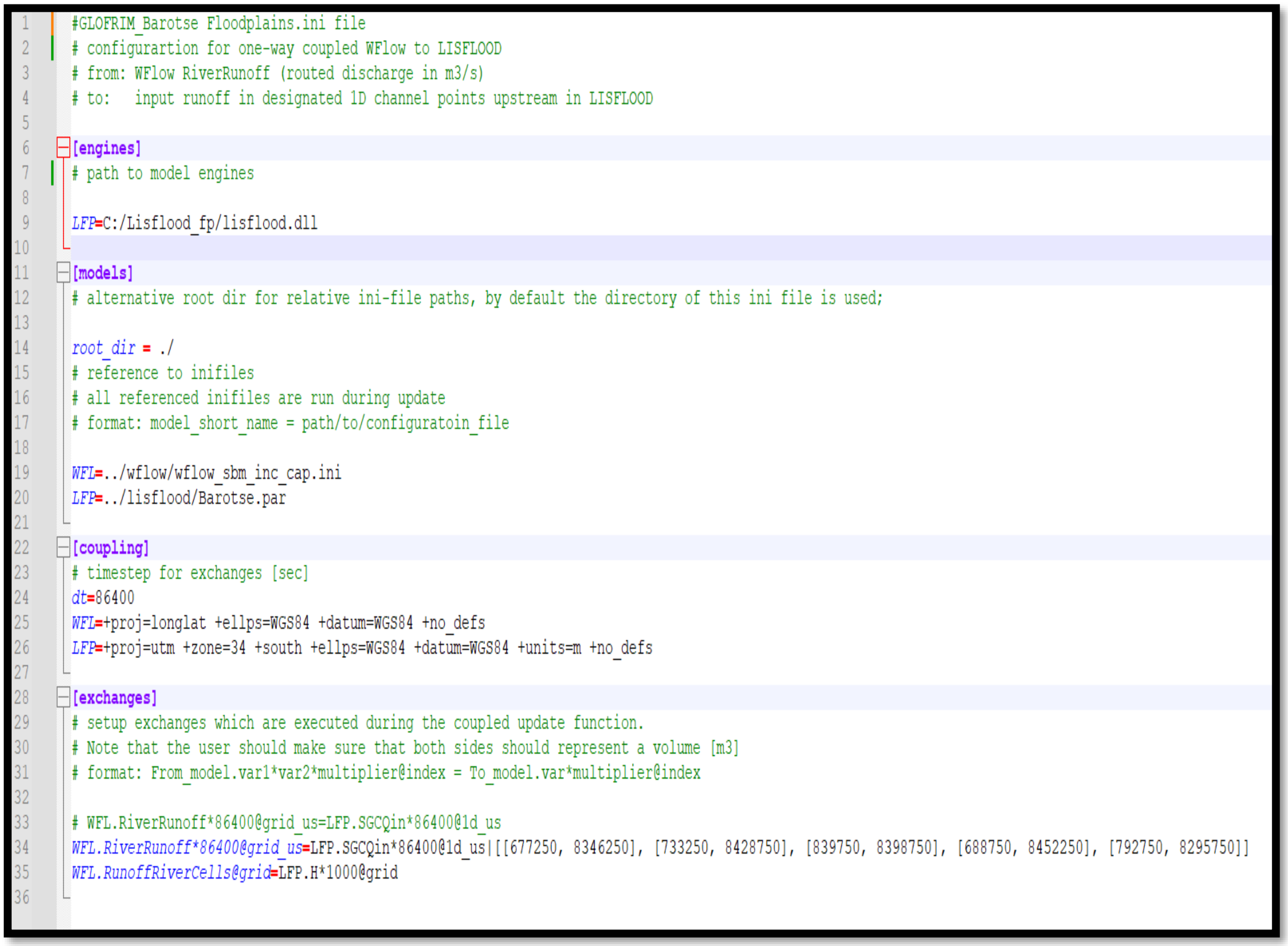
```
# retrieve the subgrid channel elevation
z = cbmi.bmimodels['LFP']._bmi.get_var('SGCz')
# retrieve the DEM
dem = cbmi.bmimodels['LFP']._bmi.get_var('DEM')
H = []
f = []
c = []
Q = []
Qx = []
Qy = []
time = []
timesteps = (t_end-t_start).days

cbmi.logger.info('Running 2-way 1d2d experiment for {:d}
timesteps'.format(timesteps))
# manually set exchange to additive
cbmi.exchanges[2][1]['add'] = True

# make a projection function from LFP to WFL
wfl_grid = cbmi.bmimodels['WFL'].grid
lfp_grid = cbmi.bmimodels['LFP'].grid
reproject_lfp_wflow = lambda data, nodata: rasterio.warp.reproject(
    data,
    destination=np.zeros((wfl_grid.height, wfl_grid.width)),
    src_transform=lfp_grid.transform,
    src_crs=lfp_grid.crs,
    src_nodata=nodata,
    dst_transform=wfl_grid.transform,
    dst_crs=wfl_grid.crs,
    dst_nodata=nodata,
    resampling=rasterio.enums.Resampling.average
    )[0]


try:
    i = 0
    while i < timesteps:
        print(cbmi.get_current_time())
        # cbmi.update()

        # run wflow and lfp (inc. reinfiltration) for one step (assuming
infiltration rate of 30./86400 mm per second)
        cbmi.update(infiltcap=1. / 86400, storagecap=1e6)

        # retrieve and reproject infiltration to wflow grid
        infilt_wfl = reproject_lfp_wflow(cbmi.bmimodels['LFP'].infilt,
np.nan)

        # remove any missing values to prevent model crash
        infilt_wfl[np.isnan(infilt_wfl)] = 0.

        # add infiltration to snow water store so that it will infiltrate
into wflow in the next step
        snow = cbmi.bmimodels['WFL']._bmi.get_value('Snow')
```

```
        snow += np.flipud(infilt_wfl)
        cbmi.bmimodels['WFL']._bmi.set_value('Snow', snow)

        # administer the current time step outputs
        time.append(cbmi.get_current_time())
        h = cbmi.get_value('LFP.H')

        # compute the flood_depth (above terrain)
        flood_depth = np.maximum(h+z-dem, 0)
        # compute channel depth (below terrain, only in channels)
        channel_depth = np.minimum(dem-z, h)
        qx = cbmi.get_value('LFP.Qx')
        qy = cbmi.get_value('LFP.Qy')
        qx_mod = 0.5*qx[:-1, :-1]+0.5*qx[:-1, 1:]
        # reverse flow so that positive is northward, and negative is
southward
        qy_mod = -0.5*qy[:-1, :-1]-0.5*qy[1:, :-1]
        # reverse flow so that positive is northward, and negative is
southward
        # append all retrievals
        H.append(h)
        f.append(flood_depth)
        c.append(channel_depth)
        Q.append(cbmi.get_value('LFP.SGCQin'))
        Qx.append(qx_mod)
        Qy.append(qy_mod)
        i += 1
except Exception as e:
    print(e)
    sys.exit('something is going wrong in updating - please check!')

cbmi.logger.info('Setting up output structures')

# set up lists of names for all variables, lists of attributes
dictionaries, and list of data
LFP_outputs = ['SGCQin', 'H', 'H_f', 'H_c', 'Qx', 'Qy']
LFP_attrs = [{'units': 'm**3 s**-1',
              'short_name': 'river_flow',
              'long_name': 'River Flow'
             },
             {'units': 'm',
              'short_name': 'water_depth',
              'long_name': 'Water Depth'
             },
             {'units': 'm',
              'short_name': 'water_depth',
              'long_name': 'Water Depth floodplain'
             },
             {'units': 'm',
              'short_name': 'water_depth',
              'long_name': 'Water Depth channel'
             },
             {'units': 'm**3 s**-1',
              'long_name': '10 metre U wind component'
```



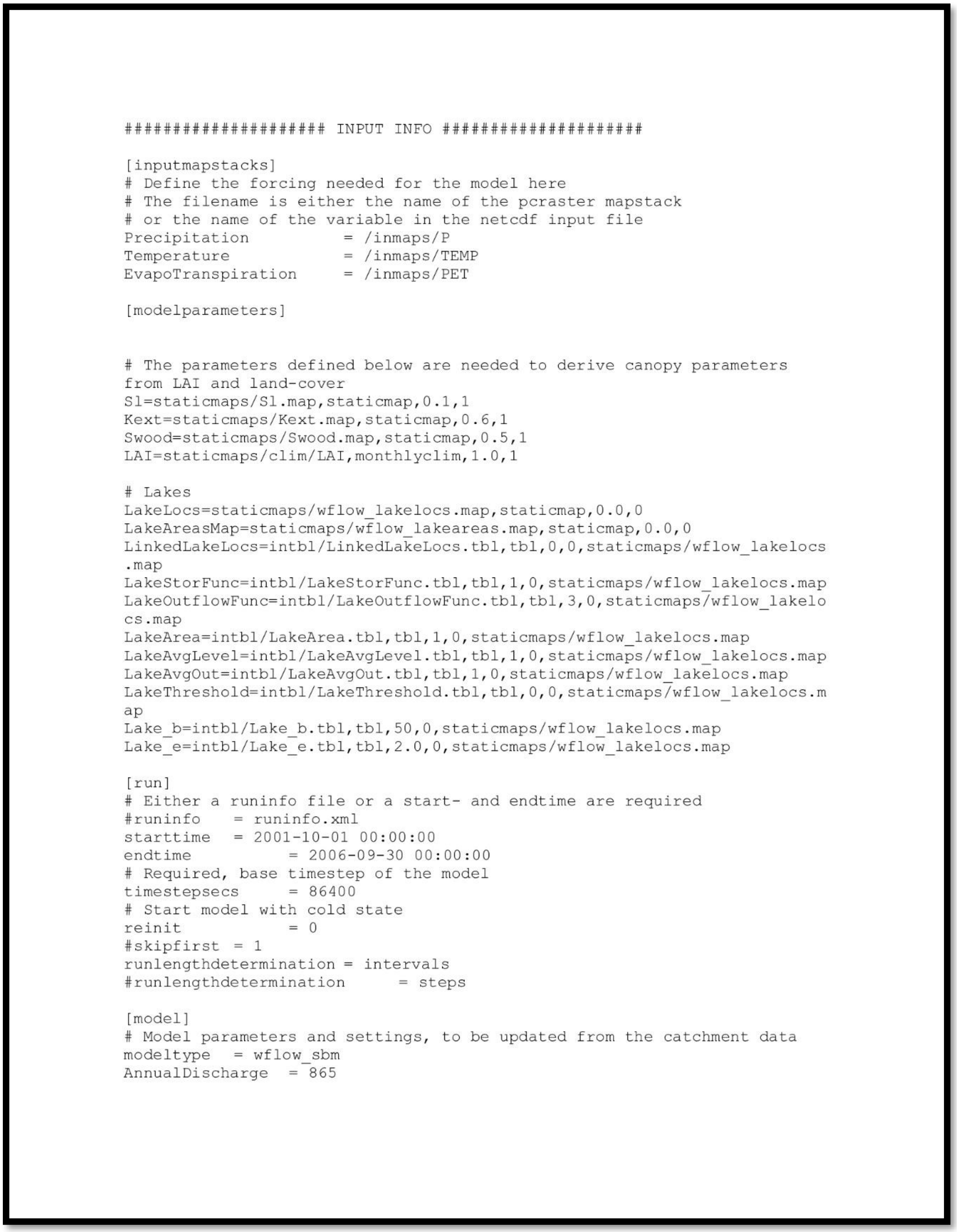
```
             },
             {'units': 'm**3 s**-1',
              'long_name': '10 metre V wind component'
             }
            ]
datas = [np.array(Q),
         np.array(H),
         np.array(f),
         np.array(c),
         np.array(Qx),
         np.array(Qy),
        ]

# extract x and y axis from grid definition
xi, yi = np.meshgrid(np.arange(Q[0].shape[1]), np.arange(Q[0].shape[0]))
x = rasterio.transform.xy(cbmi.bmimodels['LFP'].grid.transform,
yi[0,:].flatten(), xi[0,:].flatten())[0]
y = rasterio.transform.xy(cbmi.bmimodels['LFP'].grid.transform,
yi[:,0].flatten(), xi[:,0].flatten())[1]

# put everything together in one ds, and store in file
cbmi.logger.info('Merging outputs to Dataset')
ds = utils.merge_outputs(datas, time, x, y, LFP_outputs, LFP_attrs)
# xr.merge([list_to_dataarray(data, t,xs, ys, name, attrs) for data,
name, attrs in zip(datas, LFP_outputs, LFP_attrs)])
cbmi.logger.info('Writing outputs to {:s}'.format(fn_out))
encoding = {name: {'zlib': True} for name in LFP_outputs}
ds.to_netcdf(fn_out, encoding=encoding)

# close model
cbmi.logger.info('Closing model')
cbmi.finalize()
```

Appendix D: GLOFRIM Configuration initialization file



```
#GLOFRIM_Barotse Floodplains.ini file
# configurartion for one-way coupled WFlow to LISFLOOD
# from: WFlow RiverRunoff (routed discharge in m3/s)
# to:   input runoff in designated 1D channel points upstream in LISFLOOD

[engines]
# path to model engines

LFP=C:/Lisflood_fp/lisflood.dll

[models]
# alternative root dir for relative ini-file paths, by default the directory of this ini file is used;

root_dir = ./
# reference to inifiles
# all referenced inifiles are run during update
# format: model_short_name = path/to/configuratoin_file

WFL=../wflow/wflow_sbm_inc_cap.ini
LFP=../lisflood/Barotse.par

[coupling]
# timestep for exchanges [sec]
dt=86400
WFL=+proj=longlat +ellps=WGS84 +datum=WGS84 +no_defs
LFP=+proj=utm +zone=34 +south +ellps=WGS84 +datum=WGS84 +units=m +no_defs

[exchanges]
# setup exchanges which are executed during the coupled update function.
# Note that the user should make sure that both sides should represent a volume [m3]
# format: From_model.var1*var2*multiplier@index = To_model.var*multiplier@index

# WFL.RiverRunoff*86400@grid_us=LFP.SGCQin*86400@1d_us
WFL.RiverRunoff*86400@grid_us=LFP.SGCQin*86400@1d_us|[[677250, 8346250], [733250, 8428750], [839750, 8398750], [688750, 8452250], [792750, 8295750]]
WFL.RunoffRiverCells@grid=LFP.H*1000@grid

```

Appendix E: wflow Hydrological model initialization file script



```
##################### INPUT INFO #####################

[inputmapstacks]
# Define the forcing needed for the model here
# The filename is either the name of the pcraster mapstack
# or the name of the variable in the netcdf input file
Precipitation          = /inmaps/P
Temperature            = /inmaps/TEMP
EvapoTranspiration     = /inmaps/PET

[modelparameters]


# The parameters defined below are needed to derive canopy parameters
from LAI and land-cover
Sl=staticmaps/Sl.map,staticmap,0.1,1
Kext=staticmaps/Kext.map,staticmap,0.6,1
Swood=staticmaps/Swood.map,staticmap,0.5,1
LAI=staticmaps/clim/LAI,monthlyclim,1.0,1

# Lakes
LakeLocs=staticmaps/wflow_lakelocs.map,staticmap,0.0,0
LakeAreasMap=staticmaps/wflow_lakeareas.map,staticmap,0.0,0
LinkedLakeLocs=intbl/LinkedLakeLocs.tbl,tbl,0,0,staticmaps/wflow_lakelocs
.map
LakeStorFunc=intbl/LakeStorFunc.tbl,tbl,1,0,staticmaps/wflow_lakelocs.map
LakeOutflowFunc=intbl/LakeOutflowFunc.tbl,tbl,3,0,staticmaps/wflow_lakelo
cs.map
LakeArea=intbl/LakeArea.tbl,tbl,1,0,staticmaps/wflow_lakelocs.map
LakeAvgLevel=intbl/LakeAvgLevel.tbl,tbl,1,0,staticmaps/wflow_lakelocs.map
LakeAvgOut=intbl/LakeAvgOut.tbl,tbl,1,0,staticmaps/wflow_lakelocs.map
LakeThreshold=intbl/LakeThreshold.tbl,tbl,0,0,staticmaps/wflow_lakelocs.m
ap
Lake_b=intbl/Lake_b.tbl,tbl,50,0,staticmaps/wflow_lakelocs.map
Lake_e=intbl/Lake_e.tbl,tbl,2.0,0,staticmaps/wflow_lakelocs.map

[run]
# Either a runinfo file or a start- and endtime are required
#runinfo    = runinfo.xml
starttime  = 2001-10-01 00:00:00
endtime          = 2006-09-30 00:00:00
# Required, base timestep of the model
timestepsecs     = 86400
# Start model with cold state
reinit           = 0
#skipfirst  = 1
runlengthdetermination = intervals
#runlengthdetermination      = steps

[model]
# Model parameters and settings, to be updated from the catchment data
modeltype   = wflow_sbm
AnnualDischarge  = 865
```

```
# Alpha for river-width estimation (5 for mountain stream, 60 for the
river Rhine)
Alpha       = 60
kinwaveIters = 1
#ModelSnow = 1
soilInfRedu = 0
MassWasting = 1
nrivermethod = 2
# UStoreLayerThickness = 1000
estimatelakethresh=0
transfermethod=1

[framework]
# Outputformat for the *dynamic* mapstacks (not the states and summary
maps)
# 1: pcraster
# 2: numpy
# 3: matlab

# NetCDF output requires also outputformat = 1 (default) and additionally
the name of the file
outputformat     = 1
debug       = 0
netcdfinput      = inmaps/forcing-2000_2018.nc
netcdfoutput           = outmaps.nc
#netcdfstatesinput     = instates.nc
#netcdfstatesoutput    = states.nc
#netcdfstaticinput     = staticmaps.nc
#netcdfstaticoutput    = outsum.nc
netcdf_format                = NETCDF4
#netcdf_format               = NETCDF3_CLASSIC
EPSG                   = EPSG:4326
netcdf_zlib            = True
netcdfwritebuffer      = 100
netcdf_least_significant_digit    = 2

[layout]
# If set to zero the cell-size is given in lat/lon (the default)
sizeinmetres = 0

[variable_change_once]
self.SoilThickness = self.SoilThickness * 3.1
self.SoilWaterCapacity = self.SoilWaterCapacity * 6
self.RootingDepth = self.RootingDepth * 6
self.KsatVer = self.KsatVer  * 0.01
self.KsatHorFrac = self.KsatHorFrac * 1000
self.M = self.M * 1000

#################### OUTPUT INFO ####################

##### Output grids #####

[outputmaps]
self.Precipitation=P
```

```
self.ActEvap=AET
self.RiverRunoff=run
self.qo_toriver=qo_riv
self.ssf_toriver=ssf_riv
self.ExfiltFromUstore=ex_us
self.ExfiltFromSat=ex_ss
self.UStoreDepth=ustore
self.SatWaterDepth=SWD
self.SoilWaterCapacity=SWC
self.InfiltExcessSoil=in_ex_s
self.Inwater=inw


[summary_sum]
self.Precipitation=precip_sum.map

[summary_max]
self.Precipitation=precip_max.map
self.Temperature=temp_max.map

[summary_min]
self.Temperature=temp_min.map

[summary_avg]
self.Precipitation=precip_avg.map


##### Output timeseries #####

[outputcsv_0]
# Save and sample these at the gauge locations
samplemap=staticmaps/wflow_gauges.map
self.RiverRunoff=run.csv
self.WaterLevelR=lev.csv

[outputcsv_1]
# Save and average these per subcatchment
samplemap=staticmaps/wflow_subcatch.map
self.Precipitation=prec_subcatch.csv
self.Transfer=tra_subcatch.csv

[outputcsv_2]
# Save and average these per land use type
samplemap=staticmaps/wflow_landuse.map
self.PotenEvap=pet_lu.csv
self.ActEvap=aet_lu.csv

[outputtss_0]
# Save and sample these at the gauge locations
samplemap=staticmaps/wflow_gauges.map
self.RiverRunoff=run.tss
self.WaterLevelR=lev.tss

[API]
```

```
RiverRunoff=2,1
RootingDepth=3,4
SoilThickness=3,4
SoilWaterCapacity=3,4
ActRootingDepth=3,4
KsatHorFrac=3,4
KsatVer=3,4
RiverFrac=3,4
ToCubic=3,4
xl=3,4
yl=3,4
DCL=3,4
SnowWater=2,4
SnowMelt=2,1
Snow=2,4
UStoreDepth=2,4
SatWaterDepth=2,4
zi=2,4
RunoffRiverCells=2,0
InwaterMM=2,0
ssf_toriver=2,0
InwaterL=2,0
```

Appendix F: Ethical Clearance Letter

THE UNIVERSITY OF ZAMBIA

DIRECTORATE OF RESEARCH AND GRADUATE STUDIES
NATURAL AND APPLIED SCIENCES RESEARCH ETHICS COMMITTEE

Telephone: +260-211-290258/293937 P O Box 32379
Fax: +260-211-290258/293937 Lusaka,
Zambia
E-mail drgs@unza.zm

APPROVAL OF STUDY

22nd July, 2021

Mr. Innocent C. Chomba
Principal Investigator
C/o School of Mines
LUSAKA

Dear Mr Chomba,

RESEARCH ETHICAL APPROVAL (NASREC: 2021 - FEB – 002) "SPATIO-TEMPORAL DYNAMICS OF WETLAND HYDROLOGY OF THE BAROTSE FLOODPLAIN, UPPER ZAMBEZI RIVER BASIN"

Reference is made to your submission for ethical approval of the study captioned above.

The University of Zambia Natural and Applied Sciences Research Ethics Committee IRB resolved to approve this study and your participation as Principal Investigator for a period of one year.

Review Type	**Ordinary Review**	Approval No. **NASREC: 2021 - FEB - 002**
Approval and Expiry Date	Approval Date: 22nd July, 2021	Expiry Date: 21st July, 2022
Protocol Version and Date	Version-Nil	-
Information Sheet, Consent Forms and Dates	• English.	To be provided
Consent form ID and Date	• Version	To be provided
Recruitment Materials	Nil	Nil

Specific conditions will apply to this approval. As Principal Investigator it is your responsibility to ensure that the contents of this letter are adhered to. If these are not adhered to, the approval may be suspended. Should the study be suspended, study sponsors and other regulatory authorities will be informed.

Conditions of Approval

- No participant may be involved in any study procedure prior to the study approval or after the expiration date.
- All unanticipated or Serious Adverse Events (SAEs) must be reported to NASREC within 5 days.
- All protocol modifications must be approved by NASREC prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address.
- All protocol deviations must be reported to NASREC within 5 working days.
- All recruitment materials must be approved by NASREC prior to being used.
- Principal investigators are responsible for initiating Continuing Review proceedings. HSSREC will only approve a study for a period of 12 months.
- It is the responsibility of the PI to renew his/her ethics approval through a renewal application to NASREC.
- Where the PI desires to extend the study after expiry of the study period, documents for study extension must be received by NASREC at least 30 days before the expiry date. This is for the purpose of facilitating the review process. Documents received within 30 days after expiry will be labelled “late submissions” and will incur a penalty fee of K500.00. No study shall be renewed whose documents are submitted for renewal 30 days after expiry of the certificate.
- Every 6 (six) months a progress report form supplied by The University of Zambia Humanities and Social Sciences Research Ethics Committee as an IRB must be filled in and submitted to us. There is a penalty of K500.00 for failure to submit the report.
- When closing a project, the PI is responsible for notifying, in writing or using the Research Ethics and Management Online (REMO),both NASREC and the National Health Research Authority (NHRA) when ethics certification is no longer required for a project.

- In order to close an approved study, a Closing Report must be submitted in writing or through the REMO system. A Closing Report should be filed when datacollection has ended and the study team will no longer be using human participants or animals or secondary data or have any direct or indirect contact with the research participants or animals for the study.
- Filing a closing report (rather than just letting your approval lapse) is importantas it assists NASREC in efficiently tracking and reporting on projects. Note that some funding agencies and sponsors require a notice of closure from the IRB which approved the study and can only be generated after the Closing Reporthas been filed.
- A reprint of this letter shall be done at a fee.
- All protocol modifications must be approved by NASREC by way of an applicationfor an amendment prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address or methodology and methods. Many modifications entail minimal risk adjustments to a protocol and/or consent formand can be made on an Expedited basis (via the IRB Chair). Some examples are: format changes, correcting spelling errors, adding key personnel, minor changes to questionnaires, recruiting and changes, and so forth. Other, more substantive changes, especially those that may alter the risk-benefit ratio, may require Full Board review. In all cases, except where noted above regarding subject safety, any changes to any protocol document or procedure must first be approved by NASREC before they can be implemented.

Should you have any questions regarding anything indicated in this letter, pleasedo not hesitate to get in touch with us at the above indicated address.

On behalf of NASREC, we would like to wish you all the success as you carry outyour study.

Yours faithfully,

Dr.M. Kaonda

VICE-CHAIRPERSON
THE UNIVERSITY OF ZAMBIA NATURAL AND APPLIED SCIENCESRESEARCH ETHICS COMMITTEE IRB

cc Director, Directorate of Research and Graduate Studies
Acting Assistant Director, Directorate of Research and Graduate Studies
Assistant Registrar (Research), Directorate of Research and Graduate Studies
Acting Senior Administration (R), Directorate of Research and Graduate Studies.