Hydrological Evaluation and Ecosystem Valuation of the Lukanga Swamps

Final Report

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FutureWater Report 167

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Preface

Zambia's Ministry of Lands, Natural Resources and Environmental Protection is in the process of defining the policy framework and agenda to guide wetlands management. As part of this planning process, The Nature Conservancy (TNC) is partnering with the Ministry and other stakeholders to develop a management plan for the Lukanga Swamps, which is an important biodiversity area and serves as a major hydrological component of the Kafue basin.

FutureWater collaborates with TNC on this project and carries out a hydrological assessment and future hydrological outlook of the Lukanga Swamps. The work should give quantitative insight in the role the swamps play in sustaining hydrological services provided by the swamp and its connection with the Kafue River. This report presents the work done by FutureWater.

FutureWater would like to acknowledge staff of TNC and WARMA for their support in completing this study, as well as Max Karen and Hans Beuster for their suggestions at the start of this study. Especially the role of Mundia Matongo, Anne Trainor, Tracy Baker and Colin Apse has made it possible to make this project a successful one that will benefit nature and people in the Lukanga Swamp region.

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1 Introduction

1.1 Background

Zambia's Ministry of Lands, Natural Resources and Environmental Protection is in the process of defining the policy framework and agenda to guide wetlands' management. As part of this planning process, The Nature Conservancy (TNC) is partnering with the Ministry and other stakeholders to develop a management plan for the Lukanga Swamps. The swamps are an important biodiversity area and serve as a major hydrological component of the Kafue Basin.

The value and contribution of the Lukanga Swamps to the Kafue Basin has not yet been evaluated. While the biodiversity value of wetlands in general is widely accepted, evaluating the contribution of hydrological ecosystem services within basin systems is becoming a more commonplace holistic approach. There is need for solid scientific evidence regarding the role the Lukanga Swamps play in water quantity and quality within Kafue River, and the value this contributes to water security for Lusaka and other surrounding and downstream areas that rely on the inundation and recession of the Lukanga Swamps' flood waters.

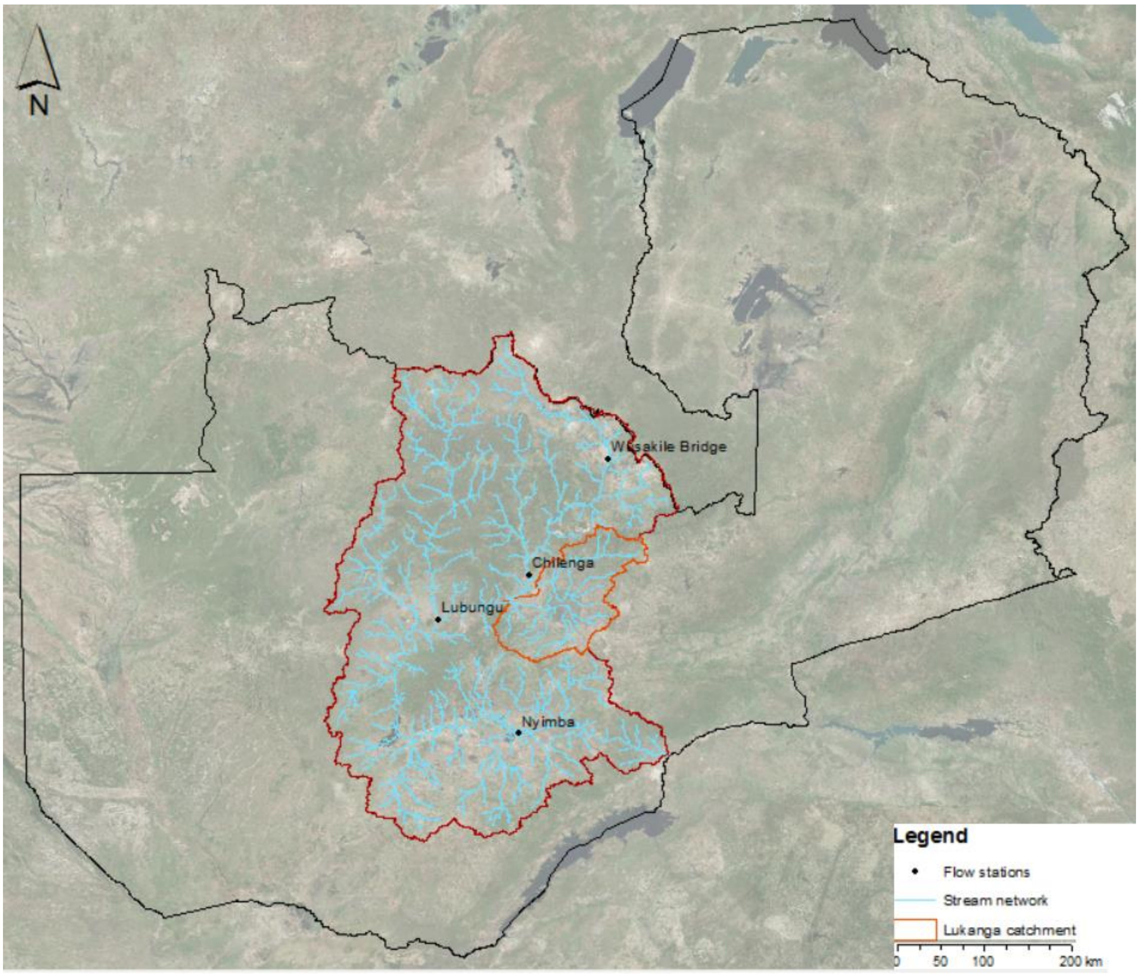


Figure 1. Location of the Kafue River Basin and Lukanga watershed in Zambia

During high flow, the Kafue River backs up into the Lukanga Swamps and even overflows into the area during the highest flows (Figure 2), returning to its normal course as the high flows dissipate. The link between the Kafue river and floodplain, and the Lukanga Swamps and watershed is not well understood, making management planning for the area a challenge. Water quality of Kafue River improves downstream between Kitwe and Ndola bridge gauge and Lubungu stream gauges.

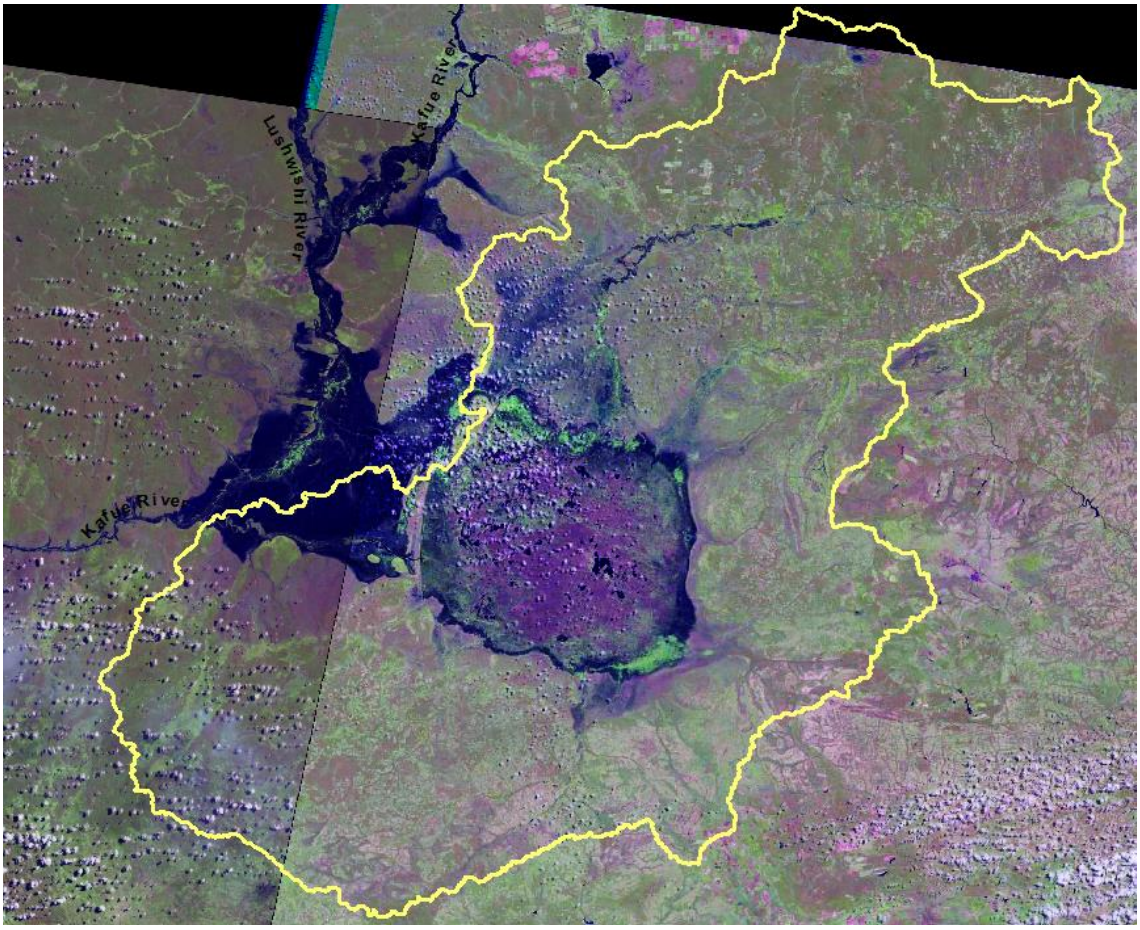


Figure 2. Exceptional flooding during March-April 2001 (source: Landsat imagery processed by Daniel Kelly, TNC)

Mining has a major influence on water quality in Kafue River, and yet these mining impacts are attenuated somehow. It is assumed that the Lukanga Swamps plays a role in attenuating mining pollution in Kafue River. If this is the case, then there is a basis to engage mining houses in payment for ecosystem services schemes to help support management of the Lukanga Swamps and its watershed. This would ensure the Lukanga Swamps continue to provide vital ecosystem services, such as water purification. Water quantity (streamflow) in Kafue River is also affected by the Lukanga swamps. The extent to which this happens, and might alter in the future is a function of the utilization and health of the Lukanga swamps.

WARMA (Water Resources Management Authority) is in the process of setting up Kafue catchment management plans and places the Lukanga as a priority sub basin, along with the lower reach between Itezhi-tezhi and Kafue Gorge. The Kafue catchment has huge socio-economic importance to Zambia not least because it provides 40% of municipal water supply, 50% of the electricity generation, and important biodiversity.

There is increasingly high competition for water resources resulting from major expansions in irrigated agriculture, the hydropower sector, a rising population and developments in the mining sector. These developments lead to degradation of the environment and impacts on the livelihoods of communities particularly downstream of the Lukanga.

This also affects the water supply of Lusaka city. The Lusaka Water Security Initiative (LuWSI) is a multi-stakeholder partnership of the public sector, private sector and civil society actors, including TNC, and has as one of its key priorities to promote a sustainable use of resources from the Kafue river.

To guide management for a functional and resilient Lukanga wetland, there is need to develop and implement a Lukanga Swamps management plan. The plan will need to be preceded by a robust situation assessment and clear future outlook understanding to inform management efforts. While the Ministry of Lands, Natural Resources and Environmental Protection are in the process of developing the overarching policy framework for wetlands, and WARMA defining the Kafue Catchment Plans, TNC-planned interventions in the Lukanga will serve as a vital opportunity to inform both processes.

1.2 Knowledge gaps

The Lukanga Swamp is a large wetland that functions like a sponge, absorbing water that comes in during the wet season, or from the periodically flooding of the Kafue through overflow. It buffers water and releases the water slowly during the dry period. There is currently little understanding of the amount of water stored, entering and leaving the swamp.

The swamp also serves as a pollution filter: it receives sediments from the Lukanga watershed produced by erosion and sub-optimal land management, and most likely also absorbs some of the pollutants coming from mining and agriculture in the Kafue river when it connects with the swamp during high flows.

Figure 3 shows a map with the Lukanga Swamp, the Kafue river in the north-east, the Lukanga River and the Mufukushi River that are part of the Lukanga watershed. The blue arrows indicate the water received from the Lukanga watershed. The red arrow the water leaving the swamp to the Kafue river. The yellow arrows indicate areas with occasional overflow during flood events. It is important to note that these flows do not occur only as surface flows, but also as sub-surface flows: the floodplain and the Lukanga swamps are probably well connected through the sub-surface.

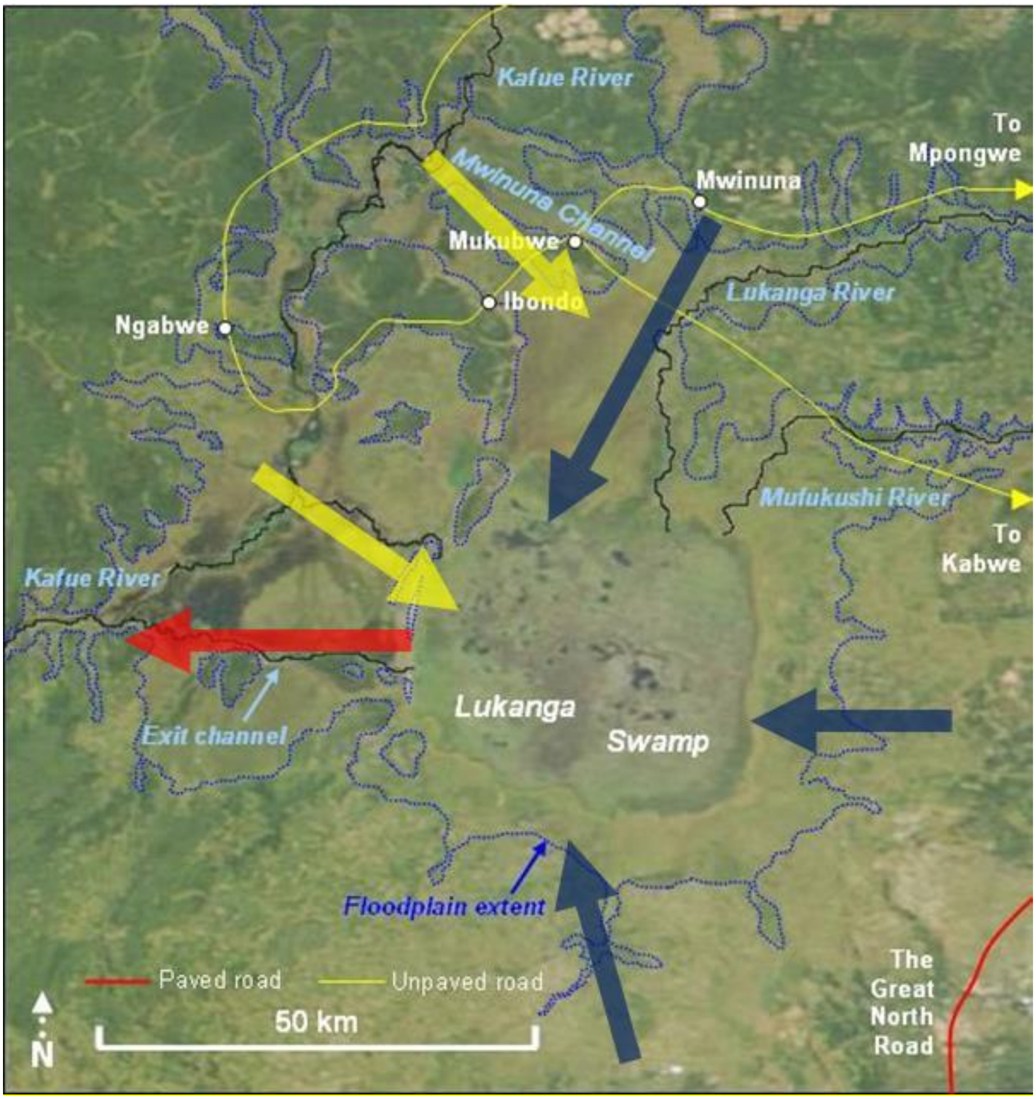


Figure 3. Map showing Lukanga Swamp, the Kafue river and the rivers part of the Lukanga watershed. See further explanation in text. Source: Wikipedia (slightly modified)

Key questions that need to be answered:

- How much water does the swamp receive from the Lukanga watershed (blue arrows)
- How much water does the swamp provide to the Kafue river, during wet and dry periods (red arrow)
- How frequent the Kafue floodplain and the swamp are connected during flood periods (yellow arrow)

These questions will be answered, among others, in this study, and are essential for the assessment of future scenarios and ecosystem services.

1.3 Relevant previous work

A short summary of the relevant previous work is provided in this section.

2007: Hydrological analysis

A technical note by IWMI on the Lukanga Swamps collects several data sources and carries out a first-order hydrological analysis (McCartney, 2007). Based on available data sources, it estimates that on average 94% of the flow occurs in the months December to May. Peak water levels are generally in May-July, and are superimposed on a longer cycle of wetting and drying (approx each 4-10 years), probably due to flood events in the Kafue plain that connects with the swamp. They estimate total evapotranspiration from the swamp to be around 2,961 Mm3, inflow from the catchment 1,482 Mm3, inflow from the Kafue on average 543 Mm3, and outflow from the wetland to Kafue 1,413 Mm3.

2007: Stakeholder analysis
A Master Thesis (Kachali, 2007) carried out a stakeholder analysis, group interviews and questionnaires, to better understand how decisions among stakeholders take place and influence each other. The work argues that an important part of achieving socio-ecological sustainability of the Lukanga Swamps should be obtained through building trust and the creation of stakeholder platforms.

2011: Conflicts and use
McCartney et al (2011) carried out social surveys in the area to assess use, conflicts and management of the Lukanga Swamps. They conclude that currently there is little opportunity within the existing legislation to translate into practice a management regime that integrates in a sustainable way all ecosystem services. It is essential that local communities be given clearly defined rights and benefits over the resources that they manage. They stress that environmental and social sustainability requires a management plan be developed that enables an equitable distribution of benefits from the wetland, based on working with local communities and a common vision for the wetland.

2013: Climate change
A study by Kampata et al. (2013) on climate change impacts on the Lukanga Swamps shows temperature and precipitation trends according to SRES ensemble model forecasts, and compares outcomes with trends observed in gauged water level data of the swamp. It also carried out a remote sensing analysis on land use change.

2010: Management plan
In 2010 IMWI and WWF-Zambia formulated the Management plan for the Lukanga area (Chabwela et al., 2010), using guidelines as prescribed by the Ramsar Secretariat for site planning. The planning was primarily driven by the desire to address the issues in the exploitation of resources of the wetland. The plan includes some estimates on hydrology but some of the numbers are flawed (e.g. 8,500 mm/year evaporation). However, the characterization of the ecosystems and stakeholders is rather complete and comprehensive.

2016: Climate Change in Water Resources Monitoring
The Government of Zambia, as represented by the Ministry of Mines, Energy and Water Development has initiated a project for integrating climate change in water resources monitoring, with support from the German Development Cooperation. The overall objective of the Project is to establish an integrated water resources management information system (IWRMIS), and application of the information system in order to incorporate climate change in water resources management. Several reports are available: Socio-economic baseline, Water quality, Water demands and Infrastructure, Hydrology, Environmental Flows, and a Climate Change impact analysis on Water Resources. The report on water quality of the Kafue river (GFA/DHI, 2016) also mentions that Lukanga Swamp is likely to be the sink for the heavy

metals from upstream Kafue (mining). However, the area is not identified as a priority area under this assessment.

2011: Climate Risk and Business – Hydropower. Kafue Gorge Lower
This study commissioned by IFC (World Bank group) carried out climate risk analysis on the hydropower sector in the Kafue River Basin. One of the key recommendations of this study was to support a comprehensive study and assessment of actual water usage in the Kafue river basin. It also recommended the sector to become proactively involved with national adaptation planning efforts and to pursue public involvement strategies.

1.4 Objectives

The goal of this assessment is to carry out a hydrological assessment of Lukanga Swamps. A water balance is established based on a combination of hydrological modelling and remote sensing analysis. Future scenario analysis is performed to understand the response of the system to future changes and to assess the impact on water-related ecosystem services it currently provides. The overall goal is that the study will inform the catchment management plan, and policy and management efforts for its conservation and provision of ecosystem services.

More specifically, the objectives are to present both a (i) hydrological assessment of the Lukanga Swamps and an (ii) evaluation of the ecosystem services provided by the swamp to stakeholders in the Kafue basin.

For the hydrological evaluation of the Lukanga Swamps the water storage dynamics in the swamp and the water balance needs to be assessed. Therefore, a wide range of data was collected on the Lukanga Basin, rainfall-runoff and erosion modelling of Lukanga watershed was carried out and a water balance tool was applied to assess the overall water balance.

The evaluation of the ecosystem services provided by the Lukanga Swamps was carried out by studying the relevance of the swamp for the Kafue basin, under the current situation and different future scenarios.

2 Methods

2.1 Analytic approach to assessment

To meet the above objectives and to address the related questions, the first step is to better understand the water fluxes flowing into and out of the Lukanga Swamps, and obtain quantitative insight in the connection with the Kafue floodplain.

To resolve the water balance, a combination of tools is used:

- Remote sensing to assess the storage variability in the swamp and the flood dynamics
- A hydrological model (SWAT) to assess the hydrological flows to the swamp, and precipitation/evapotranspiration
- A water resources system model (WEAP) to integrate and assess the water balance

The outputs of SWAT on flows are used as input into the WEAP model. The methodology followed for each of the above tools is explained in separate sections afterwards. The water balance is resolved on a monthly timestep for a period of 16 years (2000-2015).

Remote sensing analysis is also used to understand the variability in open water versus water covered with vegetation in the swamp – as this is an important indicator for the swamp, both in ecological terms, as well as socio-economic terms (vegetation affecting the fishing operations).

Finally, SWAT and WEAP are used for scenario analysis to assess how future changes may affect the flows (source function) and its function as a sink for possible contaminants.

The following water balance was established for the system:

$$P + Q_{in} + Q_{ov} - ET - Q_{out} = dS$$

The following table explains these components and its source for this analysis, and Figure 4 shows it graphically:

Table 1. Description of the water balance terms

Abbreviation	Variable	Description	Tool used
P	Precipitation	Rainfall falling directly on the swamp	Station data
Qin	Streamflow	Water inflow from the Lukanga watershed	SWAT
Qov	Overflow	Occasional surface overflow from Kafue during flood events, and subsurface flow from the Kafue river floodplain to the Lukanga swamps	Remote Sensing
ET	Evapotranspiration	Evapotranspiration from swamp (assumed to be at its potential rate)	SWAT
Qout	Outflow	Flow leaving swamp through exit channel to Kafue and subsurface flow between Kafue alluvial subsurface and swamp subsurface	Water balance / WEAP
dS	Storage difference	Difference in water stored in Lukanga swamps	Remote Sensing

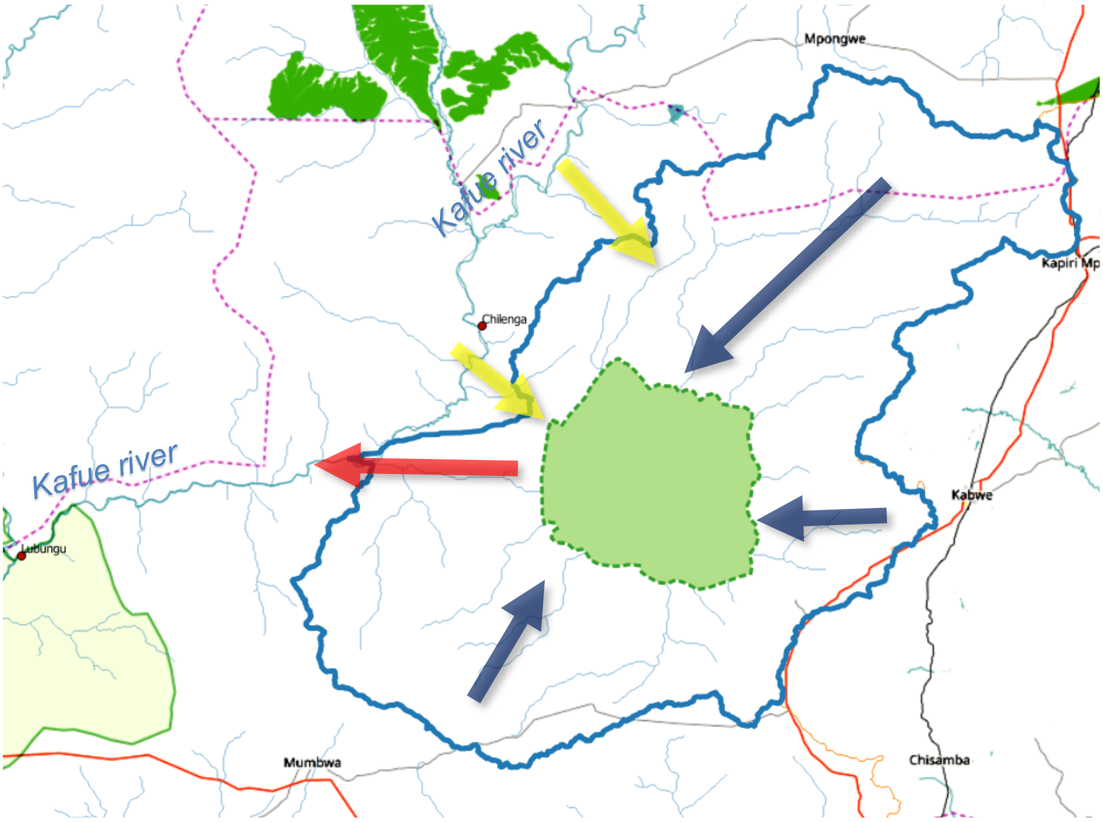


Figure 4. Schematic diagram of the study area showing water balance components and the tools used

2.2 Remote sensing analysis

Few local data are available on the storage and vegetation dynamics of the Lukanga swamps. Satellite-based remote sensing analysis can fill this gap and provides unique opportunity to assess several processes of the swamp.

More specifically, in this analysis, remote sensing was used to understand the (1) dynamics in water levels in the swamps, (2) vegetation versus open water area of the swamps, and (3) flooding dynamics in the Kafue floodplain. The information on water levels and flooding is being used for the water balance/WEAP analysis.

To assess water bodies from satellite imagery, several indices exists that detect the sharp contrast between the reflectance of water in the visible and infrared spectra. The use of normalized 2-band ratio indices is a well-established approach to identify and delineate water bodies on multispectral satellite imagery (Frazier and Page, 2000) because they: 1) improve the detection accuracy as reflectance values are normalized across the image and then the influence of localized distortion effects are reduced, 2) reduce the effect of distortions over consecutive images making possible to apply a same threshold over a period dates and thereby making easier the automation of the procedure, and 3) are better than single bands especially when turbid water or submerged vegetation need to be identified (Frazier and Page, 2000; Ogilvie et al., 2015).

Among all band-ratio indices reported in scientific literature, NDWI, MNDWI and NDMI have been demonstrated to be the best suited for the detection of open water bodies or flooded areas (see e.g. Ogilvie et al. (2015) and references therein). In some cases, a combination of these indices has also been applied successfully.

Table 2. Satellite-based Normalized Indices used in this study

Index	Acronym	Landsat5/7/8	MODIS09
NDWI	(G – NIR) / (G + NIR)	(B2 – B4) / (B2 + B4)	(B4 – B2) / (B4 + B2)
MNDWI	(G – MIR) / (G + MIR)	(B2 – B5) / (B2 + B5)	(B4 – B6) / (B4 + B6)
NDMI	(NIR – MIR) / (NIR + MIR)	(B4 – B5) / (B4 + B5)	(B2 – B6) / (B2 + B6)

NDWI: Normalized Difference Water Index (McFeeters, 1996)
MNDWI: Modified Normalized Difference Water Index (Xu, 2006)
NDMI: Normalized Difference Moisture Index (Xiao et al., 2005; Xu, 2006)

To address the flood dynamics analysis in the Kafue-Lukanga hydrosystem during the 2002-2015 period, two analyses were performed in two different areas (Figure 5). Within the swamp area (1850 km^2), the temporal fluctuation of the total area covered by open water and flooded vegetation was quantified using an automatic and calibrated procedure able to detect open water from MODIS imagery. Secondly, the flood dynamics outside the swamp was evaluated in the Kafue river floodplain located west of the swamp (1750 km^2), which connects with the swamp during high flood events of the Kafue River.

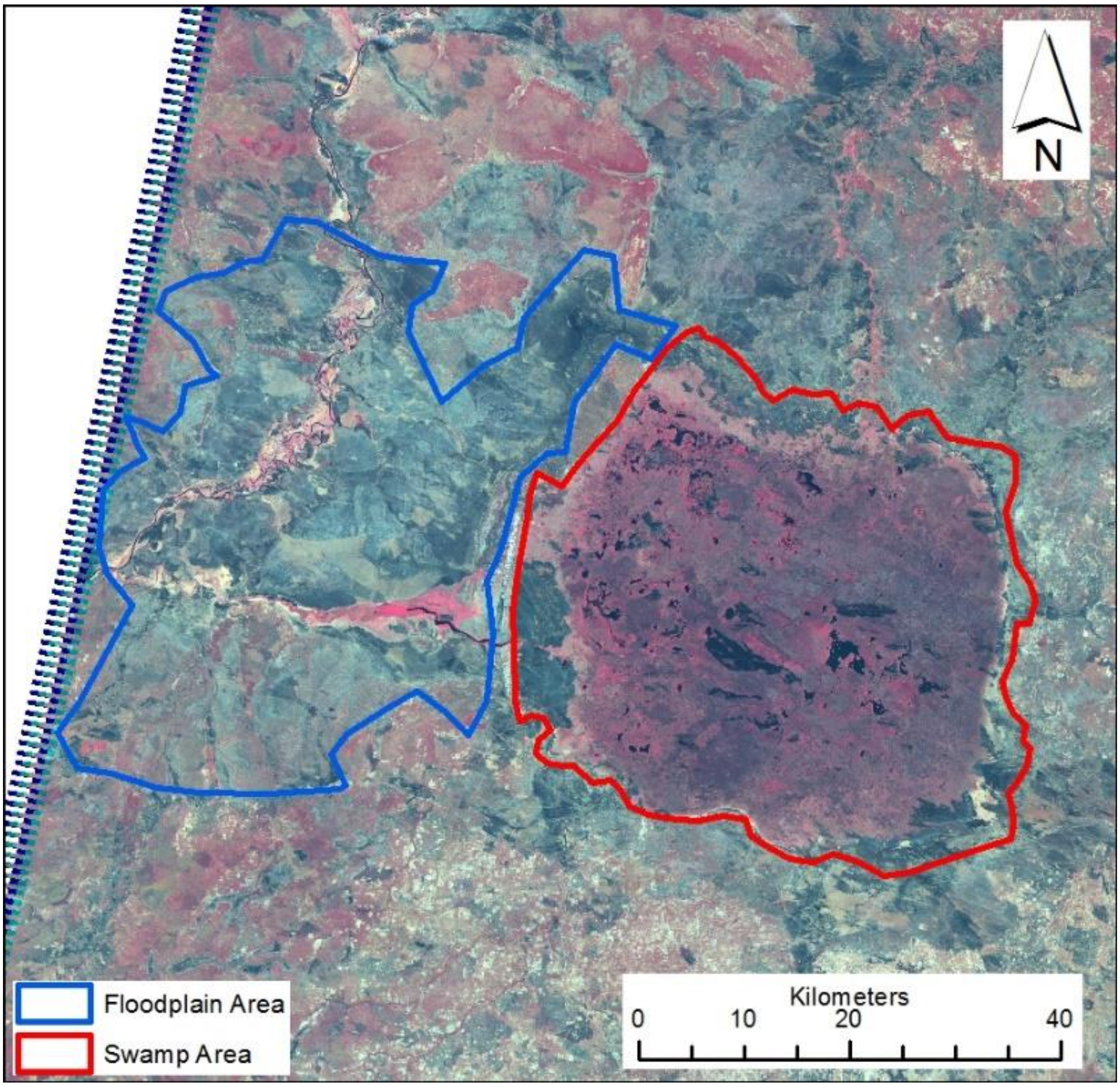


Figure 5. Study area used during the remote sensing analysis.

2.2.1 Open-water and vegetation

Remote sensing analysis was carried out to detect fluctuations during the year in open water areas versus vegetated (including algae) areas. An automatic threshold-based procedure has been designed to detect open water over MODIS maps of the NDWI. The process to retrieve NDWI maps from MODIS imagery is detailed in section 3.1.1.

Since MODIS imagery has a relatively large pixel size (500 meter) calibration using Landsat imagery (pixel size 30 meters) has been undertaken. The NDWI threshold adopted to classify a pixel as open water was calibrated against the total acreage of open water detected in two Landsat dates (14-Jun-2005 & 24-May-2009) using a supervised classification algorithm (see section 3.1). In our study the area not classified as "open water" within the swamp (including algae) is classified as "vegetation".

Figure 6. Fisherman collecting his nets in the Lukanga swamps

The best fit between the total areas of open water estimated by MODIS and Landsat was reached for a NDWI value of -0.35. This value is very close to the one reported by Ogilvie et al. (2015) in the Niger delta.

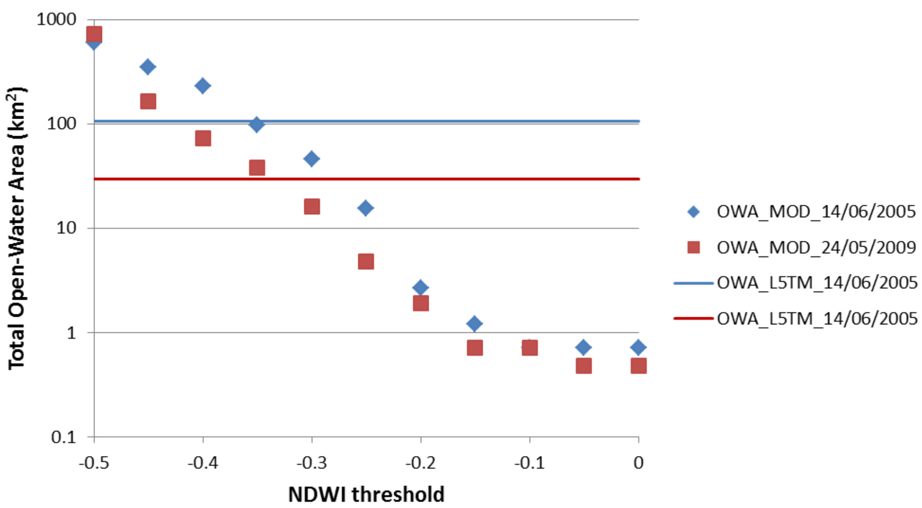


Figure 7. Calibration of the NDWI threshold value for MODIS imagery (dots) for open water. The lines represent the value obtained from supervised classification of Landsat (LSTM) imagery.

2.2.2 Flooding frequency

During high flood events in the Kafue river, the floodplain of the Kafue connects to the Lukanga swamps. Remote sensing data are used to estimate the flooding frequency of the Kafue floodplain. This will provide a good indicator of when it is likely that overflow occurs from the Kafue river to the swamps, which can then be verified in the water balance modeling using WEAP.

For the floodplain, time series of NDMI (similar to NDWI, see Table 2) values were extracted for an area prone to floods which connects Kafue River with Lukanga swamp (Figure 5 and Figure

8). NDMI spatially-averaged values from Landsat and MODIS imagery were collected using the Climate Engine App (see section 3.1.2) and processed to detect the flood events in the Kafue floodplain. Flood events were detected on a 8-day time-step, for a period the 2001-2015 period.

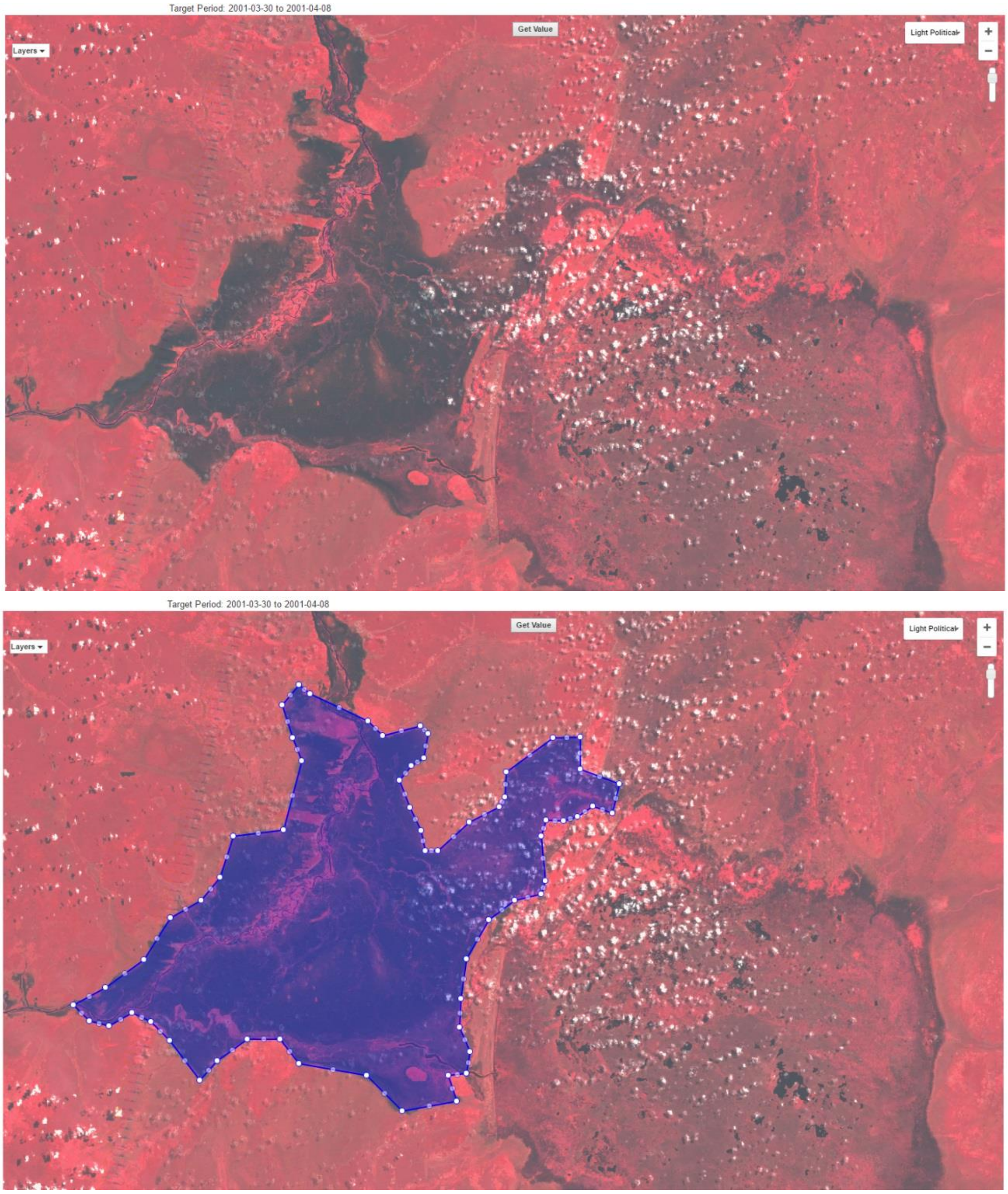


Figure 8. Landsat False Color Composite during the April-2001 flooding event. The dynamics of flooding events were evaluated within the “blue” area shown in the bottom figure.

2.3 Hydrological modeling using SWAT

The Soil Water Assessment Tool (SWAT, version SWAT2015) is used to assess hydrological flows of the different land uses and management areas upstream of the swamps. Also erosion and sediment loads from agricultural lands are assessed, with special emphasis on the Miombo woodlands that are used for grazing and often burned. The model is run on daily basis for a reference period of 10-15 years. SWAT was configured and operated through the open-source QSWAT interface (version 1.3) available for Quantum GIS.

SWAT[1] was developed primarily by the United States Department of Agriculture (USDA) to predict the impact of land management practices on water, sediment and agricultural chemical yields in complex watersheds with varying soils, land use and management conditions over long periods of time. The SWAT model has been extensively used, is in the public domain and can be considered as becoming the de-facto standard in hydrological decision support systems.

SWAT represents all the components of the hydrological cycle including: rainfall, snow, snow-cover and snow-melt, interception storage, surface runoff, up to 10 soil storages, infiltration, evaporation, evapotranspiration, lateral flow, percolation, pond and reservoir water balances, shallow and deep aquifers, channel routing. It also includes irrigation from rivers, shallow and deep groundwater stores, ponds/reservoirs and rivers, transmission losses and irrigation onto the soil surface. It includes sediment production based on a modified version of the Universal Loss Equation and routing of sediments in river channels.

Simulation of the hydrology of a watershed can be separated into two major components. The first component is the land phase of the hydrologic cycle. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin.

The second component is the water or routing phase of the hydrologic cycle which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet. Once SWAT determines the loadings of water, sediment, nutrients and pesticides to the main channel, the loadings are routed through the stream network of the watershed using a command structure.

The SWAT model estimates erosion and sediment yield with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). While the USLE uses rainfall as an indicator of erosive energy, MUSLE uses the amount of runoff to simulate erosion and sediment yield. This modification is reported to increase the prediction accuracy of the model, the need for a delivery ratio is eliminated, and single storm estimates of sediment yields can be calculated

The sediment yields of each HRU are routed to the channel of the corresponding sub-basin. The transport of sediment in the channel is controlled by the simultaneous operation of two processes, deposition and degradation. SWAT has various state-of-the-art modeling options for determining channel degradation as a function of channel slope and velocity.

2.4 Water balance assessment and WEAP

The WEAP tool is selected for this assignment for two purposes:

- Assess the water balance of the Lukanga swamp system, connected with the Kafue river flood plain

[1] http://swat.tamu.edu/

- Assess future scenarios in which new agricultural developments are likely to increase consumptive water use and return flows. See more on scenarios in the following section.

The WEAP model is developed by the Stockholm Environmental Institute (SEI) with the main aim to assist in policy evaluation and water resources planning. WEAP is an easy-to-use tool that can be used to give insight in water supplies and competing demands, and to assess the upstream–downstream links for different management options in terms of their resulting water sufficiency or unmet demands, costs, and benefits. It uses the basic principle of water balance accounting: total inflows equal total outflows, net of any change in storage (in reservoirs, aquifers and soil).

WEAP represents a particular water system, with its main supply and demand nodes and the links between them, both numerically and graphically. The concept-based representation of WEAP means that different scenarios can be quickly set up and compared, and it can be operated after a brief training period. WEAP is being developed as a standard tool in strategic planning and scenario assessment and has been applied in many regions around the world.

The WEAP model is used for all type of water availability assessments. In this study it is specifically used to analyze reservoir management and its economic consequences. The streamflows and sediment concentrations that are calculated with SWAT are used as input for the WEAP model. In WEAP the streamflows are stored in the reservoirs and released either when reservoir storage becomes larger than storage capacity or when there is an energy demand (specified by the user for each reservoir).

2.5 Scenario definition

Several future scenarios were assessed using SWAT and WEAP, in order to assess how the Lukanga Swamps, and the water-related ecosystem services they provide, may change in the future. A summary of these scenarios is provided in Table 3.

Table 3. Overview of future scenarios evaluated.

No	**Scenario**	**Description**	**Tool**
1	Deforestation (business-as-usual)	Continuous deforestation due to charcoal production, bush fires, etc. following the current trend	SWAT
2	Increase tree cover in half of basin, other half decrease	TNC and forestry department perform reforestation, leading to only half of the current forest loss rate	SWAT
3	Reducing bush fires	Reduced frequency of bush fires (increase of fire return interval)	SWAT
4	Increase use of groundwater by communities around the swamp	Better roads and improved access to markets, increase in population will lead to increase of groundwater resources around the swamp.	WEAP
5	Large irrigated farms	Similar to irrigation schemes just north of the watershed, sugarcane plantations using water from aquifers	WEAP
6	Change in flows due to climate change - projection 1	Based on the changes in flow predicted by parallel work of TNC on climate change impacts in Kafue basin. RCP4.5 projection	WEAP

7	Change in flows due to climate change - projection 2	Based on the changes in flow predicted by parallel work of TNC on climate change impacts in Kafue basin. RCP8.5 projection	WEAP
8	Change in peak flows Kafue	New dams in the Kafue, upstream of the Lukanga watershed, or increase in irrigation water use, will reduce peak flows and have an impact on the connection between the Kafue river and the Lukanga system	WEAP

3.1 Remote sensing datasets

3.1.1 MODIS and Landsat

It was decided to undertake the remote sensing analysis using data from the MODIS satellite and not from the higher resolution Landsat images, because (i) MODIS imagery has a high pass-frequency which reduces the issues with cloudiness, and (ii) the area is large enough for the resolution of the MODIS imagery (500m). However, Landsat imagery were used to derive threshold values for the water-vegetation indices.
NDWI, MNDWI and NDMI values were computed for the period 2001-2015 from spectral data retrieved from bands 1, 2, 4 and 6 of the MODIS sensor on board of the Terra satellite. Surface reflectance and the data-state quality assurance (QA) imagery was collected from the MOD09A1 land product (tile h20v10) which consists of 8-days composite maps of surface reflectance at 500 m of spatial resolution (46 scenes per year). Data-state QA layer was used to mask raw reflectance values according to the sky conditions reported at each date. Only pixel values with clear-sky conditions were retained for the spatial and temporal analysis: pixels with cloudy or mixed-sky conditions were masked and excluded. Figure 9 shows of the entire 15-year series the monthly means of the percentage of the area that was classified as valid. All data was retrieved from the NASA EOSDIS Land Processes DAAC (https://lpdaac.usgs.gov/).

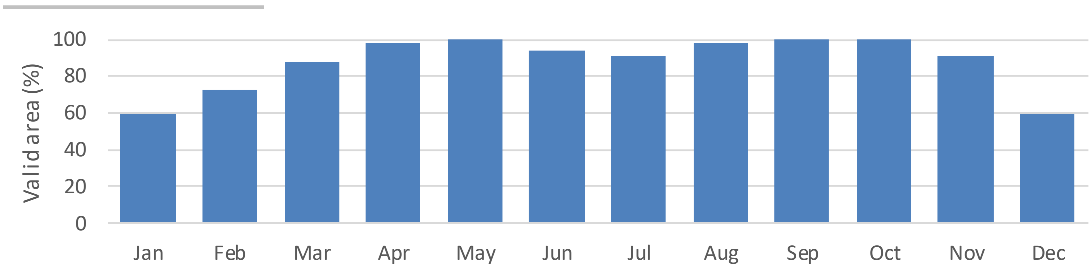


Figure 9. Percentage clear-sky area of the MODIS imagery - monthly means of the period 2001-2015

For the calibration of the NDWI threshold required for detecting open water surface in MODIS imagery, two Landsat5-TM cloud-free scenes (less than 10% of clouded area) covering the swamp area (Path: 172, Row: 70) were identified and collected using the Earth Exploring platform (http://earthexplorer.usgs.gov/). For both dates, 14-June-2005 and 24-May-2009, a supervised land use classification was conducted using the QGIS software and the SemiAutomatic Classification Plugin (SCP) (Cogendo, 2016).

Classification was primarily focused on the detection of open water bodies, so different regions of interest (ROI) for this land cover type were selected for extracting representative spectral signatures along the B1-B5 and B7 bands (**Figure 10**). Each target pixel in the scene was then classified as open-water or, by exclusion, as flooded-vegetation according the statistical distance between its spectral signature and the average representative one extracted from all the open-water ROIs selected.

Finally, the total acreage with open water within the swamp were reported at each date, and used for finding the NDWI threshold which best fitted MODIS and Landsat acreage outputs.

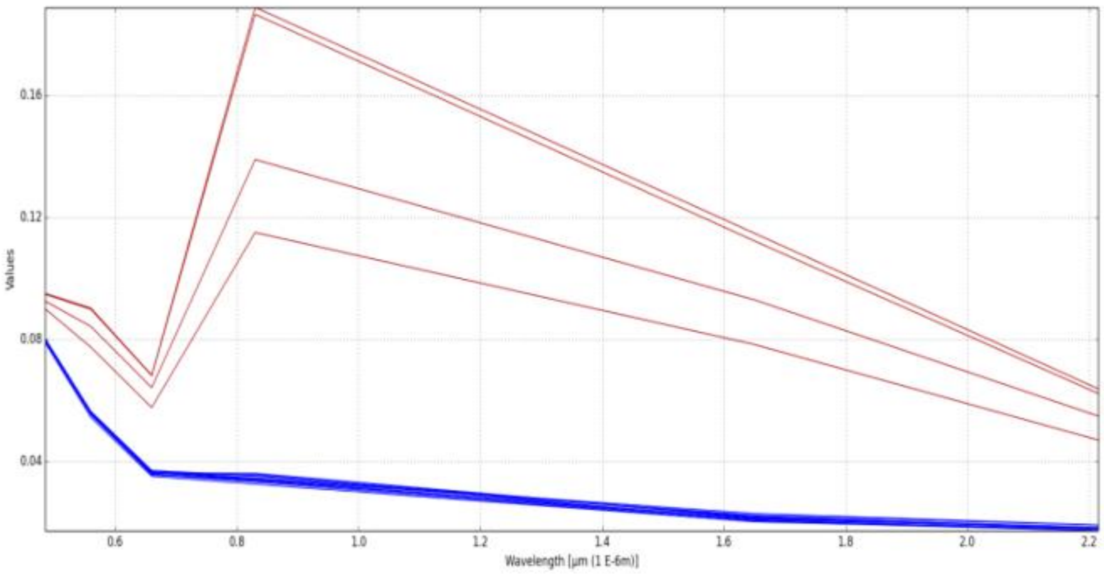


Figure 10. Example of spectral signatures for open-water bodies (blue lines) and flooded vegetation (red lines).

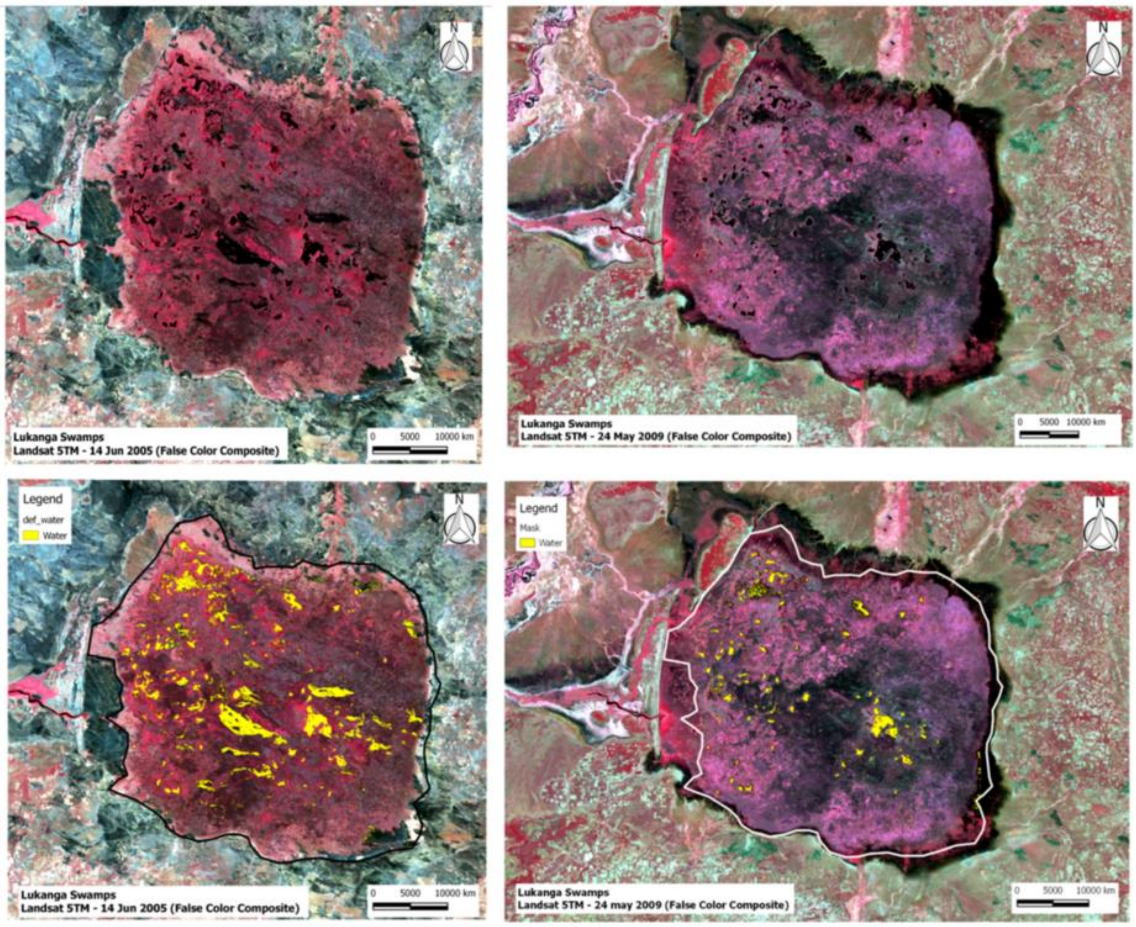


Figure 11. False Color Composite Landsat5-TM scenes of the Lukanga swamp at 14-Jun-2005 (top-left) and 24-May-2009 (top-right), and land classified as open-water (yellow in the bottom figures).

3.1.2 *Radar altimetry: DAHITI database*

Temporal dynamics of water level has been collected from the DAHITI database ("Database for Hydrological Time Series over Inland Waters") (http://dahiti.dgfi.tum.de/en/) (Schwatke et al., 2015a). DAHITI provides timeseries of water level in several rivers and lakes around the world from cross-calibrated multi-mission altimeter data extracted from Envisat, ERS-2, Jason-1, Jason-2, TOPEX/Poseidon, and SARAL/AltiKa.

Water level data from July-2002 to October-2010 were collected from the Lukanga swamp (site #109) (**Figure 12**). This dataset has been used successfully for flooding, lake and wetland studies (Schlaffer et al., 2016; Schwatke et al., 2015b; Singh et al., 2015).

Figure 12. Lukanga swamp data profile in the DAHITI database.

Lukanga Swamp Africa, Zambia Public Realtime

GENERAL INFO

Target Name:	Lukanga Swamp
Continent:	Africa
Country:	Zambia
Target Type:	Wetland
Basin:	Zambezi
Longitude:	27.7954 °E
Latitude:	-14.4054 °N
Period:	2000-01-01 - 2015-11-03
Data Points:	220
Min./Max./Avg. Height:	1115.25 m / 1118.25 m / 1116.44 m
Height Variations:	3.01 m
Last Update:	2016-09-12 09:47:01
Software-Version:	4.4

ALTIMETER DATA

The data of the following altimeter missions and corresponding passes have been used for the estimation of the water level time series. An additional '*' indicates that an additional retracking of the altimeter measurements was performed.

Mission	Pass No.
Envisat	0156, 0543
SARAL/AltiKa	0156*, 0543*

3.1.3 *Auxiliary NDWI values: The Climate Engine App*

The web service 'Climate Engine' (http://clim-engine.appspot.com/) (Huntington et al., 2016) was used in this study for retrieving timeseries of NDMI (on this website referred to as NDWI, check **Table 2** for difference) in the Lukanga swamp area and in the western floodplain sector which connects the Kafue river and the swamp. For both areas, CE was set up to extract spatially averaged values of NDWI from Landsat imagery for the 2001-2015 period.

3.2 Collection of hydrography data

A number of datasets was collected for modeling of the Lukanga hydrological system and Kafue River Basin water use. These data are used as model inputs, as well as for calibration and validation. This section describes the collected datasets.

3.2.1 Land use

The land use map of Zambia for 2010 with a 30 x 30 m spatial resolution was provided by TNC. Its original source is the National Remote Sensing Centre (NRSC) of the Zambian government. Figure 13 shows the land use in Kafue River Basin. The watershed contains large areas of different types of forest and shrubland. Large scale mining is mainly located in the upstream northeastern part of the basin, while agriculture is concentrated in the south. The major land cover types in the Lukanga watershed are Miombo woodland and similar combinations of shrubland and low density forests. The swamp itself takes up around 15% of the total watershed area (14,000 km^2), but the size of the wetland can increase to 50% of this number during peak floods.

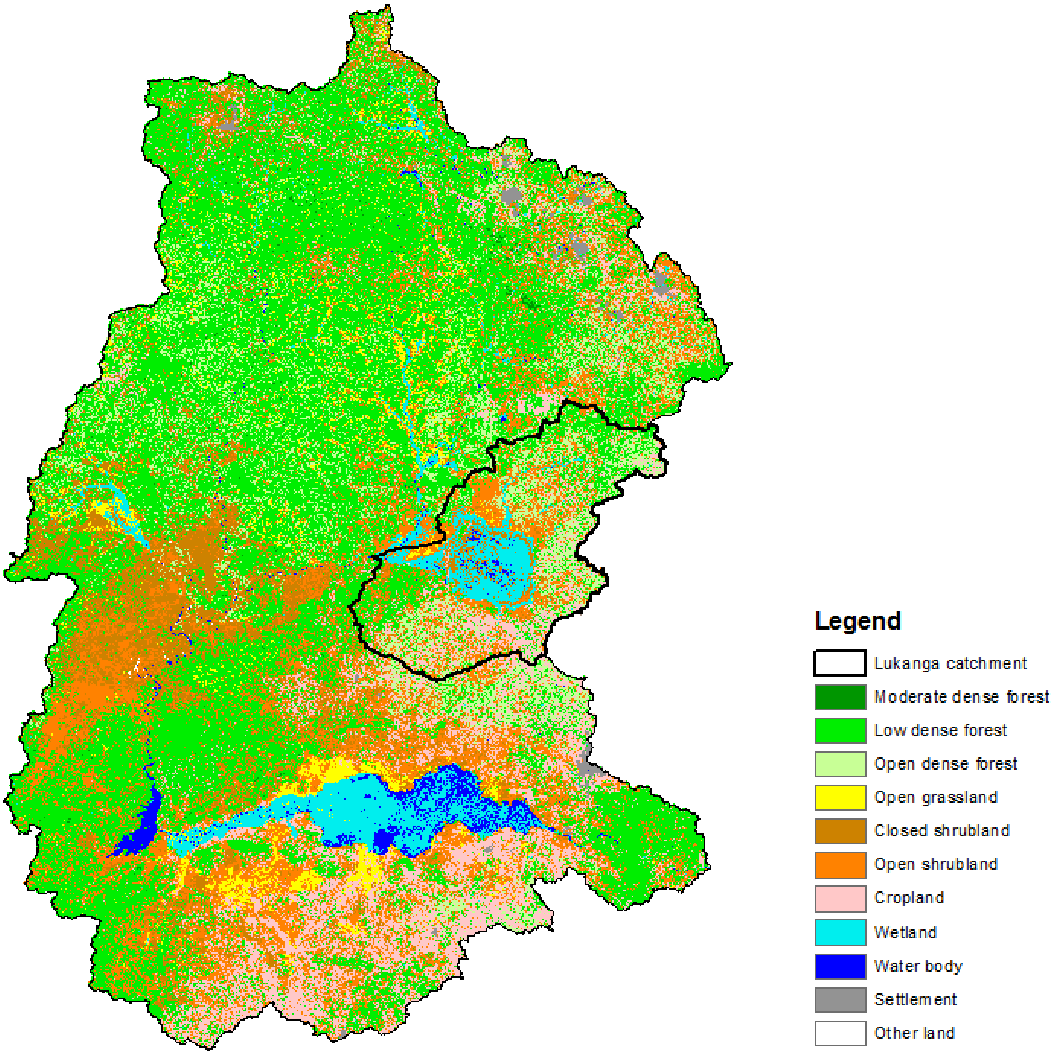


Figure 13. Land cover in the Kafue Basin and the Lukanga Swamp catchment (TNC/NRSC)

The main human impacts on land cover consist of “slash-and-burn” agriculture and associated deforestation. Figure 14 shows the burning frequency in the Lukanga watershed according to the MODIS Burned Area Product (MCD45A1), expressed in the number of years of fire occurrence in 2000 - 2015.

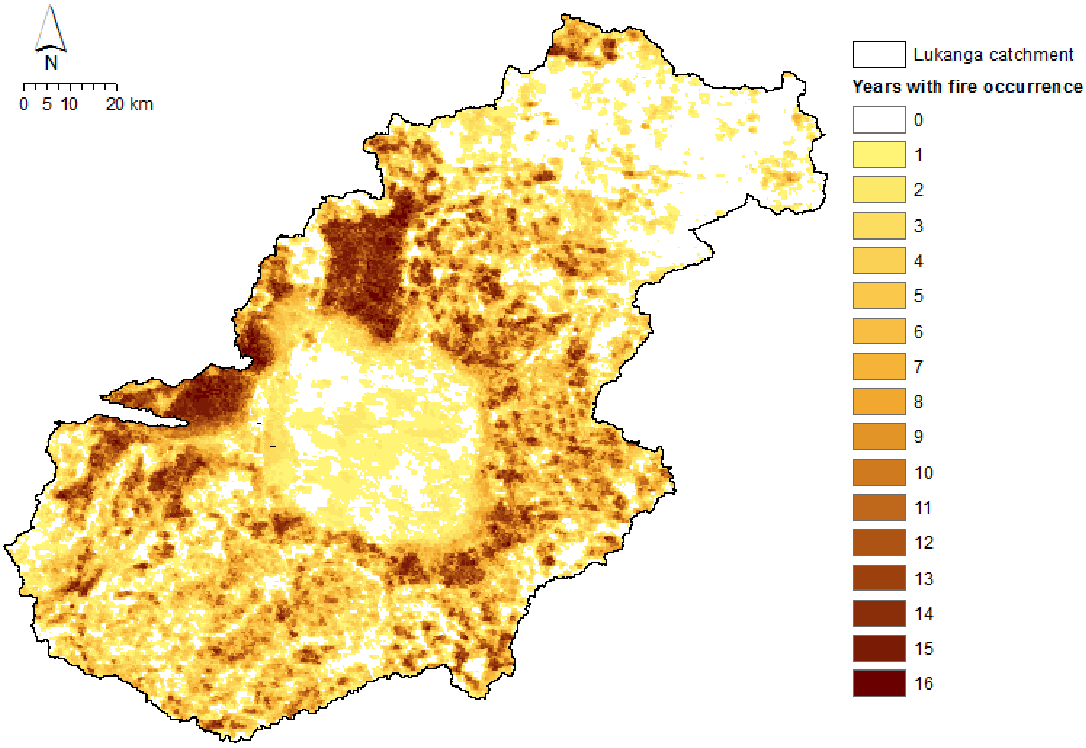


Figure 14. Burned area frequency upstream of Lukanga Swamps, 2000-2015.

As burning of the grass and woodlands for grazing can have a substantial impact on sediment flows in the watershed, the burning practices are incorporated in the SWAT model. Erosion is estimated by SWAT by means of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), which is the method most commonly used to estimate long-term erosion rates from field or farm sites that are subject to different management practices.

For the Lukanga watershed, burning practices were implemented in SWAT through the cover and management factor of the USLE equation (C), which is defined as the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow. Higher values for USLE C imply a higher susceptibility to erosion. SWAT calculates the actual USLE C based on a land-cover specific minimum (USLE C_0) and soil cover, with USLE C_0 typically ranging between 0.001 and 0.2. Table 4 shows how USLE C_0 was varied with fire return interval.

This approach should be regarded as a first order assessment of how fires impact erosion and sediment flows in the Lukanga watershed. Not only fire frequency, but also fire intensity is expected to have an important influence. Specifically for Miombo woodland, a study is available that examines the relation between fire return interval, fire intensity and biomass (Ryan and Williams, 2011). The relation between fire intensity and hydrophobicity of the soil could be used to alter land cover parameters in SWAT. As no data on fire intensity is available for Lukanga watershed, this study is limited to the impact of fire frequency. Since spatial patterns and dynamics of bush fires are an important part of this system, further attention toward fire intensity is recommended (Canfield et al., 2005; Goodrich et al., 2005).

Table 4. USLE C values for different land use classes

No. of fires 2000-2015	***Return interval (yr)***	***Burn freq.***	***USLE C_0 per class***		
			Forest	*Shrub*	*Grass*
<=1	>15.0	Negligible	0.006	0.008	0.008
1-5	3.0-15.0	Low	0.034	0.035	0.035
6-10	1.5-3.0	Medium	0.076	0.077	0.077
11-16	1.0-1.5	High	0.127	0.127	0.127

3.2.2 Soil

The dominant soil in the catchment according to the FAO World Soil Map is a sandy clay loam soil (Acrisol, FAO code *Fo76-2-3a-537*). As SWAT is mainly sensitive to the saturated hydraulic conductivity (K_{sat}) and the available water content (WC_{avail}) in the root zone, these values were obtained from the 250 m resolution HiHydroSoil database. The HiHydroSoil map was created by FutureWater (De Boer, 2014) by applying pedotransfer functions to the high-resolution soil map for Africa produced by ISRIC (Hengl et al., 2014). Figure 15 shows Ksat of the rootzone for the Lukanga watershed.

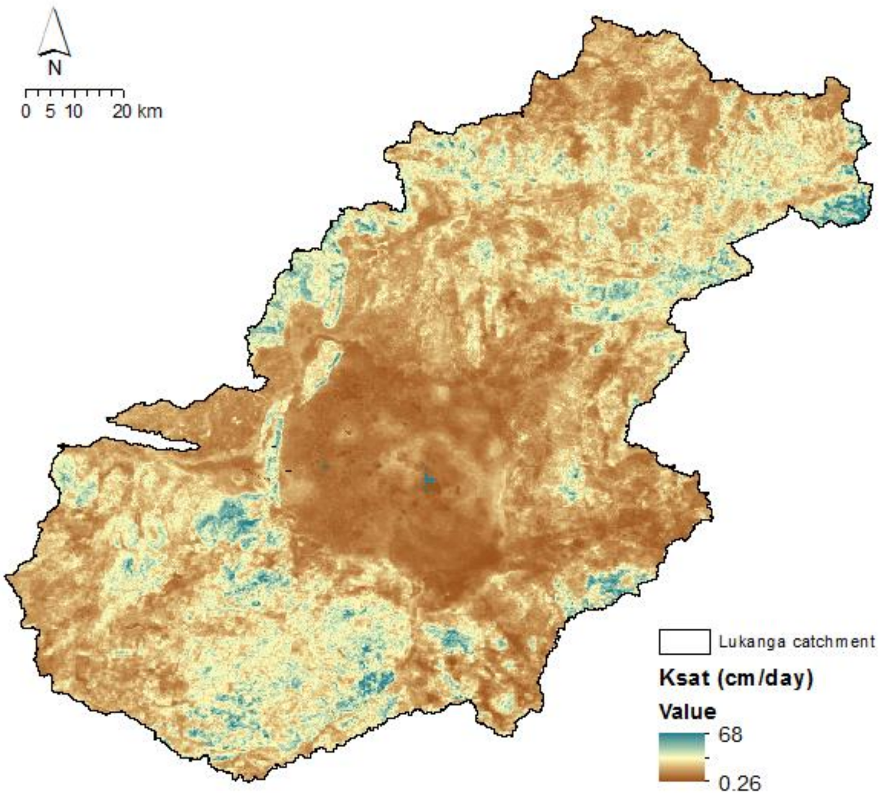


Figure 15. High-resolution saturated hydraulic conductivity based on HiHydroSoil dataset

3.2.3 Elevation, watershed delineation and calculation units

The Lukanga watershed is a relatively flat area, with elevation levels varying between 1100 and 1400 m above sea level. Elevation data was obtained from the global Shuttle Radar Topography Mission (SRTM) 90m DEM. The watershed was delineated by SWAT and partitioned into a total of 74 sub-basins, with a restriction of a minimum area of 100 km^2 per sub-basin (Figure 16). Within each sub-basin, different Hydrological Response Units (HRUs) were defined based on land use class and fire return interval, as these variables (i) are expected to substantially influence water and sediment fluxes and (ii) are the main focus of the required scenario analyses. A total of 845 HRUs were identified in the Lukanga watershed, with an average surface area of 1660 ha (Figure 17). Because of the relatively small elevation differences, it was decided not use slope as a criterion in the HRU delineation.

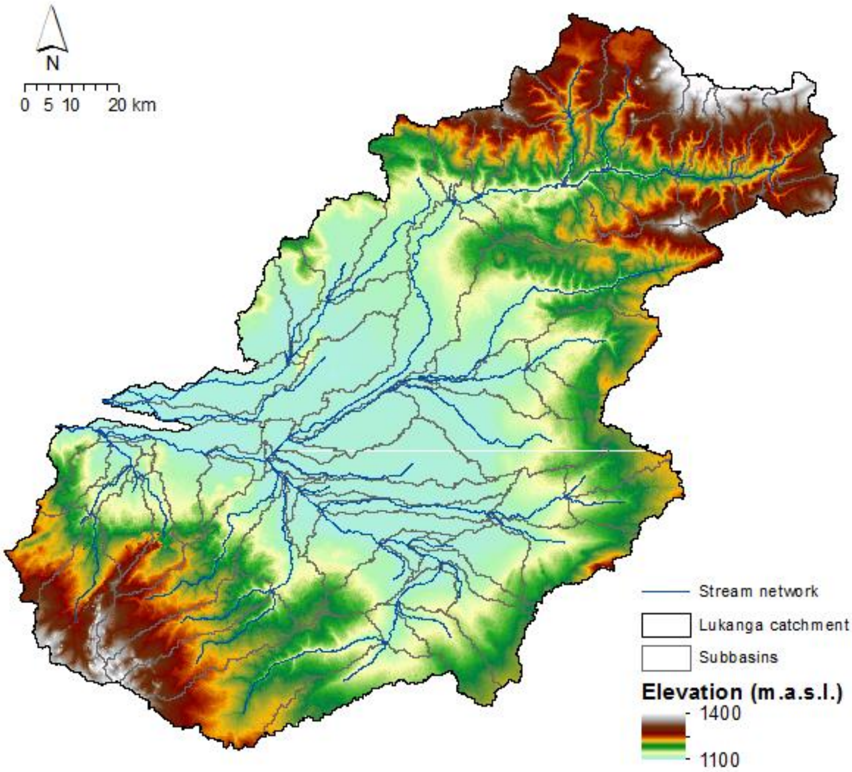


Figure 16. Digital elevation map with sub-basin delineation.

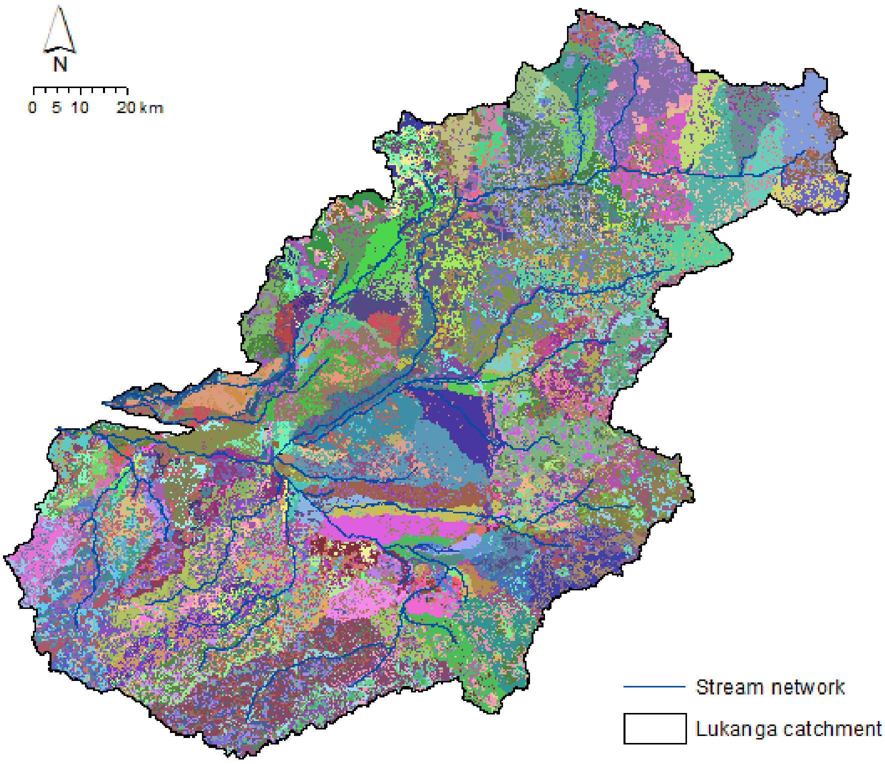


Figure 17. SWAT Hydrological Response Units in the Lukanga catchment.

3.2.4 Weather input data

Daily temperature and rainfall data were collected from eight weather stations in the Kafue River Basin. Unfortunately, meteorological records are available from inside the Lukanga catchment. Therefore, daily temperature for each subbasin in SWAT was obtained from the nearest weather station. Figure 18 shows the location of the stations.

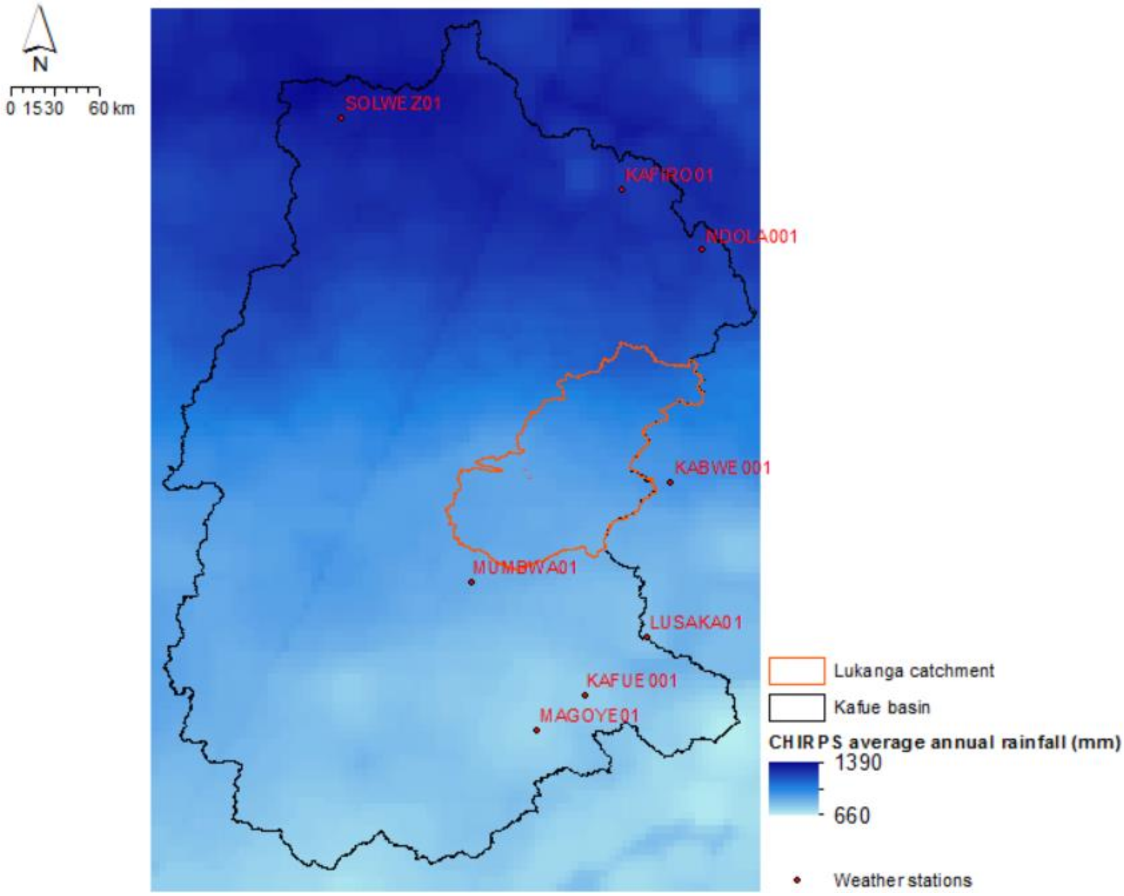


Figure 18. Mean annual CHIRPS rainfall in the Kafue Basin, with weather station locations

Climate in the region consists of very pronounced dry and wet seasons. Figure 19 shows the average monthly rainfall (2000 – 2013) for each of the weather stations. It is clear that hardly any precipitation occurs between May and September, while rainfall peaks are reached in the months December and January. Average annual rainfall for each of the stations is presented in Table 5.

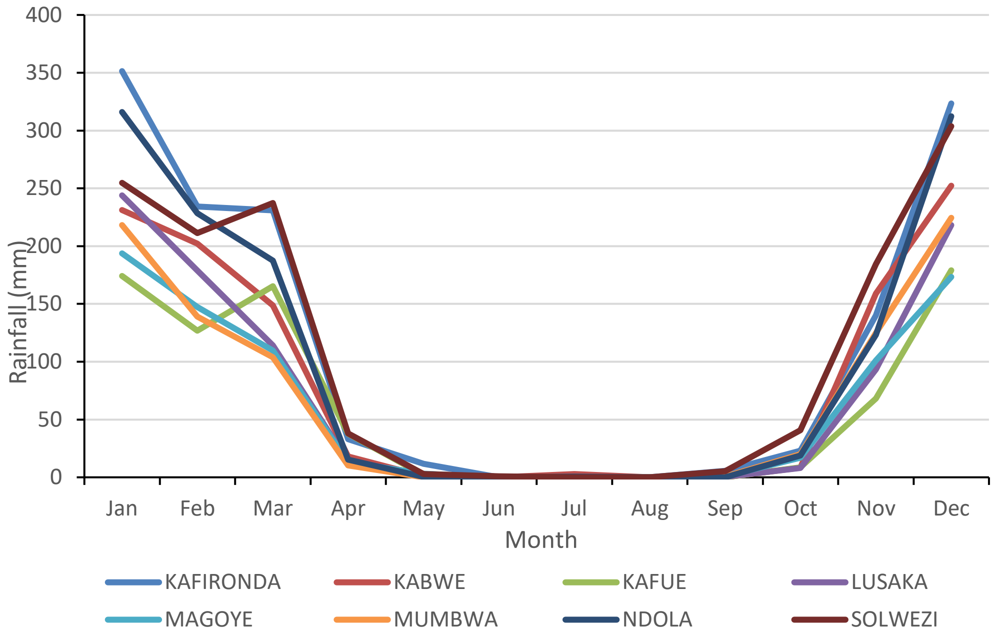


Figure 19. Monthly average rainfall measured at stations (2000-2013)

Table 5. Average annual rainfall values at each rainfall station (2000 – 2013)

Station	Annual rainfall (mm)
Kabwe	1024
Kafironda	1354
Kafue	762
Lusaka	874
Magoye	759
Mumbwa	842
Ndola	1203
Solwezi	1279

For obtaining spatially distributed rainfall data for the Lukanga watershed, the satellite-derived Climate Hazards Group InfraRed Precipitation with Station dataset (CHIRPS) v2.0 dataset was downloaded (Figure 18). This contains daily rainfall at a spatial resolution of 5 km for the entire globe. Its consistency with station measurements was verified. Figure 20 presents a comparison between CHIRPS precipitation and rainfall recorded at Kabwe, the station nearest to the Lukanga watershed. As the performance of CHIRPS is satisfactory, it was used to force the SWAT model by introducing the center of each 5 x 5 km pixel as a “station”. Based on proximity to these CHIRPS-derived stations, rainfall was assigned on a daily basis to each subbasin of the SWAT model.

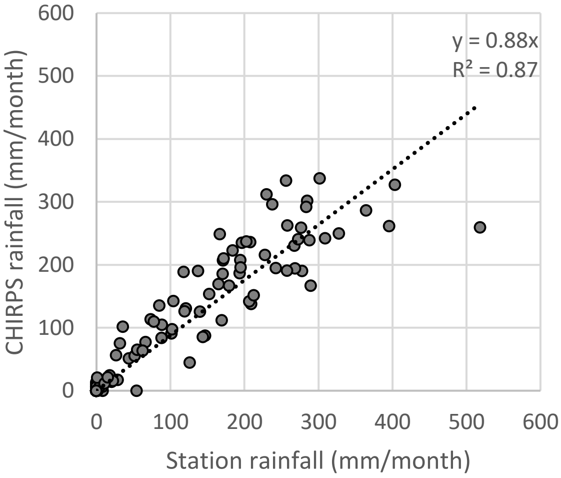
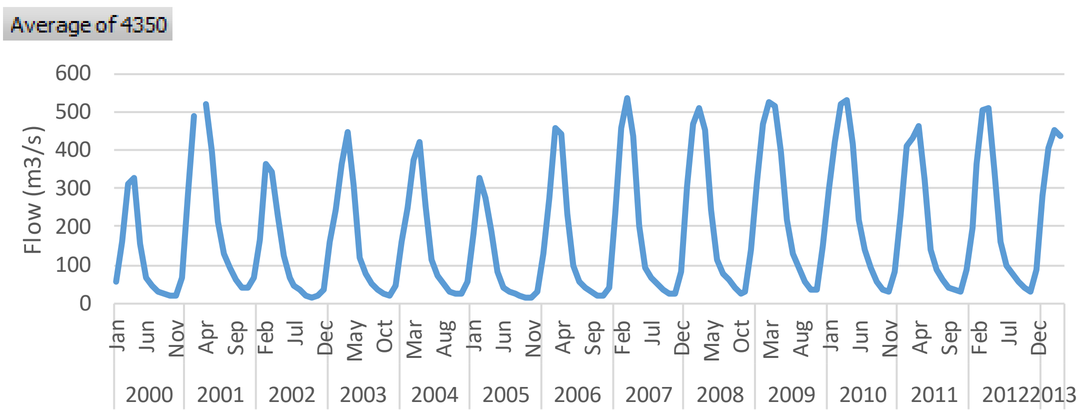


Figure 20. Comparison between station records and CHIRPS pixel values for Kabwe station

3.2.5 Streamflow and water levels

The absence of flow gauges within the Lukanga watershed means that it is not possible to calibrate or validate the SWAT model based on streamflow observations. Instead, calibration is carried out with remote sensing-based evapotranspiration (more details see next section). Of several stations of the Kafue river, data are available over the last decades. The relevant ones for this study are the stations that are closest (upstream and downstream) to the Lukanga watershed in the Kafue river. These ones were used in the water balance analysis (Figure 22):

- Kafue at Chilenga (Code: 4350), about 50 km upstream of the outlet of the Lukanga swamp/watershed
- 4450 - Lubungu station, located approximately 100 km downstream of the outlet of the Lukanga swamp/watershed. Daily observations are available from 1959 until 2013, with several data gaps.



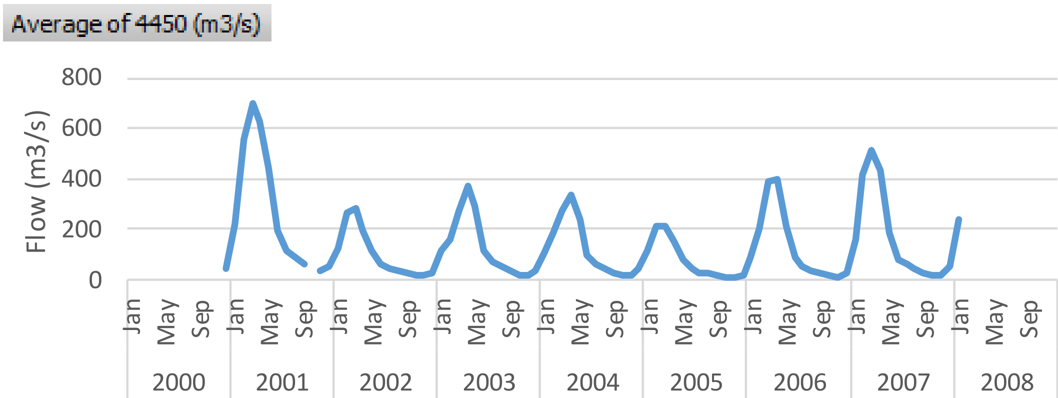


Figure 21. Average monthly streamflow at Chilenga (upper panel) and Lubungu station (bottom panel) from 2000 onwards

Besides, also historic data were available on the water levels in the swamp (see Figure 22). These data were not used directly in this study as they cover a different period (before 1987), but served to check whether the trends during the study period (2000-2015) were similar as during previous decades. The available stations are:

- Mean Corrected Surface Water Level (m) at Kafue-Lukanga confluence. Period: 1962-1971 (Code 4431)
- Mean Observed Surface Water Level (m) at Twenty Village (Lukanga Swamps), from 1962-1988 (with data gaps) (Code 4400)
- Mean Observed Surface Water Level (m) at Chilwa Island, from 1959-1986 (Code 4390)

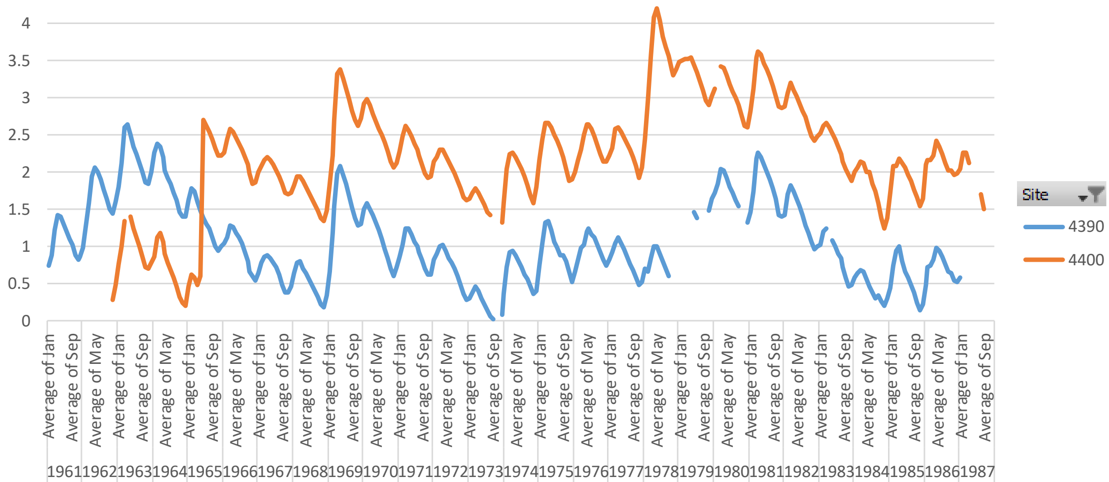


Figure 22. Surface water level at Chilwa Island and at Twenty Village in the Lukanga Swamp, from 1961-1987.

3.2.6 *Actual evapotranspiration*

Satellite-derived actual evapotranpiration products (ET_{act}) provide an innovative way of calibrating and validating hydrological models. Especially in poorly gauged catchments such as the Lukanga watershed, ET_{act} from remote sensing offers an ideal opportunity for assessment of the water balance without ground measurements.

The MODIS Global Terrestrial Evapotranspiration Product (MOD16) is a freely available ET_{act} product at a 1 km^2 spatial resolution. Currently it is the only global product that has been tested and reviewed in a substantial number of scientific articles (Simons et al., 2016). MOD16 follows the Penman–Monteith logic and relies on visible and near-infrared data to account for Leaf Area Index (LAI) variability.

In the absence of streamflow data within the Lukanga watershed, the monthly MOD16 product was downloaded with the purpose of calibrating the SWAT model. Temporal patterns were used to tune the SWAT parameters related to the vegetation growing season, and the average annual total was used for adjusting the depth of the soil profile in the model.

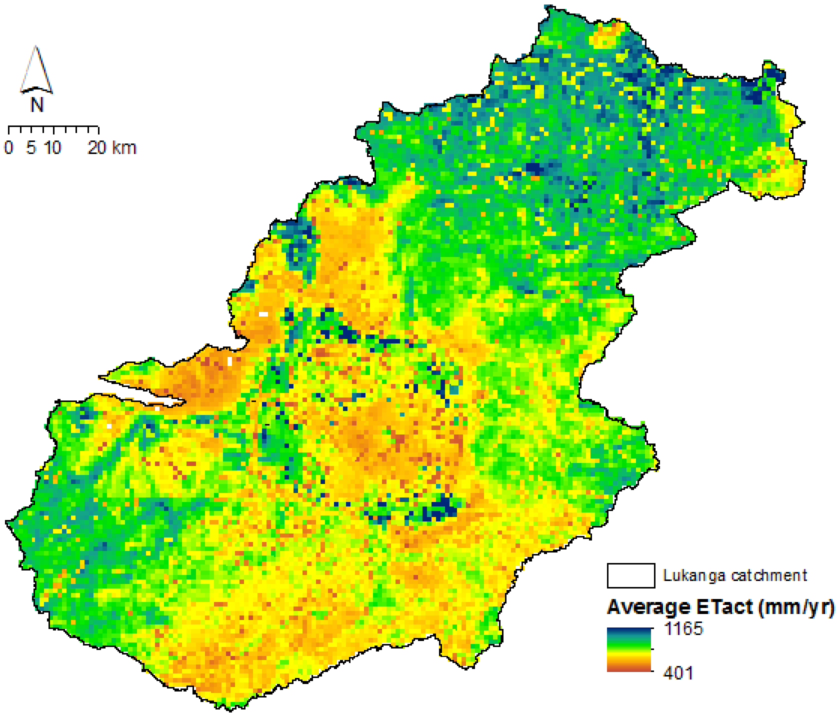


Figure 23. Annual average MOD16 ETact in the Lukanga watershed (2000 – 2014).

3.2.7 Water use and demands

The Lukanga watershed does not have any significant water demands currently for urban water supply, industry or irrigation. There are a few relevant issues however to be mentioned:

- Groundwater pumping by communities around the lake might go up in the near future, used mainly for irrigation. Roads to these communities are being improved, which makes access to markets easier
- Just north of the Lukanga watershed there are a few large irrigation schemes using water from the karstic aquifer (it is not known to which extent this is renewable water or not). The irrigated area is between 20.000 and 30.000 ha (source: Google Earth). Sugarcane is a key crop here, with high irrigation requirements (>500 mm). The withdrawals are probably from an aquifer that is partly within the Lukanga watershed (northern part). This means: (1) withdrawals might affect baseflows in the Lukanga watershed – this needs to be verified in a hydrogeological study, and (2) within the watershed there is also potential for using this aquifer for irrigation.
- The same is for the mines at Kabwe: depending on the hydraulic gradient of the aquifers on the eastern part of the Lukanga watershed, the withdrawals by the Kabwe mines might affect baseflows, or return flows and runoff might affect the Lukanga

watershed through groundwater flows. This needs to be verified in a hydrogeological study.

4.1 Remote sensing-based analysis of swamp and floodplain

4.1.1 Dynamics of open water and vegetation in the swamp

The total area with open water versus the area with vegetation (including algae, etc) was estimated using the approach described in the Methods section. The open water area estimated in the Lukanga swamp during the 2001-2015 period was relatively low compared against the total area (1867 km²), ranging between 120 to 540 km² (29% of the swamp, reached in January-2004) (Figure 24).

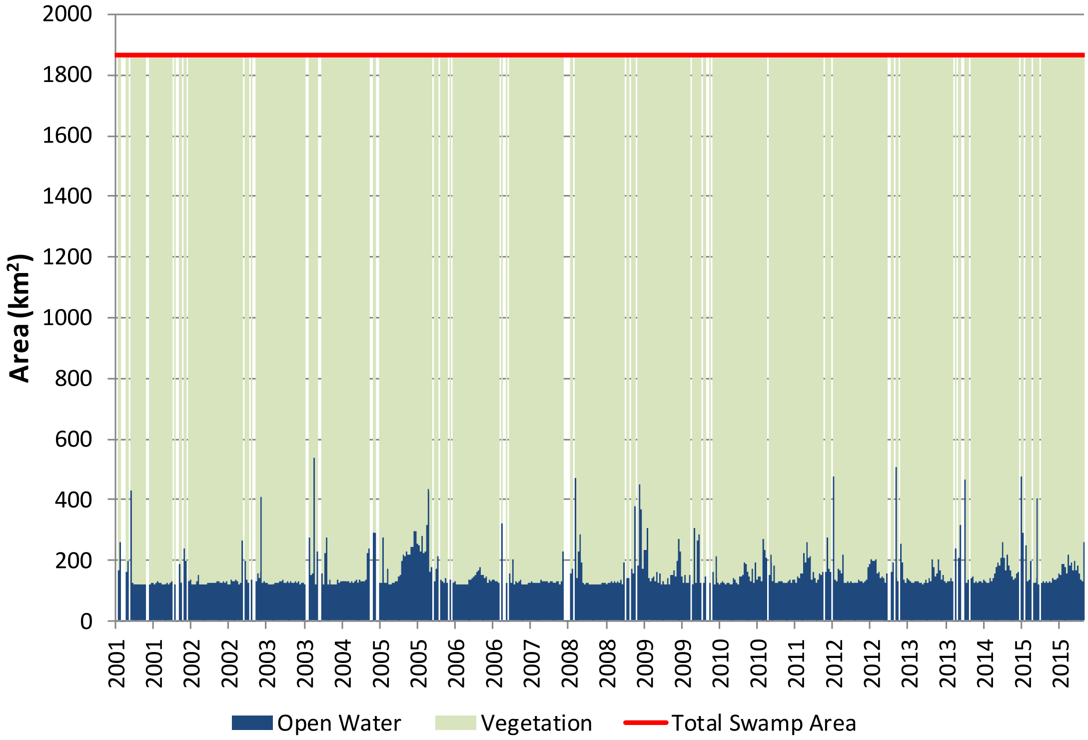


Figure 24. Top: Total open-water acreage (km²) within the Lukanga swamp estimated from MODIS-based NDWI values.

Figure 25 shows the monthly values for open water surface. As can be seen, from December to March, the surface covered by vegetation is lowest. The period with the highest vegetation cover is between April and November. Part of this vegetation is likely related to algae growth. Exotic algae species have been reported, that clog the canals used by fishermen and hinder their operations.

The analysis does not show an increasing or decreasing trend in vegetation vs open water surface, based on data of 15-year period. However, it does show that there is quite some variability among years. It seems that vegetation cover is stable and relatively high, when storage levels are more or less stable. At the start of a wet period, the system needs time to respond and vegetation cover is relatively low. More in-depth analysis could reveal what are the drivers behind the observed seasonality and inter-annual variability, but this is beyond the scope of this analysis.

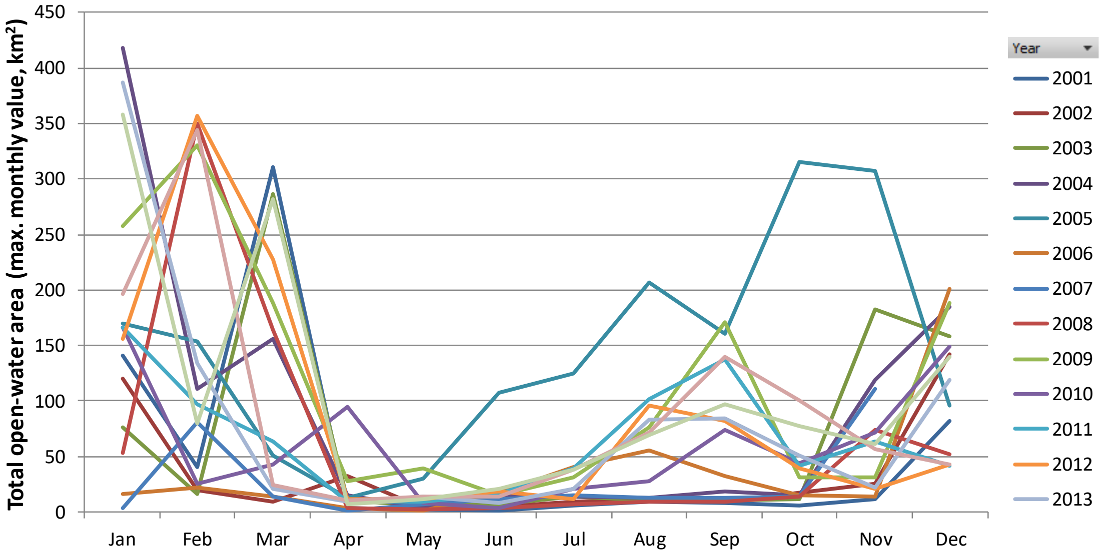


Figure 25. Seasonal and interannual variation of the total open-water acreage in the Lukanga swamp.

4.1.2 Water levels in the swamp

The water level variability of the swamps was analyzed using the data available. The historic data available on water levels (see Figure 22), show a seasonal pattern superimposed on trends of around 5 years – decreasing or increasing. As can be seen in Figure 26, the values obtained from the remote sensing-based data confirm this behavior.

For the period with available data, three periods with interannual trends in water levels can be distinguished (Figure 26):

- September-2002 to December-2006 was a period with an overall decrease of water levels. For the swamp this corresponds to a decrease in volume of approx. 4,000 MCM
- In 2007 water levels started to increase. The interannual positive trend was maintained up to October-2010. This increase corresponds to an additional volume of about 7,000 MCM. In this period, open water surface is also relatively high (Figure 24) – possibly because the vegetation needs some time to adapt to these high water levels.
- The third period with available data ranged from March-2013 to November-2015. As in the first period, this was characterized by a declining interannual trend.

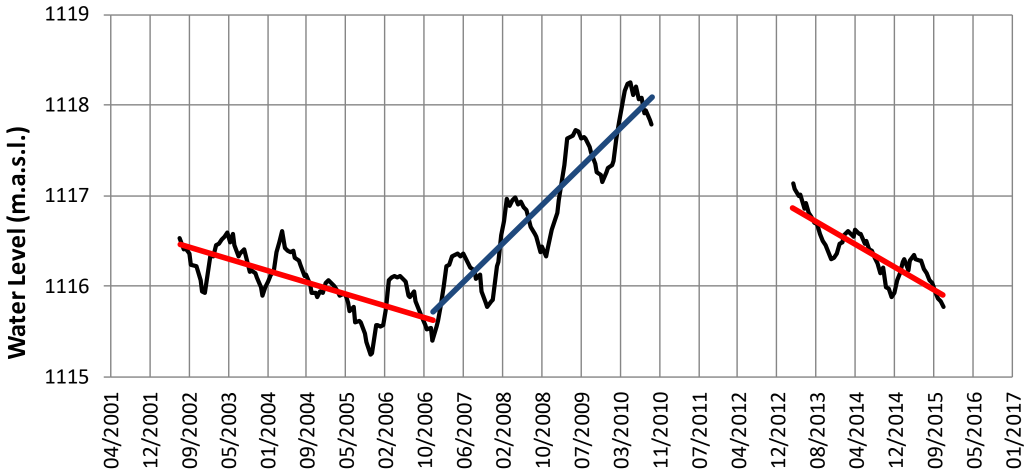


Figure 26. Water level in the Lukanga swamp.

Monthly trajectories of the water stored in the Lukanga Swamps are shown in Figure 27. In general water stored in the swamps is highest between March and July. Figure 28 shows the monthly pattern in water level, including standard deviations.

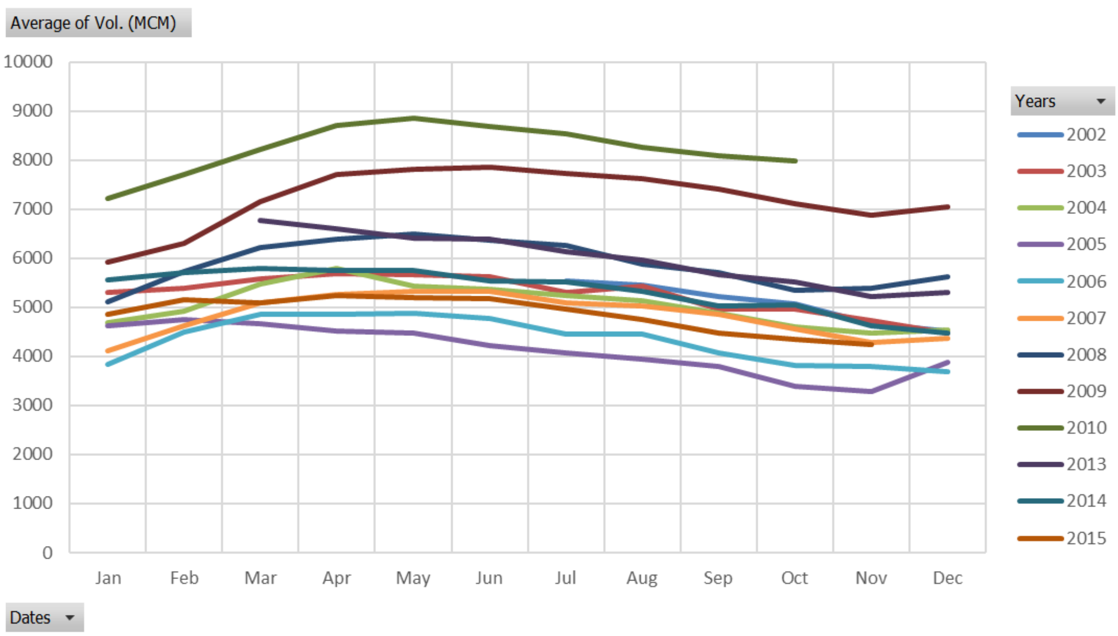


Figure 27. Average monthly values of water storage reported for the Lukanga swamp. Source: DAHITI database.

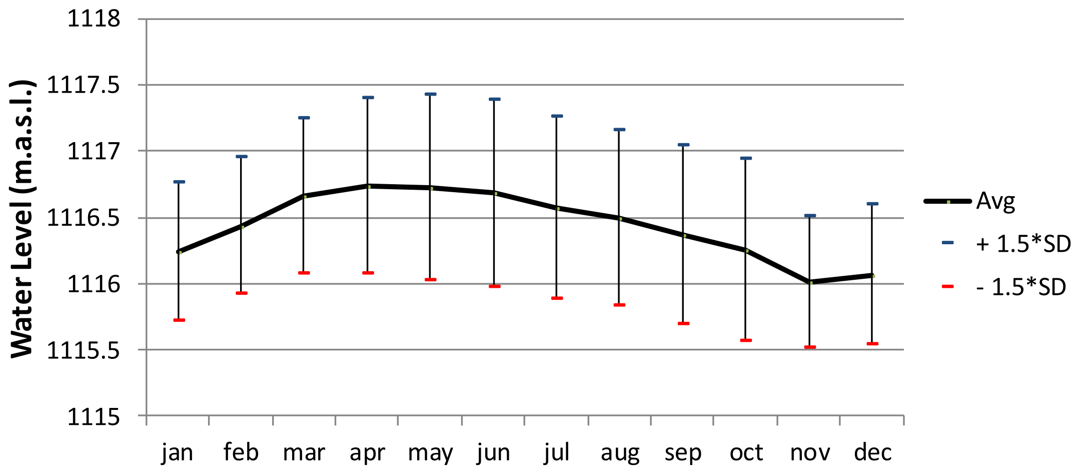


Figure 28. Average monthly variations in water level in the Lukanga swamp during the 2002-2010 and 2013-2015 periods. SD = Standard deviation.

4.1.3 Flood events in the Kafue floodplain

The water-index NDWI based on Landsat imagery was extracted for the Kafue floodplain located west of the Lukanga swamps and connecting to the swamps during high-flow periods. For this analysis, it was assumed that Landsat-NDWI values higher than 0.30 threshold value correspond to a flood event (Figure 29). Visual inspection of the Landsat imagery confirmed that with this threshold value, floods affecting a significant part of the floodplain were detected.

The analysis indicates that the floodplain was inundated on 62 images of the total of 274 available satellite images during the 2001-2015 period. Often, several images are linked with the same flood event. In Figure 29, the red intermittent line shows these events. In total, there were 13 flood events during the 15-year period.

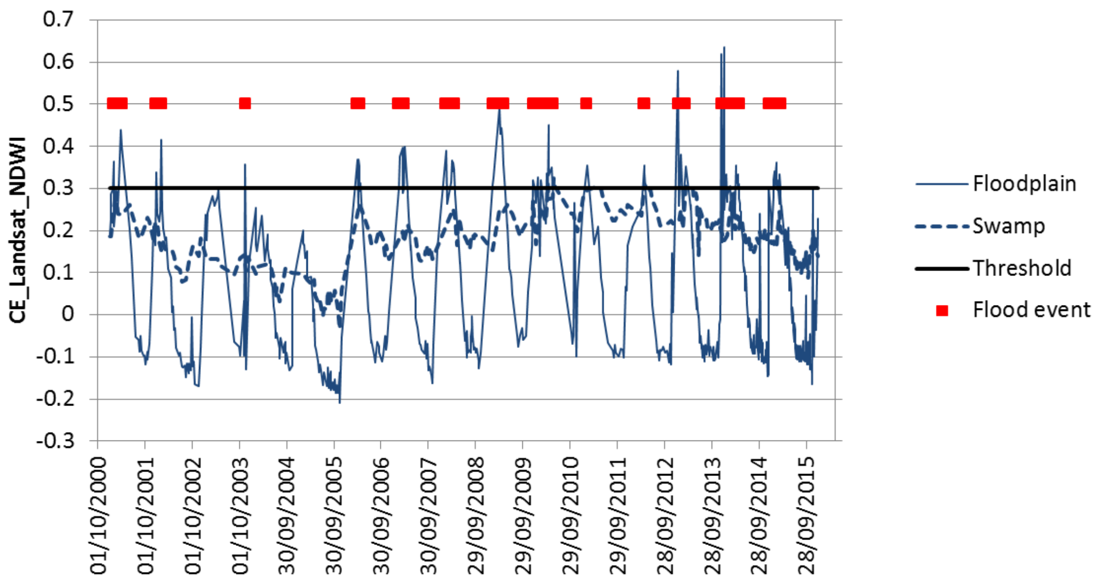


Figure 29. Spatially-averaged NDWI values in the swamp (dashed line) and the floodplain (solid line) areas. NDWI values were extracted from the Landsat imagery archive in the Climate-Engine App.

Figure 30 shows these events per month and year. Grey areas indicate areas with some flooding (close to threshold) and black areas are the events with severe flooding when overflow to the Lukanga Swamp is very likely.

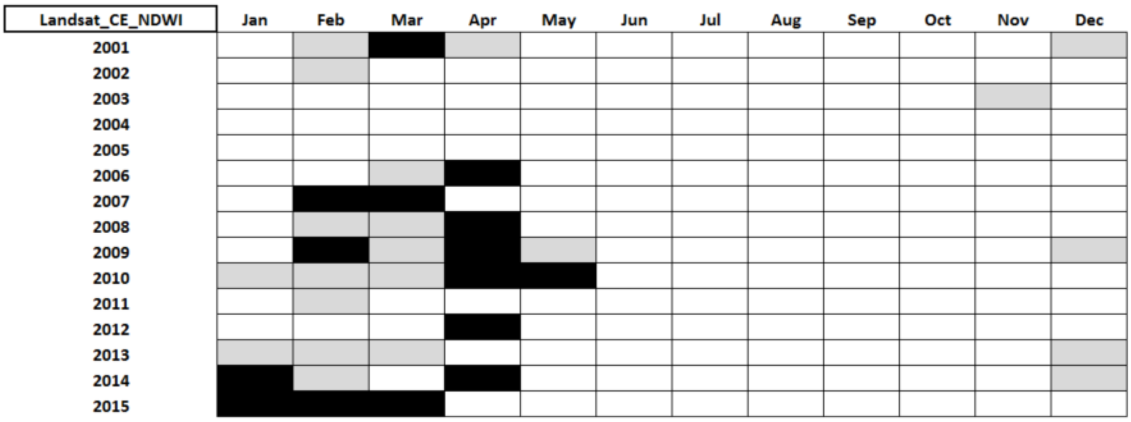


Figure 30. Flood event matrix in the Kafue floodplain computed from Landsat NDWI values. Months with severe flooding (in black) or some flooding (in gray)

Seasonal variation of NDWI values in the Kafue's floodplain sector shows that the period in which Kafue's river may contribute to the Lukanga swamp is concentrated during January-April (see also Figure 31). Most of the flood events occur in that period.

The above information is used in the water balance analysis, using the WEAP tool. During this period, the net inflow can be assessed into the swamp, as an indicator of its role as a sink for the Kafue basin.

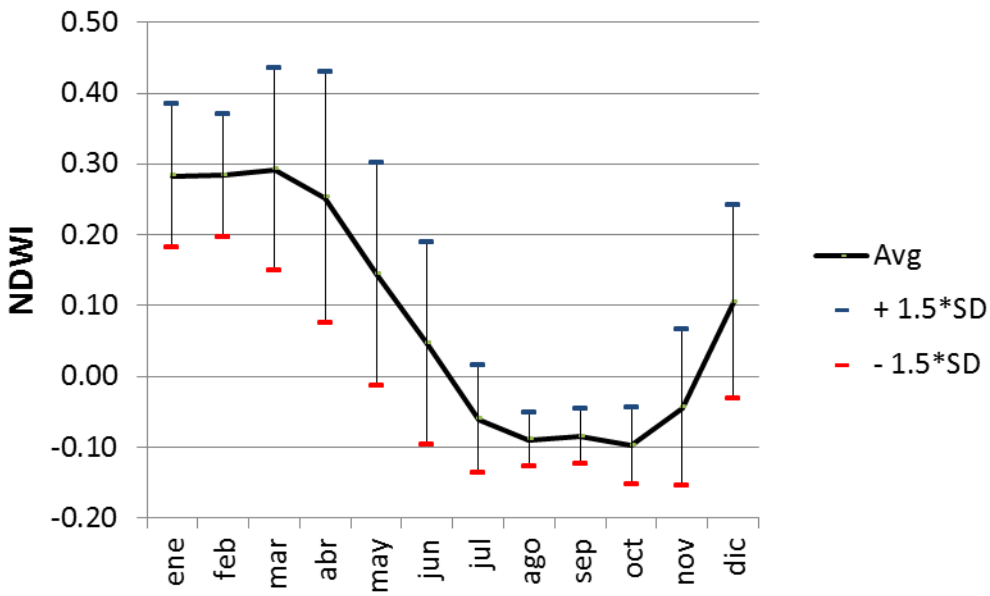


Figure 31. Average monthly variations in NDWI values in the Kafue's floodplain area. SD = Standard deviation.

4.2 Hydrological flows and erosion in the Lukanga watershed

4.2.1 Validation

The SWAT model was setup using the datasets described. The calibration of the hydrological model, in the absence of streamflow data, was done using satellite-derived ET_{act}, as described in Section 3.2.6, at the watershed scale. Total monthly evapotranspiration rates at the watershed scale were compared and used to manually adjust crop-growth-related model parameters of the SWAT model, in order to calibrate the model.

SWAT analysis shows an average annual ET_{act} of 631 mm, and the satellite observations (MOD16) are 634 mm. A satisfactory agreement in terms of monthly patterns was also achieved. Table 6 summarizes the model performance relative to the satellite-based MOD16 product. Figure 32 shows the monthly accumulated ET_{act} for MOD16 and the simulations by the SWAT model.

Table 6. Model performance relative to MOD16 monthly evapotranspiration, after manual calibration.

Indicator	***Value***
Pearson's *r* (-)	0.75
RMSE (mm)	26.0
Bias (-)	0.99

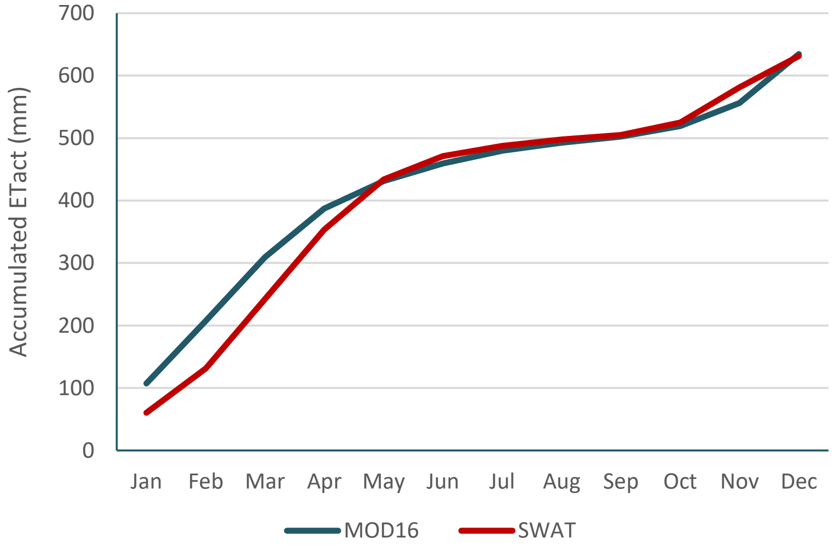


Figure 32. Comparison between MOD16 and SWAT accumulated average monthly ET_{act} in Lukanga watershed.

The calibrated SWAT model provides a wide range of hydrological output variables for all land use classes, soil types and different sub-basins of the watershed. The following section highlights the spatial outputs for the main variables of interest.

4.2.2 Spatial outputs

Average annual ET_{act} is shown in Figure 33. The spatial patterns show a reasonable correspondence with MOD16 satellite-derived ET_{act} (Figure 23). Relatively high values of over 600 mm occur in the north and southwest of the watershed, whereas less water is evaporated in the area to the south and southeast of the wetland. An exception to the general similarity between SWAT and MOD16 evapotranspiration is the region directly to the west and northwest of the swamp. This could be explained by the fact that this is the floodplain where the hydrology of Kafue River and Lukanga Swamps are highly intertwined, and processes occur that are not included in the Lukanga SWAT model. Also, at times of overflow from Kafue River, accuracy of the MOD16 algorithm relies on its capacity to simulate open water evaporation. Given the fact that the MOD16 product gives nodata values for open water (see http://www.ntsg.umt.edu/project/mod16), on average an underestimation of ET_{act} on the floodplain would be expected, which seems to be the case in Figure 23.

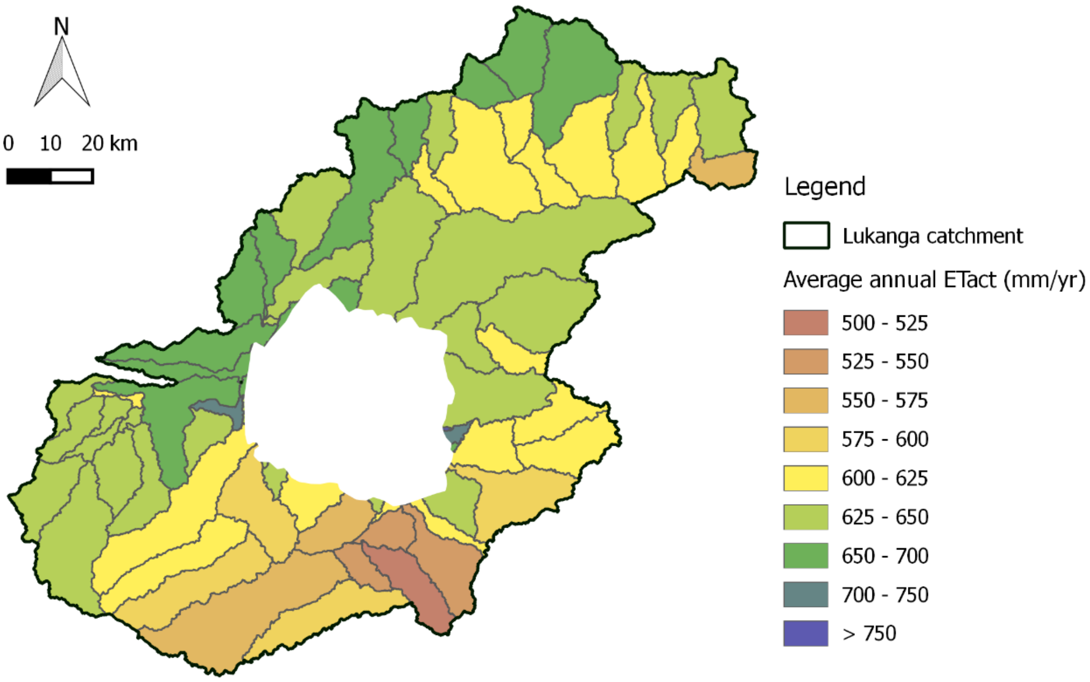


Figure 33. Average annual actual evapotranspiration in Lukanga watershed (2000 – 2015).

Figure 34 shows the spatial distribution of total water yield (water flowing into open water bodies) in the Lukanga catchment, which variations being especially a function of differences in land use, slope and soil. As can be seen, especially the far north of the Lukanga watershed is a major source of water, which is a consequence of relatively high precipitation levels.

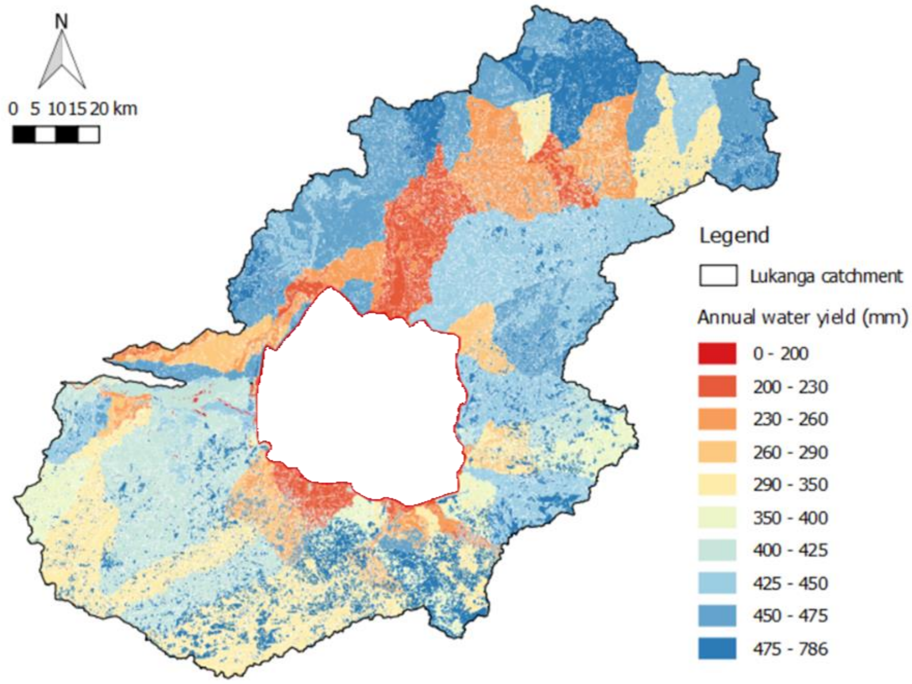


Figure 34. Average annual water yield in Lukanga watershed (2000 – 2015).

Total water yield can be partitioned in “fast runoff” (surface runoff) and “slow runoff” (baseflow). Figure 35 displays the generation of surface runoff across the watershed. As slopes in the watershed are not very steep, differences in surface runoff are mainly caused by land use. Relatively high values of around 300 mm/yr occur locally in the south and southeast, where agricultural lands are located.

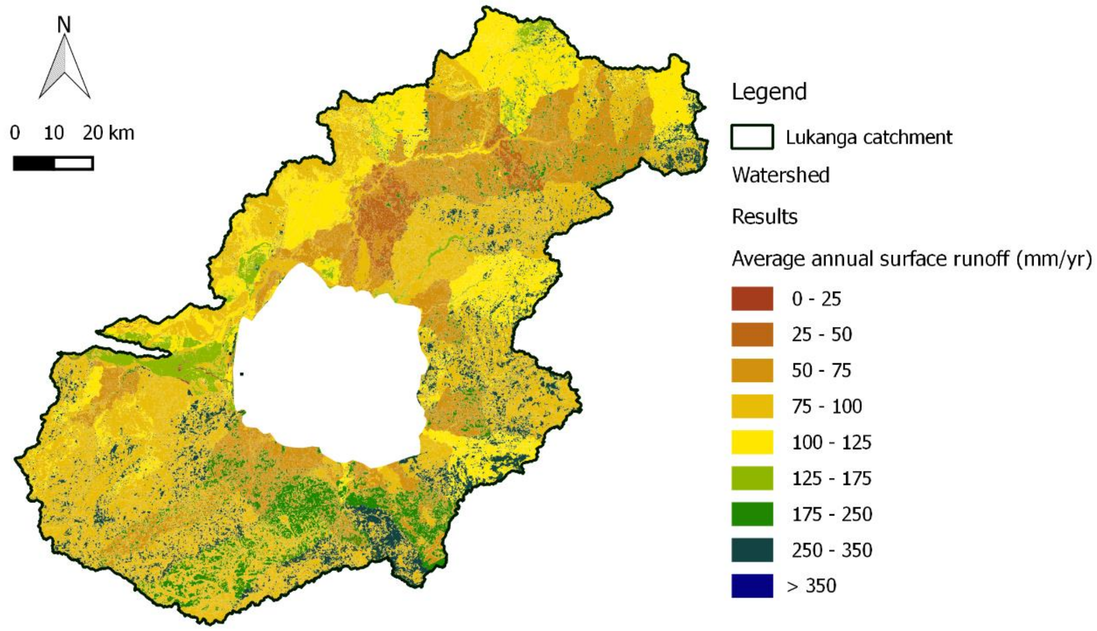


Figure 35. Average annual surface runoff in Lukanga watershed (2000 – 2015).

Figure 36 shows the portion of water yield that contributes to baseflow. High values occur in the north, where most of the precipitation percolates and contributes to the groundwater. It is clear that, although rainfall is relatively high here, baseflow exceeds direct runoff by far as a consequence of the flat topography.

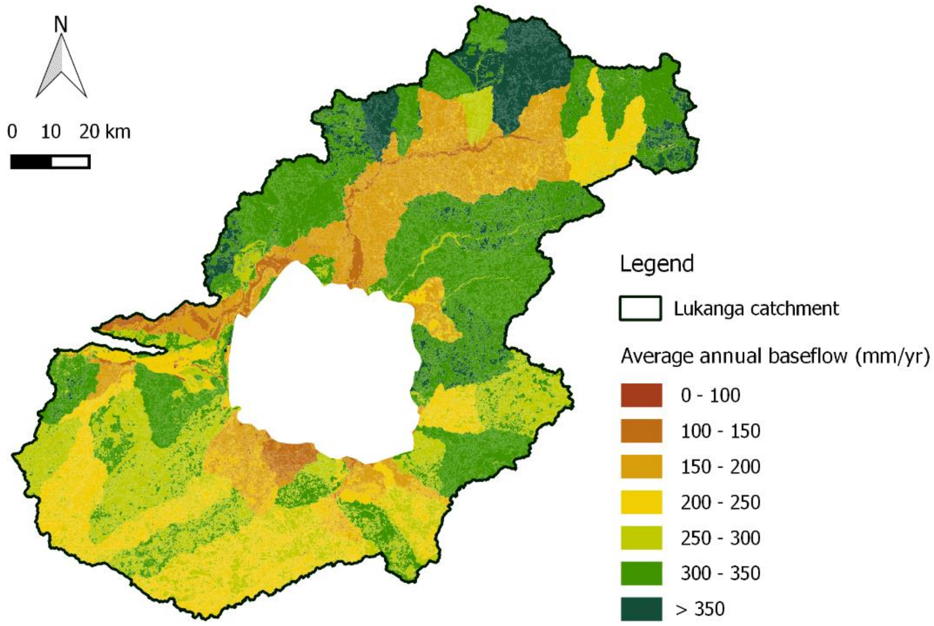


Figure 36. Average annual baseflow in Lukanga watershed (2000 – 2015).

4.2.3 Inflow to Lukanga Swamps

An important goal of the SWAT application is to determine the inflow to the Lukanga Swamps, and assess its annual and monthly fluctuation. To this end, SWAT outputs for all reaches leading into the swamp were evaluated (Figure 37). Results presented in this paragraph were obtained by summing the individual contributions of each of these branches, 11 in total. These reaches were also used to assess sediment fluxes (Par. 4.2.4).

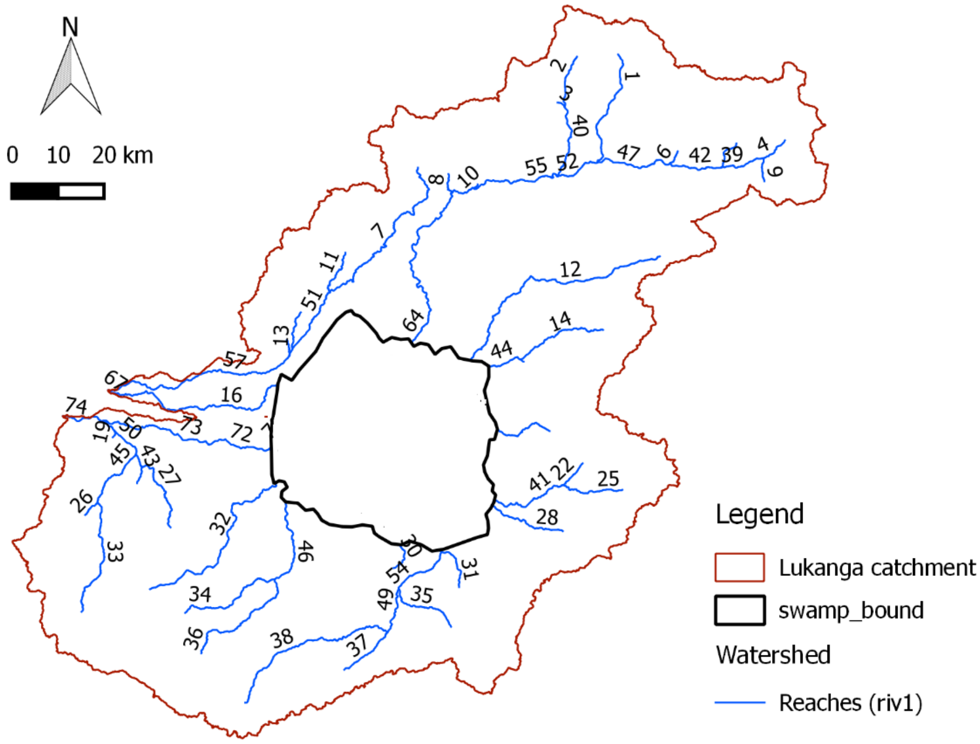


Figure 37. SWAT river network of the Lukanga watershed. Model outputs for all reaches leading into the swamp were used for assessing water and sediment fluxes into Lukanga Swamps. Due to the flat topography of the system on the flood plain from the Kafue, also reach 51 was considered as flowing into the swamp.

Figure 38 shows that the inflow into the swamp varies substantially between years. It is clear that the fluctuations are quite large, ranging from 1634 MCM (164 mm) in 2005 to 7250 MCM (729 mm) in 2001. This is caused by variations in precipitation and temperature. The average annual inflow is 4122 MCM (400 mm).

Limited data are available to verify these values. The computed inflow is consistently higher than the “back on the envelope” estimate carried out by McCartney (2007), assuming a runoff coefficient of 11%, which would correspond to a water yield of approx. 115 mm/year. However, this was a first-guess and given our model calculations are consistent with satellite-based ET, we attach more confidence to our estimates. In some years, in particular 2002 and 2005, our results do approach the estimated annual inflow of McCartney (2007).

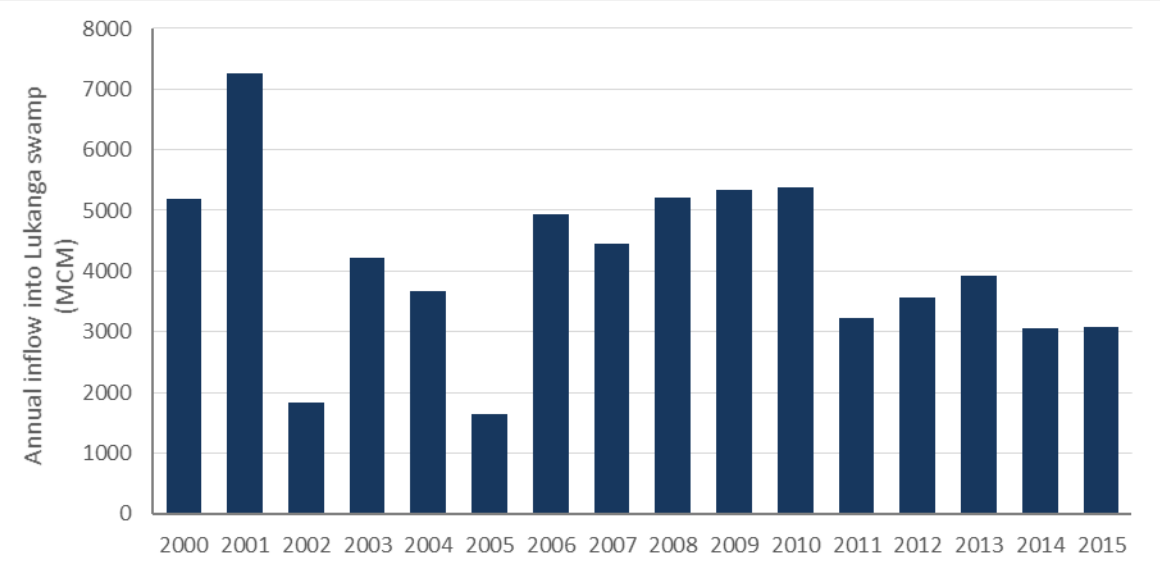


Figure 38. Annual inflow into Lukanga Swamps.

Monthly patterns of inflow clearly represent the regional dry and wet seasons (Figure 39). Peak values are observed in February to March, whereas values approach zero during the July – October period.

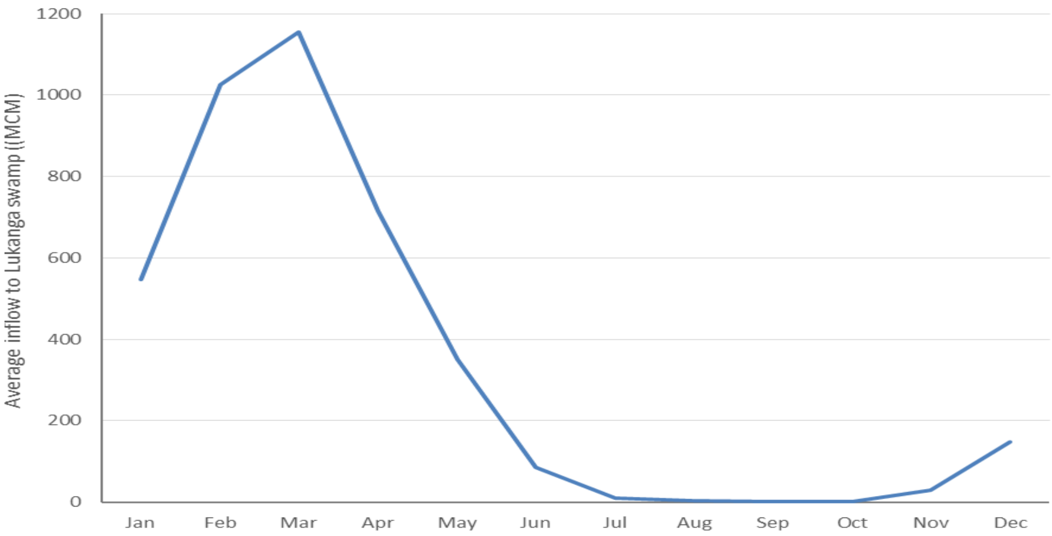


Figure 39. Average monthly inflow into the Lukanga swamps.

4.2.4 Erosion and impact on swamps

Figure 40 depicts the annual erosion rate in the Lukanga watershed, as computed by SWAT. The spatial distribution of erosion rates is more closely related to the DEM than to the burned frequency map, indicating that erosion is more sensitive to steep slopes than to the impact of burning.

However, as can be observed from Table 7, land covers with high burning frequency do show higher erosion rates than the same land use type with low frequency. Therefore, it is concluded that this very common practice in the watershed has an impact on erosion and sediment reaching the swamp. The temporal pattern of average monthly sediment loads is clearly impacted by that of streamflow, with values as high as 1.8 Mton of sediment in the month of March (Figure 41).

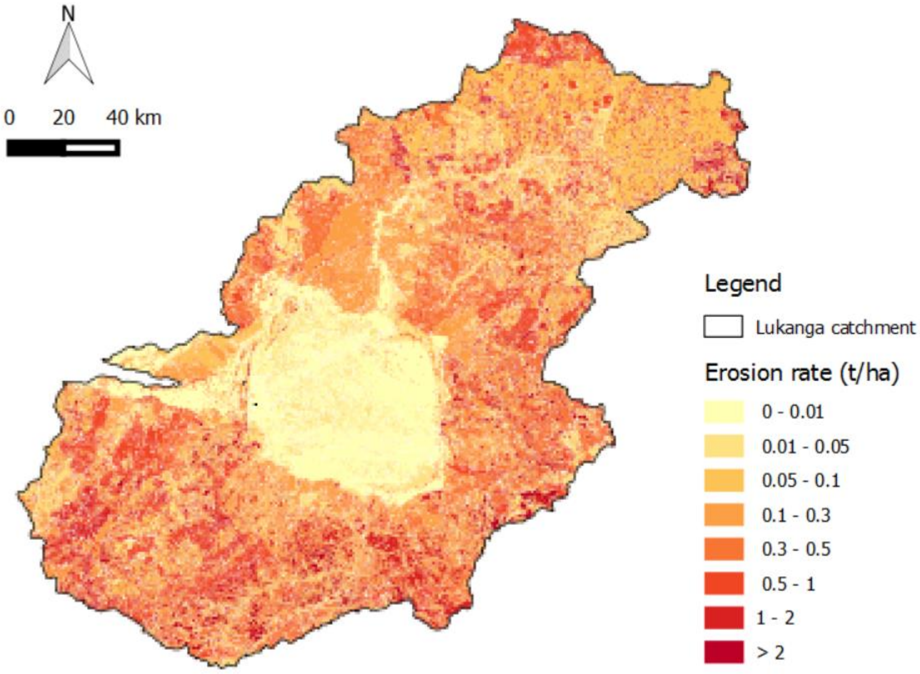


Figure 40. Annual erosion rate (t/ha) in Lukanga watershed.

Table 7. Mean annual values for water balance components and sediment yield per land use class

Land cover	Area	Evapo-transpi-ration	Surface runoff	Perco-lation to ground-water	Stream-flow	Sediment yield
	km2	*mm*	*mm*	*mm*	*mm*	*t/ha*
Cropland	2072	435	255	347	571	4.1
Forest high burning freq	572	656	80	313	360	0.7
Forest low burning freq	1351	655	80	315	361	0.3
Forest medium burning freq	1483	656	80	312	358	0.5
Forest no burning	2591	654	78	308	353	0.0
Grassland high burning freq	72	655	130	251	346	0.4
Grassland low burning freq	4	651	130	243	339	0.1
Grassland medium burning freq	17	653	130	244	339	0.3
Grassland no burning	2	650	129	244	338	0.0
Shrubland high burning freq	933	652	88	307	360	0.6
Shrubland low burning freq	822	649	86	302	354	0.1
Shrubland medium burning freq	1221	652	87	306	359	0.4
Shrubland no burning	914	649	86	302	354	0.3
Wetland	1851	660	130	244	340	0.0

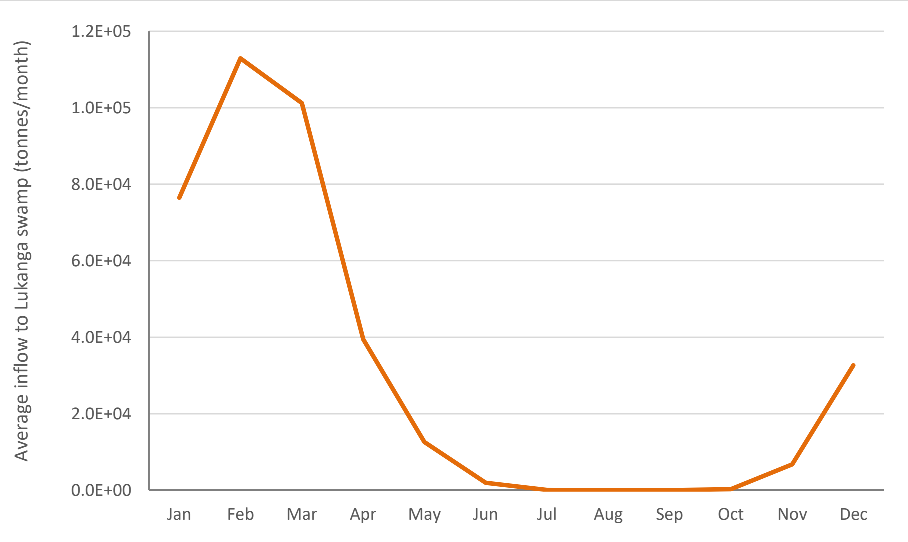


Figure 41. Average monthly sediment loads from Lukanga watershed.

Between 2000 and 2015, the total sediment load entering the swamp was 0.38 Megatonnes per year on average. Assuming a specific weight of the sediment particles of 1.237 tonnes / m^3, this corresponds with a volume of 0.31 MCM that is subtracted from the swamp storage capacity each year due to sedimentation. This is negligible compared to the volume of water generally stored in the swamp (4000 – 7000 MCM). Even after 100 years with this sedimentation rate, the swamp would lose less than 1% of its capacity.

4.3 Water balance of the Lukanga swamps

The previously presented water balance terms (water inflows to the swamp, precipitation on and evaporation from the swamp), and the remote sensing-based analysis on storage dynamics were analyzed to close the water balance. This was done by integrating these in the WEAP tool. Figure 42 shows the schematic setup of this analysis. Flows from the southern sub-basins and norther sub-basins were aggregated. The green triangle represents the swamp (simulated as a reservoir). The orange feature represents the overflow occurring during high flows in the Kafue river. The red dots are demand nodes used for the scenario analysis (see next section).

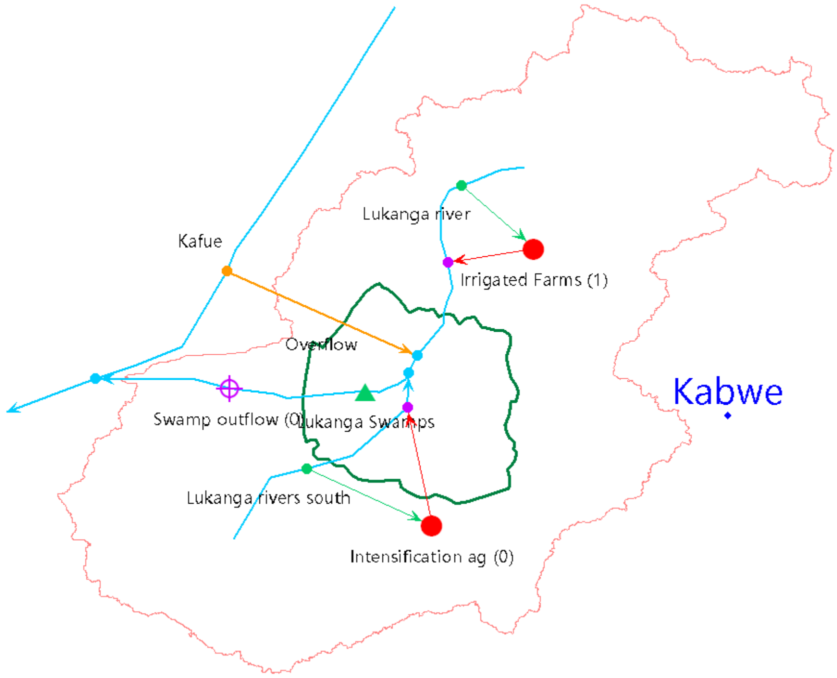


Figure 42. Schematic of the tool used for the water balance analysis (WEAP). The red dots are demand nodes used for the scenario analysis (next section).

The performance of the WEAP model was assessed by comparing modeled and observed lake levels as measured by satellites. The correlation between both series is relatively high, giving confidence in the model outcomes (Pearson correlation coefficient = 0.77). Most importantly is that the seasonal and interannual trends are well captured by the WEAP model (decreasing between 2002-2005, increasing 2006-2010, decreasing 2013-2015). There are differences in the absolute values and the amplitude of the seasonal patterns. These are most likely related to the depth-volume curve of the swamp and surrounding areas and could be subject of study for further work.

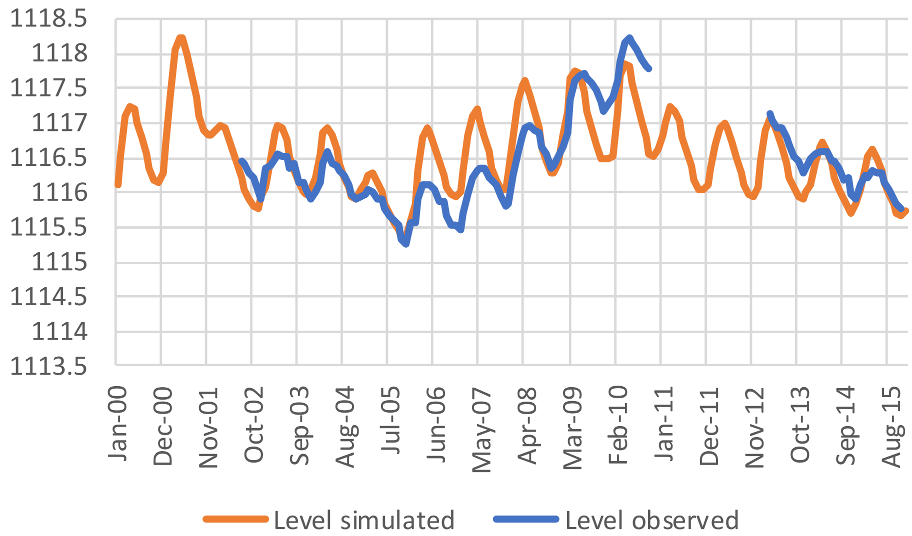


Figure 43. Simulated versus observed (remote sensing) water levels in the swamp

From WEAP, the full water balance of the swamp could be established, for the 15-years period, see Table 8, Figure 44 and Figure 45. Details on the modeling parameters and assumptions can be found in Annex A.

Table 8. The annual water balance for the swamp, based on the water balance equation used in this study (see section 2.1). All values in MCM per year.

Year	Inflow watershed Qin	Evapot. - Precipitation ET - P	Overflow Kafue Qov	Outflow to Kafue Qout	Storage diff. Swamp dS
2000	5124	345	0	-3545	-1233
2001	7149	310	205	-5317	-1726
2002	1796	1260	0	-3258	2722
2003	4166	794	0	-3106	-266
2004	3625	688	0	-2994	58
2005	1617	1625	0	-1601	1609
2006	4850	616	52	-2785	-1501
2007	4367	455	262	-3376	-799
2008	5118	690	210	-4267	-370
2009	5293	760	414	-4678	-268
2010	5282	551	446	-4797	-380
2011	3188	1021	28	-3691	1497
2012	3512	724	352	-3176	36
2013	3858	1039	50	-3196	326
2014	3018	1078	0	-2535	595
2015	3031	1118	0	-2306	393
Mean	4062	817	126	-3414	43

To understand better the swamp´s role as a regulating buffer – retaining water in dry periods and dry years – and providing water to the Kafue river, the following flows were included in one figure (Figure 44):

- Kafue flow at Chilenga (observed flows), 20 km upstream of Lukanga swamps
- Inflow into the swamp, from the Lukanga watershed
- Overflow from the Kafue river to the Lukanga swamps during flood periods
- Outflow from the Lukanga swamp to the Kafue river

Figure 44 shows the monthly balance for all years, and Figure 45 shows the annual totals, and the mean monthly values.

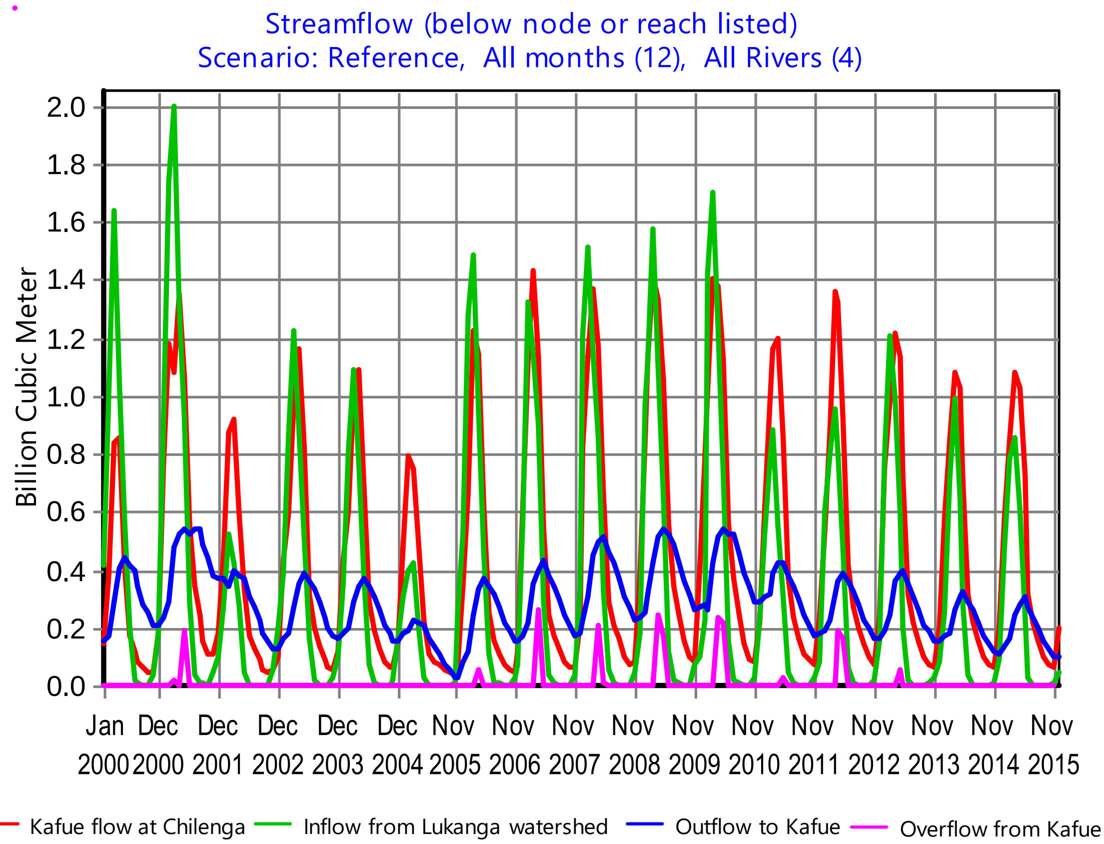


Figure 44. Monthly water balance (2000-2015) of the Lukanga swamp

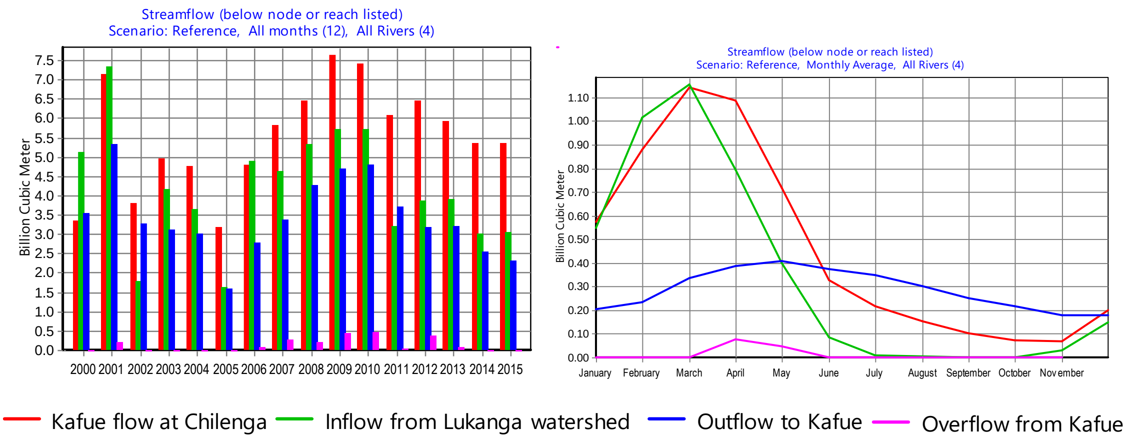


Figure 45. Annual and mean monthly water balance (2000-2015) of the Lukanga swamp

As Figure 45 clearly shows, the annual variability in the Kafue river is considerable: during some years Kafue river flows are around 7000 MCM, while in dry years it can be less than half (3000 MCM). For the Lukanga watershed, the variability is even higher: the highest volume during the period reached (2001) is around 7000 MCM, while in a dry year (2005) only around 1600 MCM is flowing into the swamps.

The volume of water that the Lukanga watershed provides to the swamp, is in the same order of magnitude as the water flowing in the section of the Kafue river, just before it receives inflow from the Lukanga watershed. In fact, in the wettest year in the study period (2001)shows that the Kafue annual river flow of about 7000 MCM, is the same as the Lukanga watershed provides. From this 7000 MCM entering the swamp, around 5000 MCM flows to the Kafue River. That means that just downstream of the swamp, that year approximately 40% of the Karfue flow originates from the swamp (5000/(5000+7000)=41%). In a dry year (2005) even about one third of the water flowing in the Kafue river downstream of the swamp, is coming from the swamp (1500/(1500+3000)=33%)

According to the analysis, overflow during high floods occurs in about half of the years, although in some years this overflow is quite limited. Maximum amounts are approximately 500 MCM (in 2010). This is about 7% of the flow in the Kafue river (Chilenga upstream). This suggests that during such a wet year, about 7% of the polluted load in the Kafue is potentially filtered and deposited in the swamp. In dry years, this effect is not occurring.

In the above figures, when comparing the monthly pattern of inflow (green lines) and outflow (blue lines), it becomes very evident how the swamp retains water received during the high-flow period and releases it slowly during the dry months. Clearly, the swamp acts as a natural reservoir: reducing within-year variability of inflows and providing a more consistent outflow to the Kafue river basin.

Another way of representing this buffering effect of the swamp is by plotting the monthly flows of Figure 44 in a flow exceedance plot (Figure 46). Here all flows are ranked from high to low, and assigned a frequency they are exceeded. As an example: about 5% of the time (x-axis), the amount of water flowing into the Lukanga swamps exceeds 1.3 billion m^3 (i.e. 1,300 MCM). But as the figure shows, this value is much lower for outflow from the swamp and exceeds about 0.5 billion m^3, during 5% of time. At the same time are flows below 0.2 billion m^3 more frequent for the swamp outflow, than for the swamp inflow. In summary, the swamp reduces high flows, and increases low flows.

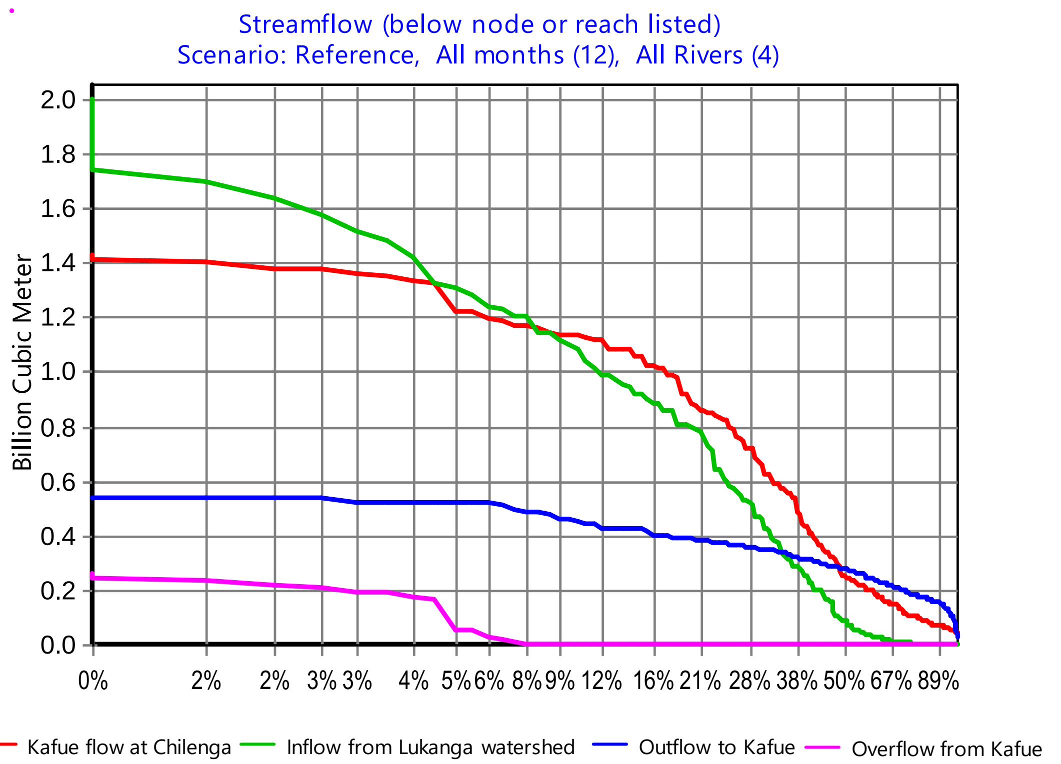


Figure 46. Flow exceedance plot based on monthly flows (2000-2015) of the Lukanga swamp

The water stored in the swamp over time is represented in Figure 47. As can be seen, the water stored ranges between about 3,000 MCM and 10,000 MCM This difference of 7,000 MCM is a considerable amount of water, comparable to the storage volume of the dams for hydropower in the Kafue River Basin.

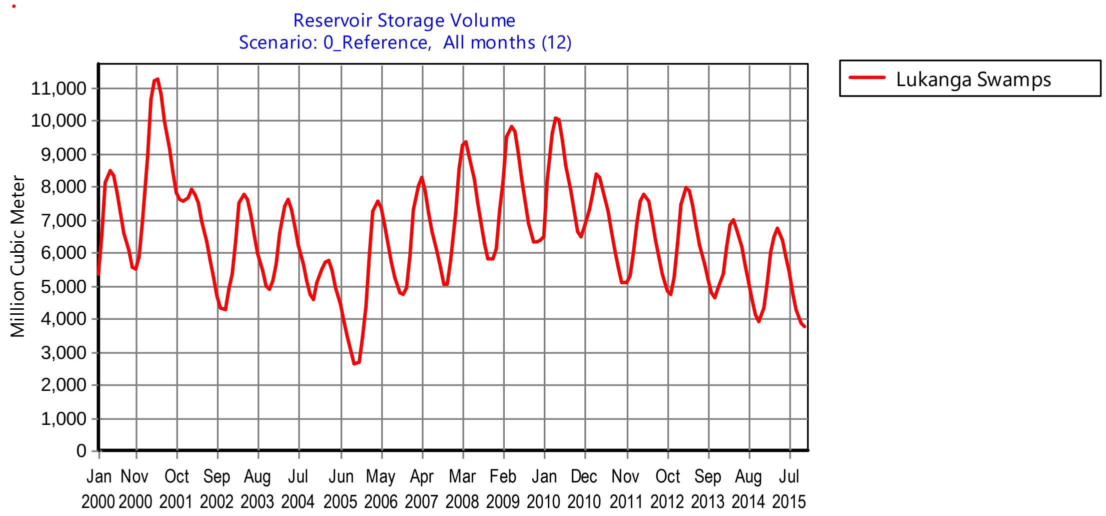


Figure 47. Water storage in the Lukanga Swamp from 2000-2015

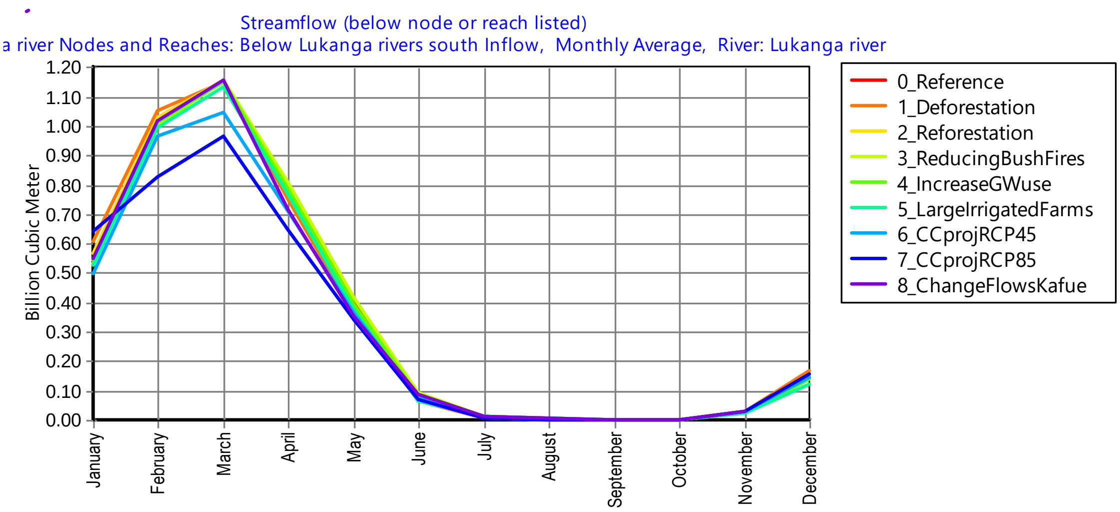
The measured flows at Chilenga upstream of the swamp, and the outflow from the swamp together sum up to a mean annual volume of around 9,000 MCM/year. For the period 2001 – 2007 there is also streamflow data of the Lubungu stream gauge, approximately 70 km downstream of the swamp. For this period, Chilenga + Lukanga = 7,700 MCM/year, while the volume gauged at Lubungu downstream is only about 4,500 MCM. In other words: about 40% of the water “disappears” from the water balance in this 70 km trajectory. The reason behind this is probably a combination of factors:

- Subsurface flows are known to be substantial in this part of the Kafue river. In fact, most likely a considerable part of the outflow from the Lukanga swamp enters the Kafue river through subsurface flow. At the Lubungu gauge station only surface water flow is measured.
- The floodplains between the swamp and Lubungu gauge possibly consume part of the water. Also there may be withdrawals from the river in this transect (not studied here)
- Data quality may also be an issue – both for the Chilenga as well as the Lubungu gauge. This type of rivers is difficult to gauge especially during high flows.

4.4 Impact of future scenarios

4.4.1 Overall outcomes

The scenarios defined previously (paragraph 2.5) were analyzed using the modeling framework (SWAT and WEAP). The next sections discuss the findings for the scenarios in detail. This section provides an overview of the impacts of the scenarios in terms of the water balance and flows. These are described in more detail in the sections hereafter.



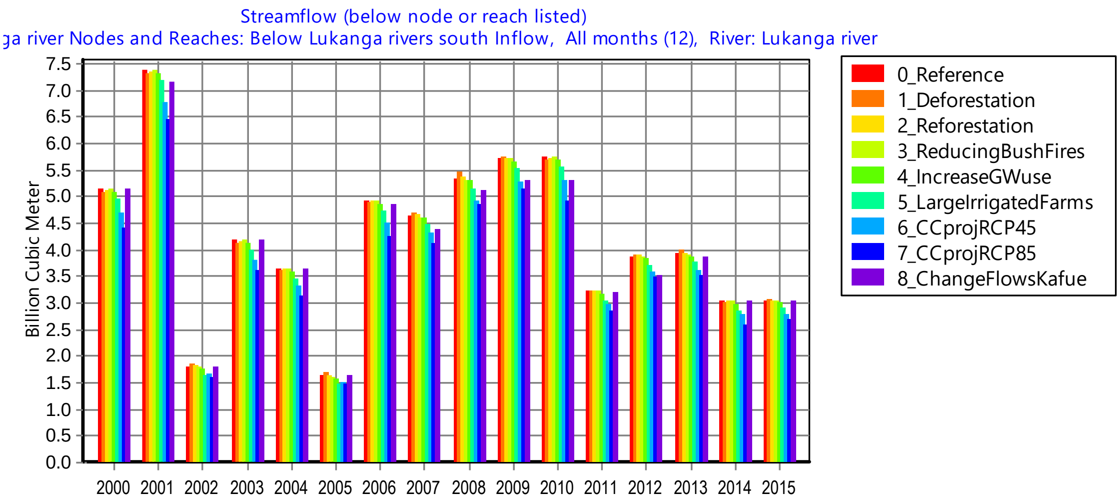
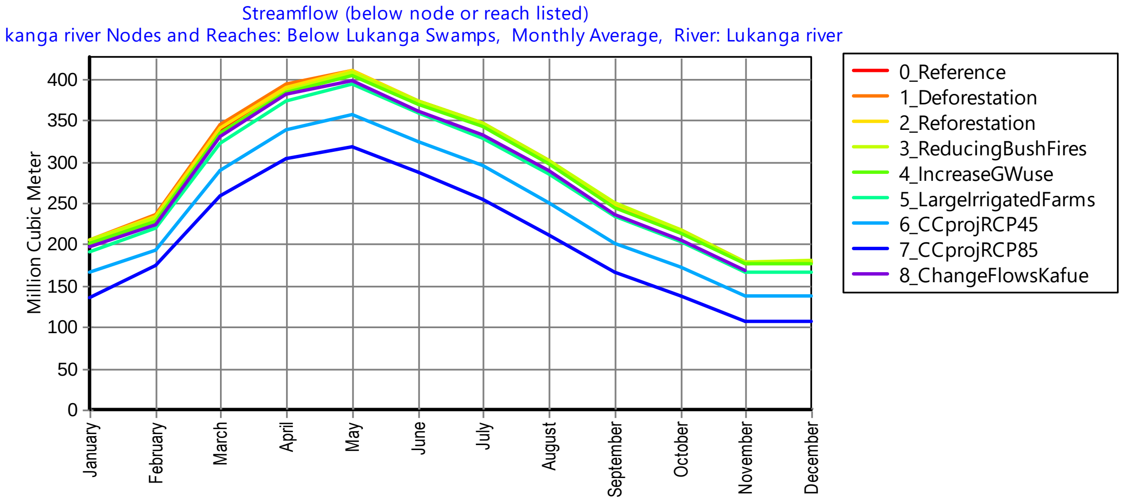


Figure 48. Mean monthly (top) and annual (bottom) inflow into the swamp for the different scenarios.

Table 9 presents the relative changes for the different scenarios, for flows in the wet period (Feb-Apr), and flows just after the wet season when baseflow is dominant (May-Jul), and for mean flows.

Table 9. Overview of scenario results for: inflow into Lukunga Swamps during the rainy season (Feb-Apr), inflow during start of the dry season (May-Jul), and annual flows. Values in MCM per year and per month

Scenario	Total inflow May-July		Total inflow Feb-Apr		Mean annual inflow	
0_Reference	494	0%	2964	0%	4188	0%
1_Deforestation	437	-12%	2953	0%	4199	0%
2_Reforestation	475	-4%	2967	0%	4196	0%
3_ReducingBushFi	518	5%	2959	0%	4184	0%
4_IncreaseGWuse	483	-2%	2946	-1%	4142	-1%
5_LargeIrrigatedFar	451	-9%	2892	-2%	4018	-4%
6_CCprojRCP45	451	-9%	2724	-8%	3853	-8%
7_CCprojRCP85	418	-15%	2438	-18%	3686	-12%
8_ChangeFlowsKaf	446	-10%	2886	-3%	4062	-3%



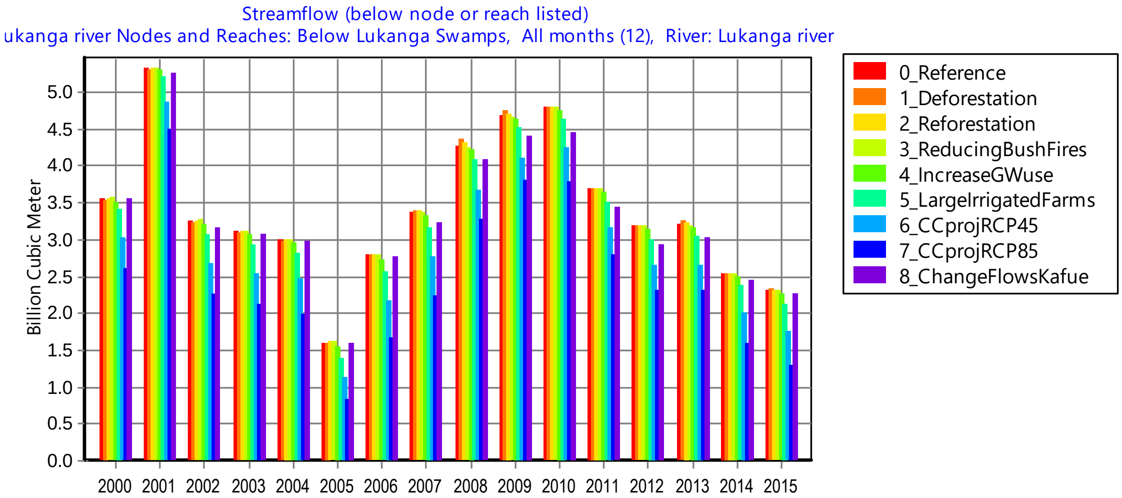


Figure 49. Mean monthly (upper panel) and annual (bottom panel) outflow from the swamp for the different scenarios.

Table 10. Overview of scenario results for: outflow from Lukanga swamps during a dry year (2005), during a wet year (2010), and mean annual flows.

Scenario	Outflow dry year 2005		Outflow wet year 2010		Mean annual outflow	
0_Reference	1601	0%	4797	0%	3199	0%
1_Deforestation	1599	0%	4791	0%	3195	0%
2_Reforestation	1604	0%	4801	0%	3203	0%
3_ReducingBushFi	1604	0%	4797	0%	3200	0%
4_IncreaseGWuse	1552	-3%	4751	-1%	3152	-1%
5_LargeIrrigatedFar	1389	-13%	4626	-4%	3007	-6%
6_CCprojRCP45	1121	-30%	4232	-12%	2677	-16%
7_CCprojRCP85	832	-48%	3772	-21%	2302	-28%
8_ChangeFlowsKaf	1595	0%	4447	-7%	3021	-6%

4.4.2 Scenario 1: Deforestation

There is currently a trend of deforestation due to charcoal production, bush fires, etc, in Lukanga watershed, and this scenario can therefore be viewed as a "business-as-usual" scenario. To assess deforestation currently occurring in the area, the global forest loss dataset published by Hansen et al. (2013) was downloaded from *https://earthenginepartners.appspot.com/science-2013-global-forest*. Figure 50 indicates where in the watershed removal of forest has occurred between 2000 and 2014. "Hotspots" of deforestation can be found in the northeast and the southwest of the catchment.

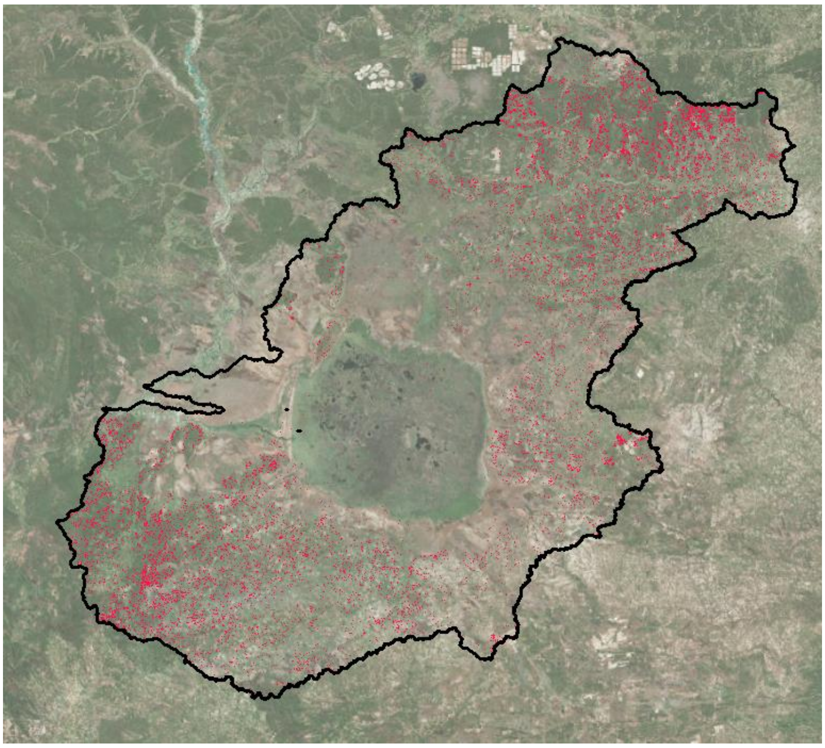


Figure 50. Locations of forest cover loss in Lukanga watershed 2000-2014, in red (Data from Hansen, 2013)**.**

Table 11 provides an overview of forest cover loss per land use class (with classes taken from the recent land use map). An important observation is that of the current agricultural land, 12% was covered by forest in the year 2000. In total, 663 km^2 of forest was removed in the Lukanga watershed in this period of 15 years, amounting to a deforestation of approximately 10% of forested land in the year 2000.

Table 11. Forest cover loss in 2000 - 2014 per land use class.

Class	*Area (m^2)*	*% of forest cover loss*
Agriculture	2071.9	12%
Wetland	1849.7	0%
Water bodies	117.6	0%
Other land	0.1	9%
Forest no burning	1.5	7%
Shrubs no burning	2588.6	6%
Grassland no burning	915.9	3%
Forest low burning	1.9	5%
Shrubs low burning	1351.0	5%

Grassland low burning	823.6	1%
Forest medium burning	4.2	3%
Shrubs medium burning	1482.1	3%
Grassland medium burning	1223.8	1%
Forest high burning	16.8	1%
Shrubs high burning	571.9	0%
Grassland high burning	932.4	0%

In the SWAT parameterization of scenario 1, all forests were converted to the shrubland class with medium burning frequency. The deforestation factor of 10% was applied to increase the SCS Curve Number and decrease the groundwater delay of these land use classes, in order to represented the expected changes in the hydrological response as a consequence of forest cover removal. All other SWAT inputs were kept at their baseline values.

Figure 51 shows the monthly changes in inflow and incoming sediment load, predicted by SWAT as a consequence of deforestation in the Lukanga catchment. Peak values of inflow in February increase as a consequence of the faster catchment response, and the hydrograph has a steeper decrease compared to the baseline. However, the mean annual inflow into the swamp remains similar. This is not the case for the incoming sediment load, which on the annual scale increases to 0.47 Megatonnes, an increase of 22% compared to 0.38 Mton/yr in the baseline. This increase particularly takes place in the December – March period.

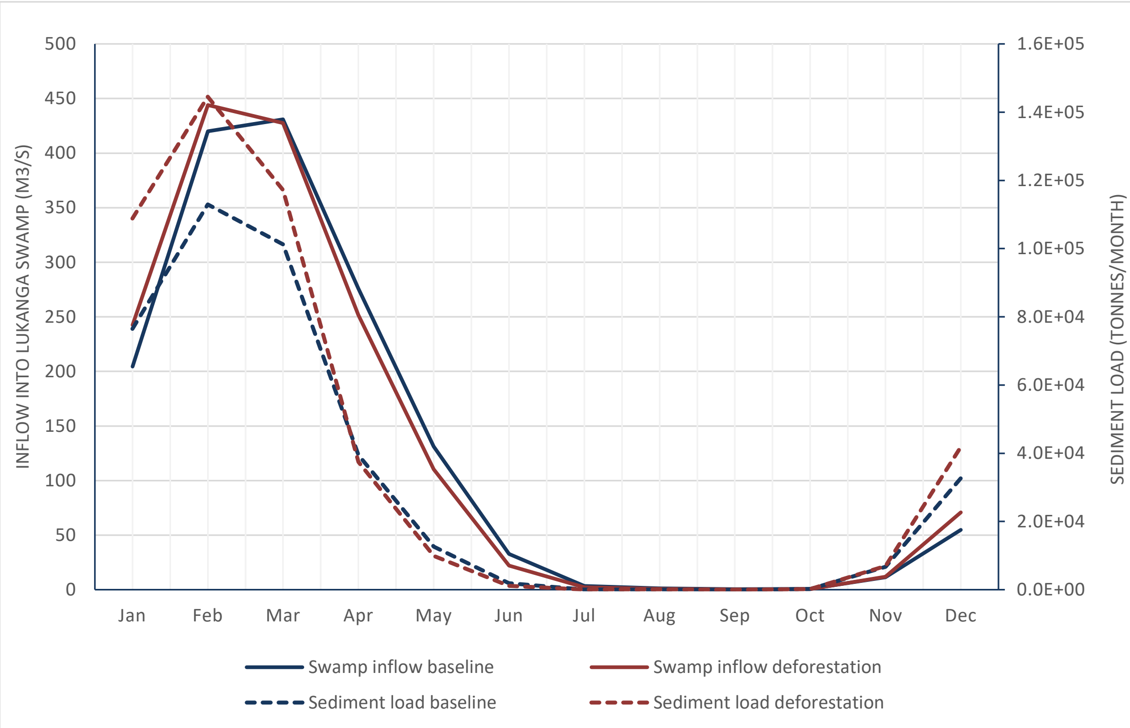


Figure 51. Water and sediment fluxes entering Lukanga Swamps, under baseline conditions and the deforestation scenario ("business-as-usual").

Predicted changes in surface runoff generation and erosion rates under continuing deforestations are displayed spatially in Figure 52 and Figure 53 respectively. Particularly in the north and the southwest of the basin, the increase in surface runoff will lead to higher erosion rates when compared to the 2000 – 2015 baseline conditions.

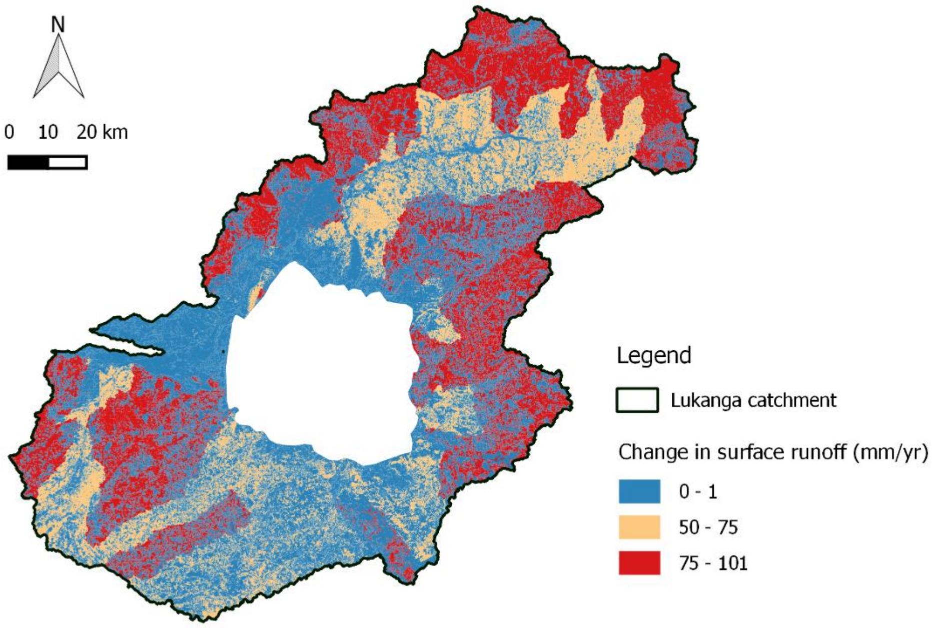


Figure 52. Difference between surface runoff generated under the deforestation scenario and baseline conditions. Positive values indicate an increase in surface runoff compared to the baseline.

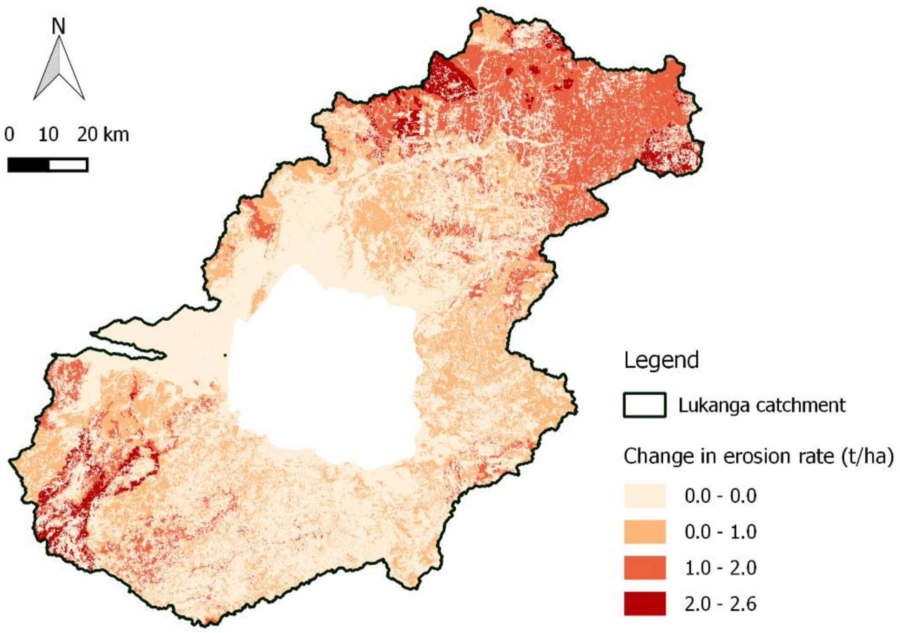


Figure 53. Difference between erosion rate under the deforestation scenario and baseline conditions. Positive values indicate an increase of erosion compared to the baseline.

4.4.3 Scenario 2: Reforestation

In the reforestation scenario, it is assumed that trees are planted to partly compensate the deforestation losses. In this case, only 2 of the 4 forest classes in the original land use map are converted to shrubland. It is assumed that the other two classes, which have the highest burning frequencies, are replaced in conservation efforts. For the two converted classes, Curve Number and groundwater delay values are adjusted with 5% change factors.

Figure 54 compares SWAT outputs of swamp inflow and total sediment load for the reforestation scenario to baseline values. The temporal pattern of the changes are similar to those observed under scenario 1, although the magnitude of the changes is smaller. On average, an increase of 11% of annual sediment load is predicted under the reforestation scenario, amounting to a total of 428,000 tonnes of sediment from the Lukanga watershed.

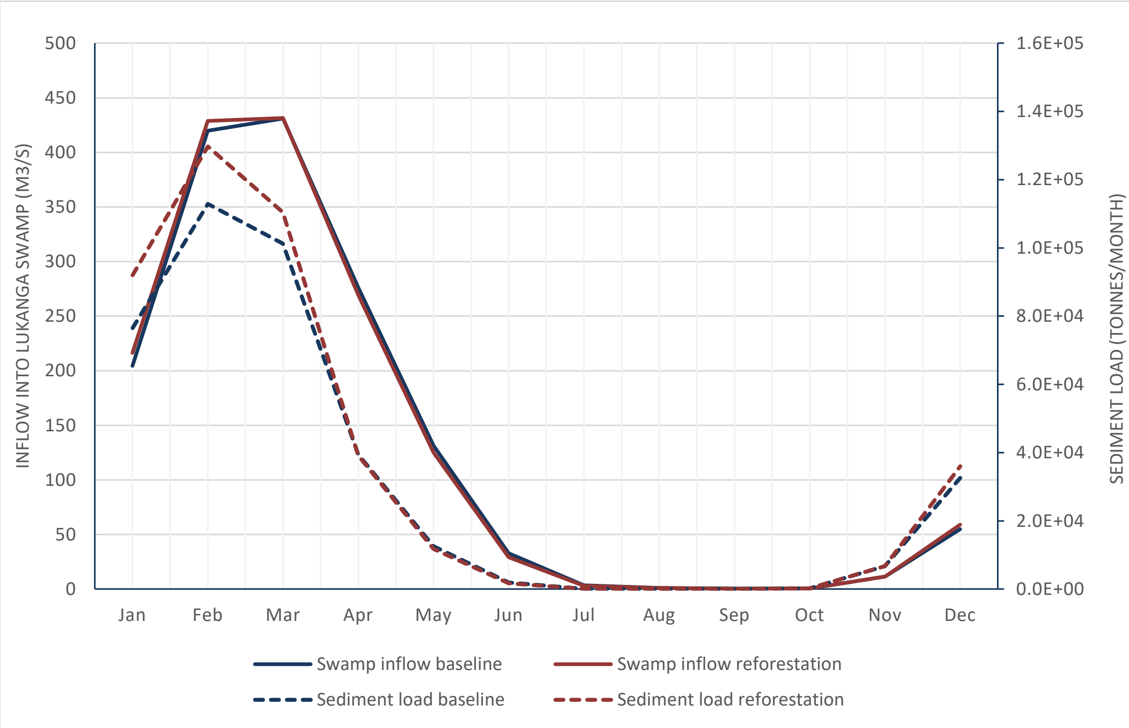


Figure 54. Water and sediment fluxes entering Lukanga Swamps, under baseline conditions and the reforestation scenario.

Figure 55 and Figure 56 show the expected changes in surface runoff and erosion rates under the scenario of partial reforestation. Spatial patterns are similar to what was obtained under the deforestation scenario, although the magnitude of the differences are logically smaller.

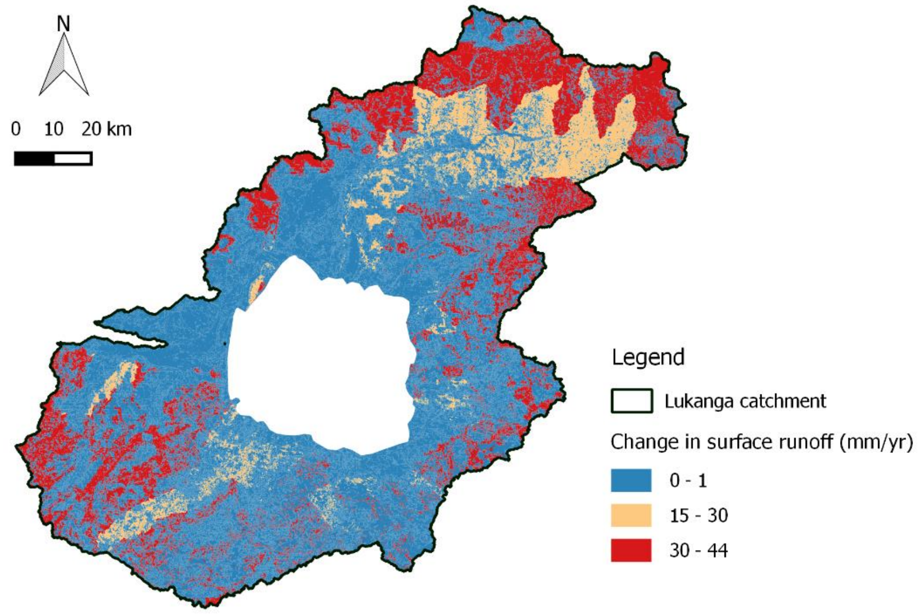


Figure 55. Difference between surface runoff generated under the reforestation scenario and baseline conditions. Positive values indicate an increase in surface runoff compared to the baseline.

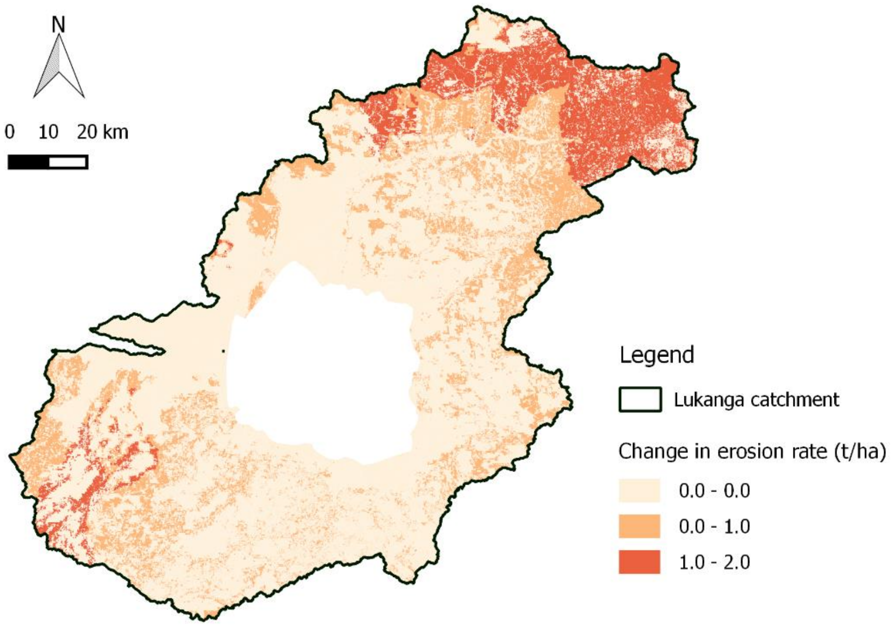


Figure 56. Difference between erosion rate under the reforestation scenario and baseline conditions. Positive values indicate an increase of erosion compared to the baseline.

4.4.4 Scenario 3: Reducing bush fires

In the third scenario evaluated with the SWAT model, it is assumed that farmers are encouraged to reduce slash-and-burn agriculture, thus reducing the frequency of bush fires in the Lukanga watershed. This scenario is implemented in SWAT by assuming lower burning frequencies for all forest, shrubs and grassland classes. High-frequency classes are converted to medium-frequency, medium to low, and bush fires in classes with a low burning frequency in the original land use map are assumed to disappear altogether. In terms of model parameters, this results in shifts in USLE C values following the approach explained on page 29 of this report. In addition, Curve Number values of these classes are reduced by 5% and the groundwater delay value is increased by 5%, in order to simulate a slower hydrological response as a consequence of enhanced vegetation cover.

SWAT results of this scenario are depicted in Figure 57. Inflow to the swamp remains largely the same, both in terms of monthly variability and annual average, with only minor changes to peak flows in February. Sediment fluxes are reduced thanks to the soil being less susceptible to erosion. A total sediment load of 360,000 tonnes/year is simulated, amounting to a reduction of 6% compared to the baseline.

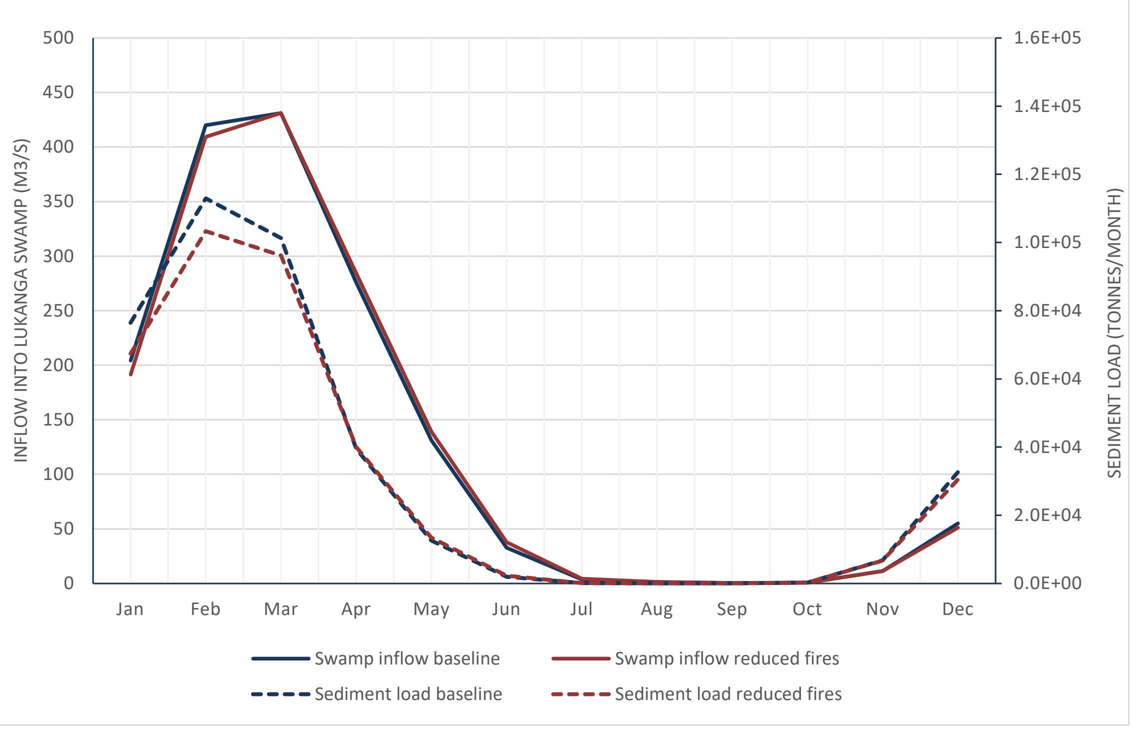


Figure 57. Water and sediment fluxes entering Lukanga Swamps, under baseline conditions and the reduced bush fires scenario.

Maps of the impact of reduced fire frequencies on surface runoff and erosion rates are shown in Figure 58 and Figure 59 respectively. As is to be expected, reduction of surface runoff especially occurs in regions mostly covered by forests, shrubs or grassland classes. The striking red northern region in Figure 58 consists of forests where no burning occurs in the baseline runs, therefore nothing changes here. A relatively large change in runoff is predicted for the flood plain area, but due to the flat topography the resulting changes in erosion are not very significant. The greatest reductions in erosion are achieved in the far north and southwest of the watershed.

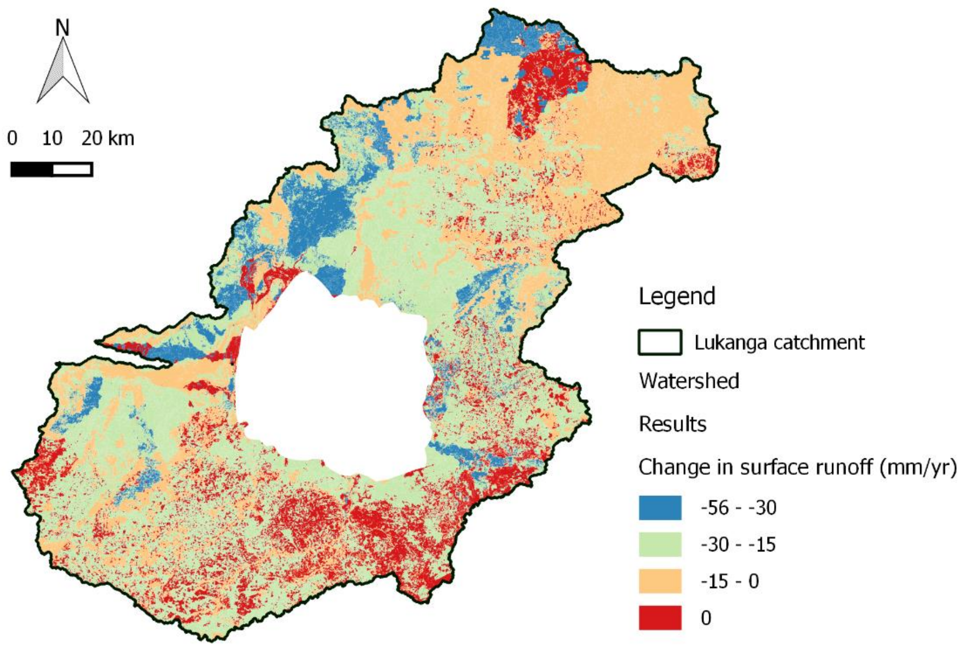


Figure 58. Difference between surface runoff generated under the reduced bush fires scenario and baseline conditions. Positive values indicate an increase in surface runoff compared to the baseline.

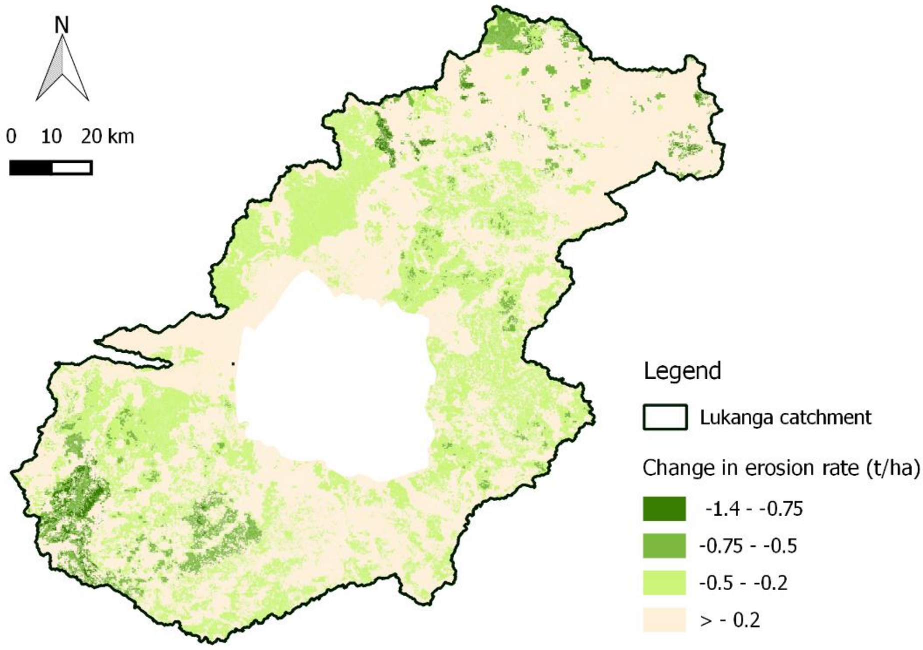


Figure 59. Difference between erosion rate under the reduced bush fires scenario and baseline conditions. Positive values indicate an increase of erosion compared to the baseline.

4.4.5 Scenario 4/5: Increase irrigation

Scenario 4: This scenario assesses a near future in which communities around the lake are developing due to better roads to urban centres and access to markets, and an increase in population. This will likely increase the use of the shallow groundwater resources around the lake by groundwater pumping. The scenario assumes that around 10.000 ha are being developed, requiring a supplemental irrigation amount of 200 mm per year, during the dry period.

This scenario leads to a decrease in annual inflow into the swamp of about 1%, from which it can be concluded that the impact of these additional withdrawals are relatively low. However, it would be recommendable to assess them in an integrated model for the entire Kafue river basin.

Scenario 5:
Just north but outside of the Lukanga watershed there are already large irrigated farms, mainly cultivating sugarcane, making use of karstic aquifers in that area. A possible scenario is that within the watershed these irrigation schemes will also being developed in the future. For this scenario it was assumed that 30.000 ha will be developed, requiring an irrigation amount of 800 mm per year, concentrated in the dry period (see for details the Annex).

This scenario leads to a decrease of 4% in inflow, and 6% in outflow of the swamp. This can have considerable consequences for the overall water balance of the Kafue and also needs to be assessed in an integrated water resources assessment for the Kafue river basin. During a dry year, the decrease in outflow can go up to 13%, which is likely to have a notable impact on water availability for downstream users.

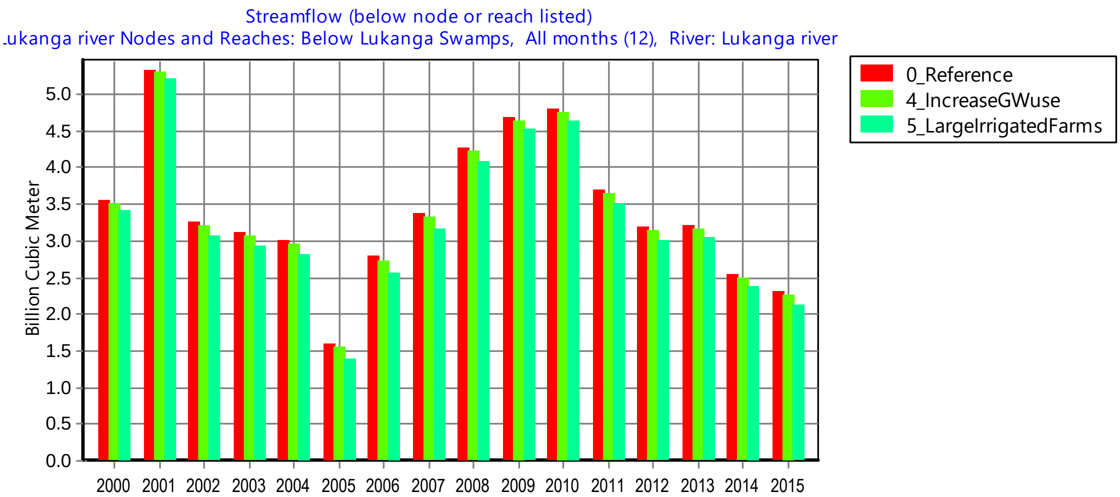


Figure 60. Annual outflow from the swamp for scenario 4 and 5 compared to reference

4.4.6 Scenario 6/7: Climate change impacts

The impacts of climate change are due to changes in flows but also changes in temperature and evapotranspiration from the swamp. Therefore, relative impacts on the outflow from the swamp can be higher than impacts on the inflow to the swamp.

This analysis was based on relative changes in flows that were simulated by a parallel project carried out by TNC on climate change impacts in the Kafue Basin, using the model SWAT (lead: Yuri Kim). Scenario 6 corresponds to an RCP4.5 projection (global emissions peak around 2040) and scenario 7 with RCP8.5 (emissions continue to rise throughout the 21st century). Both projections are based on the climate CMIP5 model GFDL (NOAA).

The scenarios show a decrease in inflow between -8% and – 12%. For the outflow, the relative decrease is between – 16% and -28% (between 500 and 900 MCM reduction). Clearly the impacts of climate change are more severe for outflow due to increment in evapotranspiration.

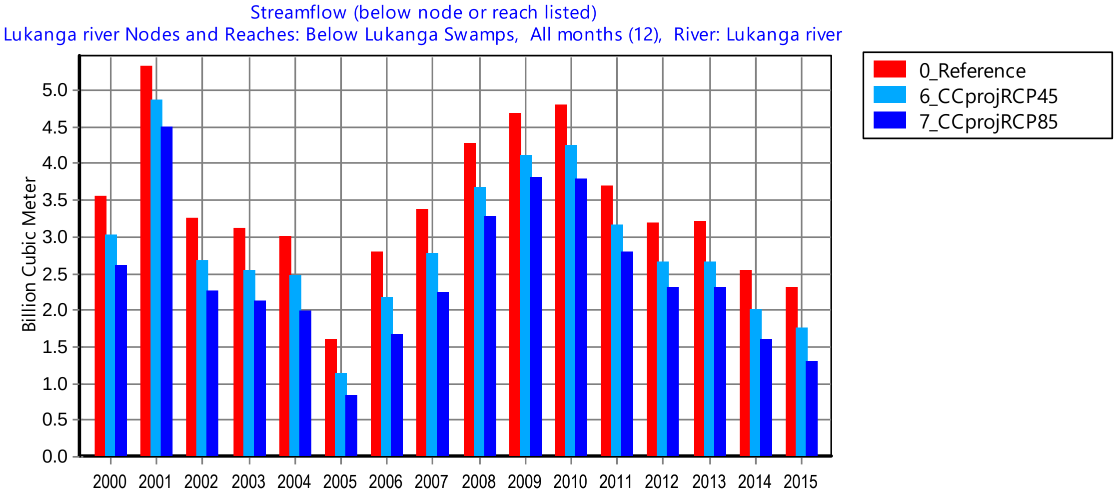


Figure 61. Annual outflow from the swamp for scenario 6 and 7 compared to reference

Also the flow exceedance curves (Figure 46) show a significant impact on flows. Low flows (90% exceedance) reduce from 150 m3/s for the current situation (reference) to 110m3/s for scenario 6, and 70 m3/s for scenario 7.

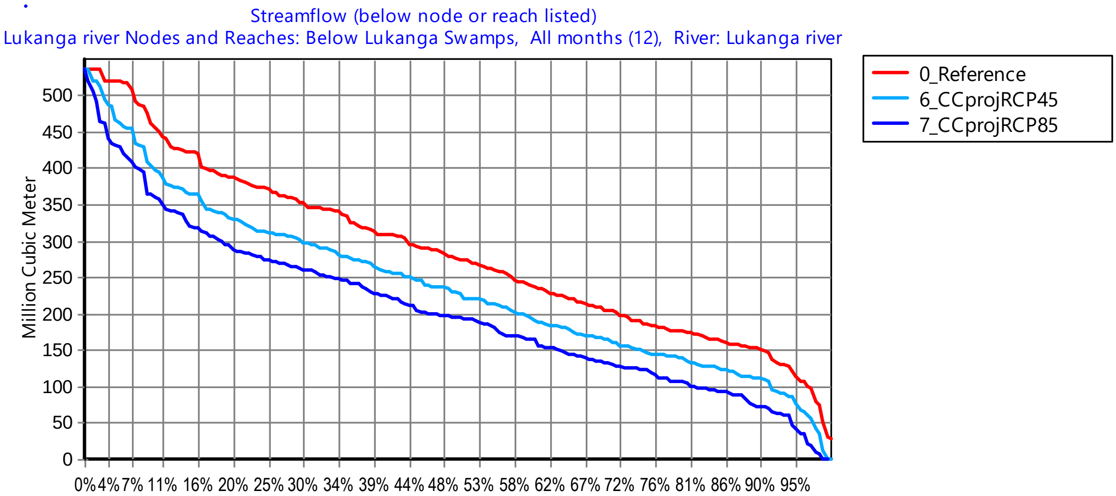


Figure 62. Flow exceedance plot based on monthly flows (2000-2015) for the climate change scenarios and the reference

4.4.7 Scenario 8: Flow regime change Kafue

The flow regime in the Kafue river will affect the Lukanga swamp directly through the surface water (overflow during high floods) but most likely also during normal or dry years through the groundwater. This analysis only took into account a possible connection during high floods.

Changes in the flow regime will affect this connection between the Kafue floodplain and the Lukanga Swamps. Changes can be due to:

- Climate change, affecting the volumes and seasonality of the flows
- New dams, affecting the seasonality and probably also the volumes
- Increase consumptive water use in the upper Kafue basin due to new irrigation schemes for example.

This scenario assumed the connection to disappear so no overflow occurs from the Kafue floodplain to the Lukanga Swamp. The impacts are only seen in the wet years obviously and lead to a decrease of maximum 6% in outflow to the Kafue river basin (Figure 63).

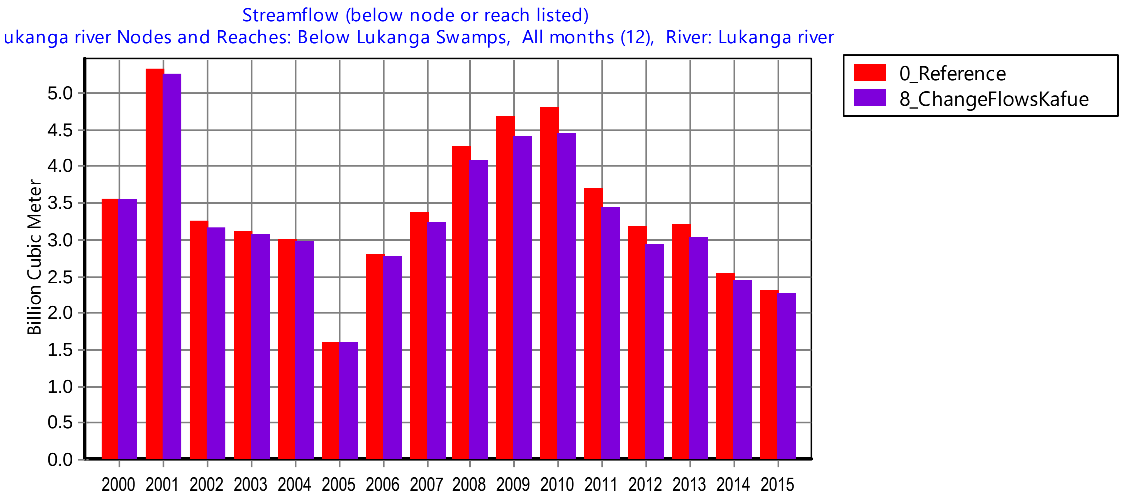


Figure 63. Annual outflow from the swamp for scenario 8 compared to reference

5 Key Findings on Ecosystem Services

5.1 The Lukanga Swamp as a source of water

The Lukanga Swamp acts as a nature-based reservoir in the Kafue river basin, by retaining water in wet periods and releasing it slowly during the dry season and during dry years. The following key findings that follow from this study describe this role as a source of water and reliable water supplier:

- Annual variability of the Lukanga swamp inflow is very high. The swamp provides carryover storage: during a wet year water is stored and part of it released during the next year. This is typically about **1,500 MCM** (27 % of annual flow in Kafue River at Chilenga) from a wet year that is stored for the following years.
- This role as “sponge” is even more important at the monthly time scale: water entering during the wet period is around 1,000 MCM/month in the wet period and 0 MCM/month in the dry period. This water is **released slowly** by the swamp to the Kafue river basin, ranging between **200 and 400 MCM/month** (during the dry month November, approx. 25% of the mean Kafue river flow (at Chilenga)
- The Lukanga Swamp and its watershed is a **significant contributor** to the Kafue River Basin. The analysis shows that on average **about 1/3** of the water flowing just downstream of the Lukanga Swamp is coming from the swamp. This finding confirms that the Lukanga Swamp and its watershed are a very important asset for downstream water users in the Kafue River Basin (Lusaka water supply, hydropower, Kafue Flats, etc).
- The water the swamp receives through surface water by overflow from the Kafue during floods is a limited amount compared to the overall water balance (between 0 and 6%).
- In the future, the **flow regime** (peak flows) may **change** in the Kafue river upstream due to climate change, new upstream dams or an increase in consumptive water use. This will have an impact on the water balance of the swamp, as no (or less) overflow will occur. A considerable impact can also be expected on the inflow towards the swamp from the Lukanga watershed itself, resulting in **reductions of about 20% in outflow** from the swamp to the Kafue
- The scenarios on an increase in irrigation and groundwater use, have indicated that large-scale irrigation schemes will have a notable impact on the water balance (**6% less outflow from the swamp to the Kafue**). An increase of groundwater pumping around the wetlands by the communities for small-scale irrigation is not expected to lead to concerning impacts on the water balance.

The above indicators have implications for the downstream water users in the Kafue river basin. Below, these are described for the main users in the basin, in section 5.3.

5.2 The Lukanga Swamp as a water purifier

The Lukanga Swamp improves water quality by trapping sediments, filtering out pollutants and absorbing nutrients that would otherwise result in poor water quality for downstream users. The following key findings that follow from this study describe this role as a sink for sediments, pollutants and nutrients:

- The swamp receives water from the Lukanga watershed with a mean **annual sediment load of 0.4 Mtons/year**. With further deforestation of the watershed, this rate can go up by around 20%. The large size of the swamp and the low velocities in the swamp assure that all these sediments settle to the bottom and is **retained** in the swamp, improving water quality of downstream water users in the Kafue river basin.
- Agricultural practices so far within the Lukanga watershed are extensive and use of fertilizers and pesticides is limited. However, upstream in the Kafue river basin, there are a few intensive irrigation schemes that likely produce **high nutrient loads** in runoff coming from the schemes and thus affecting water quality. Similar irrigation schemes may arise in the future within the Lukanga watershed that take advantage of the karstic aquifer in the North of the watershed: the role of the swamp to filter out excess loads will become critical in that case as it could **mitigate most** of the negative impacts due to excess nutrient loads. This would however also lead to an increase in consumptive water use, and could thus reduce the role of the swamp as a water provider to downstream users (**-6% decrease in outflow** if irrigation water is withdrawn from renewable sources).
- The years that floods occur in the Kafue floodplain, water levels increase in the Lukanga swamp. Subsequent years with flood occurrence lead to a gradual increase in water levels and explain part of the multi-annual trend that was observed. However, wet years in the Kafue floodplain are normally also wet years in the Lukanga watershed. Most of the surplus water that the swamp receives during wet years comes from the Lukanga watershed itself, and not from overflow from the Kafue river. The overflow was estimated to be **maximum 6% of the surface water in the Kafue**.
- Excess loads from upstream in the Kafue river basin, as well as pollutant loads from the mining industry are likely filtered to some extent in the floodplain of the Kafue river itself (this was not studied in this work). But when the Lukanga swamp connects with the floodplain it also receives part of the nutrient and pollutant loads. The swamp likely **filters these, contributing to cleaner water for downstream users**.
- In the future, the **flow regime** (peak flows) may **change** in the Kafue river upstream due to climate change, new upstream dams or an increase in consumptive water use. This means that the connection with the swamp will change during flood events and that the role of the swamp as an absorber of pollutants and excess nutrients will become **less important**.

There is likely also **an important role of subsurface and groundwater flow** in improving water quality of water coming from upstream polluters. It is likely that there is a strong connection through the subsurface between the Kafue river floodplain and the swamp. This means that the water dynamics and the functioning of the swamp are of influence on the dynamics of the Kafue floodplain. In other words: during high flow periods, when no surface-connection is evident with the swamp, the swamp may still absorb part of the excess waters through the subsurface. This means that the beneficial role the Kafue floodplain has on water quality and flood prevention downstream, is likely to be conditioned and influenced positively to some extent by the swamp through the subsurface. The water balance of the swamp has highlighted the important role of subsurface flows in the Kafue river system (water budgets at Chilenga swamp outflow and Lubungu).

5.3 Potential benefits for stakeholders

5.3.1 Mining industry

This study has confirmed by combining various data sources and analysis, that it is likely that a fraction of the water during extreme flood events in the Kafue river enter the Lukanga swamp. This fraction can go up to around 6% in very wet years. Given the size of the swamp, it is likely that a small part of the pollutants coming from the copper mines upstream in the Kafue basin will be absorbed by the swamp during these peak flow events. At the same time, this positive impact of the swamp may be limited as pollutant concentrations may be relatively low during high flows due to dilution. This will very much depend on the source of the pollutants: peak runoff may also cause peak concentrations, at least in the beginning of the peak event but no data are available on this behavior.

Probably to a larger extent than by the swamp, the Kafue floodplain also absorbs part of the pollutant load. The Kafue floodplain, including the Lukanga swamp, is thus an effective mitigation nature-based infrastructure to mitigate the negative impacts of the mining industry, and improve water quality downstream. Important: is that this function may change in the future when floods become less frequent. The floods are critical in improving water quality downstream by recharging aquifers and sustaining clean subsurface and groundwater flows. Reduced flows in the Kafue river due to climate change, but also new upstream dams will reduce the effectiveness of this nature-based mitigation solution.

5.3.2 Irrigated agriculture upstream

The above considerations on the mining industry also apply to irrigated agriculture in the Kafue river basin. The Kafue floodplain and the Lukanga swamp act as a natural filter to excess nutrient loads and pesticide loads coming from this industry. The current irrigation schemes take water principally from aquifers, of which it is not known to which extent the withdrawals are taken from renewable resources or not. If they are taken from renewable resources (or if future irrigation schemes will) this will lead to lower water availability in the Kafue river. This may also reduce the mitigating role the Kafue floodplains and the Lukanga swamps play by reducing nutrient and pollutant loads coming from this industry.

5.3.3 Hydropower

The variability of water stored in the Lukanga Swamp is in the same order of magnitude as the total storage capacity of the dams in the Kafue River downstream (approx. 7,000 MCM). This stresses the value the swamp has for the hydropower business in the Kafue river. Without the swamp, flows would be less reliable and more irregular and storage capacity in the lower Kafue would be insufficient to maintain the current hydropower generation (approx. 2,000 GWh/year).

Clearly, the hydropower sector has a vested interest in the conservation of Lukanga Swamp. Key threats for the sector are:

- Changes in land use in the Lukanga watershed, leading to an increase in consumptive water use
- Climate change, leading to changes in flow regime of the Lukanga watershed and most likely a decline in several of the ecological functions of the swamp, including its buffering capacity

The above threats are at the same time an opportunity for the hydropower to invest in sustainable land use and development, and climate adaptation in the Lukanga watershed, including the swamp.

5.3.4 Urban and industrial water supply, Lusaka

The role as “sponge” of the Lukanga Swamp is equally important for the water supply to Lusaka and the industrial sector. Water supply is dependent on consistent river flows in the Kafue. Lusaka Water and Sewerage Company is extracting currently 40MCM/year from the Kafue river. This is most important for the withdrawals from surface waters. Withdrawals from groundwater (about 60% for Lusaka City) are less dependent on the variable flow regime in the river, but might also be affected negatively in case the buffering role of the swamp decreases.

Total water demand in 2020 in the Kafue river basin (rural and urban) is expected to be 258 MCM/year (GFA report). Industrial demand is expected to go up to 474 MCM/year. Clearly the Lukanga Swamp (providing about 3,000 MCM/year to the Kafue river) is a crucial source of water that can support in meeting this water demand. Critical however is that the buffering capacity of the swamp will be preserved.

Thus, the threats (and at the same time opportunities) listed for the hydropower sector also apply to the water supply sector. But besides, this sector also benefits from enhanced water quality. Pollutants (potentially from Kabwe mines through groundwater) and nutrients (potentially from future large irrigation schemes) in the Lukanga watershed are or will be absorbed by the swamp.

5.3.5 Irrigation schemes

Irrigation water demand is expected to increase drastically in the basin. From around 1,000 MCM/year to 2,400 MCM/year in 2020 (GFA report). This demand is however highly variable of the year: high crop water requirements generally coincide with the dry period. Thus, the “sponge” function of the Lukanga Swamp is crucial to be able to meet this demand in the Kafue river.

An implementation of the WEAP for the entire Kafue basin can be used to evaluate how and to which extent this demand can be met in the future, taking into account the locations of the new irrigation schemes. Currently most of them are located in the Kafue Flats (mostly sugarcane).

New irrigation schemes within the Lukanga watershed also have an indirect interest in the health of the swamp: excess nutrient loads or pesticides are largely filtered through this system and could significantly reduce negative impacts on water quality for downstream users in the Kafue basin.

5.3.6 Biodiversity/tourism downstream

Changes in the sponge function of the Lukanga swamp can have a direct impact on the ecology of the river sections and floodplains downstream in the Kafue. The Kafue river downstream of the Lukanga swamps up to Itezhi–tezhi reservoir is categorized by a mixture of Miombo and Munga woodland, interspersed with open floodplain grasslands and swamps, and more downstream the Kafue National Park. The area is largely undisturbed, as large portions are in protected areas where use of resources is controlled. There are many tourism activities in the area, but it is still largely pristine with a large diversity of mammals. An ecological study should be carried out to assess the dependence of the ecology and tourism on the flow regime in the Kafue. This assessment would allow a valuation of the Lukanga Swamp for the biodiversity and tourism industry downstream of the swamp, including the national park.

6 Recommendations

Recommendations on catchment management issues:

- Integrate the outcomes of this analysis in the catchment management plan. The analysis has made evident that the Lukanga Swamp is a crucial feature in the Kafue River Basin, as water provider, natural storage reservoir and water purifier. The quantitive figures of the water balance could be integrated in the catchment management plan and the tools used
- Increase the understanding of the link between the Kafue floodplain and the Lukanga swamp, both by surface water as well as through subsurface flows. A detailed modeling study of the floodplain dynamics is necessary, with emphasis on subsurface flows
- Quantify the amount of groundwater recharge occurring in the Kafue river floodplains and the Lukanga swamps, in order to value the role these features have in mitigating the impact of pollutants upstream.
- The mines at Kabwe (lead): outside of the Kafue basin and just outside of the Lukanga watershed but these may still have an impact through groundwater bodies on the water quality in the Lukanga watershed. This needs to be studied. If indeed the pollutants enter the Lukanga watershed through the aquifers, the swamp is critical in mitigating these impacts.

Recommendations on improving current findings:

- The WEAP tool used for this study is found to be very adequate for the complex Kafue system. The model developed for this study was limited to the Lukanga domain, but could be further extended to the Upper Kafue or the entire basin, integrating and improving on:
    - Floodplain dynamics
    - Water quality
    - Water uses upstream and downstream
    - Hydropower
    - Climate change impacts (informed by SWAT modeling carried out currently)
    - Storage-elevation relationship of the swamp
- For the adoption of the WEAP to be successful further capacity building is found to be crucial: a beginner´s course was given within the scope of this assignment that was very well received. Several technical staff from WARMA were interested in integrating it in their decision-making support. However, a follow-up of the workshop is deemed necessary
- Particularly for the Lukanga Swamp and connected Kafue floodplain there are also further challenges in assessing the link by surface water and subsurface water, during dry periods and floods. These questions could be answered using more detailed hydrodynamic models and groundwater modeling.

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Appendix A. Model parameterization

WEAP model parameters

The following assumptions were done and parameters were included in the WEAP model:

- Key/KafueLukangaFloodLevel = 450; when flow (m3/s) in Kafue river at Chilenga is above this level, overflow occurs if swamp is not full in the WEAP model:
    - Supply and Resources\River\Overflow:Maximum Diversion[CMS] = Max(PrevTSValue(Supply and Resources\River\Kafue\Reaches\Below Kafue Headflow:Streamflow[m^3])/(60*60*24*30)-Key\KafueLukangaFloodLevel,0)
- Key/MinOutflow = 200; to make sure that WEAP gives priority to releasing water instead of storing it in the swamp (i.e. reservoir), this environmental flow requirement was applied (200 m3/s). In the WEAP model:
    - Supply and Resources\River\Lukanga river\Flow Requirements\Swamp outflow:Minimum Flow Requirement[CMS] = Key\MinOutflow
- Key/MaxOutflow = 50; Key/MinLevel = 1114.5; These parameters define maximum outflow from swamp, depending on water level. Minimum level below which no outflow occurs is assumed to be 1114.5. In WEAP:
    - Supply and Resources\River\Lukanga river\Reservoirs\Lukanga Swamps:Maximum Hydraulic Outflow[CMS] = Max(Key\MaxOutflow*(PrevTSValue(Storage Elevation[m])-Key\MinLevel),0)

SWAT scenario parameters

The following table gives an overview of the specific changes that were applied to the baseline model for each of the scenarios.

Table 12. Parameterization of SWAT scenarios. Changes in input parameters are given relative to the baseline run. Land use classes are denoted as follows: *F*, *S* and *G* indicate forest, shrubland and grassland respectively. Subscripts indicate frequency of bushfires: $_{NOB}$ = negligible burning, $_{LOB}$ = low burning frequency, $_{MEB}$ = medium burning frequency, $_{HIB}$ = high burning frequency.

Scenario	Land use classes affected	Change to land use class	Curve number	Groundwater delay
1. Deforestation ("business-as-usual")	F_{NOB}, F_{LOB}, F_{MEB}, F_{HIB}	S_{MEB}	+10%	-10%
2. Reforestation: tree cover in half of basin increases, other half decreases	F_{NOB}, F_{LOB}	S_{MEB}	+5%	-5%
3. Reducing bush fires	F_{HIB}, F_{LOB}, F_{MEB}, S_{HIB}, S_{MEB}, S_{LOB}, G_{HIB}, G_{MEB}, G_{LOB}	Same class, but with lower burning frequency*	-5%	+5%

Shifts in land use classes affect USLE C as explained in Table 4.

WEAP scenario parameters

The following parameters were included in the WEAP model for the scenario analysis

No	Scenario	Parameterization
4	Increase use groundwater local communities / agricultural intensification	15.000 ha – generic crop Irrigation water requirements 200 mm / year Monthly variation: Apr-Sep: 100%
5	Large irrigated farms	30.000 ha sugarcane Irrigation water requirements 800 mm / year Consumption: 80%. As this water is actually taken from the aquifer, it was assumed that the impact of withdrawing in the dry period, occur in the wet period (Nov-Feb)
6	Change in flows due to climate change - projection 1	RCP 4.5 scenario. Based on monthly relative change in flows, see Figure 64. Net evapotranspiration (ET – P) from swamp is assumed to increase by a factor of 1.05 *(Key/NetETfactorCC).*
7	Change in flows due to climate change - projection 2	RCP 8.5 scenario. Based on monthly relative change in flows, see Figure 64. Net evapotranspiration (ET – P) is assumed to increase by a factor of 1.1 *(Key/NetETfactorCC).*
8	Change in peak flows Kafue	New dams in the Kafue, upstream of the Lukanga watershed, or increase in irrigation water use, will reduce peak flows and have an impact on the connection between the Kafue river and the Lukanga system

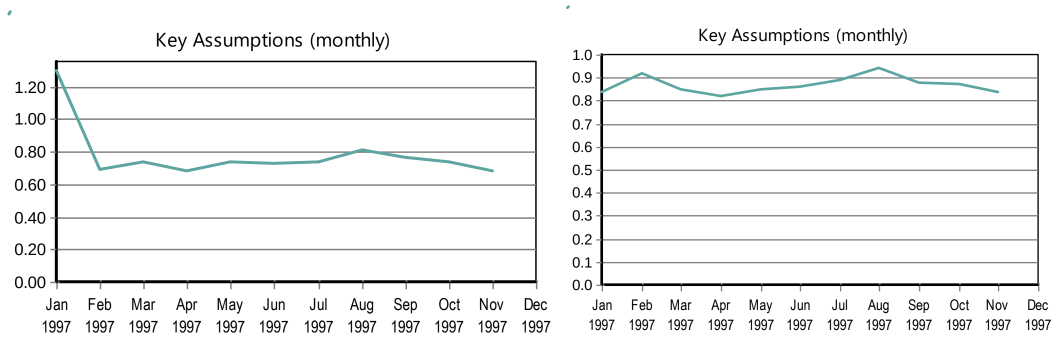

Figure 64. Delta change coefficients for headflows in Lukanga watershed: RCP4.5 scenario (left) and RCP8.5 scenario (right)