Assessment of the Current and Future Available Water Resources Under Different Climate Scenarios in the Lake Bunyonyi Catchment, Uganda

February 2019

The Republic of Uganda
Ministry of Water and Environment

This report is a joint initiative of the Ministry of Water and Environment (MWE) of the Government of Uganda, the NAP Global Network and the University of Natural Resources & Life Sciences, Vienna (BOKU).

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Abstract

The Government of Uganda identified the Ruhezamyenda catchment as one of 15 hotspot catchments threatened by increasing population pressure, water scarcity, loss of wetlands, deforestation and soil erosion. A management plan for the catchment was developed in 2015 but it did not integrate climate change concerns. The objective of this study was to assess current and future potential water resources under different climate scenarios in the Lake Bunyonyi catchment given the lake's important role in the hydrology of the entire catchment. The COSERO hydrological model was calibrated for historic conditions (1951 to 2000) for the Ruhezamyenda catchment. The model achieved good calibration results for the historic period, especially considering the general challenge of dealing with missing in-situ observation data. The model was then run with an ensemble of 30 climate simulations for the mid-term future (2041–2070) and for the far future (2071–2100), each with two representative concentration pathway (RCP) scenarios (RCP4.5 and RCP8.5). The results showed that higher temperatures and more annual precipitation will lead to higher actual evapotranspiration amounts. The runoff for the catchment for future periods showed much uncertainty, but an overall trend toward increasing runoff, especially in the far future. Based on this analysis and given that the climate impacts on the catchment may be broad, a combination of no-regrets adaptation options were identified; most of which have already been selected in the catchment management plan. These adaptation options were validated during a local stakeholder workshop held in November 2018 in Kabale, Uganda. Participants also identified additional adaptation actions based on the results of this assessment.

List of abbreviations

AET	actual evapotranspiration
CDF-t	cumulative distribution function transform
CMP	Catchment Management Plan
COSERO	COntinuous SEmi-distributed RunOff hydrological model
CRU TS	Climatic Research Unit Timeseries
CMIP5	Coupled Modelling Intercomparison Programme in its fifth phase
GCM	Global Climate Model
GoU	Government of Uganda
IWD	inverse weighted distance
IWRM	integrated water resources management
KGE	Kling Gupta Efficiency
RCP	Representative Concentration Pathway
SWAT	Soil and Water Assessment Tool
NAP	National Adaptation Plan
NSE	Nash-Sutcliffe-Efficiency
PET	potential evapotranspiration
WMZ	water management zone

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1.0 Introduction and Objectives

The Ruhezamyenda catchment belongs to one of the 15 hotspot catchments identified as at risk by the Government of Uganda (GoU), in particular due to increasing population pressure, water scarcity, loss of wetlands, deforestation and soil erosion.

The Ruhezamyenda catchment lies in the southwestern corner of Uganda. The river drains via Lake Mutanda, Lake Edward and the Semliki River toward Lake Albert. As such, it is part of the White Nile River Basin and a water drop would eventually (if it does not get lost to evaporation or transpiration), after travelling 6,500 km, drain into the Mediterranean Sea. The catchment is dominated by a montane food crop production system mainly located above 1,800 metres (m) in elevation. Farming plot sizes are small and fragmented due to high population density. The area has experienced a decline in soil fertility, mainly in phosphorus levels (Carswell, 2002), due to repeated cultivation (Osiru, 2006).

Lake Bunyonyi lies in the Ruhezamyenda catchment, and is a deep freshwater lake that provides important habitats for unique fish, bird (including the threatened Grey Crowned Crane) and other species (Maclean et al., 2003). The lake's watershed (381 km^2) comprises 53 per cent of the Ruhezamyenda catchment and constitutes a vital part of the natural, environmental, socioeconomic and cultural aspects of the region. From 1987 to 2014 the wetland areas around the lake declined by 3.8 per cent (Kizza et al., 2017) mainly because of conversion into agricultural land (Kizza et al., 2017; Carswell, 2002) or due to the over-harvesting of papyrus (Maclean et al., 2003). The conversion of wetland to farmland and the significant areas of eucalyptus plantations were also confirmed during the July 2017 site visit (Crerar & Akurut, 2017). The hydrological impacts to the lake and in the catchment due to climate change have not been assessed.

The GoU has identified the water resources sector as one of the country's priority sectors for climate adaptation. Water management planning in Uganda is based on the principle of integrated water resources management using a catchment-based approach. This is being done by assigning water resources development and management functions to four water management zones (WMZs), which are further divided into water catchments. Catchment management plans (CMPs) are a central participatory tool to help balance the growing water demands of different users with the limited resources available and to guide the implementation of water management measures to protect and conserve the catchments within each WMZ. The approach was first piloted in 2006 and is being rolled out progressively with a common framework for catchment planning to guide WMZ developed in 2014. So far, climate change concerns have not been systematically addressed in the development of the CMP, including in the Ruhezamyenda CMP developed in 2014. To address this gap, the catchment management planning guidelines were revised in 2016/17 to integrate climate change concerns.

The purpose of this study was to support the integration of climate change adaptation in the Ruhezamyenda CMP. This was done by scientifically assessing the impacts of a group of future climate simulations on the water resources in the Ruhezamyenda catchment, specifically on the Lake Bunyonyi water balance (given the important role of the lake in the hydrology of the entire catchment) and comparing the future changes to current hydrological conditions. The specific research objectives were:

i) To establish a monthly water balance for Lake Bunyonyi under current and future climate change conditions.

ii) To analyze and compare the results of the lake water balance under current and future climate change conditions and draw some conclusions for the overall hydrology of the catchment.

iii) To present the impacts of climate change on the hydrology of the watershed, with a focus on Lake Bunyonyi, that will be used to infer possible implications for climate change adaptation in the watershed.

2.0 Approach

2.1 Study Area

The Ruhezamyenda catchment (Figure 1) has a total size of 722 km^2 and is dominated by Lake Bunyonyi (49.6 km^2), which has an average depth of 39 m. Lake Bunyonyi discharges into River Ruhezamyenda. The long-term mean average precipitation is 1,074 mm (WorldClim data 1950–2000 mean monthly precipitation (Hijmans et al., 2005)) with a bimodal rainfall pattern; heavy rains fall between March and May and light rains from September to November (the first dry season is from June to August and the second is from December to February). The mean monthly minimum and maximum temperatures from 1971–2000 are 10.6 and 22.6°C respectively.

Much of the Ruhezamyenda catchment is densely populated and among the most populated areas of Uganda, just after Kampala, which is the most densely populated area in Uganda. The population densities of the two districts[1] covered by the catchment, Kabale and Kisoro, are 320 and 416 persons/km^2, respectively (Geo-Ref.net, n.d.) and are intensively cultivated.

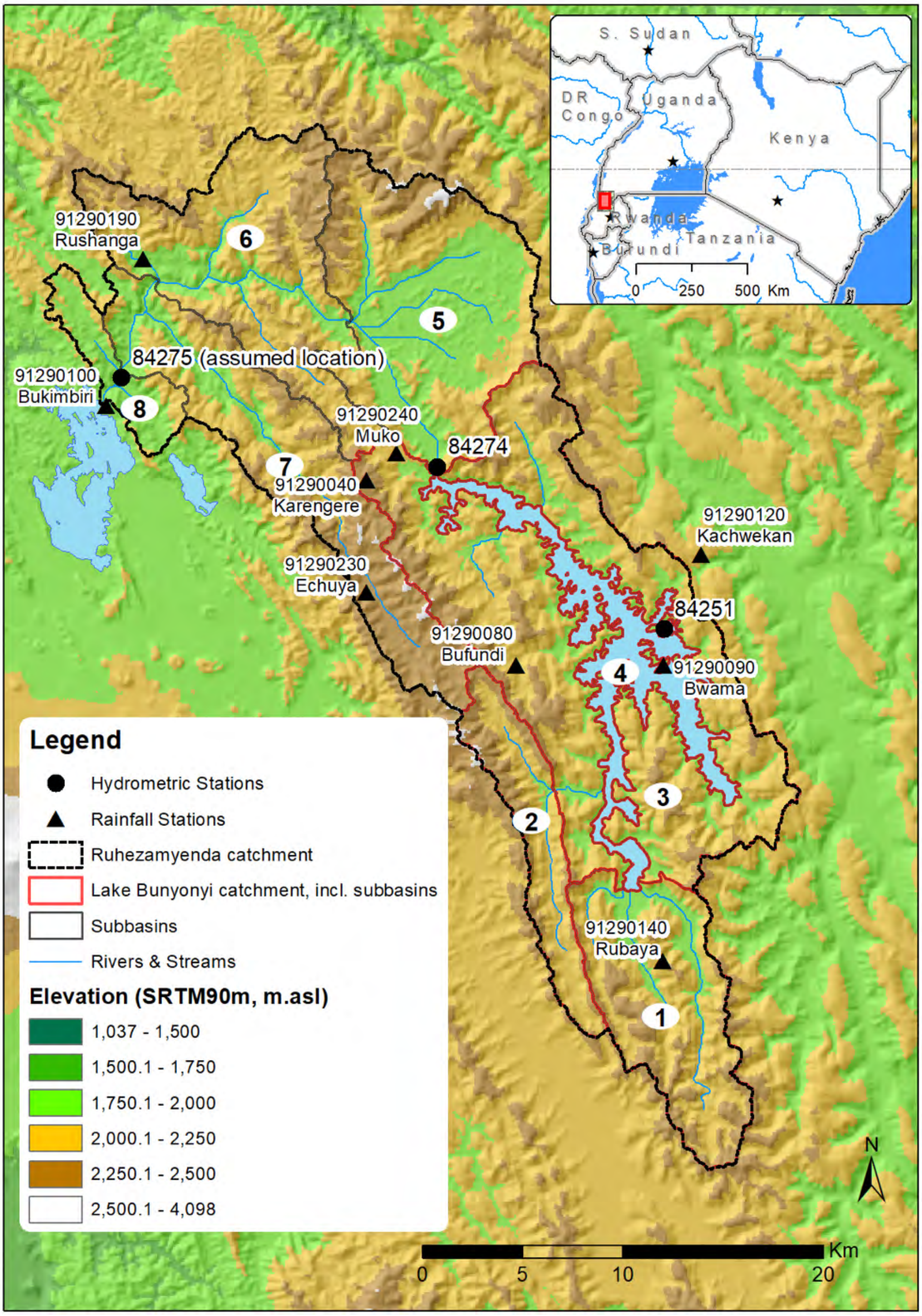
The Ruhezamyenda catchment is very hilly with steep slopes. Elevation in the catchment (based on the SRTM 90 m Digital Elevation Model) ranges from 1,784 to 2,597 m, with a mean of around 2,100 m. The geology is characterized by volcanic rock, and the soils are mainly ferralitic/ferralsols (Osiru, 2006) with peat soils in the swampy areas (Rukundo, 2015). The valley bottoms are often wide and flat and filled with wetlands. In many cases these have been drained and converted to arable farmland, consisting mainly of Irish potatoes, sweet potatoes, sorghum, beans and bananas (Crerar & Akurut, 2017) other crops grown in the catchment include field peas, maize, wheat and vegetables (Osiru, 2006). Grazing land is scarce, and animals are grazed on marginal hillsides, valley bottoms and fallow land (Osiru, 2006). Less than about half of the farmers own livestock (Crerar and Akurut, 2017). Outside of the Echuya Forest Reserve, very little, if any of the original forest cover remains but there are significant areas of eucalyptus plantations.

As already mentioned, from the scoping mission conducted as part of this study in July 2017 (Crerar & Akurut, 2017), it was observed that despite the steep slopes there is very little evidence of terracing throughout the catchment. As a result, there are high levels of erosion, especially during intense rainfall events. This results in soil (and often pebbles, cobbles and rocks) being washed from the upper slopes to the lower slopes and valley bottoms, and in extreme cases, landslides. In recent years, farmers located on the upper farmed areas of the catchment have subsequently experienced decreasing crop yields.

Figure 1 also shows the sub-catchment delineation used. The boundaries are based on the SRTM 30 m DEM and were derived using the GIS software Global Mapper. The sub-catchment divisions are based on hydrological consideration and therefore differ from the delineations used in CMP (2015). In total, the Ruhezamyenda catchment is divided into eight sub-catchments, of which sub-catchment 4 belongs to Lake Bunyonyi. Sub-catchments 1 to 4 constitute the Lake Bunyonyi catchment, which is the focus of the hydrological components of this report.

[1] On 1 July 2016 a new district named Rubanda was created. It shares boundaries with the districts of Kanungu, Kisoro and Kabale. In fact Rubanda was previously one of three counties (Ndorwa, Rubanda and Rukiga) under Kabale district, whereas Kisoro District comprises only one county (Bufumbira).

Figure 1. Study area: Overview map, topography and sub-catchments



Source: Author diagram.

From 1987 to 2014 (Table 1 and Figure 2) the most significant and predominant land-use change that took place in the catchment was the conversion of tropical high forests to small-scale farmland and woodlots. Another significant change that took place during this time was the decline in the wetland areas (Kizza et al., 2017).

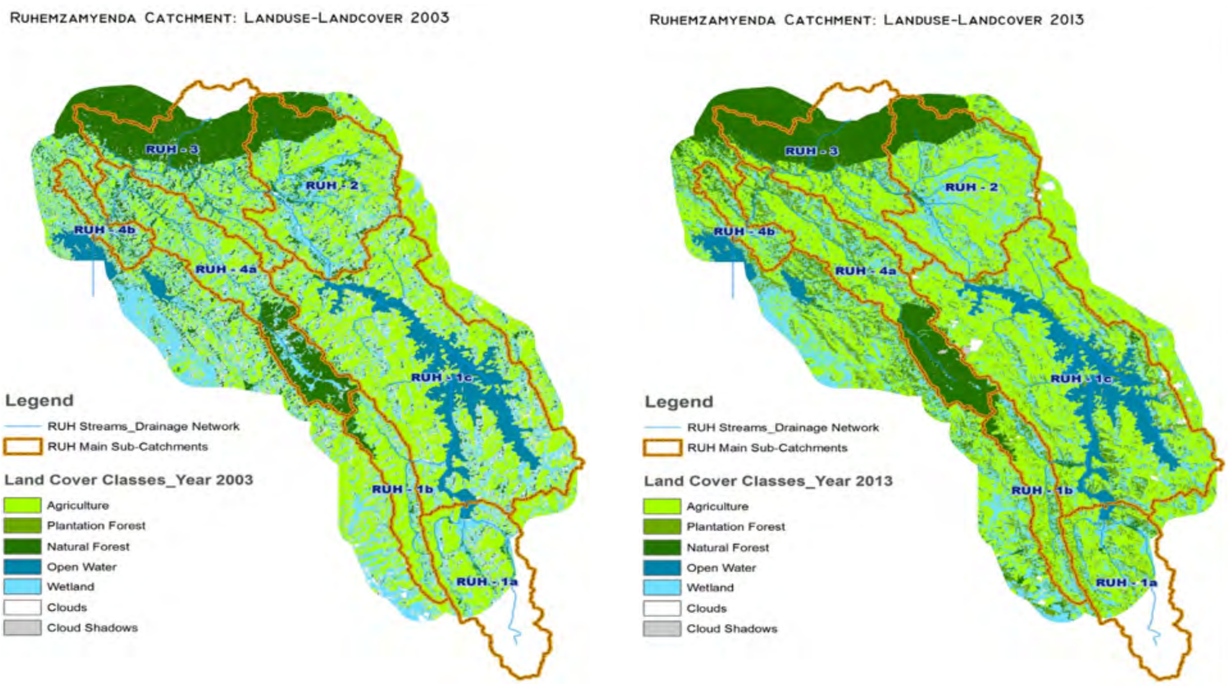
The change in land use has mostly been driven by population pressure in the entire Ruhezamyenda catchment, where the destruction of natural vegetation to meet household food and fuel needs is widespread. Hillslope areas in particular have been cleared of trees; as well, swaths of wetland have been reclaimed for agricultural purposes or planted with eucalyptus trees. This has resulted in more frequent floods and landslides (Rukundo, 2015).

Table 1. Land use/cover for 1987, 1999, 2005 and 2014 for Lake Bunyonyi catchment

Period	**1987**		**1999**		**2005**		**2014**	
Land use/cover types	**km²**	**%**	**km²**	**%**	**km²**	**%**	**km²**	**%**
Small scale farmlands	189.1	56.6	215	64.4	211.2	63.2	215.7	64.6
Tropical High Forest	12.4	3.7	9.7	2.9	9.5	2.8	7.2	2.2
Grasslands	0.2	0.1	0.15	0.04	0.4	0.1	0.09	0.09
Open water	52.5	15.7	50.8	15.2	49.8	14.9	40.6	12.2
Wetlands	21.4	6.4	13.3	4.0	11.9	3.6	8.7	2.6
Woodlots	58.6	17.5	45.1	13.5	51.5	15.4	61.8	18.5

Source: Kizza et al., 2017.

Figure 2. Land use/cover map for years 2003 and 2013 for Lake Bunyonyi catchment.



Source: CMP database (Rukundo, 2015). The land use/cover classifications were undertaken using 2003 and 2013 satellite images. The sub-basins in Figure 2 are the ones denoted in the CMP and differ somewhat from this study's setup, which uses eight sub-basins (Lake Bunyonyi has its own sub-basin).

The main climate hazards identified by local stakeholders consulted as part of this study include: flash floods, droughts, and more frequent and heavy rains. They associate these hazards with a range of negative impacts including:

- An increase in landslide occurrences caused by heavy or prolonged rains, particularly on steep agricultural slopes.
- Decreased water availability in the catchment due to more variability in rainfall events and potentially longer dry spells, leading to less water for crop production, health and sanitation. This can translate into an increased workload for women and children (who have to fetch water) and also into a reduced attendance in schools for children and increased domestic violence.
- An increase in food insecurity due to crops being more often destroyed by landslides, flooding events, dry spells, new diseases, etc.
- No or low access to markets due to the poor road networks caused by the roads being washed away by heavy rains and/or more frequent runoff, or landslides. This in turn leads to lower incomes for the population.

2.2 Data Sources Available for Hydrological Modelling

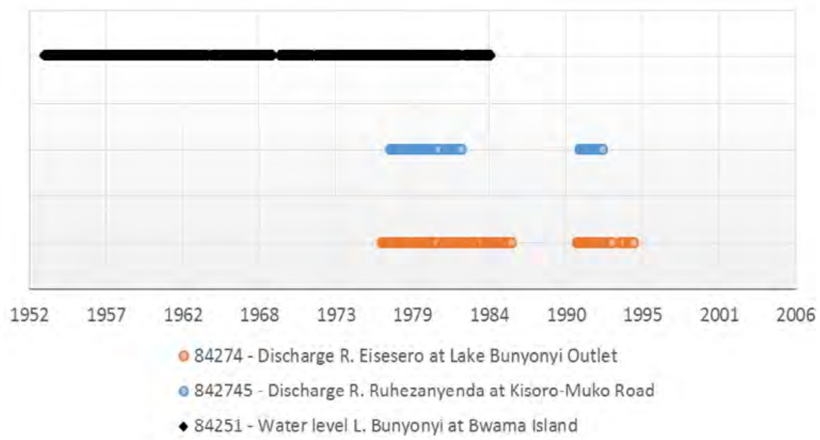
2.2.1 Historical Hydrological Data

There are two hydrometric stations that measure discharge in the catchment and one station that measures the water level of Lake Bunyonyi (Figure 1). At the time of the field scoping mission in July 2017, none of the gauges were in operation (Crerar & Akurut, 2017). For this study, two of the hydrometric stations were used (number 84274 at the Lake Bunyonyi outlet and number 84251, which measures the water level of the Lake Bunyonyi at Bwama Island).

The time series of discharge from the gauge number 84274 for the outlet of Lake Bunyonyi is available from 1971–1995, however with substantial gaps. The time series of the water level of Lake Bunyonyi at Bwama Island has fewer gaps and covers the period 1953–1984 (Figure 3).

For the gauge number 842745 at Kisoro-Muko Road, it is unclear where the gauging site is located. For this reason, and since the focus of this report is the Lake Bunyonyi catchment, the data was not used.

Figure 3. Availability of Lake Bunyonyi discharge data and water level measurements



Source: Authors diagram.

2.2.2 Historical Precipitation Data

Nine stations that monitor precipitation located in, or in proximity to, the catchment are used for the observed precipitation data. The mean annual rainfall for the period ranges between 922 and 1,202 mm/yr (Table 2). Data was provided by the Directorate of Water Resources Management (DWRM).

The available station precipitation data from 1951 to 1977 had a relative unbroken time series, with between 2 and 5 stations contributing data during this time period. However, after 1978 the number of stations with available data dropped to between 0 to 3 stations that contributed data, with the exception of the period from 1992 to 1995, which had more data and had 2 to 6 stations that provided precipitation data. Annex 1 depicts the availability of the precipitation data in graphic form.

Table 2. Rainfall station data obtained from the Directorate of Water Resources Management (DWRM) database; the location of the stations marked "*" were estimated based on secondary information[2]. Stations marked "+" have identical data. The mean annual rainfall values are based on the available time series (with data gaps filled).

Station-ID	Name	Longitude	Latitude	Mean annual rainfall (1971–2000) [mm]
91290080	Bufundi	29.867	-1.300	1,011
91290090	Bwama	29.933	-1.300	922
91290120	Kachwekan	29.950	-1.250	998
91290140	Rubaya	29.933	-1.433	953
91290190	Rushanga+	29.700	-1.117	1,108
91290230	Echuya+	29.800	-1.267	1,108
91290100	Bukimbiri*	29.683	-1.183	1,026
91290040	Karengere*	29.800	-1.217	1,202
91290240	Muko*	29.814	-1.204	978

Precipitation is both one of the water balance components and an input to the hydrological model, thus the estimation of the spatially distributed precipitation is an important task. To cope with the many data gaps in the time series, the missing precipitation data from the stations was filled using correlation analysis and linear regression. For every station, the correlation with the other stations was calculated. Next, a linear regression model was then derived between the station with a data gap and a corresponding station with data and exhibiting the highest correlation. The linear regression model was then used to fill the missing value. When no station data was available, which was the case for some periods, data from a global gridded data set (CRU TS v4.01; see next section) was used. The precipitation data files of stations Rushanga and Echuya showed identical time

[2] The missing station coordinates were obtained from The Nile Basin Initiative and from ArcGIS websites: http://atlas.nilebasin.org/treatise/the-lake-albert-sub-basin/ https://www.arcgis.com/home/item.html?id=070094fdad50425bb7b74453aa87b728

series. It was not possible to determine to which station the time series belonged to and therefore it was decided to keep the data from both stations due to the generally limited data availability.

2.2.3 Historical Gridded Data

CRU DATA

Since no air temperature data was available from local weather stations, the data for air temperature and for the diurnal temperature range was acquired from the freely available CRU TS v.4.01 global gridded data. The CRU TS (Climatic Research Unit Timeseries) gridded climate dataset stems from the University of East Anglia and is available at a 0.5° resolution (50 km at the equator) for all land areas except Antarctica (Harris et al., 2014).

The air temperature and the diurnal temperature range from CRU TS were used to calculate the potential evapotranspiration (PET) using the Hargreaves equation (Hargreaves & Samani, 1982):

$$\text{PET (mm / month)} = 0.0023 * R_a * (T_{max} - T_{min})^{1/2} * (T_{mean} + 17.8) \qquad \text{(Eq. 1)}$$

where R_a = extraterrestrial radiation expressed in mm/month as equivalent of evaporation, Tmax = maximum temperature (°C), T_{min} = minimum temperature (°C), T_{mean} = maximum daily temperature minus daily minimum temperature (°C). The R_a values were calculated as a function of latitude and the day of the month.

Some periods also had substantial data gaps or even no in-situ observations of precipitation. Thus, the missing precipitation data was filled with the gridded data set. The CRU TS monthly data for the period 1900 to 2015 pertaining to the grid cell with its centre coordinates on -1.25 / 29.75 (lat/lon) was extracted from the CRU TS v4.01 data set (Harris et al., 2014). This one grid cell almost entirely covers the entire study area. This is far from ideal, since local temperature or precipitation characteristics and variations are not captured. Due to missing in-situ observations, however, no other options were available. This highlights the importance of operating and maintaining a hydrometric observation network.

GLOBAL PET DATA

To check the plausibility of the potential evapotranspiration (PET) data used in this study, the Global PET dataset (Trabucco & Zomer, 2009) was used. This dataset also uses the Hargreaves equation to calculate PET for Africa and is based on data available from the WorldClim Global Climate Data (Hijmans et al., 2005) which is a set of global gridded climate data with a spatial resolution of about 1 km^2. This is a dataset available as monthly averages (12 data layers, i.e., one layer for each month, averaged over the 1950–2000 period). The data is available from the CGIAR-CSI (Consultative Group for International Agriculture Research - Consortium for Spatial Information; http://www.csi.cgiar.org) as global gridded data with a spatial resolution of 1 km at the equator.

2.2.4 Historical Discharge at Lake Bunyonyi Outlet and Lake Water Level

The discharge measurement at the outlet of Lake Bunyonyi (84274) has shown to be unreliable. Therefore, two different mathematical relationships between the Lake Bunyonyi water level and discharge have been developed in the past.

The first linear relationship between the Lake Bunyonyi water level and the discharge from Lake Bunyonyi at gauge 84274 was determined empirically as being:

$$Q_{WL_{LinFunct}} = 5.1062 \times WL - 5.4412 \qquad \text{(Eq. 2)}$$

where Q_{WL} is discharge and *WL* is the water level.

The Eq. 2 is based on a linear relationship using discharge (m^3/s) data and the water level height (m) for the period April 1, 1977 to December 31, 1979. This relationship shows a coefficient of determination R^2 of 0.62.

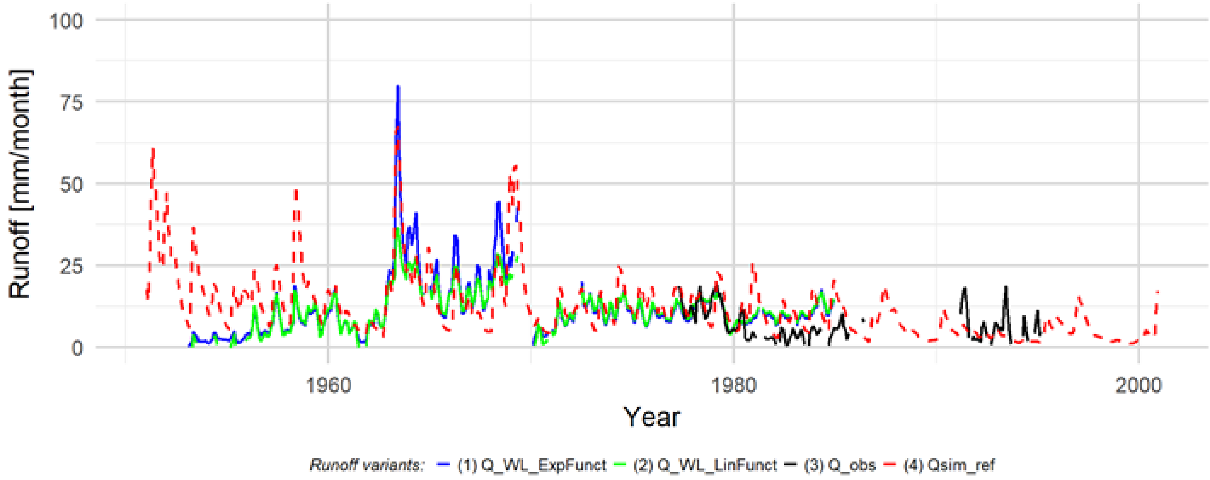
An exponential equation was also determined between discharge and the lake water level shown in Eq. 3.

$$Q_{WL_{ExpFunct}} = 0.3213 \times WL^{4.8121} \quad \text{(Eq. 3)}$$

Additionally, it is necessary to adjust the Lake Bunyonyi water height data due to the distinct and abrupt change in water level that takes place after 1970. This may have been for example, due to the water level indicator being shifted after some occurrence or event. The difference between the mean monthly lake levels from 1953–1969 and 1970–1984 is 0.54 m. By simply subtracting 0.54 m from the lake levels recorded from the 1953–1969 original monthly lake level data, the data appeared to make a lot more sense. For the current study, the exponential relationship (Eq. 3) was used.

Figure 4 shows the different runoff variants at the outlet of Lake Bunyonyi, including the simulation with the hydrological model as a reference.

Figure 4. Runoff from Lake Bunyonyi at gauge 84274, with different time series available: discharge calculated using Eq. 2 (blue; exponential relationship), using Eq. 3 (green; linear relationship), the observed data (black), and the COSERO model simulation as a reference (red).



2.2.5 Future Climate Change Simulations

Thirty climate simulations (Annex 2) were available from the CMIP5 global climate model (GCM) ensembles (Taylor, Stouffer, & Meehl, 2012) at a spatial resolution of 0.5° (50 km by 50 km at the equator). The required climate variables to run the hydrological model were: surface precipitation amount (*pr*), minimum temperature (*tasmin*) and maximum temperature (*tasmax*). The period of data availability from the climate simulations was from 1950 to 2100; for this study two Representative Concentration Pathways (RCPs) of RCP4.5 and RCP8.5 were used to capture a wide range of possible outcomes. These selections represent one of the lowest and the highest future GHG emission scenarios, respectively. The mean monthly averages were calculated from the output variables. All data was obtained from the ESGF (Earth System Grid Federation; https://esgf.llnl.gov/) and downloaded and bias corrected for the grid cell of interest to this study by The Climate Data Factory (https://theclimatedatafactory.com/). Annex 2 lists the final GCMs used for this study.

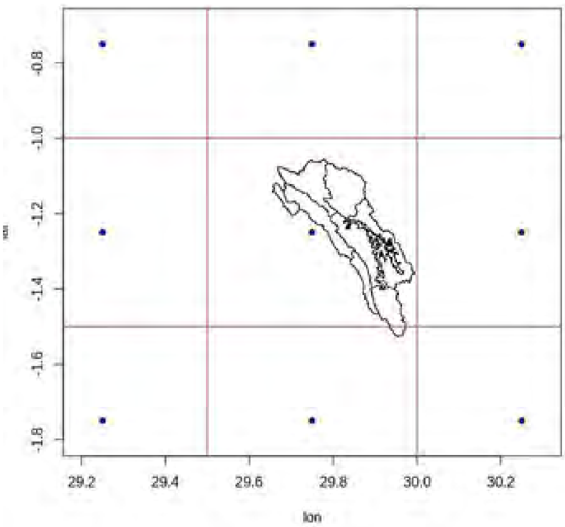
The climate simulations were bias-adjusted using the CDF-t (cumulative distribution function transform) method which is a quantile mapping method. The observed-based reference dataset for bias-adjusting the CMIP5 GCM data is the WATCH-Forcing-Data-ERA-Interim data

(WFDEI: http://www.eu-watch.org/data_availability). The CDF-t method for *tasmin* and *tasmax* variables uses a moving time of the large-scale CDF from the historic to the future time period (Michelangeli, Vrac, & Loukos, 2009; Vrac et al., 2012). The adjusted climate simulations have the same CDF as the re-analysis observed-based data. The *pr* variable was adjusted with an updated CDF-t which considers rainfall occurrence as well as intensity (Vrac et al., 2016).

Finally, the climate variables underwent a quality control for compliance with the community's climate standards, data consistency and metadata. For more information see Cochard, Loukos, & Noel (2018). In this study, for the RCP4.5 future, 22 climate simulations were used, and for the RCP8.5 future all 30 climate simulations were used (see Annex 2).

All the simulated climate data was downloaded for one grid cell which encompassed almost the entire area of the Lake Ruhezamyenda catchment (Figure 5). The centroid of the grid cell was located at longitude 29.75° and latitude -1.25°.

Figure 5. CMIP5 grid cells shown in red, with centroids depicted as blue dots. The Lake Ruhezamyenda catchment is outlined with the eight sub-basins



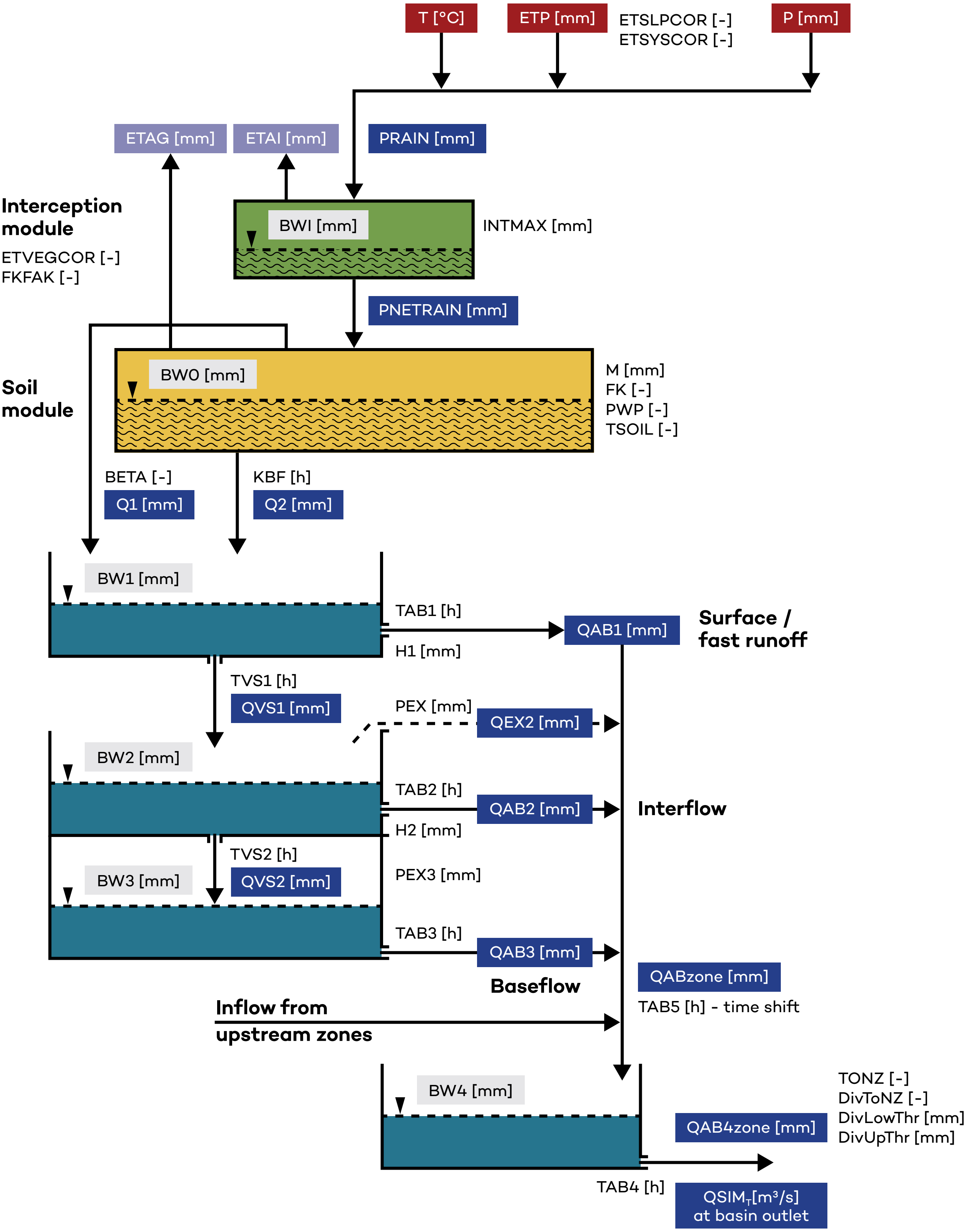
Source: The Climate Data Factory, 2018.

2.3 The Hydrological Rainfall-Runoff Model COSERO

The COSERO (COntinuous SEmi-distributed RunOff) rainfall-runoff model is used in the present study to assess the water balance of the Lake Bunyonyi catchment. COSERO is a continuous, (semi-distributed), conceptual rainfall-runoff model that was developed at the Institute of Water Management, Hydrology and Hydraulic Engineering (IWHW). Different hydrological models could have been used for this study. Given our experiences and wide applications of the model, we decided to use COSERO. An additional advantage of COSERO is the flexibility of its application, depending on the availability of data. Given the limited availability of spatially distributed data in the Ruhezamyenda catchment, i.e., for soil texture and meteorological inputs, the model was setup in a lumped manner, whereby the soil parameters are estimated in the calibration step. However, if more detailed data had been available, a distributed COSERO model could have been setup.

The COSERO model concept is very similar to the open source HBV model (Hydrologiska Byråns Vattenbalansavdelning model, Bergström, 1992). It accounts for actual evapotranspiration, interception storage, soil water storage, separation of runoff into different flow components and routing by means of a cascade of linear and non-linear reservoirs. Figure 6 shows the model structure, model parameters, system states and other fluxes used for the assessment.

Figure 6. The structure of the hydrological model COSERO used for rainfall-runoff simulations in the Ruhezamyenda catchment



Source: Author diagram.

The COSERO model evolved from a model structure that was originally developed for real-time runoff forecasting for the Enns River in Austria (Nachtnebel, Baumung, & Lettl, 1993). Since then, substantial modifications have been incorporated into the model (i.e., enhancements in the snow module [Fuchs, 1998] and automatic calibration [Kling, 2002]). Further modifications were undertaken, e.g., for the application of COSERO to water balance studies, real-time flood forecasting systems, distributed routing issues or for implementing new optimization methods.

Different versions of COSERO were successfully applied in numerous scientific and commercial projects all over the world. Model simulations have been performed at different spatial scales, ranging from plot scale to catchments of thousands of square kilometres. For water balance studies, the model was applied at a monthly temporal resolution, but also at a temporal resolution of 15 minutes for flood forecasting systems. The model has also been used to investigate the effects of climate change on runoff regimes (e.g., Hebenstreit, 2000; Nachtnebel & Fuchs, 2004; Stanzel & Nachtnebel, 2010; Nachtnebel et al., 2011) and the assessment of anthropogenic impacts on floods (Nachtnebel & Debene, 2005). The water balance of several catchments, including the spatio-temporal water balance of the Danube Basin was modelled with COSERO (e.g., Herrnegger, Nachtnebel, & Haiden, 2012; Herrnegger & Nachtnebel, 2011; Kling, 2006; Eder et al., 2005). The model was also applied in real-time flood forecasting and runoff prediction systems (Stanzel et al., 2008; Nachtnebel et al., 2008, 2009a, 2009b, 2010a, 2010b, 2013; Herrnegger, Senoner, & Nachtnebel, 2018; Wesemann et al., 2018a, 2018b). Additional references to applications of COSERO can be found in Kling et al. (2015). Lately, an inverse model with runoff observations as input to calculate areal rainfall was developed on the basis of COSERO (Herrnegger, 2013; Herrnegger et al., 2015; Herrnegger & Nachtnebel, 2012a; 2012b).

For the application of the COSERO model, and as mentioned previously, the Ruhezamyenda catchment was divided into eight sub-catchments (Table 3, Figure 1). The physical Lake Bunyonyi is occupied by sub-basin number 4 (Table 3). The sub-basins 1 to 4 belong the catchment of Lake Bunyonyi, which has its outlet at the gauging station 84274 at the end of sub-basin 4.

Table 3. The sub-basins in the Ruhezamyenda catchment (sub-basins 1-4 (red) belong to the Lake Bunyonyi catchment)

Sub-basin	Catchment area [km²]	Accumulated catchment area [km²]	Mean elevation [masl]
1	76.82	76.82	2,153
2	40.64	40.64	2,218
3	213.96	331.42	2,119
4	49.58	381.00	1,947
5	120.40	501.40	2,074
6	104.42	605.82	2,154
7	95.30	701.12	2,191
8	20.92	722.04	1,952
Total	722.04	—	2,101

The driving input for the COSERO model is a time series of precipitation data that is needed. If temperature time series are provided, COSERO can internally calculate potential evapotranspiration input with the Thornthwaite method. In the current study however, the Hargreaves method was used to calculate PET in a pre-processing step and provided to the model as input. The reason for using Hargreaves was that the Thornthwaite method showed unrealistic low PET values, also compared to the Global PET product.

3.0 Results – Hydrological Assessment of the Lake Bunyonyi Catchment

3.1 Calibration of the COSERO Hydrological Model for the Ruhezamyenda Catchment

The COSERO model was calibrated at a monthly time step for the period from 1951–2000. A warmup (or spin-up) period was used prior to the calibration from 1951–1958. The warmup period is used to guarantee that the system states in the model are in an equilibrium and that the modelling results are not influenced by the initial model states (e.g., soil moisture or ground water levels at the beginning of the simulation).

The observed runoff (Qobs) was based on the water level of Lake Bunyonyi and an exponential relationship (Eq. 3) between Bunyonyi Lake water level and discharge.

Potential evapotranspiration using Hargreaves equation with minimum, maximum and mean temperatures obtained from the CRU TS v4.01 dataset were used as input for the parameter calibration of the model. No temperature data from weather stations in the catchment was used, since this data was not available.

The precipitation data used was from the filled station data, using a correlation analysis and linear regression over the entire simulation period. Thiessen Polygons were used to calculate areal precipitation values for the sub-basins. The mean precipitation for every sub-catchment is thereby calculated as an area-weighted mean of the surrounding station time series. More complex interpolation procedures (e.g., External Drift Kriging) were not applied, since the potential benefits were estimated to be limited, especially considering the significant higher level of effort involved.

To determine the performance of the simulations from COSERO compared with the observations described above, the Kling Gupta Efficiency (or KGE) (Gupta et al., 2009) objective function was used:

$$KGE = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2} \quad \text{(Eq. 4)}$$

The values of r, β and γ provide individual explanations of the performance of a model; the r is the correlation coefficient, β is the bias ratio (i.e., ratio between the mean simulated and mean observed discharges), and γ is the variability depicted as the ratio between the standard deviation of the simulated and observed discharges. All parameters strive for unity, so the closer the KGE is to 1, the better the model performance (a value of 1 indicates a perfect model simulation).

For the parameter optimization, the Shuffled Complex Evolution (SCE) algorithm, with the KGE as objective function, was used.

The Nash Sutcliff Efficiency (NSE) was used as a further criterion to evaluate the output:

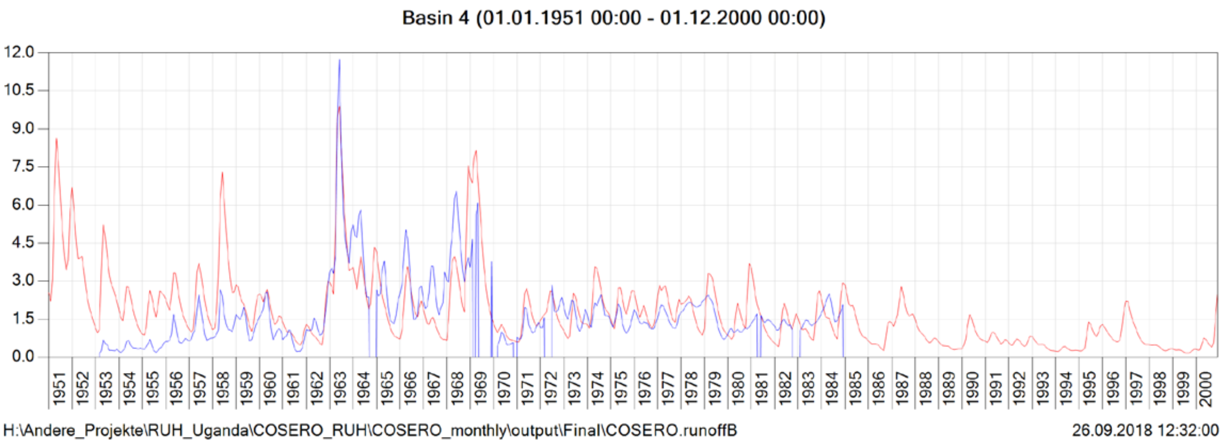
$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_m^t - Q_o^t)^2}{\sum_{t=1}^{T}(Q_o^t - \bar{Q}_o)^2} \quad \text{(Eq. 5)}$$

where Qm is the modelled discharge, Q_o^t is the observed discharge at time t, and Q_o is the mean observed discharges. The NSE can range from - ∞ to 1. An NSE = 1 corresponds to a perfect simulation of modelled to observed discharge. An NSE = 0 indicates that the model simulations are as good a predictor as the observed mean.

Table 4. COSERO model performance from 1951–2000 at the outlet of Lake Bunyonyi

KGE	r (correlation coefficient)	β (bias normalized by the standard deviation in observed discharge)	γ (relative variability in simulated and observed discharge)	NSE
0.78	0.78	1.00	0.98	0.57

Figure 7. Monthly observed (blue) and simulated (red) discharge (m³/s) for Lake Bunyonyi catchment outlet



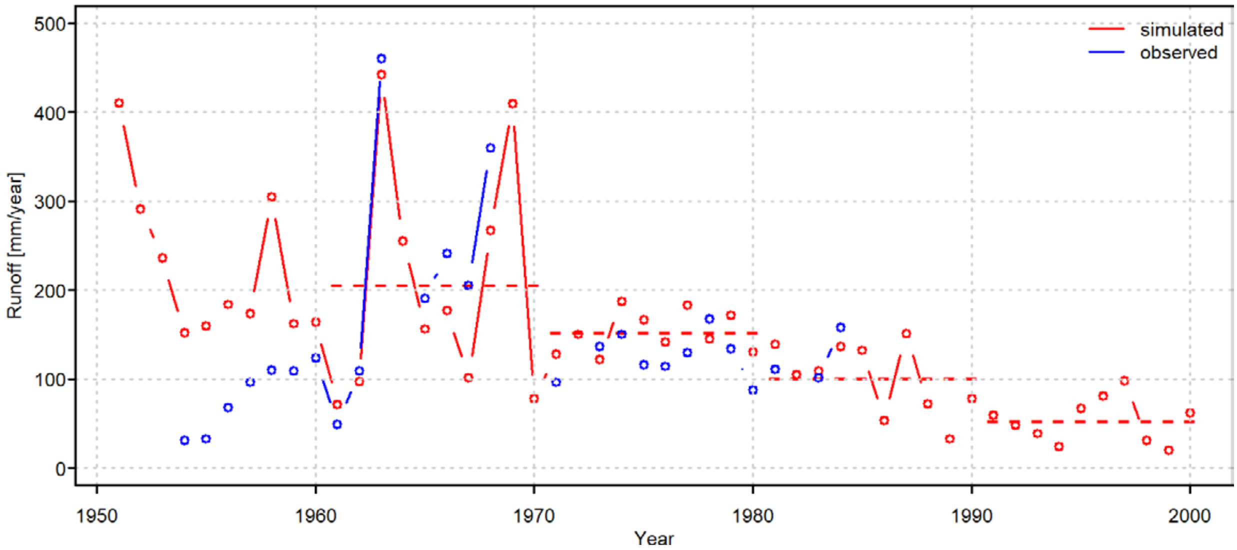
Source: Author diagram.

From Figures 7 and 8 as well as the corresponding objective function values obtained in Table 4, the COSERO model performed quite well for the historic period, especially considering the general data availability and the number of missing monthly discharge values to validate the model results with (Annex 3). The high KGE value (close to 0.8) indicated that the three components performed well: specifically, the correlation (r) was close to 0.8, and the ratio of the relative variability in the simulated and observed runoff was almost equal to 1.0 and the bias term ratio is equal to 1.0. All of these indicate a very good overall fit of modelled to observed values.

The NSE of 0.57 did not indicate as good a fit as the KGE, since it was not used as the objective function in the parameter calibration. Additionally, the lower NSE can be explained by the observed high peaks not being met by the model (Figure 7). The NSE is particularly influenced by the peak values, since the nominator term of the differences between simulated and observed values (Eq. 5) are squared, which amplifies larger offsets in high values, compared to the smaller values.

With the exception of the period 1951–1960, Figure 7 shows that the observed dynamics and magnitudes of annual runoff are captured quite well by the simulations. The discrepancies between simulations and observations in this period can currently not be fully resolved. It is unclear, if the discharge from the lake water level is biased, or if there are uncertainties in the rainfall inputs. It must also be considered that the first years in the simulation also depend on the initial system states of the model, which are unknown. When compared to Lake Victoria water levels and Nile discharge data at Jinja, the simulated high flows in the 1950s seem too high (Howell et al. 1988; Sutcliffe and Petersen, 2007). However, when ignoring this uncertainty, an obvious declining trend in the decadal means in runoff is visible. In the 1960s, a mean annual runoff of around 200 mm/yr was observed. This value is halved between 1980 and 1990 and between 1990 and 2000 a mean annual runoff of only slightly over 50 mm/yr is calculated, this is a significant reduction of –75 per cent.

Figure 8. Annual observed (blue) and simulated (red) runoff (mm/year) for the period 1971-2000 for the Lake Bunyonyi catchment outlet. The decadal means for the simulated runoff are shown as dashed lines.

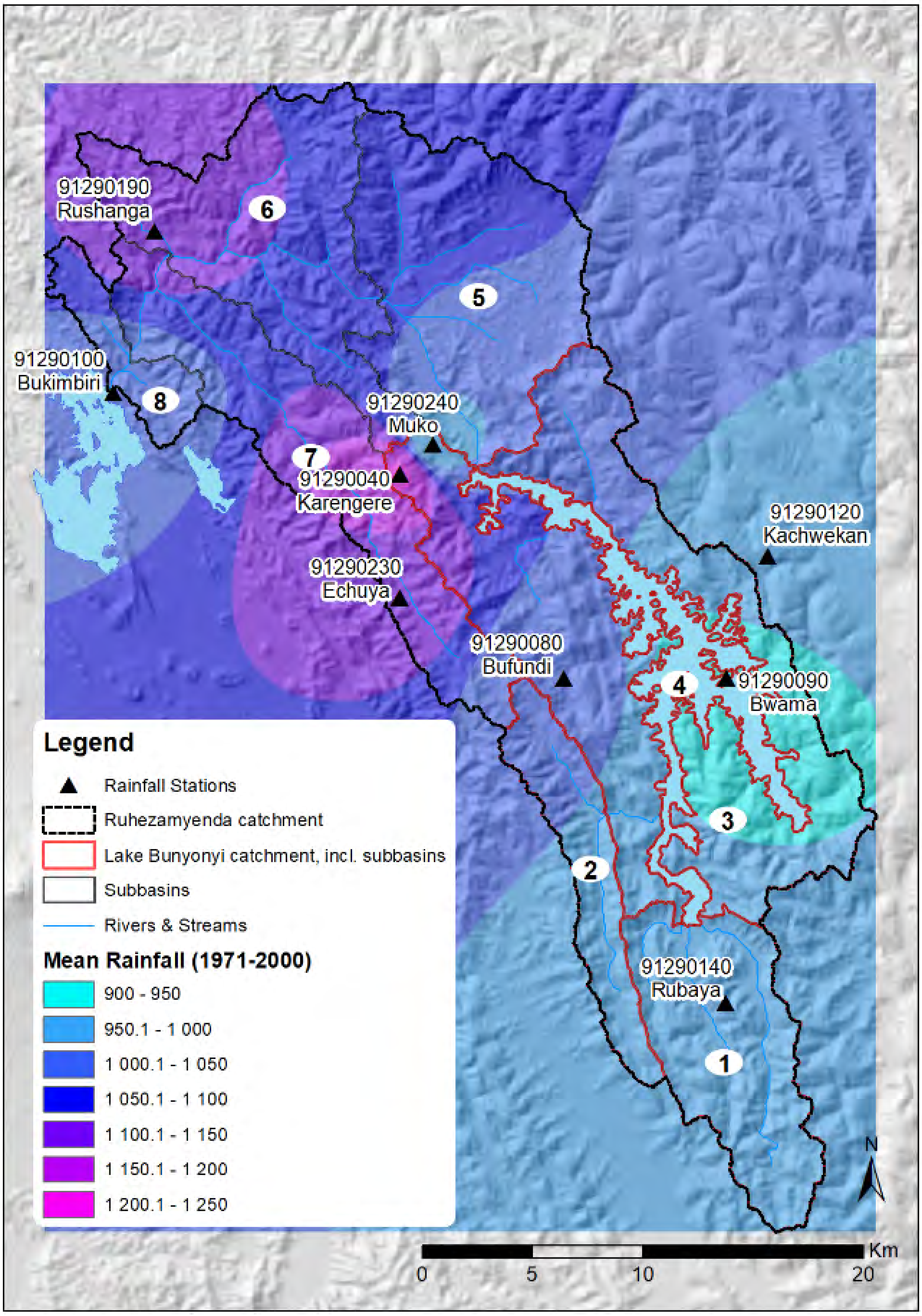


3.2 Climate Data Analysis

HISTORIC PRECIPITATION PATTERN

The spatial pattern of mean annual precipitation in the region is depicted in Figure 9, with the highest amounts (1200–1250 mm) found in a hotspot in the north-eastern part of the catchment over hilly terrain and the lowest amounts (900–950 mm) found in the eastern part of the catchment, over the eastern branch of the headwaters of Lake Bunyonyi. The precipitation pattern was derived by using spatial interpolation with inverse distance weighting (IDW, with an exponent of 4) of the missing data filled with station precipitation data.

Figure 9. Mean annual precipitation distribution (1971–2000) for the Ruhezamyenda catchment by IDW-interpolation.



Source: Author diagram.

3.3 Future Climate Simulations for the Ruhezamyenda Catchment

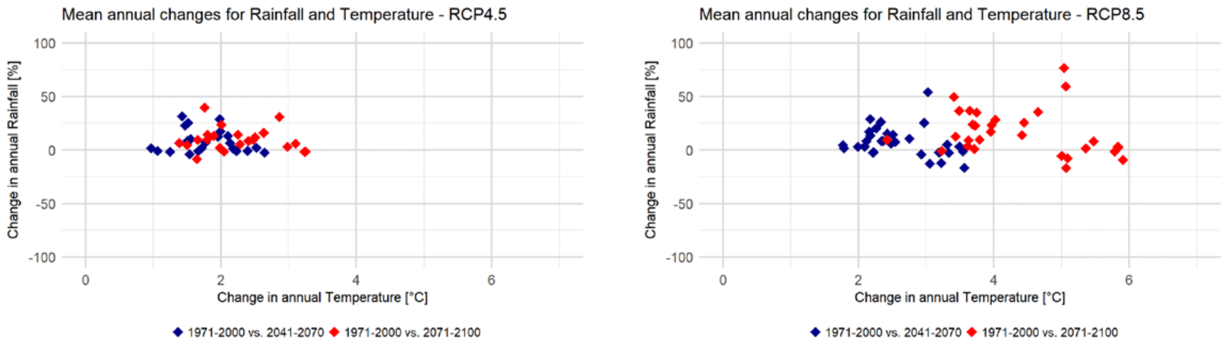
3.3.1 Overview

The climate simulation results (temperature, precipitation, PET) refer to the whole Ruhezamyenda catchment (Figure 5), and the results of the COSERO hydrological simulations (AET and runoff) refer to the Lake Bunyonyi catchment (sub-catchment 1 to 4; Figure 1). However, the general trends and results found for Lake Bunyonyi can be extrapolated to the whole Ruhezamyenda catchment.

All GCM simulations show increases in the mean annual temperature for the Lake Bunyonyi catchment (Figure 10). For the RCP4.5 scenario and compared to 1971–2000, all models show an increase in mean annual temperature of +1°C to slightly over +3°C in the far future period (2071–2100). In contrast, significant larger changes are calculated for the RCP8.5 scenario, especially for the far future. Here, single GCM models forecast an increase in mean temperature of around +6°C, however with a large spread, since a single model shows an increase of only around +2.5°C.

The simulations also indicate that the future climate in the Ruhezamyenda catchment can expect to have increases in precipitation. Compared to 1971–2000 and for RCP4.5, all models show an increase in mean annual precipitation between approximately 0 per cent and +50 per cent. In contrast, a larger spread and larger changes are calculated for the RCP8.5 scenario of between -25 per cent and +75 per cent.

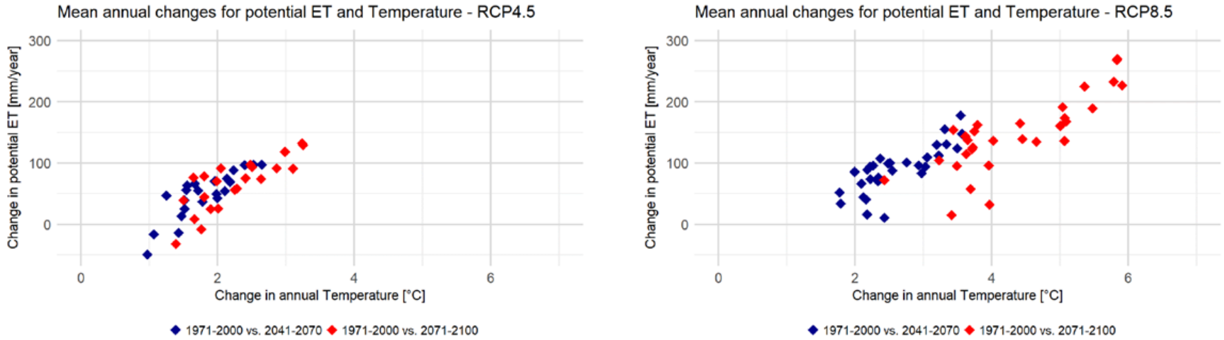
Figure 10. Mean annual change in precipitation [%] and temperature [°C] for future periods 2041–2070 and 2071–2100, compared to 1971–2000 (left - RCP4.5, right - RCP8.5) for the Ruhezamyenda catchment.



Source: Author diagram.

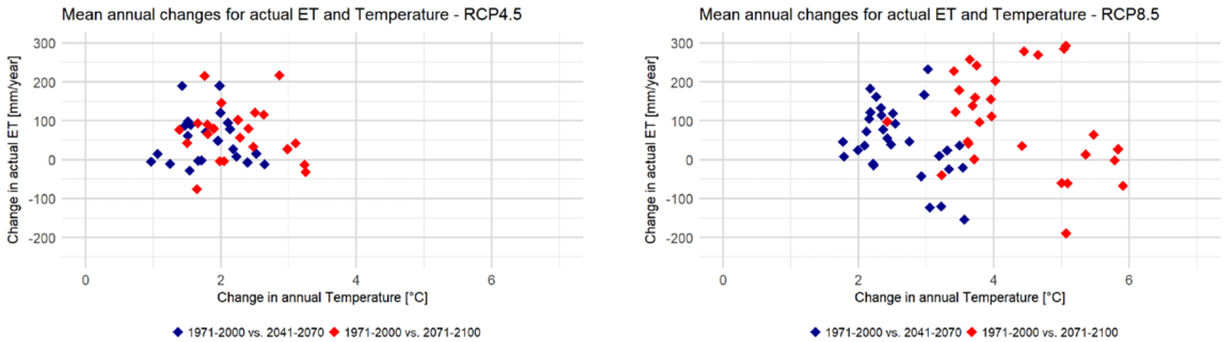
The increases in temperature simulated for the future also lead to increases in PET. Depending on the RCP scenario and the future period considered, increases of about 150 mm/yr (RCP4.5) to 275 mm/yr are calculated, compared to 1971–2000 (Figure 11). The changes in AET show a more heterogeneous picture, with a change in AET of -100 to +220 mm/yr (RCP4.5) and -200 to +300 mm/yr (RCP8.5). AET was simulated in the hydrological model and is influenced by vegetation and soil moisture availability, which is again also a function of the precipitation input. Hence, the change in AET with air temperature is not linear (Figure 12).

Figure 11. Mean annual change in potential evapotranspiration [mm/year] and temperature [°C] for future periods 2041–2070 and 2071–2100, compared to 1971–2000 (left - RCP4.5, right - RCP8.5) for the Ruhezamyenda catchment.



Source: Author diagram.

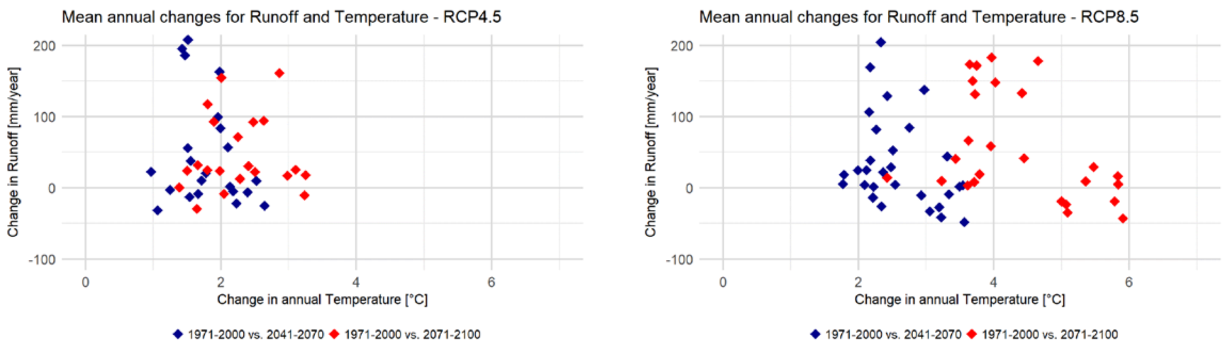
Figure 12. Mean annual change in actual evapotranspiration [mm/year] and temperature [°C] for future periods 2041-2070 and 2071-2100, compared to 1971-2000 (left - RCP4.5, right - RCP8.5) for the Lake Bunyonyi catchment.



Source: Author diagram.

Changes in runoff and temperature for both future periods and RCPs indicate some decreases in both the RCP scenarios of around 50 mm/yr, but for the most part an increase in annual runoff for the catchment, especially for the far future and RCP8.5. Here increases of up to 200 mm/yr are simulated (Figure 13).

Figure 13. Mean annual change in runoff [mm/year] and temperature [°C] for future periods 2041–2070 and 2071–2100, compared to 1971–2000 (left - RCP4.5, right - RCP8.5) for the Lake Bunyonyi catchment.



Source: Author diagram.

Box 1. How to interpret the results

Climate simulations are one of several tools available to help decision-makers identify specific adaptation needs for their water catchment.

The climate simulations provide a range of possible outcomes to the hydrology in the catchment. The benefits of using results from the multimodel CMIP5 ensemble are different than the value of any individual model alone. The multimodel represents the best-effort techniques by the climate community to simulate the climate system (Taylor et al., 2012). The collection of models is furthermore not systematically biased and can be used to represent a consensus of the future climate based on the spread of the results.

Using a suite of climate simulations from 30 GCMs (22 RCP4.5 and 30 RCP8.5) in this study captured a large range of uncertainty in the modelling exercise. Using several climate model outcomes is desired because all model simulations are probable outcomes of future scenarios. Using a climate ensemble is recommended, as it leads to more robust median and mean values by considering all of the possible outcomes instead of using only a few. However, the difficulty in interpreting the results is that the decision-makers and stakeholders have to work with a wide range of possible outcomes.

The quantiles provide a certain amount of confidence. For example, if the simulated outcomes for the future lie between the 33 per cent and 66 per cent quantiles, it can be interpreted that there is a 33 per cent probability that the outcomes may occur, based on the available models. Of course, if more or less climate change models are used, the outcome range may be altered, but by increasing the model ensemble the information about the uncertainty in the projections is improved (Wilcke & Bärring, 2016), which helps to provide more information about the possible range of the impacts to expect.

According to the International Panel on Climate Change (Mastrandrea et al., 2010), when 99-100 per cent of the climate models indicate the same change for the future, it is virtually certain that the change can be expected; when 90-100 per cent of the models indicate the same change for the future, it is very likely that the change will take place; when 66-100 per cent of the models indicate the same change, the change is likely to occur; and when 33-66 per cent of the models agree, then the change is about as likely as not to occur.

3.3.2 Changes in Temperature

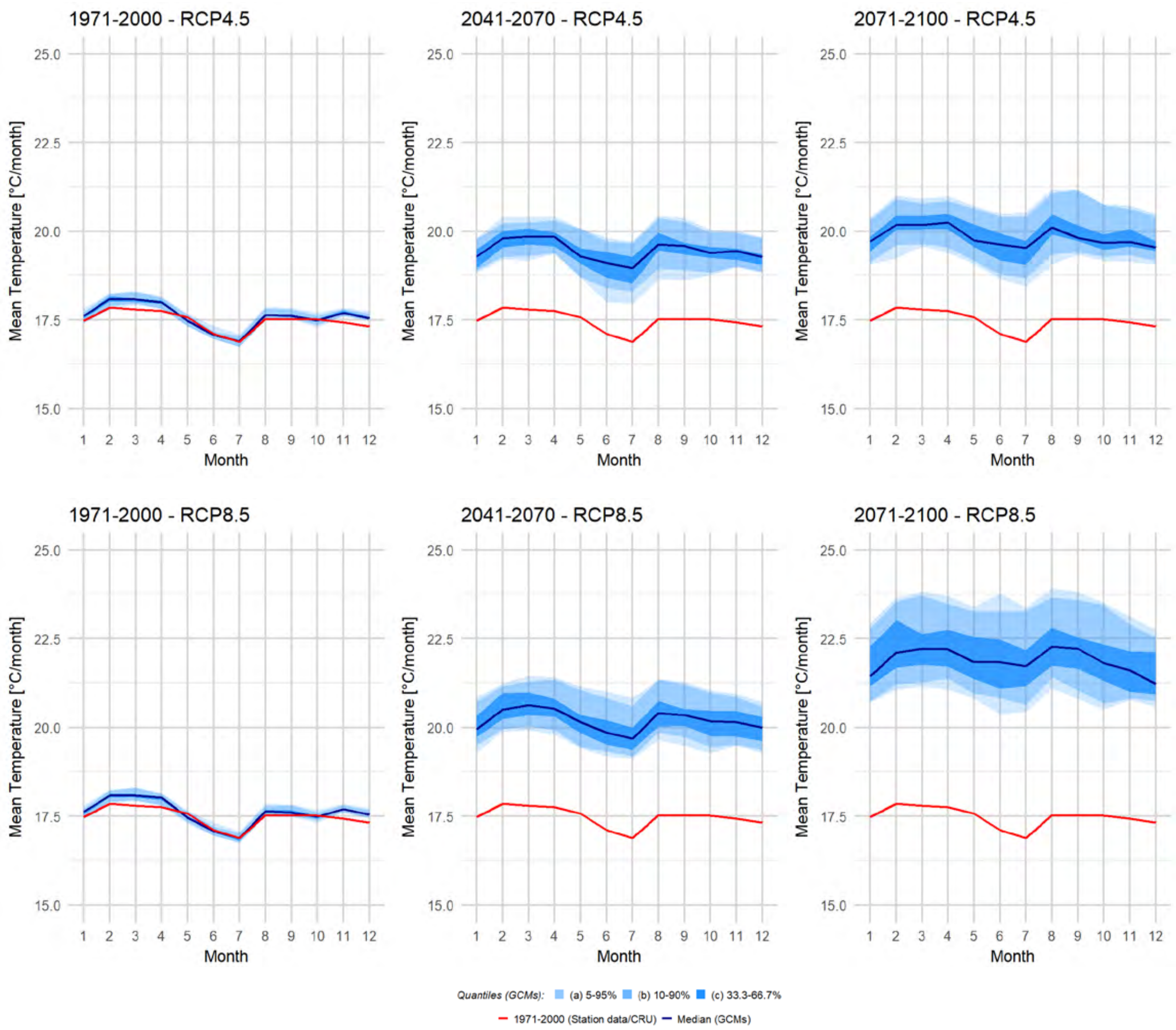
The mean monthly temperature graphs for the Ruhezamyenda catchment are shown in Figure 14. The red line represents the CRU TS v4.01 data, and the blue areas represent the temperature from the GCMs. Here (and in the other plots) the different shadings of blue indicate the quantiles of the GCM ensemble. The dark blue area around the median (thick blue line) constitutes the range, in which 33.6–66.7 per cent of the GCMs lie. The next lighter blue shaded area represents the 10–90 per cent quantiles, and finally the light blue area represents the 5–95 per cent quantiles. The larger the overall blue area is, the larger is the spread of the climate simulations and modelling results and thus the larger are the uncertainties in the future impact.

For the historic period 1971–2000, the observed data is very similar to the GCMs (first panel).

The mean annual temperature for future periods increases in all scenarios (Figure 14 and Annex 4). For RCP4.5 by 2041–2070, the median of the GCMs increases is approximately 1.5°C compared to historic data and by 2071–2100 the increase is about 2.0°C. For RCP8.5 by 2041–2070, the GCM median increases by approximately 2.5oC and by 2071–2100 the increase is about 4.0°C.

The future shows a general increase in temperature in all GCMs. This is not only the case for the median, but for all single GCM ensemble members. However, a large spread in the results is also evident. The dry season remains the cooler season, but by 2071–2100 in the RCP8.5 scenario, the mean monthly temperature remains almost as high as during the wet seasons.

Figure 14. Mean monthly temperature [°C] for the period 1971–2000 (left), 2041–2070 (middle) and 2071–2100 (right) (top - RCP4.5, bottom - RCP8.5) for the Ruhezamyenda catchment.



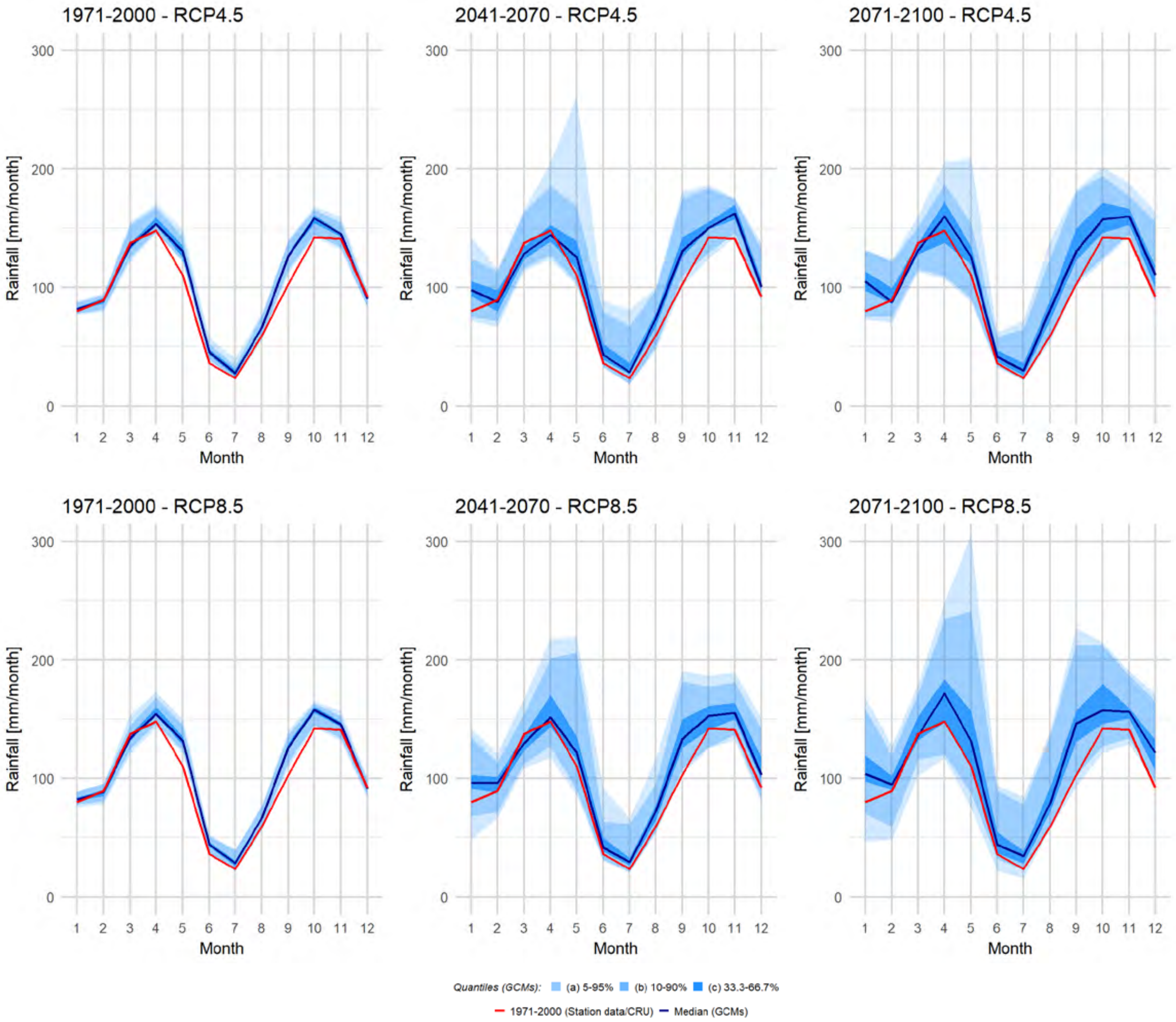
Source: Author diagram.

3.3.3 Changes in Rainfall

In Figure 15, the monthly precipitation values for the period 1971–2000 from the station precipitation data (with missing values filled) indicated a good fit with the output of the GCM data. Only in the months April to November were values from station data slightly lower than the median of the GCMs.

The future periods for both RCPs show higher uncertainties in precipitation, especially from April to May, indicating that the GCM models do not agree. The reason for the large peak during this time was due to one of the GCMs simulating rather large events during these months. Since all climate simulations are plausible future outcomes, this indicates that more uncertainty may be expected in precipitation received during the spring months.

Figure 15. Mean monthly rainfall [mm/month] for the period 1971–2000 (left), 2041–2070 (middle) and 2071–2100 (right) (top - RCP4.5, bottom - RCP8.5) for the Ruhezamyenda catchment.



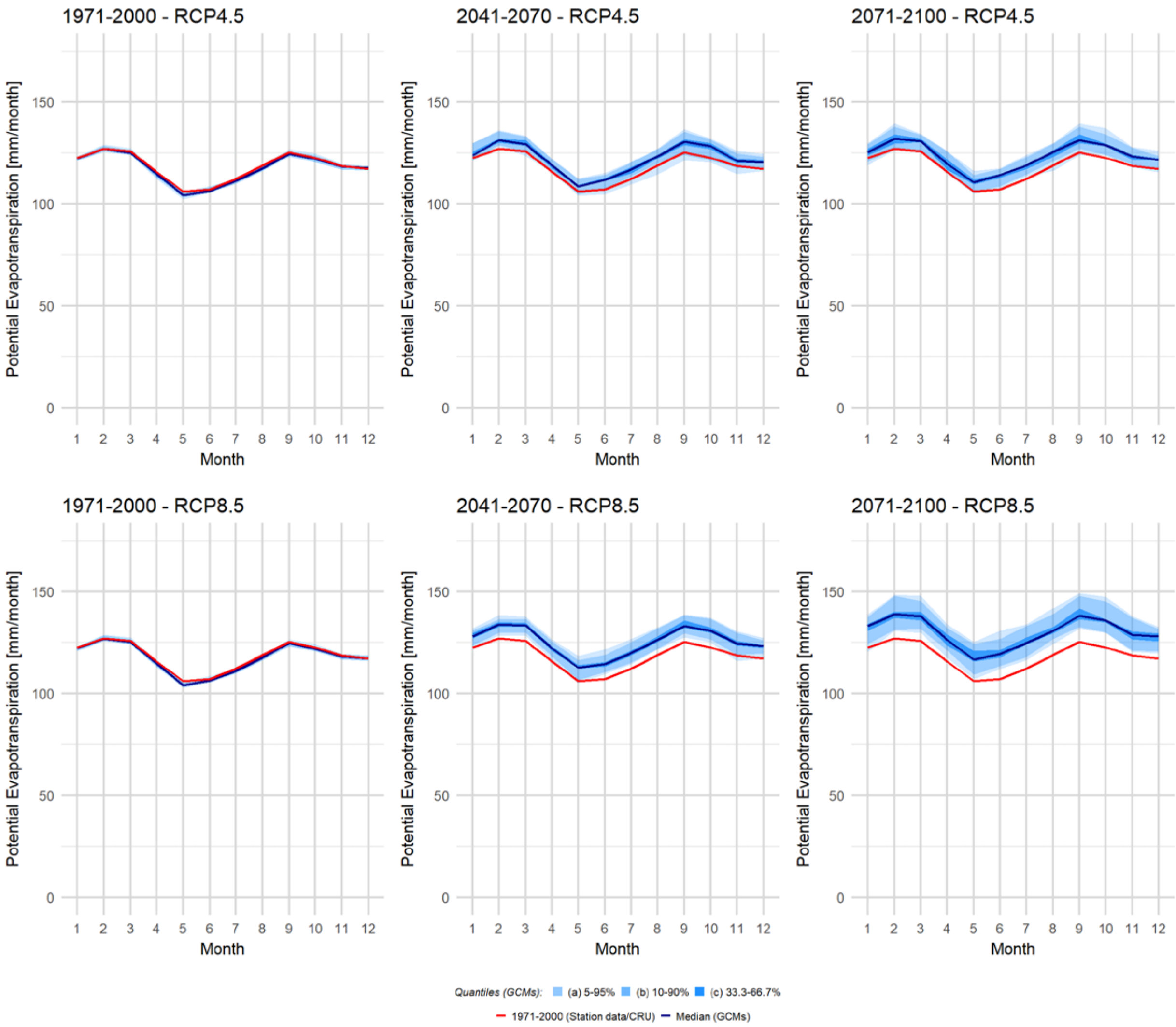
Source: Author diagram.

3.3.4 Changes in Evapotranspiration

POTENTIAL EVAPOTRANSPIRATION

For 1971–2000, the simulated PET values using the CRU TS data as the observed data are shown as a red line in Figure 16. The other PET (blue) lines were calculated by using the Hargreaves equation with the minimum and maximum temperature data obtained from the GCM climate simulations. The fit between the simulated with the GCMs and with CRU TS data was very good for monthly PET values. Although the seasonality appears to stay very similar under future climate conditions, a general increase in PET is visible.

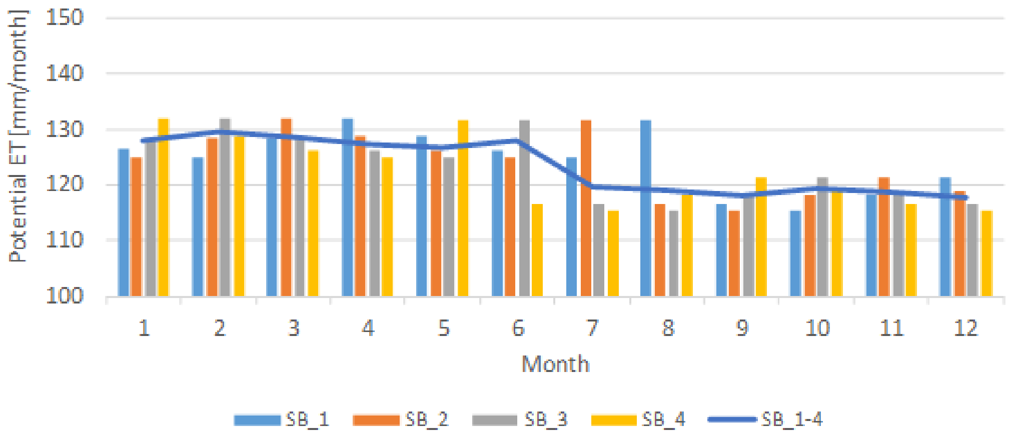
Figure 16. Mean monthly potential evapotranspiration [mm/month] for the period 1971–2000 (left), 2041–2070 (middle) and 2071–2100 (right) (top - RCP4.5, bottom - RCP8.5) for the Ruhezamyenda catchment.



Source: Author diagram.

To compare and check the plausibility of the PET values calculated using the Hargreaves equation for the Lake Bunyonyi catchment, the global gridded data called Global PET (Trabucco & Zomer, 2009) was used. For each sub-basin, the monthly PET was calculated (Figure 17). The monthly PET trends reproduced the lowest values during the dry season.

Figure 17. Long-term (1950–2000) mean monthly potential evapotranspiration per sub-basin (SB) of the Lake Bunyonyi catchment



Source: Global PET; Trabucco & Zomer, 2009.

Table 5. Long-term (1950–2000) mean annual potential evapotranspiration from Global PET per sub-basin (SB) of the Lake Bunyonyi catchment

	SB 1	SB 2	SB 3	SB 4	Mean SB (1-4)
PET [mm/year]	1,495	1,487	1,479	1,466	1,481

Source: Global PET; Trabucco & Zomer, 2009.

The PET from the Global PET data (Table 5) is 60 mm, or 4 per cent higher compared to the PET calculated with the Hargreaves equation and using the CRU TS v4.01 temperature data (Table 6).

Table 6. Long-term mean annual water balance components for the period 1971-2000 for the sub-basins of the Lake Bunyonyi catchment. *simulated with COSERO

Water balance 1971–2000 [mm/year]	Rainfall	Potential ET	Actual ET*	Runoff*
Sub-basin 1	1,202	1,420	1,127	75
Sub-basin 2	987	1,420	949	38
Sub-basin 3	990	1,420	954	36
Sub-basin 4 – Outlet of Lake Bunyonyi	1,163	1,420	1,055	108

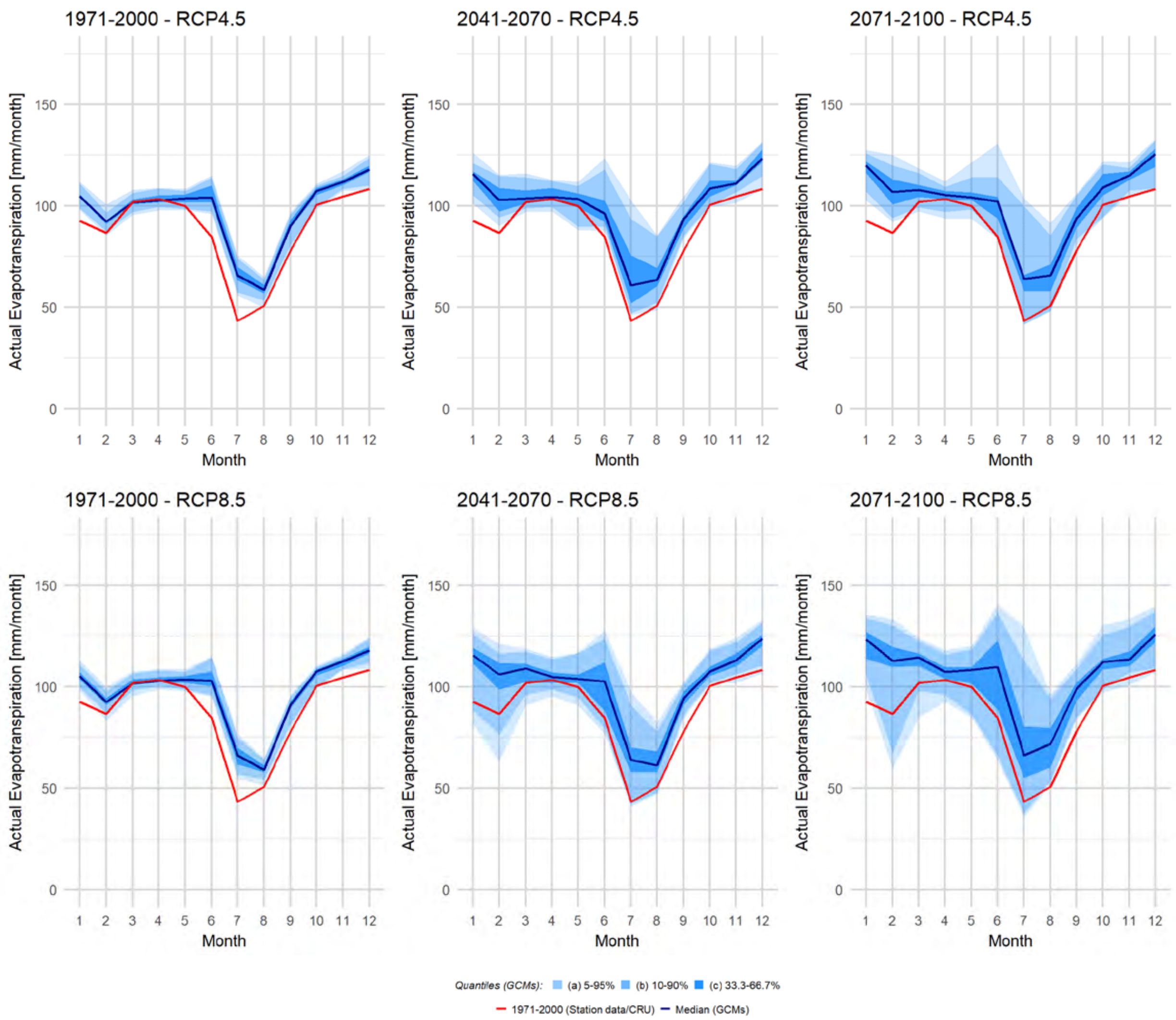
In summary, for the historic period 1971–2000, we compared PET values obtained from Global PET data to the calculated PET using two datasets: 1) the CRU TS minimum and maximum temperature, and 2) GCMs minimum and maximum temperature. The latter two compared well, however the Global PET values were 4 per cent higher overall; this could be due to the period of comparison being longer (1950–2000) and also a finer resolution of the Global PET data (1 km).

Overall, the PET values calculated with Hargreaves using either method compared well with another independent Global PET product, so that we have confidence for the further simulation of AET using the hydrological model, which requires the calculated PET values from the GCM data as input.

ACTUAL EVAPOTRANSPIRATION

The hydrological model calculates the monthly AET thereby considering the available energy for evapotranspiration (PET), vegetation cover and soil moisture dynamics.

Figure 18. Mean monthly actual evapotranspiration [mm/month] in the Lake Bunyonyi catchment for the period 1971–2000 (left), 2041–2070 (middle) and 2071–2100 (right) (top - RCP4.5, bottom - RCP8.5)



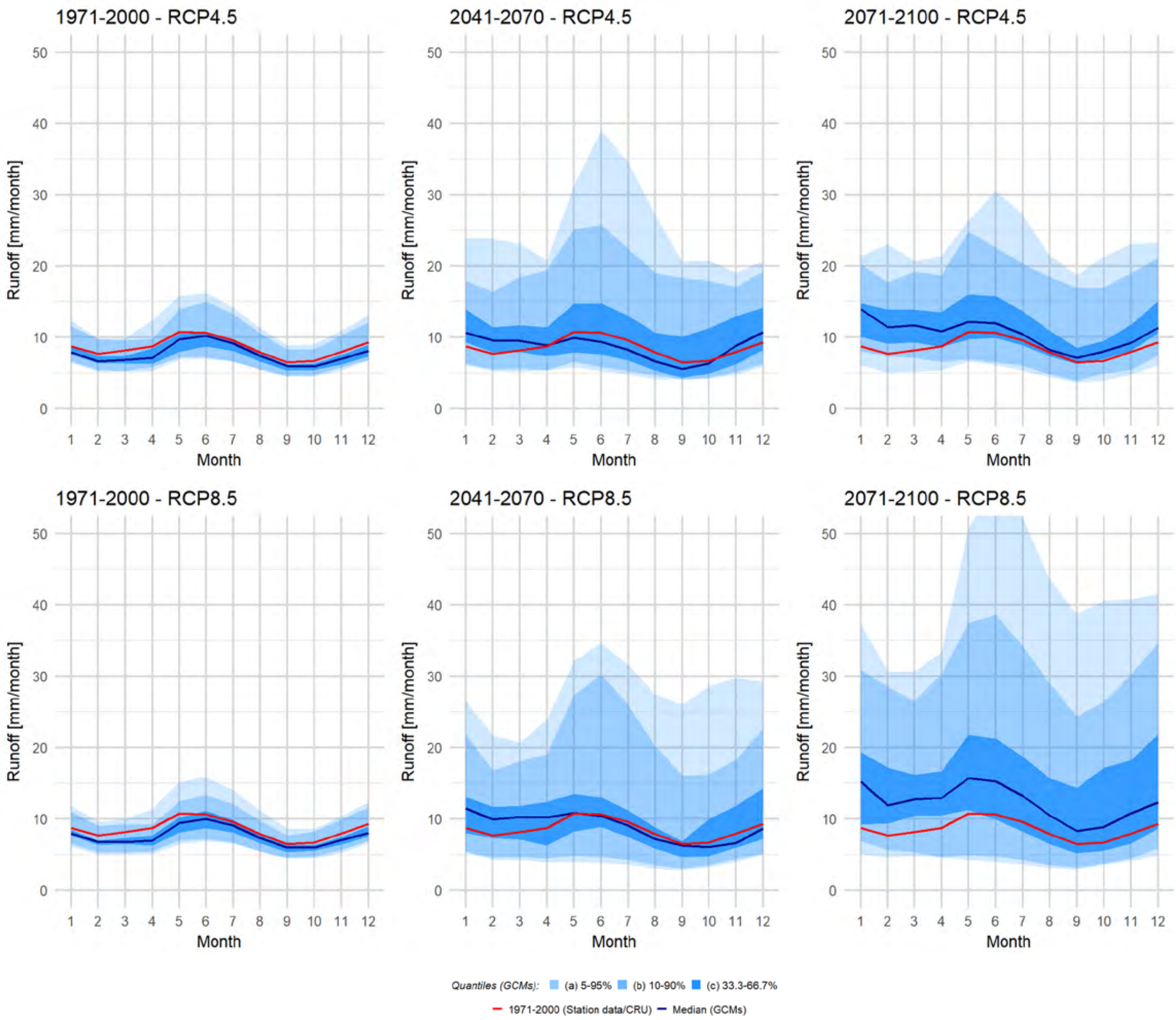
Source: Author diagram.

For the historic period 1971-2000, the AET values were lower in the simulation, although the PET values were similar using the CRU TS and the GCM temperature data. The reason for the higher AET values in the GCM simulations is because the GCM data has somewhat more precipitation in most months (see Figure 18), and therefore more water is available in the system and can be lost to AET. In the future, a tendency of increase in AET is visible; however a large spread in the modelling results also indicates substantial uncertainties.

3.3.5 Changes in Runoff

The annual runoff simulations for the period 1971-2000 using observed values (CRU TS data) are (at least for the median), in the range of the GCM data (Figure 19). Here, however, already a larger spread in the GCM results is visible. For 2041-2070, the median of the GCMs shows a similar seasonality compared to the reference period. There is an indication that the runoff at the beginning of the year could increase slightly. For the far future, most GCMs simulate an increase in runoff for all months of the year. For both future periods it is also evident, that the GCMs do not fully agree, since the spread in the results is very large.

Figure 19. Mean monthly runoff [mm/month] in the Lake Bunyonyi catchment for the period 1971–2000 (left), 2041–2070 (middle) and 2071–2100 (right) (top - RCP4.5, bottom - RCP8.5)



4.0 Conclusions

LESSONS LEARNED

The Ruhezamyenda catchment is experiencing many challenges such as soil erosion, landslides, floods, soil fertility loss, deforestation and wetland degradation. How will climate change affect these processes? This study is a first step in providing water managers and stakeholders with information to understand the potential impacts of climate change on the hydrological components of the Ruhezamyenda catchment, with a focus on the Lake Bunyonyi catchment, and to assess the vulnerability of the catchment to climate change. Making concrete statements to answer this question lies much outside of the scope of this study and it is difficult to infer precise answers from our results obtained. Yet, the following trends are discernable:

- **The overall trends from the hydrological components simulated for the Lake Bunyonyi catchment show that the risk for significant shortcomings in water availability for the future 2041–2070 and 2071–2100 is *low*.** An exception may be if future implementation of large-scale irrigation schemes or dam construction projects takes place or other (e.g., domestic) water demands increase significantly. Almost 65 per cent of the Lake Bunyonyi catchment is farmland and therefore already heavily influenced by human activities. A large unknown is how land use in the catchment will develop in the future. Further changes in land use/land cover need to be assessed for impacts on runoff, infiltration or soil storage components of the hydrological cycle. If the wetland areas continue to be drained, it may affect the lake levels.
- **Precipitation in the Ruhezamyenda catchment will *increase* in most years, *but the uncertainty in precipitation amounts is high* especially for the far future 2071–2100.** Overall, most of the GCM climate simulations show increases in precipitation amounts for both RCPs and both future periods, with higher uncertainty in the increases in precipitation in the RCP8.5 by 2071–2100, especially during the rainy seasons. The precipitation in the wet months is simulated to increase more than for the dry months in all future scenarios. Compared to 1971–2000, the mean annual precipitation is generally simulated to increase for the mid-term future and for the far future. For the future, the RCP4.5 scenario has simulated increases between approximately 0 per cent to 50 per cent and for RCP8.5 simulated changes lie between -25 per cent and +75 per cent (for RCP8.5, the mean monthly precipitation may be in the order of 100–150 mm higher during the first rainy season).
- **Based on the median of all GCMs and for both RCPs, the mean monthly air temperature in the Ruhezamyenda catchment is simulated to *increase* by approximately 1.5–3.0°C in the mid-term future 2041–2070 and by roughly 2.0–4.5°C in the far future 2071–2100.** For all of the GCM simulations, the air temperature shows rather uniform increases in all months and in all future scenarios. The increase in temperature rises continuously with time. The temperature increases as indicated by the median of the GCMs in RCP8.5 for the period 2041–2071 is 2.5°C higher in August, and it increases even more in the RCP8.5 scenario, in which the median of the GCMs is 4.5°C higher in August for the period 2071–2100. Although all models agree that temperature will increase, the range of uncertainty for the increases remains large.
- **The increase in air temperature will lead to *higher* potential evapotranspiration (PET).** The PET increases in almost all simulations, and it increases uniformly in all months, with the

most extreme RCP8.5 scenario by 2071–2100 indicating the median of the GCMs to be higher by about 12 mm/month.

- **The actual evapotranspiration (AET) in the Lake Bunyonyi catchment is simulated to *increase* in all months, with the median of the GCM simulations increasing the most during the months from May to August.** The AET was simulated with COSERO and is mostly dependent on the availability of water and on the PET, but it is also determined by vegetation cover and land use. In the Lake Bunyonyi catchment, the AET was simulated to increase in all months for the future periods, with an increase of approximately 8 mm/month in the median of all GCMs in the RCP8.5 scenario for the far future, although with notable uncertainty concerning the magnitudes. In contrast to the PET values, the AET increased the most during the months of May to August in all scenarios. It is worth noting that for the RCP8.5 scenario, the months of January and February show the largest uncertainties (due to the direction of change that is not consistent).
- **For the future periods 2041–2070 and 2070–2100, there is a slight trend toward increasing runoff from the Lake Bunyonyi catchment compared to the period 1971–2000, *but with large uncertainties*.** The runoff simulated at the outlet of Lake Bunyonyi for the future periods 2041–2070 and 2071–2100 shows that there is no overall trend toward only an increase in runoff. In all months, lower runoff and higher runoff are simulated, once again highlighting the uncertainties due to a large spread in the GCM simulations. Under the far future and RCP8.5 scenario, the runoff exhibits a stronger increasing trend. The simulations show that due to the overall monthly increases in precipitation and temperature, and despite the simulated increases in monthly PET and AET, the runoff in the Lake Bunyonyi will be altered; lower runoff amounts in some months, but overall higher runoff amounts are simulated, particularly in the far future (2071–2100) in the RCP8.5 scenario. Much uncertainty remains in the direction of mean monthly runoff changes, especially for the mid-term future.
- **Overall, the climate risks facing the catchment in the future are broad.** They include dealing with too much water (higher precipitation amounts in general) and more variability in precipitation (for RCP8.5, the future periods 2041–2070 and 2071–2100 had mean standard deviations in mean monthly precipitation amounts of 56 mm/month and 65 mm/month, respectively compared to the historic period 1971–2000, which had a mean standard deviation of 44 mm/month). The uncertainties in the discharge cannot exclude more low-flow periods occurring as well. It is important to stress that while total annual precipitation may increase, we have not studied the intensity of the rainfall events nor the occurrence of dry spells, which require precipitation data at a higher temporal resolution than the monthly time step used in this study.

CHALLENGES AND UNCERTAINTIES

- **These results should be interpreted with caution and ought to provide an indication of what changes may occur given the selected scenarios (see Box 1) and the hydrological modelling tool.** As in all modelling exercises, it should be cautioned that these results contain a number of inherent uncertainties. For example, the modelling uncertainties due to applying climate simulations in a hydrological model are related to the natural climate variability; the greenhouse gas emission (RCP) scenario; the GCM structure; the downscaling technique (from GCM to regional scale); the choice of the hydrological model, the data input, as well as the calibration process (Wilby, 2005; Poulin et al., 2011).
- **The purpose of the study was not to explicitly predict the future hydrological components and their absolute values, but rather to evaluate the trend and the magnitude of these.** A calculation of the water balance for Lake Bunyonyi for the future with absolute numbers was not deemed to be realistic given the large uncertainties in some of the hydrological

components for the future. Instead, the trends and the magnitude of hydrological change are presented as monthly means for the periods 2041–2070 and 2071–2100.

- **This study was not able to make any statement on the future occurrence of extreme events or on the intensity of precipitation events.** Monthly data was used as an input into the modelling exercise, and this is the time scale at which statements can be made. It is possible that with increasing climate variability in the future, the frequency of heavy rainfall intensities, water stress days or droughts may be altered.
- **The COSERO hydrological model was set up as a spatially aggregated model for each sub-catchment and achieved good calibration results for the historic period, especially considering the general challenge of dealing with missing in-situ observation data.**[3] It should be noted that the hydrological model did not take into account detailed soil maps, land uses or water abstractions. Nevertheless, we are highly confident that using another hydrological model would not have resulted in other hydrological outputs and different conclusions being drawn.

LOOKING BEYOND THE CATCHMENT

- **The significant variability in lake water levels and discharge is confirmed in other studies conducted in the region.** The historic hydro-meteorological observations within the Nile basin show significant variability in Lake Victoria water levels and discharge at Jinja. For the period 1901–1960, the mean annual outflow from Lake Victoria was around 20 km^3 per year, with small variations (± 10 per cent) in the decadal means. In contrast, in the period 1961–1970, the discharge doubled to over 40 km^3. Since then, the flows have declined, but are still high compared to the first half of the last century. Assuming the hydrology of the Ruhezamyenda is comparable to the Lake Victoria catchments, these numbers show that the area has in the past experienced significant changes in hydrology. A review and in-depth analysis of the results of this study in relation to historic observations would be useful to decrease the uncertainties in the conclusions. For example, it would be useful to compare the simulated seasonal variability and changes in the long-term means of runoff for the future with observed patterns and changes in the past.
- **This type of modelling study can be quite easily replicated in other catchments in Uganda and elsewhere, if the necessary data to setup the hydrological model is available.** Any hydrological model (COSERO or open source models) can be set up in other watersheds of interest. The success of the model setup and performance will to a very large extent depend on the availability of reliable and trustworthy observed hydrological and meteorological data sets for longer time periods and with few data gaps. If these data sets are not available, the challenges will be large to replicate the historic conditions of the catchment, and thus the model performance may not simulate the hydrological components with the necessary confidence (as judged by the objective function, such as the KGE and further statistical criteria, such as the NSE, bias, correlation and variability), and therefore the simulations may not be trustworthy, as the errors are propagated to the future conditions. In this study, for the Ruhezamyenda catchment, we have confidence that COSERO model was able to replicate the historical conditions of the catchment quite well.

[3] For examples: The missing precipitation data was estimated using a correlation analysis with other station data in the catchment, based on the highest correlation coefficient. In periods where no station data was available, time series from the CRU TS v4.01 gridded dataset was used. Potential evapotranspiration (PET), another essential COSERO model input, was calculated using the Hargreaves equation. This was estimated using the temperature time series extracted from the CRU TS v4.01 gridded dataset, since no in-situ station data for air temperature or other potentially useful meteorological variables were available. Despite these shortcomings, the PET calculated is very comparable to an independent global PET data set. In essence, the simulations of the past show plausible results.

5.0 Recommendations for the Catchment

Based on the results of the assessment, the Ruhezamyenda catchment can benefit from no-regrets (or low-regrets) adaptation options. No-regrets adaptation options aim at providing benefits regardless of future climate changes. They neither disregard climate change impacts nor make it the determining factor in decision-making. Instead, the strategy ensures prudent climate risk management considering a range of possible impacts. Several no-regrets adaptation actions have already been identified in the Ruhezamyenda CMP report (Rukundo, 2015) and remain relevant based on the results of this assessment. As in most cases, a combination of different types of adaptation actions is needed— beyond structural or technical adaptation actions solely.

Importantly, the recommendations listed below were discussed considering the findings of this study and validated with local stakeholders at a workshop co-organized by the GoU (Ministry of Water and Environment) and IISD on November 2018 in Kabale, Uganda. The event brought together 32 stakeholders working in the Ruhezamyenda catchment to discuss the results of the hydrological modelling and to identify adaptation actions that can be implemented in the catchment to reduce the current and future potential impacts of climate change in the catchment (see Annex 5 for the participant list).

The proposed no-regrets adaptation options fall under five themes: governance; capacity development and communication; water, soil & land management and livelihoods improvement; data management; and research.

GOVERNANCE

- **Accelerate and scale up the implementation of adaptation measures identified in the 2015 CMP, some of which have already been successfully piloted in the catchment.** Some pilot projects focusing on water, soil and land conservation are underway to support climate change adaptation while also improving peoples' livelihoods (see Box 2). Workshop participants highlighted that they have dealt with extreme weather events in the past through implementing various soil and water conservation measures, including water harvesting technologies, implementing agroforestry, planting early maturing crop varieties, integrating chicken in crop production systems, and diversifying enterprises. As such, relevant adaptation actions are already being implemented in the catchment demonstrating that local stakeholders are proactive and eager to adapt to climate change if it can also improve their livelihoods. The approach of establishing pilot demonstration sites in partnership with some farmers—and sharing these experiences with neighbours—is useful, but the process needs to be accelerated and scaled up to have a real impact. Too little is still being done on the ground, leading to the continuous deterioration of the environmental and socioeconomic situation. For example, many rivers and lakes are being silted up (Kizza et al., 2017; Osiru, 2006).

Box 2. No-regrets adaptation measures implemented in the Ruhezamyenda catchment

No-regrets adaptation measures being implemented in the Ruhezamyenda catchment include:

- **Community engagement in IWRM (Kigezi Diocese):** The diocese engages communities in mapping key impacts that affects their livelihoods and trains them on IWRM practices such as terracing, channeling and stabilizing slopes. The consequences in areas where IWRM has been implemented include fewer floods in rehabilitated areas with fewer landslides, leading to improved protection of fields and the houses. Increased agricultural production on the terraced slopes (bench terraces) has also been reported.
- **Degraded land restoration for agricultural production using rainwater harvesting (Kabale Diocese):** Rainwater is harvested to prevents rapid runoff. The collected water is used during dry times as irrigation water, which in turn saves time for women who are traditionally in charge of fetching water for the household. The Diocese also supported the building of trenches to divert the excess water from the fields. Elephant grass or Napier grass is grown along the trenches to stabilize them.
- **Sustainable land management through linking farmers to suppliers, financial institutions and insurance providers (Reign Group).** The Reign Group, a business development partner supporting climate-smart agriculture, works with farmer groups and cooperatives on pilot landscapes to promote runoff water harvesting, check-dams, the building of trenches and implementation of agroforestry measures. Challenges include workers' lack of technical knowledge in installing dams; clashes between livestock farmers and crop farmers; and lack of political buy-in. The key lessons include: pilot projects require enough time for sustainable land management interventions; agroforestry is a challenge, as the trees planted on farms needs a lot of work (long payback time); and sustainable land management practices need to be mainstreamed into existing programs and projects.

- **Prioritize access to climate finance to implement adaptation priorities in the catchment.** The change required for adaptation to occur in the catchment is slow to take place in the community and necessitates appropriate and steady stream of financial resources.
- **Engage with women and men in the communities and local stakeholders to introduce improved farming practices.** As identified inn the CMP under objective 1, actions include: to stimulate the formulation of functional institutional frameworks through generally acceptable and universally respected platforms with active involvement of stakeholders and local council leaders to promote sustainable land management practices and integrate available Indigenous knowledge of women and men into the new farming methods for faster adoptability.
- **Develop, communicate and enforce bylaws to protect the catchment.** To implement adaptation actions successfully, bylaws need to be developed and communicated to the stakeholders of the catchment to increase awareness so that the most vulnerable areas are protected. For example, encroaching on wetlands currently has no legal consequence in the Lake Bunyonyi catchment. The communities living around Lake Bunyonyi require specific bylaws to prevent the draining of wetland for agricultural crops and eucalyptus woodlots. These bylaws should be developed and enforced by the local population.
- **Enhance coordination and collaboration across sectors and levels of governance to support alignment between the CMP and other sectoral and local development plans and their effective implementation.** Ensuring that the adaptation actions identified in

the CMP are reflected in other sectoral and district development plans could support their effective implementation. The assessment of climate change impacts and the implementation of adaptation measures requires the collaboration of many actors from the international to the local level. This is a major challenge to implementing the Ruhezamyenda CMP, as well as other CMPs in Uganda. Specifically, there seems to be a governance challenge or mismatch in terms of:

  - The scale of implementation – i.e., water management zones are not matching administrative units (district, parish).
  - The thematic structure – i.e., how to implement water catchment management plans that are cross-sectoral when the government is still organized into sectors? The workshop participants indicated that the sectors are not working well together, which is perceived as a barrier to implementing adaptation measures.

COMMUNICATION AND CAPACITY DEVELOPMENT

- **Develop and implement a communication strategy on climate change impacts and adaptation in the catchment.** Existing reports (such as this assessment and the 2015 CMP) will have limited impact if they are not communicated appropriately to the end users. A communication strategy targeting the different stakeholders of the catchment (and possibly beyond) is urgently needed. Findings from this study together with information associated with the CMP and other relevant information must be communicated to the end users in an appropriate format. Communicating climate change impacts to various stakeholders and decision-makers is a challenging task. Climate simulations often have a large range of uncertainty associated with them, as is the case for this study. Using quantiles can assist to interpret the outcomes in terms of probabilities (Daron et al., 2015). Ideally, this needs to be supported with capacity building for the scientific community on the use and application of hydrological models and on the use of climate model outputs (IPCC guidelines) to improve the communication—and therefore the impacts—of the study results. A communication strategy could contribute to, for example:

  - Promoting regular updates to the communities on the current and future impacts of climate change to help them prepare for the changes.
  - Collecting regular communities' feedback on adaptation priorities and barriers to adaptation—to improve the effectiveness of adaptation responses.
  - Promoting dialogues on climate adaptation (what is working well, or not, in specific contexts) among communities but also between international and local scientists and between scientists and decision-makers. This will help accelerate the effective implementation of adaptation actions.

  Existing institutional arrangements such as the disaster management committees could be mobilized to sensitize communities on these issues, if they are provided with adequate training and resources.

- **Train farmers and other actors on no-regrets adaptation options.** All the proposed measures will be very difficult to introduce and implement effectively unless stakeholders can see the benefits. Discussions with local stakeholders highlighted that adaptation to climate change *alone* is not a priority for people living in the catchment. Adaptation measures will only be successful if they also improve the livelihoods of the smallholder farmers, the fishermen and other local entrepreneurs who are mainly concerned with feeding their families. All the priority adaptation actions identified need to be combined with customized communication and trainings programs to support community engagement. This aspect is already captured in the CMP, for example:

- Objective 1 highlights the need to "establish demonstration farms and promote farmer-to-farmer learning approaches."
- Objective 2 states the need to "mobilize a critical mass of local stakeholders to enforce soil and water conservation technologies such as check-dams, at village and sub-catchment scale."
- Objective 3 focuses on the need to "increase awareness and enhance skills in improved farming methods through an evolving capacity-building process for water and natural resource users in the catchment."
- Objective 4 focuses exclusively on capacity building and on raising awareness ("build the capacity of existing institutions to effectively respond to the changing needs and situations in the catchment"). All the strategic interventions recommended under this objective are relevant, and particularly:
  - Enable the local-level institutions to raise water and environmental issues to be included in the district and national development plans.
  - Institute an annual performance monitoring and evaluation framework and regularly initiate refresher courses, workshops for the staff on best industry practice in catchment restoration.

WATER, SOIL & LAND MANAGEMENT AND LIVELIHOODS IMPROVEMENT

- **Implement and maintain terraces and bund systems to improve crop yields and manage soil erosion in the catchment.** Terraces and bund systems can contribute to attenuating rainfall erosivity, reducing soil erosion and encouraging infiltration instead of surface runoff. Improving the productivity and therefore livelihoods of farmers on the hillside will reduce pressure on the wetlands. Up to the 1960s, farmers managed the steep agricultural land well with the use of terraces or stone bunds, but these have not been maintained over the years. Many terraces are now destroyed, leading to increased soil erosion and landslides which contributes to the loss of arable land, sediments and nutrients (Osiru, 2006). Field observations conducted as part of this study in July 2017 confirmed very little terracing on steep slopes throughout the catchment and high levels of soil erosion in agricultural areas, especially in the upstream areas (Crerar & Akurut, 2017). Discussions with local stakeholders also revealed that soil (and often pebbles and rocks) including fertilizer was being washed from the upper slopes to the lower slopes and valley bottoms, and that landslides were a problem (Crerar & Akurut, 2017). The CMP identifies several structural measures that are relevant under "Objective 2: To restore the catchment health and address priority water-related risks and disasters" including:
  - Stabilizing the incipient gullies forming in the catchment before they enlarge, elongate or deepen.
  - Rehabilitating the gullies in the sub-catchment using environmentally friendly materials such as gunny bags, vegetation species such as *Grevillearobusta*, *Polysciasfulva*, *Acacia mearnsii* and bamboo, etc., around restoration structures.
  - Promoting stone bunds in areas where deep volcanic soils occur and water retention ditches could trigger landslides.
  - Promoting immediate stabilization of sheet and rill erosion.

  Given the steep hills that are used for farming and for planting eucalyptus, the upkeep of the terraces or bund systems to manage soil erosion is a very important measure to attenuate soil loss during heavy rainfall events.

- **Manage excess surface water runoff in the catchment to reduce soil erosion and infrastructure damage.** The workshop participants identified the need to manage—and take advantage of whenever possible—excess surface water runoff. From past experiences, they perceive that heavy rainfalls exacerbate surface runoff. Measures identified for surface water runoff collection and management include:
    - Collecting water from roofs and using the water for irrigation needs during the dry periods.
    - Insuring that road construction plans include surface water runoff control to redirect the water from the roads away from the fields.
    - Engaging communities in a coordinated approach to implement other soil and water conservation structures such as constructing trenches and terraces.
- **Stop the conversion of wetlands to farmland or to eucalyptus woodlots in the catchment.** The degradation of wetlands threatens to change the hydrology of the basin and should be halted, and the wetlands restored. The CMP under "Objective 2: To restore the catchment health and address priority water-related risks and disasters" already identifies measures for wetland conservation, including:
    - Promote the use of wetlands that does not inhibit their buffering capacity, such as wetlands edge gardening.
    - Mobilize resources to adequately compensate land users on wetlands of conservation concern and promptly commence the restoration process.
    - Ensure a minimum vegetative buffer around wetlands.
    - Restore eucalyptus-degraded hillslopes by introducing alternative economically rewarding and environmentally friendly tree species such as bamboo—and then identify potential markets to stimulate economic driven shift toward the new tree species.

  A large proportion of the lowland wetland systems has been converted into productive agricultural land, and this conversion continues. Given the predicted high population density in the catchment, this conversion is expected to continue into the future period. The population pressure, coupled with the reduced productivity levels of the uplands due to soil erosion, may increase the pressure on farmers to move into wetland areas. Wetlands play an important hydrological role to store water and are a valuable natural barrier for attenuating lake level fluctuations, small floods and sedimentation caused by heavy rains. This measure should be associated with complementary measures such as: encouraging alternative sources of fuel wood, which would help free up land for agriculture instead of for biomass; providing training for sustainable land management practices to rehabilitate the degraded wetlands, which would restore already degraded wetlands; and implementing awareness campaigns to promote the benefits of wetlands and further prevent wetland drainage.

  These adaptation actions are essential for ensuring sustainable livelihoods and addressing environmental concerns. They would have more impact if they are combined with the following actions identified in the CMP under "Objective 1: To promote sustainable land management practices for co-existence of human land use and environmental sustainability in Ruhezamyenda Catchment," which include:

    - Integrating native vegetation species of protective and productive values into improved farming technologies including agroforestry, riverbank restoration through enrichment planting.
    - Establishing a monitoring and evaluation mechanism to track the progress and address emerging issues in a timely way.

DATA MANAGEMENT

- **Install and maintain hydrometric and meteorological stations throughout the catchment,** but especially at the outlet of Lake Bunyonyi and the outlet of the Ruhezamyenda catchment, to monitor the precipitation and particularly the discharge and the lake levels in the catchment. Recorded historic data is the foundation to observing changes in the catchment and assessing potential impacts caused by climate or other geophysical events, including for calibrating models. Several critical points concerning the input data for the simulation of the historic conditions from 1971–2000 arose during the study.[4] As such, the establishment and strengthening of a continuous system to monitor the bio-physical conditions in the catchment are necessary so that the current situation can be assessed and changes monitored. This will assist in future modelling studies. The workshop participants stated that local institutes and governments have been equipped with automated weather stations to collect and store data. This data needs to be made available for research and it needs to be quality controlled. Maintaining a hydro-meteorological observation network is a complex task. More satellite-based, hydrologically relevant, data time series have recently become available, but this development does not eliminate the necessity of in-situ field observations. Instrumented on-site measurements are essential to observe and monitor ongoing changes in the hydrological cycle to make objective, data-based decisions for the management of water resources or to assess potential changes in the hydrological components in the future. A good example in this context are the long-term observations of the Nile at Jinja or the Lake Victoria water levels (Sutcliffe & Petersen, 2007; Sutcliffe & Parks, 1999).
- **Monitor sub-daily precipitation events at 15- or 30-minute intervals particularly in a variety of landscapes found in the catchment,** such as steep hills and lowlands. This data is highly useful to calculate erosion rates and assist in future modelling studies. Furthermore, an analysis of the data will help determine any changes in rainfall intensity that may occur. Soil erosion is one of the main challenges in the catchment, according to the 2014 CMP report. According to the Universal Soil Loss Equation, soil erosion is a product of several factors—namely the rainfall erosivity (R), the soil erodibility factor (K), the slope/length factor (LS), the cropping practice (C) and the farming support management factor (P)—that may reduce the erosion. The rainfall erosivity (R) is the total storm kinetic energy per unit area, and it is related to the precipitation intensity, which is a major factor that will influence the potential for soil erosion, especially on farmed steeper slopes (generally greater than 8 per cent). The lack of rainfall data for short-term intense events is a major challenge to understanding the soil erosion processes in the catchment. With sub-daily precipitation data, statistical analysis can also be applied to determine the number of extreme rainfall events in the recorded time period and make inferences about any changes in the catchment.
- **Strengthen the exchange of data between the Uganda National Meteorological Authority (UNMA) and the Ministry of Water and Environment by establishing and implementing protocols for climate data management.** Getting the data from UNMA is, in theory, possible, and a memorandum of understanding (MoU) between the two exists but if successful can take months.

[4] For example: we relied on in-situ measurements for the hydrological model, and the main challenge in this context lies in the data quality of the discharge time series. Although some discharge observations exist, we had to rely on an exponential lake water level to discharge relationship, which has been previously established and used, and which seems plausible. Nevertheless, robust recorded data would have been preferred so that we do not have to adjust it. In addition, although several weather stations are available with precipitation data, many gaps exist in the time-series, and no in-situ temperature data was available. Concerning the third water balance component—the actual evapotranspiration (AET)—no data was available to compare our simulations to. Fortunately, the simulations of the historic period show that the magnitude of the evapotranspiration fluxes is trustworthy and seems plausible.

RESEARCH

- **Undertake site-specific assessments of climate change impacts in the catchment.** Many workshop participants stressed the importance of carrying out local interventions of soil management at the sub-catchment or at the community level. This assessment focuses on the impacts of climate change on the Lake Bunyonyi catchment, and the next step needs to address site-specific assessments of climate change impacts to assess the quantity of runoff in specific vulnerable areas in the catchment that consider a diversity of physical terrains, water availability, infrastructure and other factors.
- **Determine the drivers of land-use change in the catchment to understand how land use/land cover will evolve in the future, especially due to the growing population.** This will enable future hotspots of change to be identified (also related to potential soil erosion) and allow appropriate incentives and policies to be put in place to promote sustainable land management practices, and also to improve the implementation of soil and water conservation measures. It could be done in part by surveying farmers to understand their decision-making with respect to planting certain crops and their farming practices (Mehdi, Lehner, & Ludwig, 2018). According to Osiru (2006), the main driver for widespread degradation of the land is the population density, which has pushed farming to marginal areas (i.e., on steep slopes). In the CMP, it is stated that "human induced land-use change has adversely affected the hydrological conditions of the area with local stakeholders reporting regular drying of streams and small wetlands during dry seasons" (Rukundo, 2015). From the field scoping exercise conduced in July 2017, discussions with stakeholders supported the impression that as a result of a combination of population pressure on the land, and more extreme rainfall events being observed, soil erosion is getting worse. Subsequently, the local characterization of soils should be undertaken, as the soil type strongly influences the hydrological processes that occur. Given that two thirds of the basin is already farmed for food and fuel, the changes in the land use must be examined as a future task. Future changes in land use, especially the farming of steep hillside slopes, may impact the catchment hydrology and be a driver for soil erosion and water quality changes. Furthermore, the combined effects of land use and climate change are not linear (Mehdi, Ludwig, & Lehner, 2015) and can impact the hydrological components of infiltration, evapotranspiration and surface runoff in particular.
- **Carry out additional modelling studies to examine anthropogenic changes in the catchment.** If the next research question is to examine specific land-use changes, or alterations in field management practices, and how these may affect the hydrology and water quality in the catchment (or in a sub-catchment) this can be further explored with a more detailed eco-hydrological model that accounts for crops and soil layers, such as the Soil and Water Assessment Tool (SWAT). The SWAT model takes into account detailed land uses in a watershed, including agricultural management practices carried out by farmers. However, the hydrological quantity modelling component will surely achieve results similar to what we found in this study.

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Annex 1. Availability of precipitation data (1951–2001) in the Ruhezamyenda catchment

Figure A1. Number of weather stations with precipitation data for each year between 1951 and 2001. Each coloured line represents one precipitation station for which data was available. The gaps represent missing data values. The red line depicts the total number of stations with data available for each year.

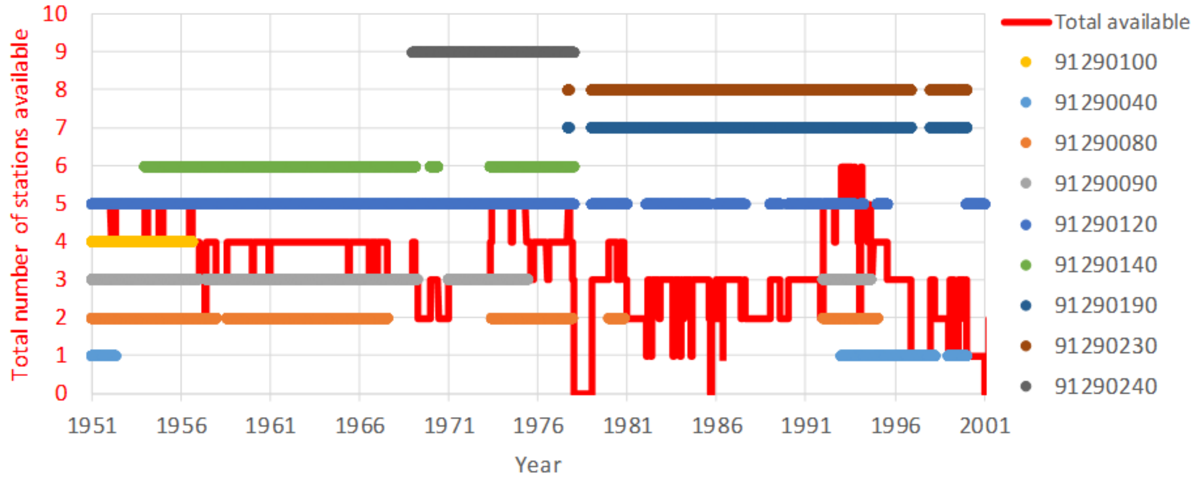
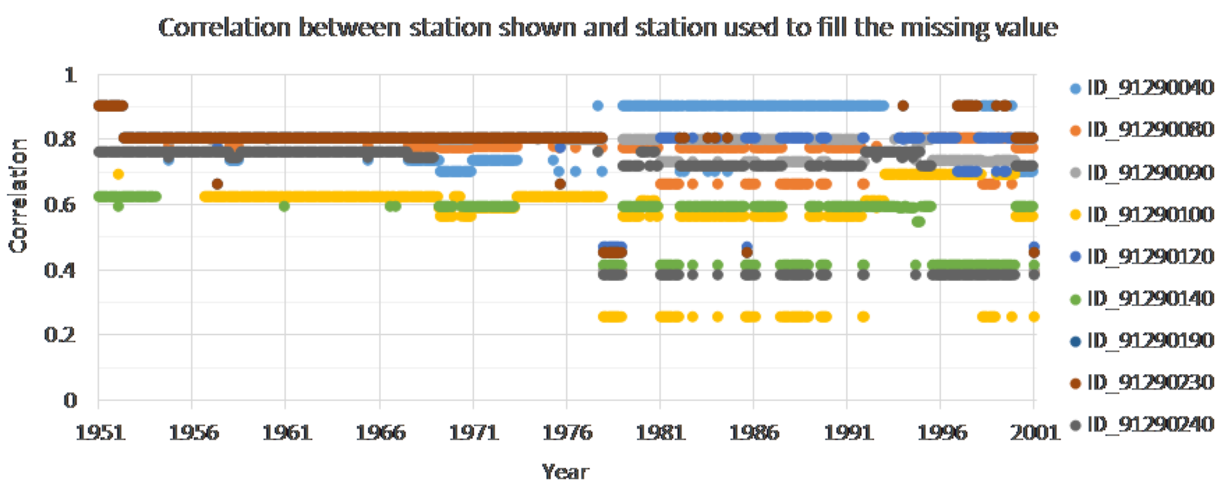


Figure A2. Correlation between the station shown in colour and another station (not shown which one) with the highest correlation to the station shown, which was used to fill the missing values using a linear model

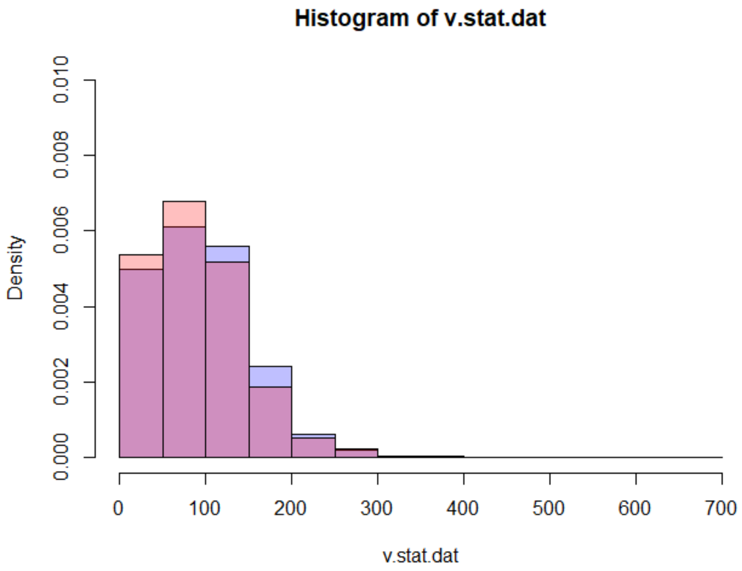


The precipitation time series from one station was correlated to all other stations in the catchment. The station with the highest correlation to the station with missing data was used to fill in the missing data (Figure A2), thereby using a linear regression model. When, after using this method, precipitation data was still missing in the time series (i.e., in particular after 1976), the CRU TS v4.01 data was used to fill the data.

The correlation analysis (Figure A2) shows that the correlations between precipitation data when another stations was used for filling the missing data gaps was for the most part >0.6. However, in some periods rather low correlations (i.e., <0.5) are found for single stations. This means that the data gaps are filled with information pertaining to a station that shows a very low interrelationship. These low correlation values emerge when no station data is available to fill the missing values so that the CRU TS data is used to fill the precipitation data gaps.

To check how good the filling of the missing precipitation data was, a distribution of the precipitation data with missing values and without missing values was plotted (Figure A4). The precipitation distributions were similar (see purple area in Figure A4), which indicates that the method was successful.

Figure A3. Histogram of all mean monthly precipitation values; blue bars indicate station data with precipitation data gaps; red bars indicate station time series that were filled (i.e., without missing values); purple area indicates the overlapping areas of both.



Annex 2. Global Climate Models (GCMs) used for the climate simulations

Table A1. List of the CMIP5 projects' GCMs used for maximum temperature, minimum temperature and precipitation after quality control undertaken by The Climate Data Factory.

ID	RCP4.5	RCP8.5
1	BCC.CMS.1.M	BCC.CMS.1.M
2	BNU.ESM	BNU.ESM
3	CMCC.CM	CanESM2
4	CNRM.CM5	CMCC.CM
5	ACCESS1.0	CMCC.CMS
6	ACCESS1.3	CNRM.CM5
7	EC.EARTH	ACCESS1.0
8	INM-CM4	ACCESS1.3
9	IPSL.CM5A.MR	EC.EARTH
10	IPSL.CM5B.LR	INM-CM4
11	MIROC5	IPSL.CM5A.MR
12	MIROC.ESM.CHEM	IPSL.CM5B.LR
13	MIROC.ESM	FGOALS.g2
14	HadGEM2.CC	MIROC5
15	MPI.ESM.LR	MIROC.ESM.CHEM
16	MPI.ESM.MR	MIROC.ESM
17	MRI.CGCM3	HadGEM2.CC
18	GFDL.CM3	HadGEM2.ES
19	GFDL.ESM2G	MPI.ESM.LR
20	GFDL.ESM2M	MPI.ESM.LR.1

ID	RCP4.5	RCP8.5
21	CESM1.BGC	MPI.ESM.MR
22	CESM1.CAM5	MRI.CGCM3
23		MRI.ESM1
24		CCSM4
25		NorESM1.M
26		GFDL.CM3
27		GFDL.ESM2G
28		GFDL.ESM2M
29		CESM1.BGC
30		CESM1.CAM5

Annex 3. Observed discharge data available for simulating discharge and runoff

Figure A5. Number of missing values per year used in the derived discharge time series for model calibration

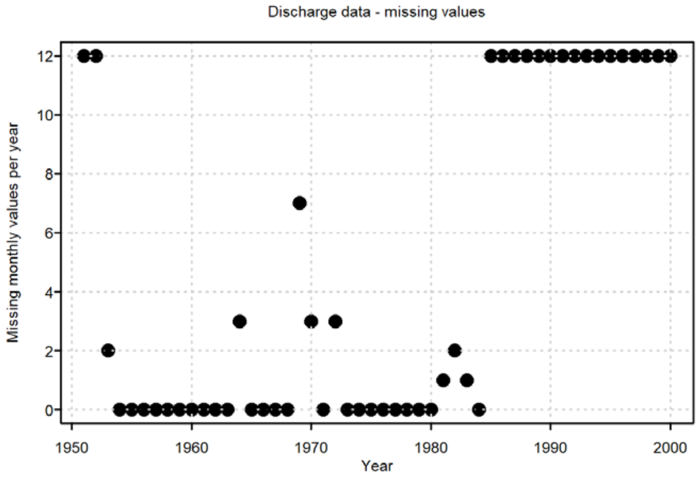
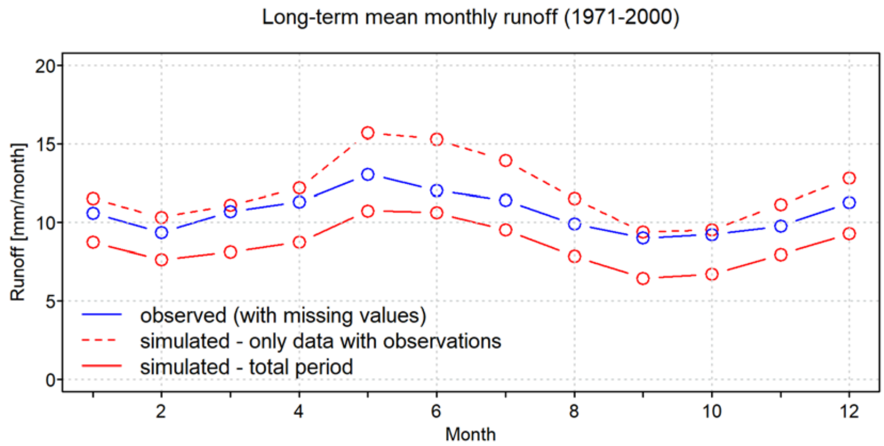


Figure A6. Long-term mean monthly observed and simulated runoff (mm/year) for the period 1971–2000 for the Lake Bunyonyi catchment



Annex 4. Global Climate Models (GCMs) simulation outputs

Figure A7. Mean annual temperature [°C] for the period 1971–2100 (top - RCP4.5, bottom - RCP8.5)

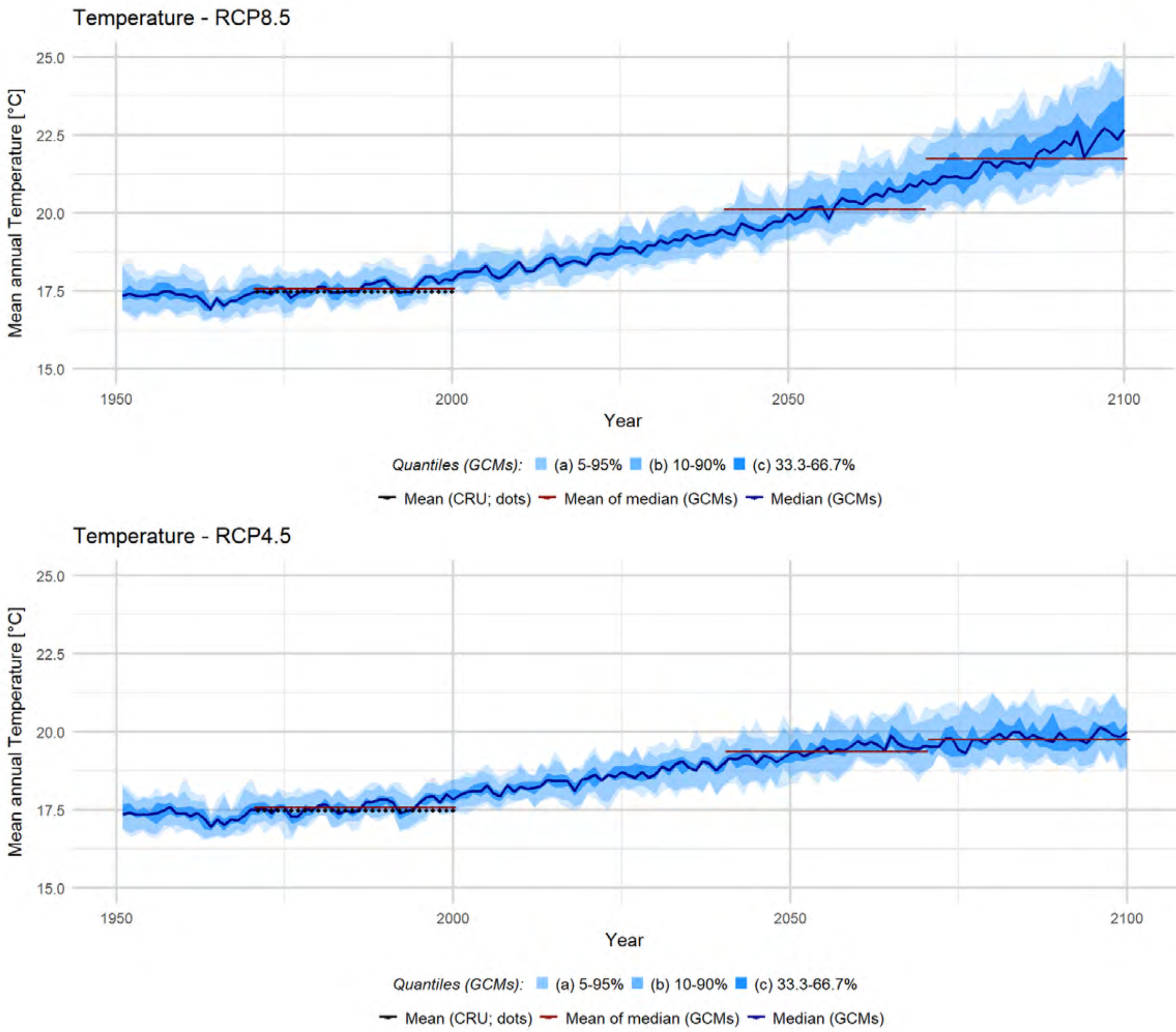
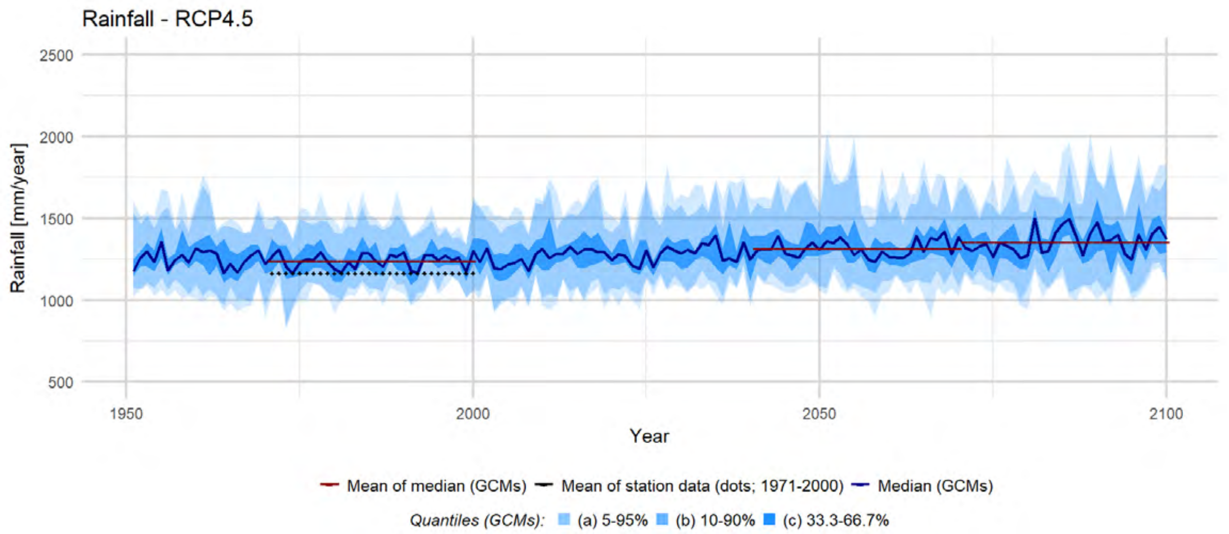


Figure A8. Annual precipitation [mm/year] for the period 1971–2100 (top - RCP4.5, bottom - RCP8.5)



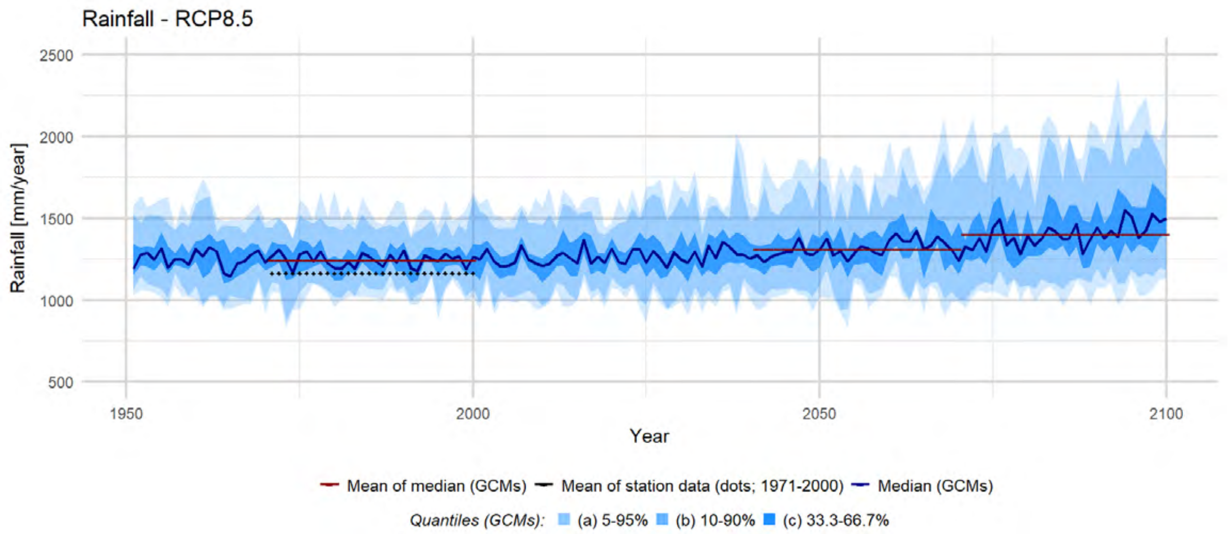
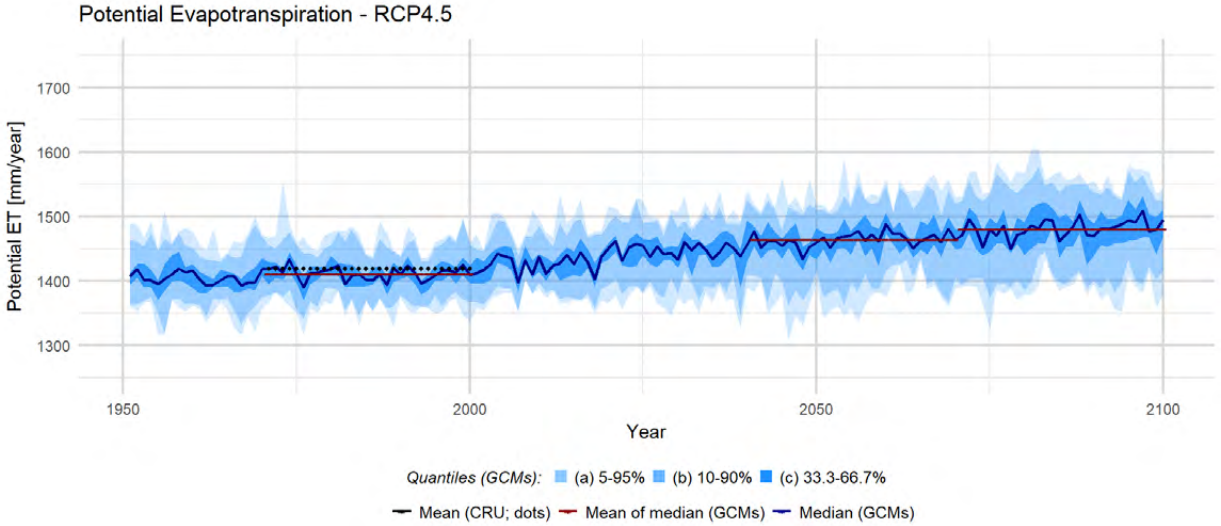


Figure A9. Annual potential evapotranspiration [mm/year] for the period 1971–2100 (top - RCP4.5, bottom - RCP8.5)



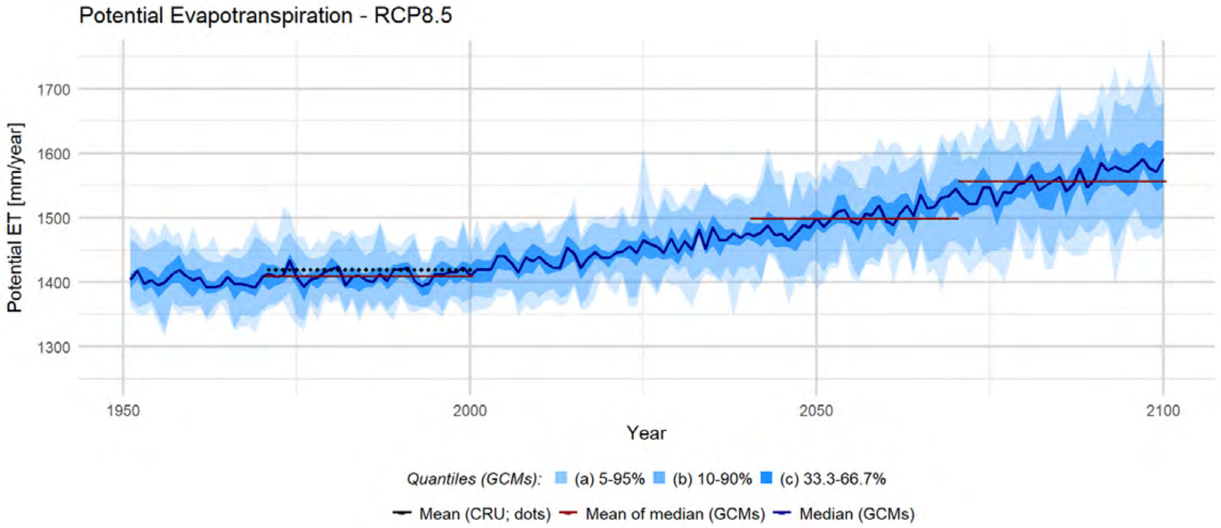
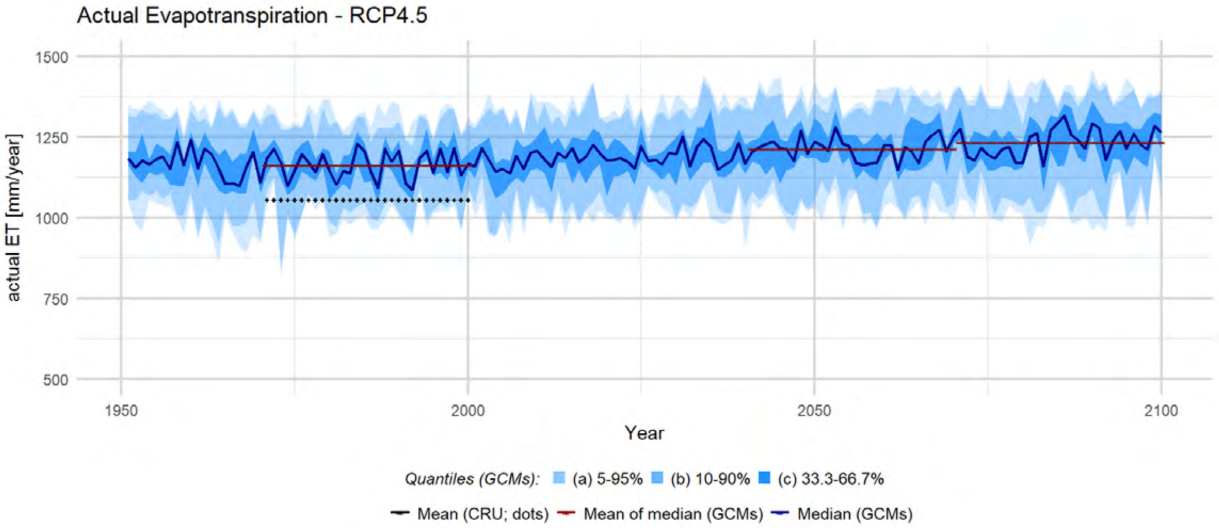


Figure A10. Annual actual evapotranspiration [mm/year] for the period 1971–2100 (top - RCP4.5, bottom - RCP8.5)



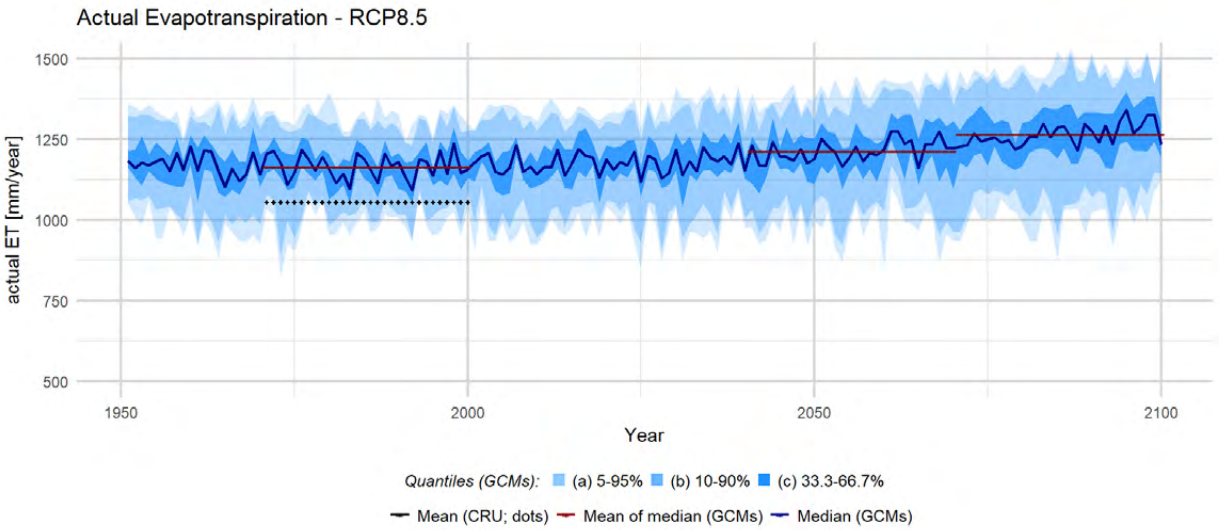
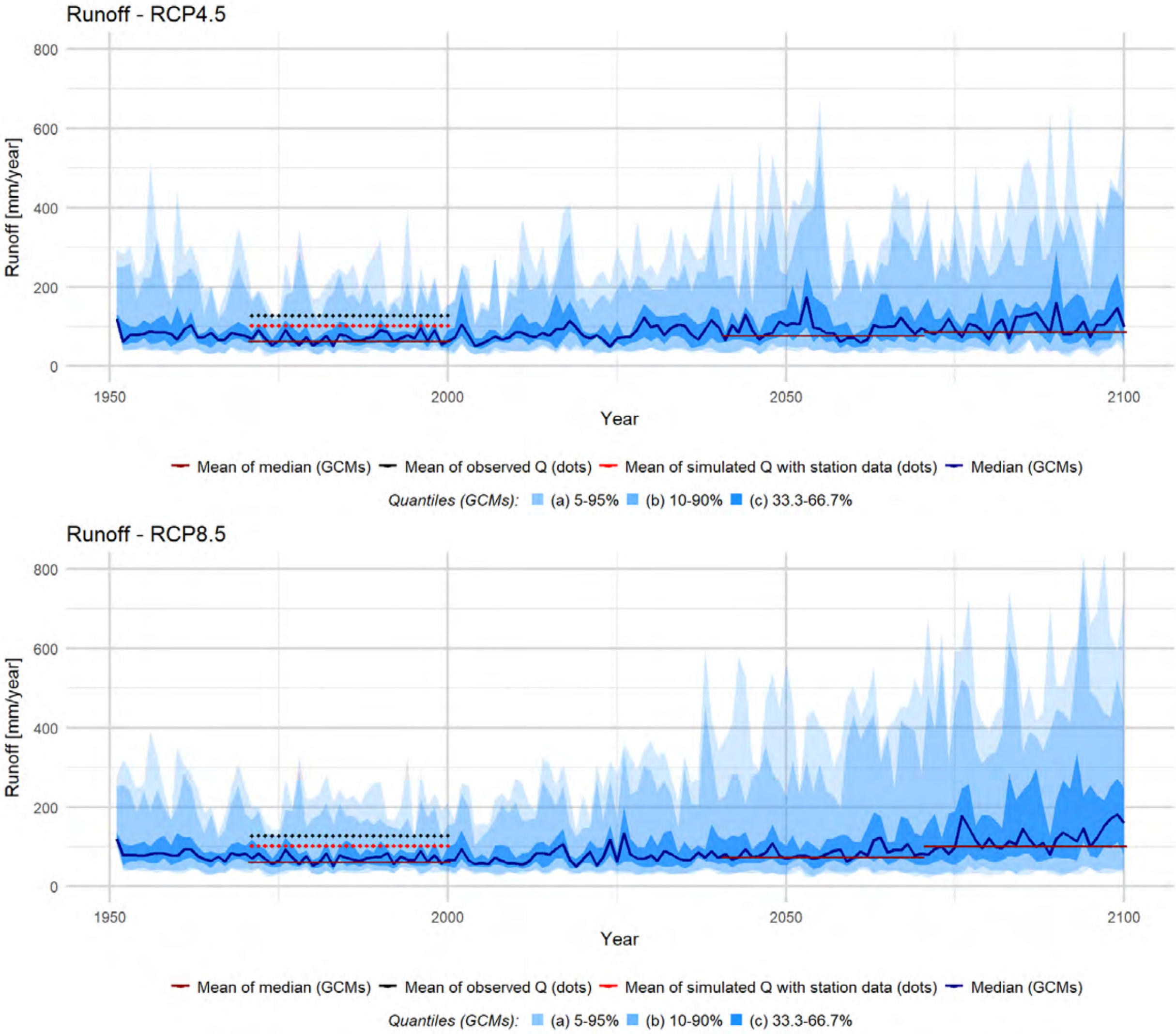


Figure A11. Annual runoff [mm/year] for the period 1971–2100 at the Lake Bunyonyi catchment outlet (top - RCP4.5, bottom - RCP8.5)



Annex 5. List of stakeholders consulted (November 2018, Kabale, Uganda)

1. Albert Orijabo, Assistant Commissioner, Directorate of Water Resource Management (DWRM), Ministry of Water and Environment (MWE)
2. Vincent Mudanga, District National Resources Officer (DNRO), Kisoro District Local Government (DLG); and Secretary, Ruhezamyenda Catchment Management Committee
3. Jackson Kitamirike, Team Leader, Albert Water Management Zone (AMWZ), MWE
4. Caroline Mwebaze, Hydrologist, DWRM, AWMZ
5. Deneth Mugaura, Social Scientist, DWRM, AWMZ
6. Nicholas Magara, Wetlands Management Department (WMD), MWE
7. Richard Musota, Victoria WMZ, MWE
8. K.B. Jogo, Local Council V (LCV), Kabale DLG
9. Johnson Baguma, LCV, Kabale DLG
10. George Kwizera, LCV, Kisoro DLG
11. James Mugisha, Chief Administrative Officer, Kabale
12. Stephen Habimana, District Water Officer (DWO), Kisoro
13. David Otika, DWO, Rubanda
14. Patience Aharinta, DWO, Kabale
15. Eunice Akankwasa, District Environment Officer, Kisoro
16. Monica Muhumuza, District Community Development Officer (DCDO), Kabale
17. Pamela Katushabe, Acting District Natural Resources Officer, Rubanda
18. Honest Tumuherwe, Kabale DLG Production and Marketing
19. Frank Karusya, Caritas Kabale Diocese
20. Swithen Nyokaami, Kigezi Diocese Water and Sanitation Project (KDWSP)
21. Vivian Safari, KDWSP
22. Giles Agambe, REIGN Group / REBDA
23. Ramueli Ahabwe, REIGN
24. Amos Niringire, Diocese of Muhabwa
25. Jane Amumpaire, Self Help Africa
26. Faith Tushabe, African International Christian Ministry
27. Simon Byamukama. Let Us Save Uganda (LUSU)
28. Herbert Ahabwe, FAO-Uganda
29. Robert Muhezera, Daily Monitor
30. Kevin Tuheirwe, Journalist
31. Sheilah Kembabazi, Journalist
32. Sopha Mwamanya, Journalist

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