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Modelling Report for the

Kagera Aquifer System

Draft Report






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1. Background

1.1. Project Background

The Nile, one of the world's major rivers, has a coverage area that traverses eleven countries including Burundi, the DRC, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda. The Nile serves a vital role in the social and economic development of these countries which are highly dependent on surface water resources within the river basin for basic needs, agriculture and hydropower. Recognizing the need to preserve and sustainably benefit the Nile, global, regional and national attention has been drawn towards the riparian countries in ensuring inter-country cooperation and sustainable and equitable utilization of the resource.

With the growing populations in all eleven countries, increasing demand for water, and the risks posed by climatic and land use change there is a growing need for alternative sources of water. One target area is the groundwater that tends to hold the key for bridging the gap between the heightened demand for water and available supply volume. According to available literature Water bearing geologic formations are known to cover most of the area of the Nile basin with some of them crossing international boundaries forming significant transboundary aquifers. Most of these aquifers are of high storage and possess high yield.

In spite of its abundance within the Nile Basin as a reliable source of perennial good quality water, groundwater is nevertheless a hidden resource which must be explored and well mapped before it can be exploited in an effective and sustainable fashion. The fact that these groundwater resources are not well measured in terms of quantity or quality is what hampers the efforts to plan for the effective development and utilization of this valuable resource.

The Nile Basin Initiative (NBI) is a cooperative arrangement initiated and led by the Nile riparian countries to promote joint development, protection and management of the common Nile Basin water resources. The NBI Secretariat (Nile-Sec) with the financial support of the Global Environment Facility (GEF) and in collaboration with the United Nations Development Program (UNDP), is in the process of implementation of a Nile Basin wide program which

focuses on transboundary groundwater aquifers. The aim of the project of the five phase project to strengthen the overall water resources management nationally and basin-wide. The first phase of the program is geared towards the enhancement of knowledge and capacity for sustainable use and management of transboundary aquifers and aquifers of regional significance in the Nile Basin.

Three aquifer areas have been chosen for intervention, namely the Kagera aquifer shared among Uganda, Tanzania, Rwanda and Burundi; the Mt Elgon aquifer shared between Uganda and Kenya; and the Gedaref-Adigrat aquifer shared between Sudan and Ethiopia. The aquifers are located in diverse ecological zones ranging between arid, semi-arid and tropical. The first phase of the project was geared towards the compilation of available data and the generation of a Shared Aquifer Diagnostic Report (SADA) for the three aquifers. The second phase is oriented towards the modelling and establishment of the water balance within the selected aquifer systems.

1.2. Study Region

The study area is within the Kagera basin which is spread over Burundi, Rwanda, Tanzania and Uganda with a total area of 59,800 Km2, contributed as shown in Table 1.2 The study area is also endowed with several of wetlands, they are formed in the depressions within the elevated (plateau) part of the basin. The most significant of these depressions are those within the path of the Kagera River. The Kagera aquifer is within these alluvium depressions and it covers an area of bout 6,300 Km2.

Table 1-1: Distribution of Kagera Basin Catchment within Riparian Countries

Country	Catchment Area (Km^2)	% of Total Catchment Area
Burundi	13,060	22
Rwanda	20,550	34
Tanzania	20,210	34
Uganda	5,980	10
Basin	59,800	100

1.3. Objectives

The aim of this study is to generate water balance modelling scenarios under various stress conditions including climate change for the Kagera aquifer with quantified: recharge, outflows (base flow, deep percolation, etc) and withdrawals from 2021 to 2050 applying different management parameters.

1.4. Terms of Reference (TOR)

This study was sponsored Global Environment Facility (GEF) and in collaboration with the United Nations Development Program (UNDP) under the auspices of the Nile Basin Initiative (NBI). The Nile Basin Initiative (NBI) is a cooperative arrangement initiated and led by the Nile riparian countries to promote joint development, protection and management of the common Nile Basin water resources. The terms of reference of the study include:

- Development of conceptual and numerical groundwater models at a transboundary scale
- Development of numerical models projecting different socio economic and climate scenarios from present to the year 2050 in the horizon for selected SSPs (Shared Socioeconomic Pathways), and range of climate change scenarios to identify strategic recommendations for sustainable management and utilization of
- Kagera aquifer.
- Identification of key threats to sustainability of shared groundwater aquifers (climate change scenarios, increased/unsustainable withdrawals, land use/change).
- Prepare Training materials on transboundary GW modelling for the aquifer system
- Provide Recommendations for sustainable conjunctive groundwater – surface water use covering technical aspects.

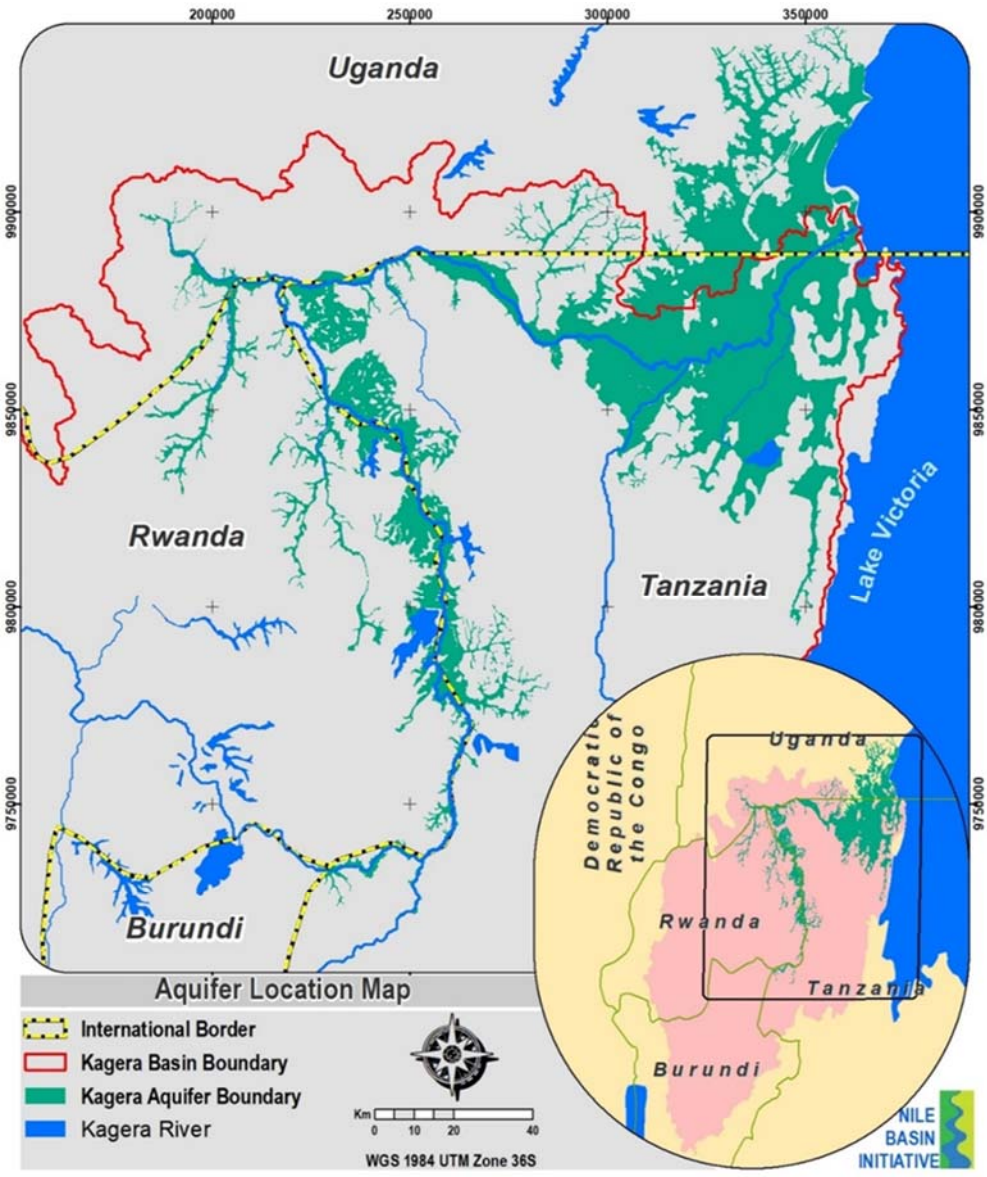


Figure 1-1: Project Area Location

2. Geological Setting

2.1. Geological Formations

The simplified regional geological map of the Kagera Basin was established through the compilation of the national geological maps of the four countries (Burundi, Rwanda, Uganda and Tanzania). The geology of the basin can be itemized from younger to older into four main geological groups:

- Unconsolidated Deposits } Cenozoic (Late Pleistocene- Recent)

- Consolidated Sedimentary Deposits} Proterozoic (Neoproterozoic- Mesoproterozoic)
- Metasedimentary Basement } Proterozoic (Paleoproterozoic)
- Basement Complex } Archean

Basement Complex: (> 2500 Ma) The basement complex is the oldest rock unit in the area. They are highly deformed metamorphic rocks which consist of migmatites, granitic gneisses and gneisses with local intercalations of amphibolites and metaquartzites.

Metasediments: (1000-1800Ma) cover the largest part of portion of the Kagera Basin, these are Geologically, folded and slightly metamorphosed clastic sediments of the Mesoproterozoic Karagwe-Ankole Belt (formely known as Kibarana Belt) which underlie most of Burundi and extend through Rwanda into northwest Tanzania and Uganda in an east-northeast direction. They consist of quartzitic metasediments, other metasediments comprising micashists, schists psammites and psammoschists as well as magmatic intrusions represented mainly by granitoids and basic to ultrabasic rocks.

Consolidated Sedimentary Rocks: (635 – 1000 Ma) This unit is made up of consolidated sedimentary rocks, mainly consisting of sandstone, quartzite, schist, limestone, dolomite and local intercalations of volcanic rocks. The supergroup lies unconformity upon the older Burunidan Supergroup/Northeastern Kibaran Belt, its sedimentary succession may comprise two or three layers based on the degree of metamorphism of each layer. The Lower Series, comprises formations of quartzites and various undifferentiated rocks including argillaceous sandstones, basal conglomerates, and shales. The middle series comprises Silicified domomitic limestones and lava. The upper series which is mostly noted in north western Tanzania comprises Fine-grained sandstones, shales, conglomerates, limestones and dolomitic limestones.

Unconsolidated Sediments: These are Late Tertiary to Quaternary deposits: which comprise unconsolidated sediments of different soil types derived from the weathering of the various older formations including crystalline basement rocks. Deposits include the more recent

Alluvium and fluvio-lacustrine sediments as well the older deposits of beach terrace gravel and sand

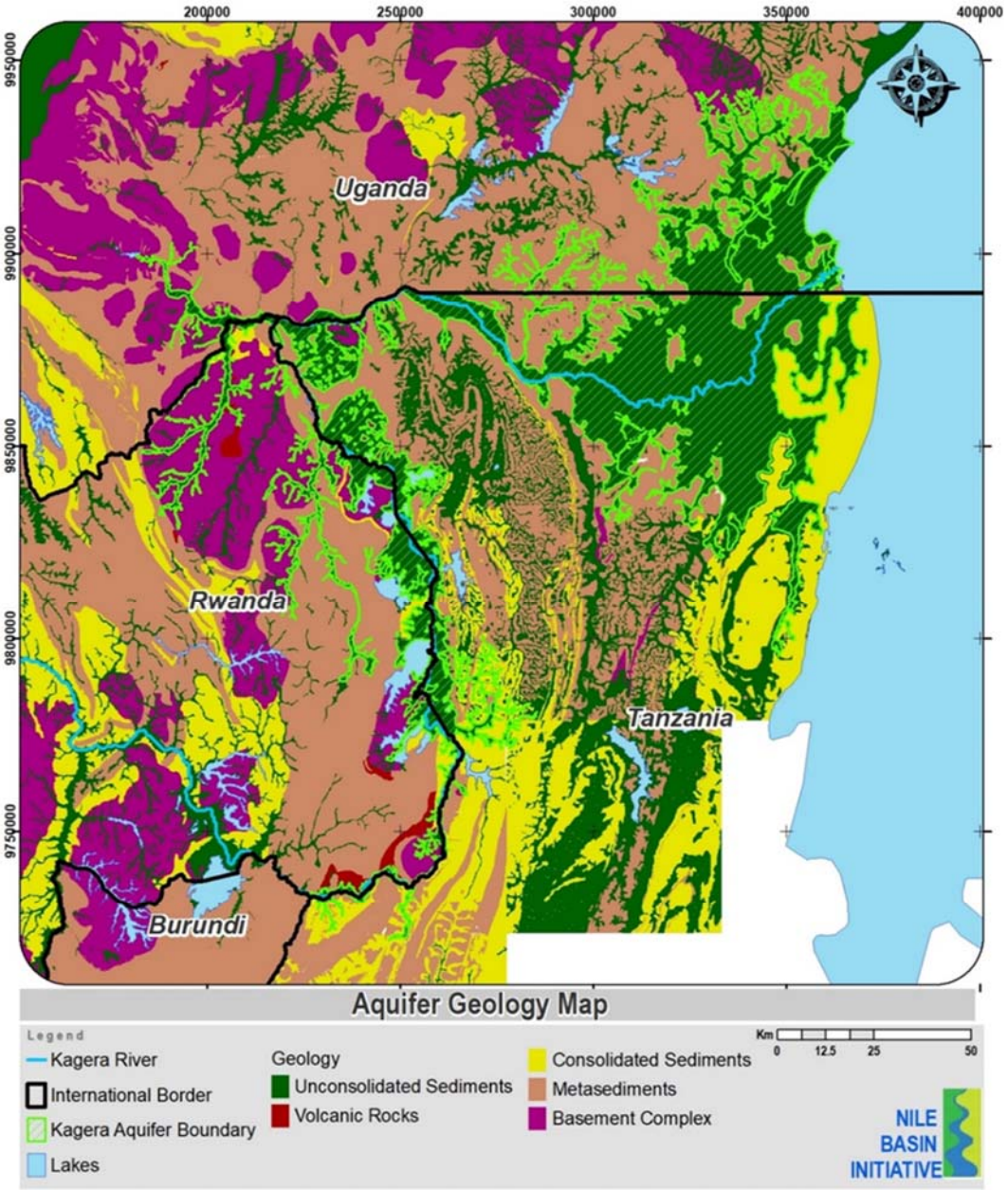


Figure 2-1: Geological Map

2.2. Geological Structure

Structural Geology: the structural control of the Kagera Basin is related to the formation of the Eastern Africa Rift Valley, an active continental rift zone in East Africa, which began developing some 25 to 30 million years ago, (Miocene) for the eastern branch and some 10 to

15 million years ago, for the western branch in which the Kagera Basin is found. [other source 22 to 25 million years ago]. The major faulting trends are NE – SW and NW – SE

Geophysical investigations were conducted during the course of the project to compile additional information about the aquifer lithology at the downstream and upstream parts of the aquifer in Tanzania and Burundi. The limited data were used in conjunction with the available well lithology data to ascertain the type and thickness of water bearing formations within the aquifer area. The information obtained from the well lithology data were limited due to the drilling depth limitations and absence of geological logs in many cases.

Results of the geophysical investigations in Tanzania revealed that the existence of four distinct geological layers in the downstream part of the aquifer. The first layer is the alluvial layer which is relatively large in terms of both horizontal and vertical extension, vertically it extends from about 10 to 80 meters. Furthermore, the profiles show the presence of weathered formation as the second layer which extends to about 180m. The presence of weathered zone/formation in the profiles indicate the potentiality of groundwater in specific zones. Although all the profiles consist of the weathered layer as the second layer but they are characterized by the alteration of geological materials with contrasting weathering intensity thus, the degree of weathering differs from one point to another.

The third layer is a fractured basement which constitute a semi-confined water bearing layer with a considerable vertical extension (~90 m). It exhibited low resistivity values suggesting the presence of groundwater with dissolved ions.

The fourth layer is the basement layer consisting of the hard formation characterized by high resistivity values indicated. The extent of the bottom layer (basement) is not well defined since the maximum depth of the investigation was 300m. The basement starts at depth of 280 m below.

The results of the geophysical survey in Burundi did reveal the presence of two layers before the hard basement. The top alluvium layer is very thin with thickness of less than 5.0 meters. It

is followed for the most part by a fractured basement layer that is about 50 meters thick overlying the basement complex. The presence of weathered basement of varying thickness overlying the fractured basement layer was detected in some areas.

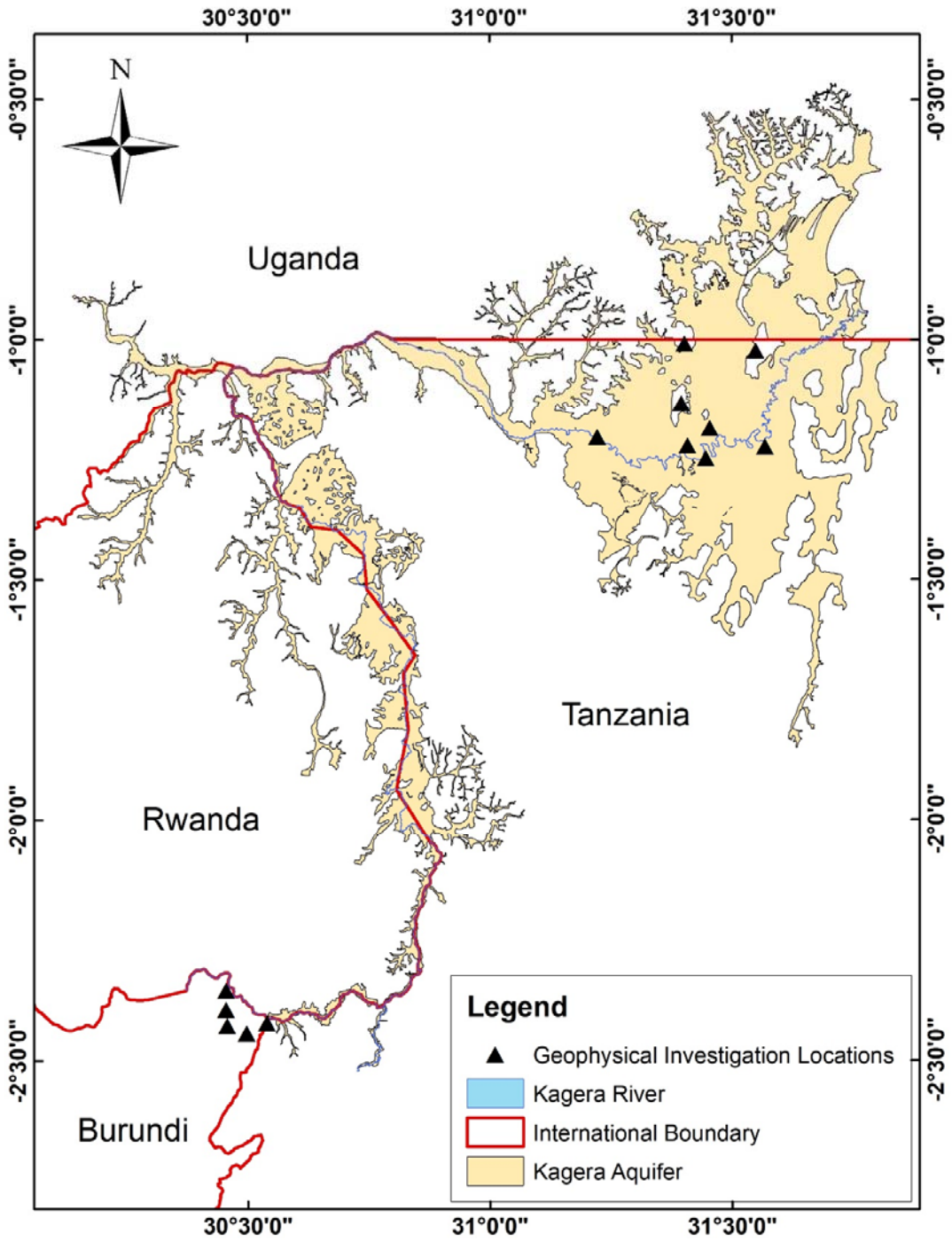
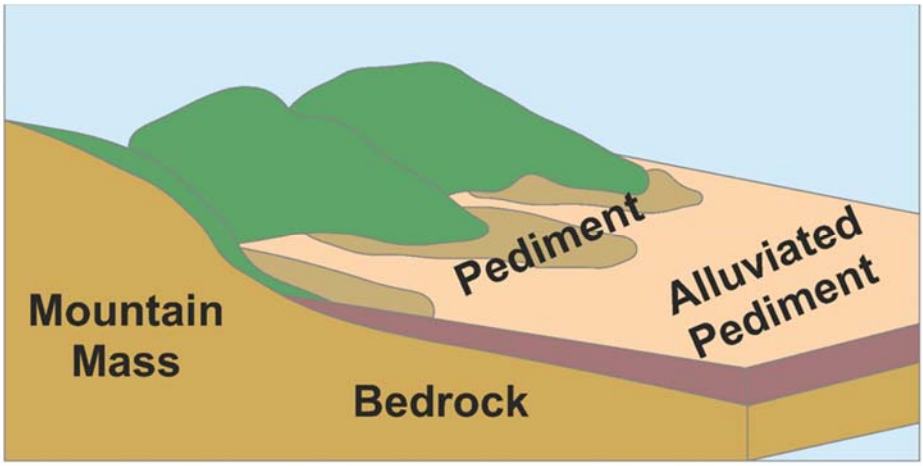


Figure 2-2: Location of Geophysical Investigation Points

3. Hydrogeology

3.1. Hydrogeological Conditions of Kagera Aquifer

The Kagera aquifer is for the most part defined as the low areas of alluvium deposits around the Kagera River. These shallow unconsolidated sediments were formed through the slow erosion and disintegration processes of the rock surfaces of the mountains by rain in the humid conditions of the basin area. These sediments were washed to the base of the mountains forming a series of pediments and these pediments gently slope outward, where they coalesce with each other to form one large pediplain. The pediplain is the basic formation of the Kagera Aquifer its thickness is not known but is expected to be in the order of 50-80m based on drilled well depths. The alluvium layer, is underlain in either by a fractured basement complex / Metasedimentary rocks or by consolidated sedimentary formations. Interpretation of compiled data reveals that the source of recharge to the Kagera aquifer emanates from three sources:



- Direct Recharge from the Kagera River: Aquifer replenishment apparently occurs when the river stage is higher than the groundwater level thus generating a hydraulic gradient where by the river loses to the aquifer. The process may be reversed when the river stage becomes lower than the groundwater level in which condition the river gains water from the aquifer
- Direct Recharge from Wetlands: The Kagera basin features a number of wetlands in its low elevation areas, a number of which around the depressions of the Kagera River. These wetlands are contact zone through which the aquifer may be recharged.

Wetlands may also be points of groundwater discharge to the surface of the land, such as springs.

- Flow from the surrounding fractured basement complex: The heterogeneous mixture of crystalline rocks forming the basement complex around the Kagera River are highly fissured and thus have the ability to store and transmit rain water through these fissures. Water moves slowly through these fissures and often emerge in the study area in the form of spring in the side of the mountain, the flow may also emerge below the ground surface to latterly recharge the alluvium aquifer in the pediplain. The storage of the basement complex is finite and relatively small, however the large contact area of these hills along the boundaries of the aquifer means that significant volumes of recharge may be introduced to the aquifer with recharge sources as far west as the Congo-Nile Ridge.

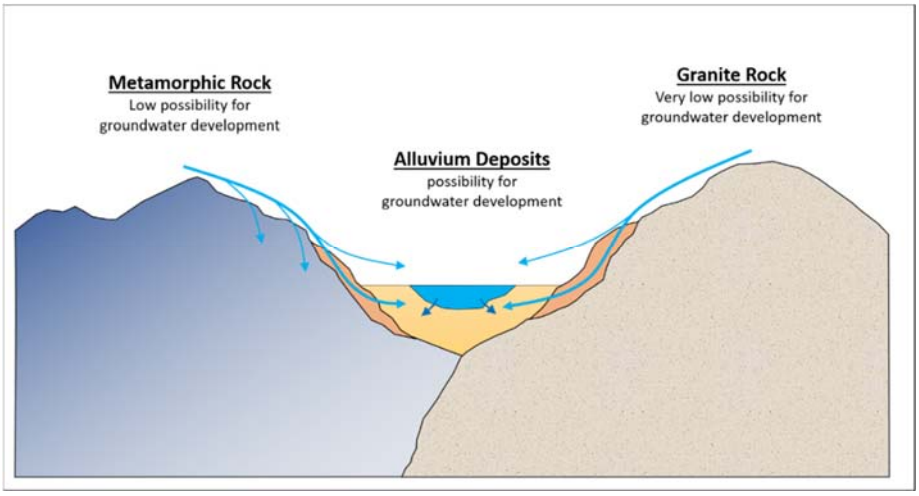


Figure 3-1: Schematic of the Conceptual Model of Kagera Aquifer

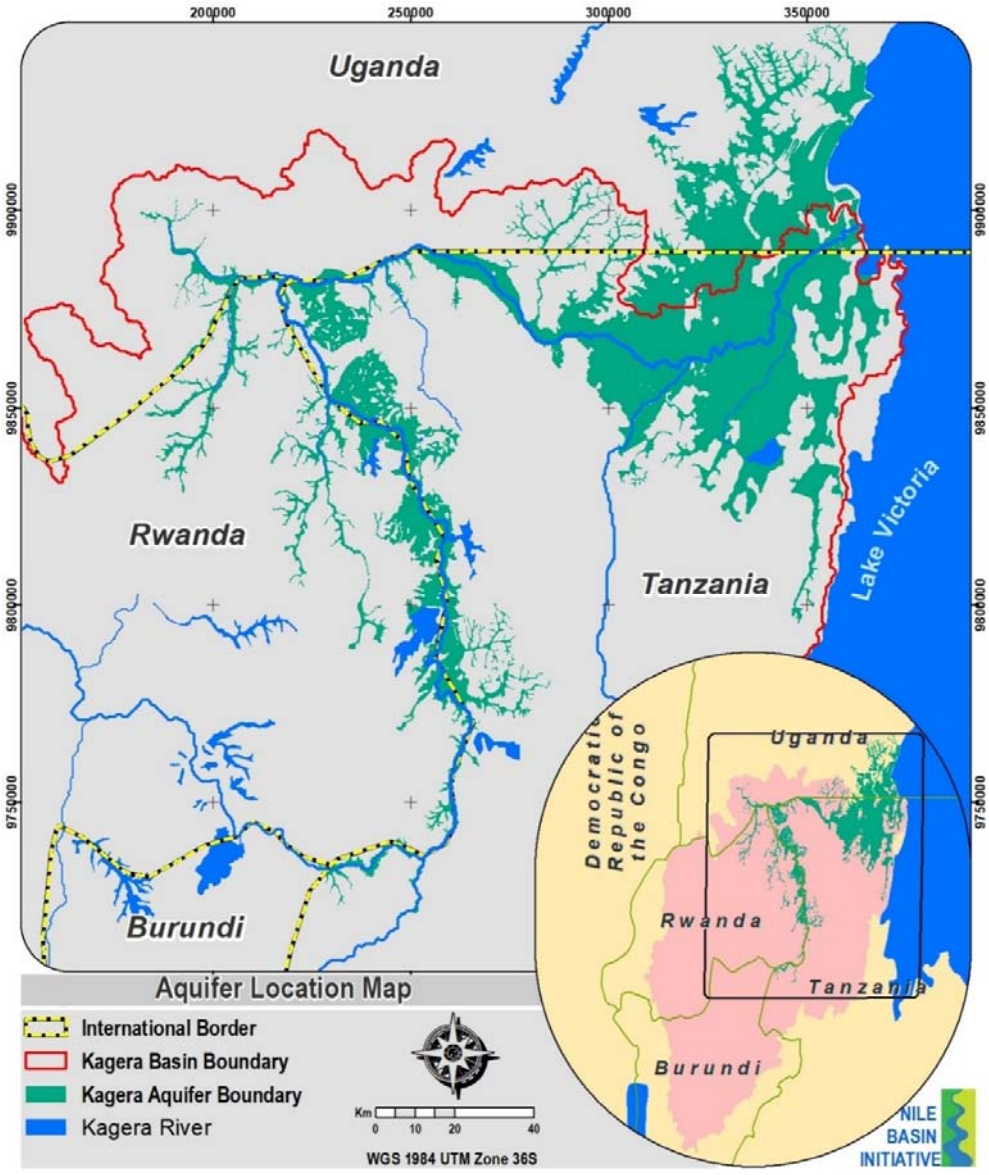


Figure 3-2: Kagera Aquifer Extent

The boundaries of the Kagera aquifer were ascertained from the geological maps of the four riparian countries as well as the topographic maps of the area. The area of the whole aquifer is estimated to be 6300 Km2 with 1 % of it within Burundi, 13% within Rwanda, 22 % within Uganda and 64 % within Tanzania.

Groundwater occurs in Kagera aquifer in unconfined conditions and flow direction is expected to follow the Kagera River flow direction initially in a north trending direction and eventually eastwards towards Lake Victoria.

The Kagera aquifer in actuality is comprised of a series of alluvium deposit aquifers that are hydraulically or hydro-geologically connected. It can however be divided into three main sections. The lowland (delta) segment which is comprised of a contiguous alluvium deposit aquifer, constitute the most potential part of the aquifer as it forms about 70% of the total aquifer area and is expected to be the thickest part of the aquifer.

The Plateau (middle) segment is comprised of a series of discontinuous alluvium deposit aquifers that are hydraulically connected though the Kagera River and hydrogeologically connected. The average width of the aquifer in this section is generally greater than 10 km and there are indications that metasedimentary and basement rocks containing these deposits are extensively fractured thus facilitating the hydrogeological connection between the alluvium subbasins. This segment extends upstream from the apex of the delta section to Rusumo falls and it constitutes about 28% of the total aera of the Kagera aquifer.

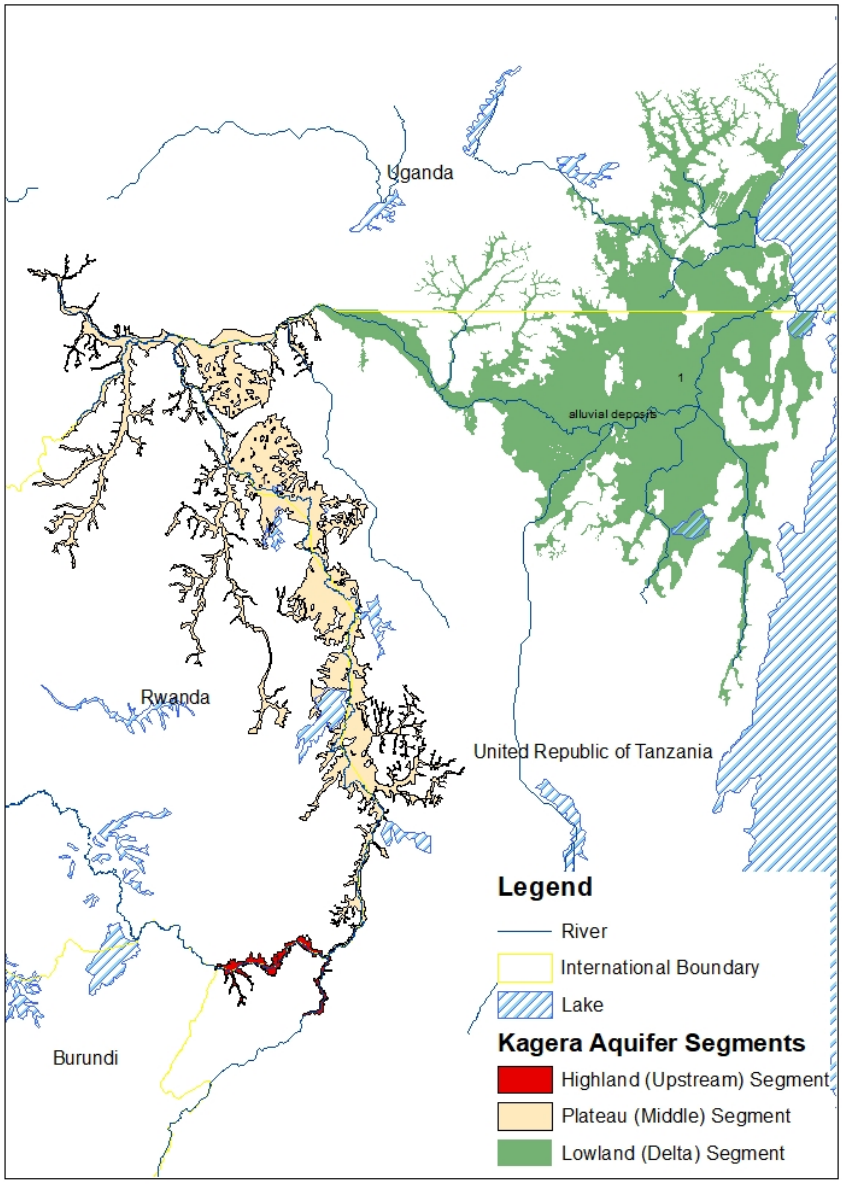


Figure 3-3: Kagera Aquifer Segments

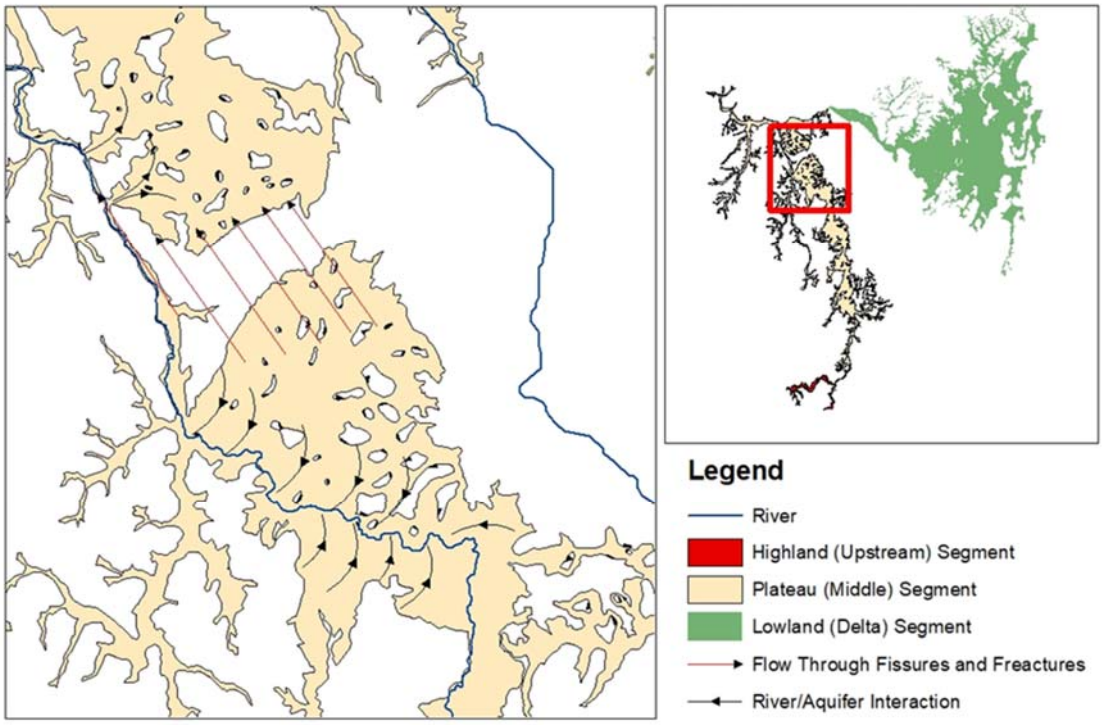


Figure 3-4: Hydraulic (River) and Hydrogeologic Connection of Sub-basins of the Middle Segment of Kagera Aquifer

The third (highland) segment is comprised of thin alluvium deposits along the Kagera river course. The aquifer width on both sides of the river is less than 1.5 Km in average indicating significantly lower potential than the other two downstream aquifer segments. Aquifer connectivity in this segment is expected to be mainly through interaction with the river due to the limited extent and storage capacity of the alluvium aquifer as well as the relatively low potential hydrogeological connectivity through the basement complex rocks containing the alluvium deposits. The upstream of extent of the highland segment in not well delineated, while it was currently extended to 30 kilometres upstream of Rusumo falls per available geological and topographic data, there are arguments that it could be extended upstream up to lake Rewru (approximately 60 Km upstream of Rusumo falls).

The hydraulic connectivity between the upstream and downstream segments of the aquifer is maintained through their interaction with the Kagera River. Hydrogeological connectivity between the plateau and delta segment is believed to be significant due to the extent of fractures

in the basement rocks adjacent to the alluvium deposits. It is however deemed to be very weak and almost non-existent between the highland and the plateau segments across the Rusumo falls.

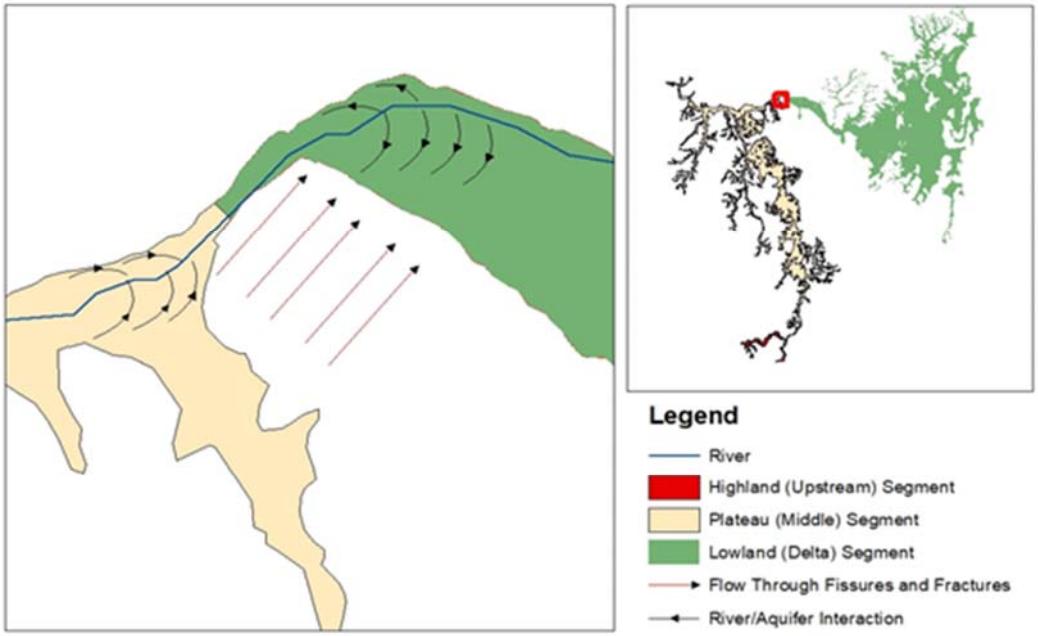


Figure 3-5: Hydraulic (River) and Hydrogeologic Connection of the Middle and Lowland Segments of Kagera Aquifer*

*Groundwater drains from the upstream Middle segment which has a relatively small storage capacity into the river which conveys these waters into the downstream Lowland segment (hence the term hydraulic connection) where it recharges the downstream segment of the aquifer. Significant subsurface flow also occurs through the fissures and fractures of the basement complex.

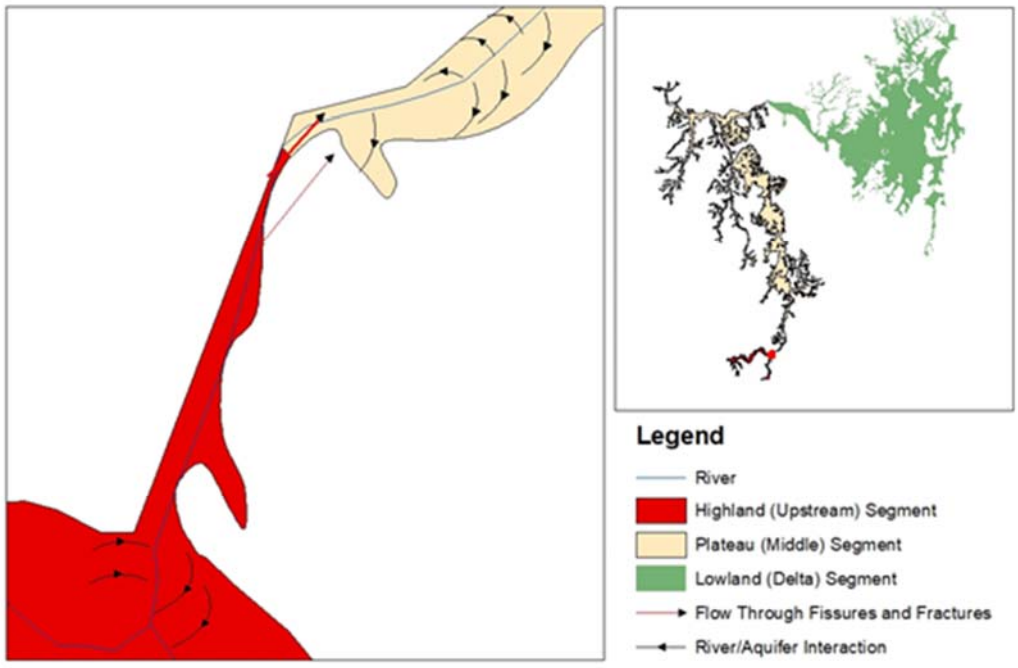


Figure 3-6: Hydraulic (River) and Hydrogeologic Connection of the Upstream and Middle Segments of Kagera Aquifer**

** Groundwater drains from the upstream Highland segment which has a relatively small storage capacity into the river which conveys these waters into the downstream Middle segment where it recharges this segment of the aquifer. Limited subsurface flow occurs through the fractures of the basement complex

The Kagera aquifer is isolated for the most part from Lake Victoria by the basement rocks of the crustal block which formed the lake. Zones of contact between the aquifer and the lake water occurs in small segments at the estuaries of the rivers flowing into the lake (Kagera and Kisomo). Groundwater water levels along the beaches of these contact zones is visibly high with full soil saturation conditions close to the lake shores. The length of contact zones with the lake is estimated to constitute about 15% of the total length of the aquifer alongside Lake Victoria. Figure 2-24

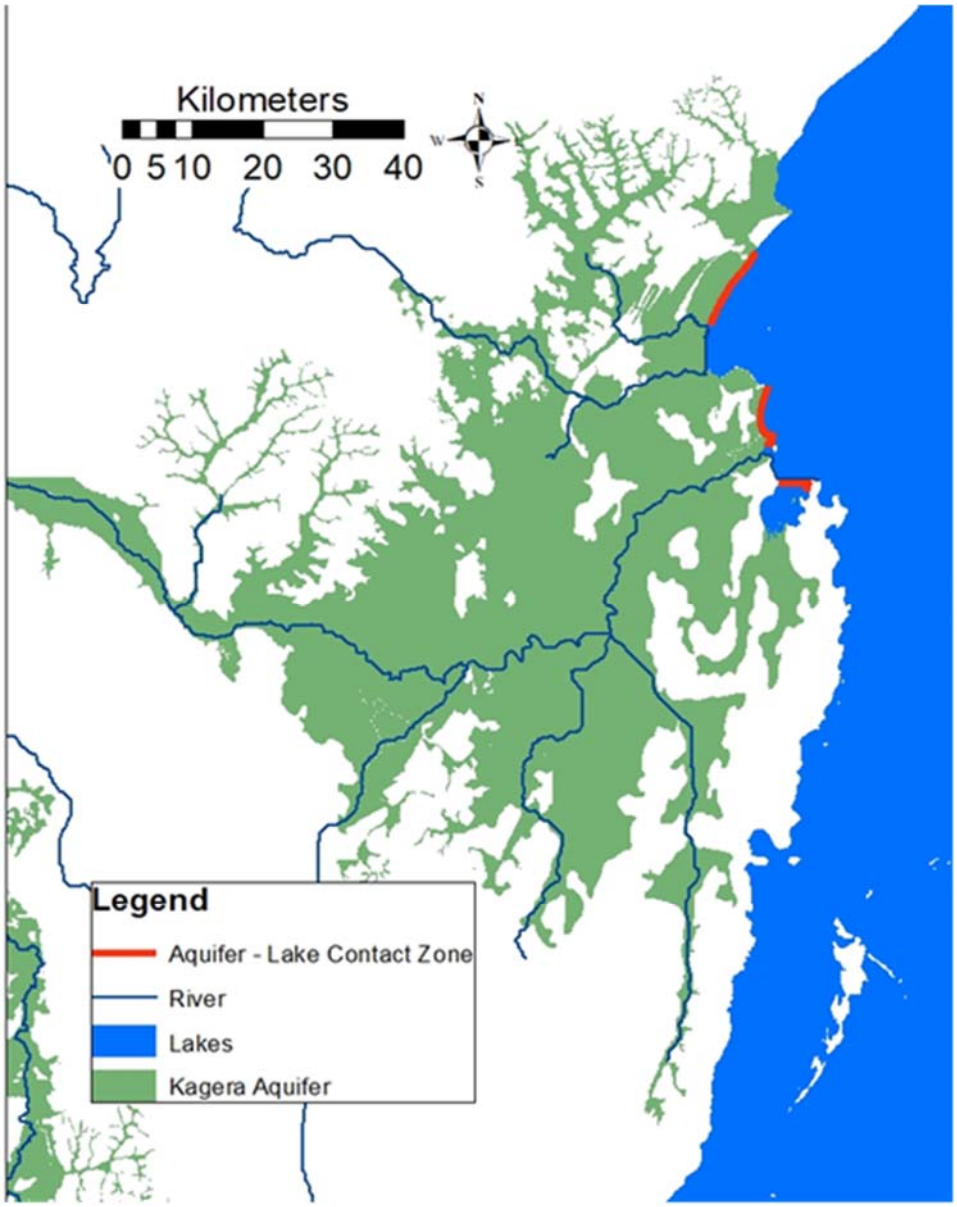


Figure 3-7: Kagera Aquifer/Lake Victoria Contact Zones

3.2. Hydraulic Properties

The estimation of the hydraulic properties is an indispensable element in the characterization of any aquifer. These properties can be ascertained by conduction extensive field investigations that include pumping tests. In the absence of the results of such investigations, estimate of hydraulic properties can be assigned using cited literature and previous experience according to the classification of geologic formation. Three types of water bearing formations are reported to dominate the project area. The alluvium deposits which comprise most of the Kagera aquifer is known to have hydraulic conductivity values that ranges between 20 – 100 m/day and a porosity of 38-40% (Walker et.al. 2018). The processes of consolidation and cementation which transform the unconsolidated sediments to sedimentary rocks affect the hydraulic properties of these geologic formations. Sedimentary rocks generally have porosities that range between 10% to 30% some of which may be secondary (fracture) porosity. The hydraulic conductivity of these formations is known to range between 1.0 and 10 m/day. The hydraulic properties of fractured basement vary considerably according to the rock type and the degree of wreathing and fissuring as well as fracture intensity and connectivity in the fractured layer. The values of hydraulic conductivity in fractured basement varies between 0.01 – 1.0 m/day and the porosity between 10-3 to 10-4.

4. Hydrology

The hydrology of the Kagera basin is governed by the climatic conditions in the regions which is moderated by altitude relief and many water bodies (lakes, rivers and wetlands). The climate ranges from tropical to humid with a bimodal rainfall pattern with two distinguishable rainy seasons, one centred around March to May and the other October to December with the wettest months in April and November. The average rainfall for the whole basin is between 700 to 2000 mm per year. The basin can be divided into three climatic zones.

The High ridge areas which correspond to the high-altitude areas in the basin along the Congo-Nile Ridge at the western part of the basin. This area has a humid climate with annual rainfall between 1000 to 1600 mm and average annual temperature ranges between 12°C and 17°C. This zone covers 39 % of the basin areas.

The plateaus area 39 % of the total surface area of basin with a sub-humid climate characterized by a mean annual rainfall which fluctuates between 800 mm and 1200 mm and average temperatures ranging between 16°C and 20°C.

The lowlands correspond to low-lying lands in the eastern part of the basin in which the climate is affected in by Lake Victoria which cause an increase in relative humidity and annual precipitation. Total annual precipitation gradually increases eastwards from about 800 mm/year to about 1400 mm/year towards the Lake. The mean annual temperature exceeds 20°C.

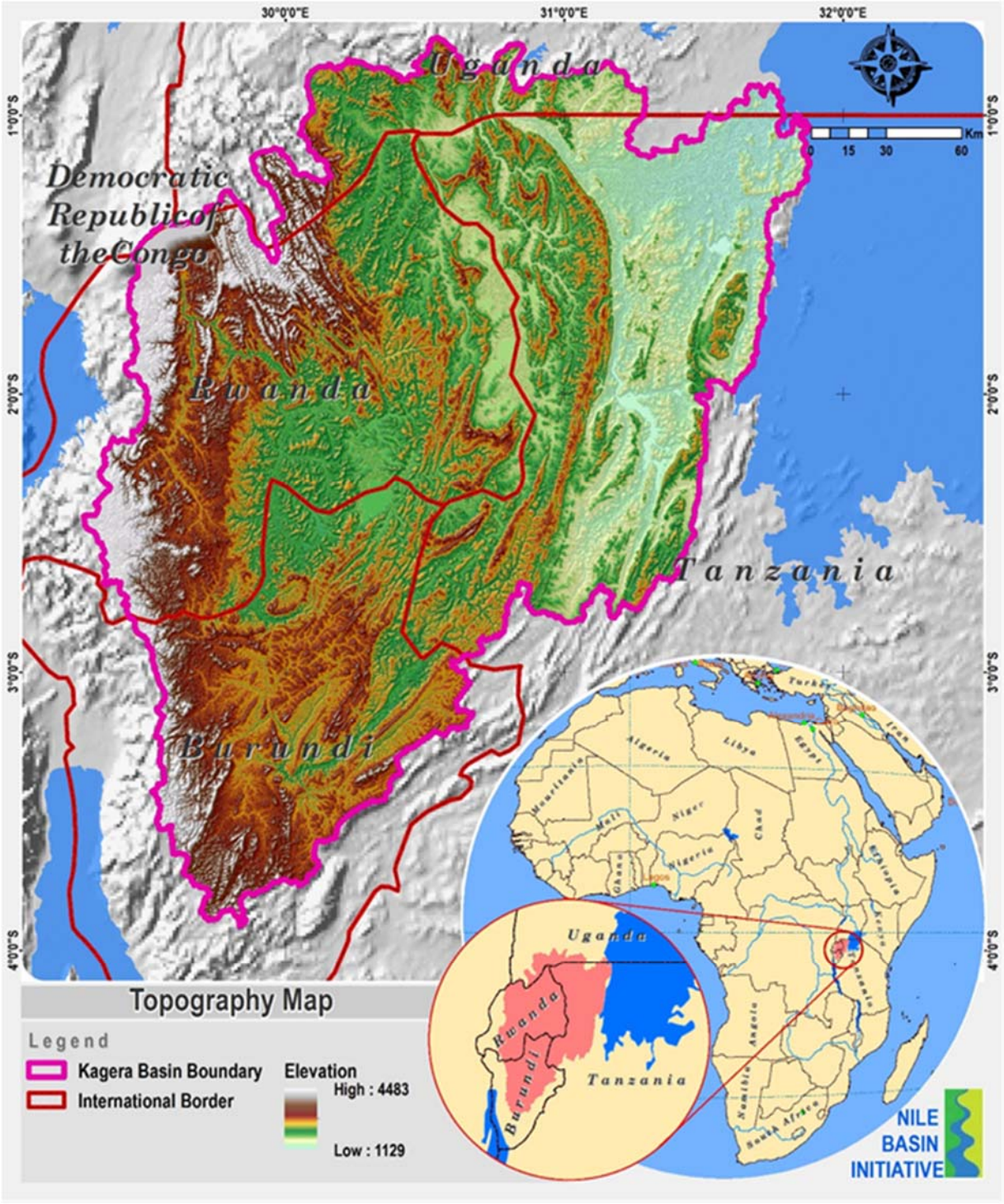


Figure 4-1: Topography Map

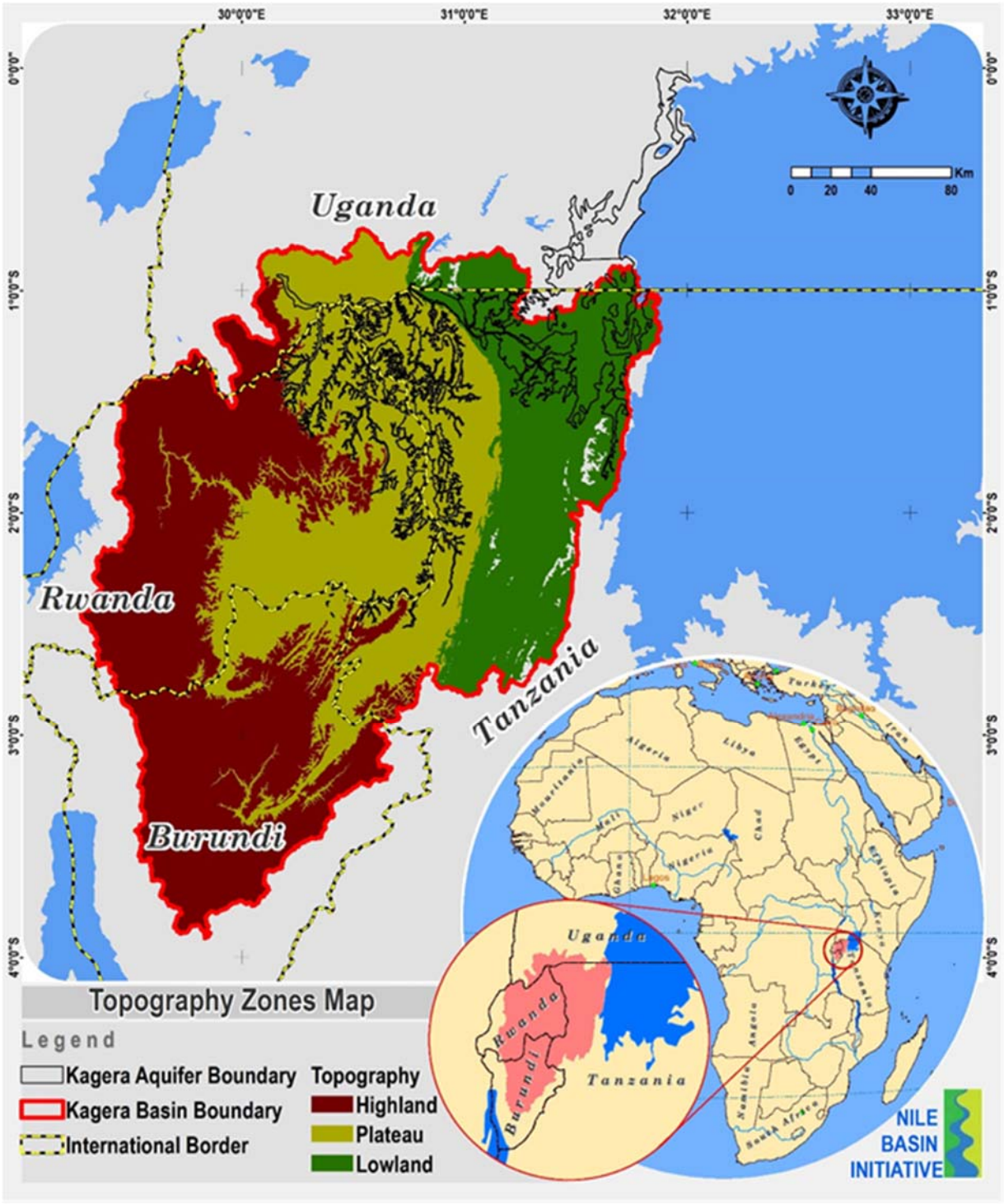


Figure 4-2: Topography Zoning Map

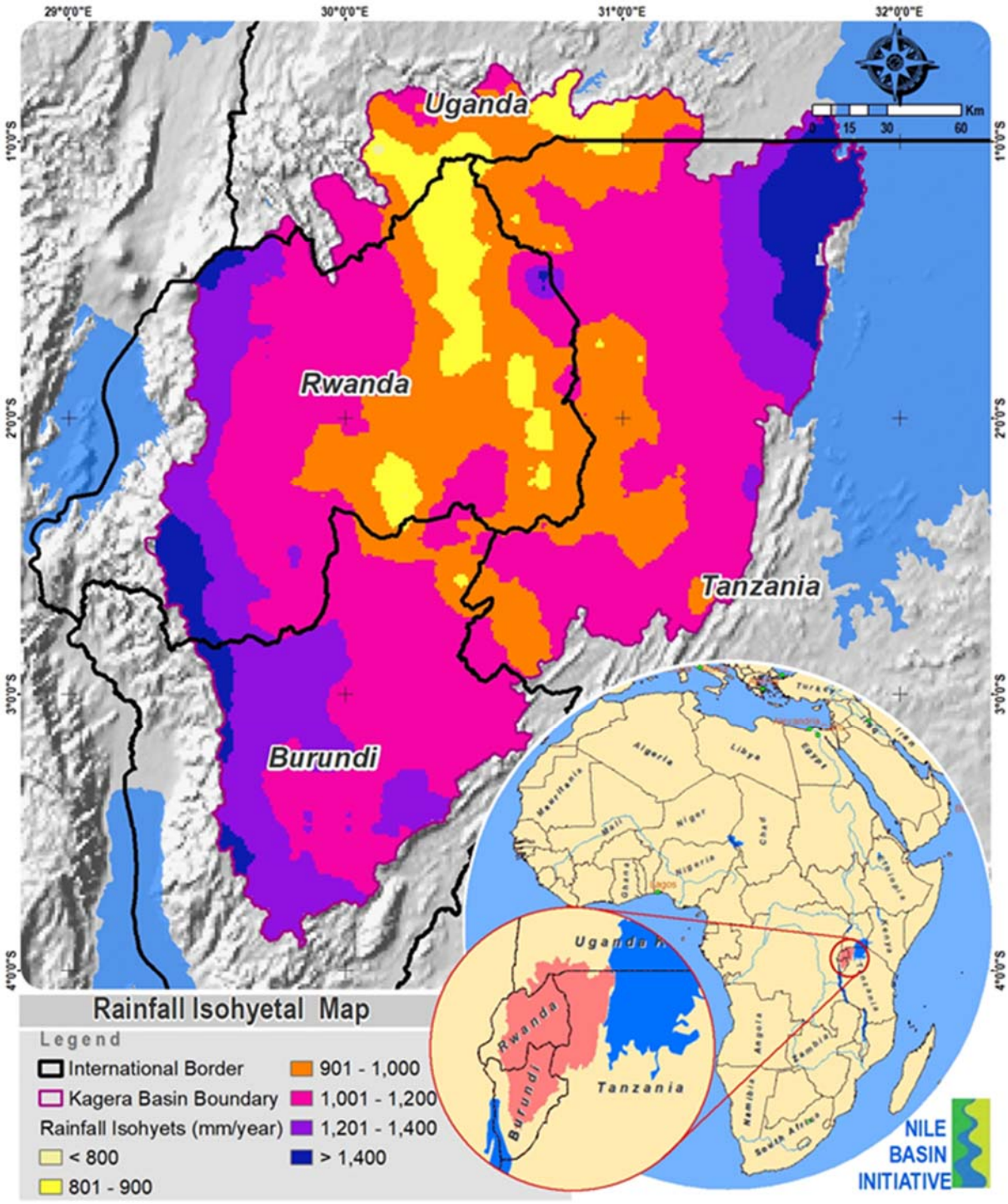


Figure 4-3: Rainfall Isohyet Map

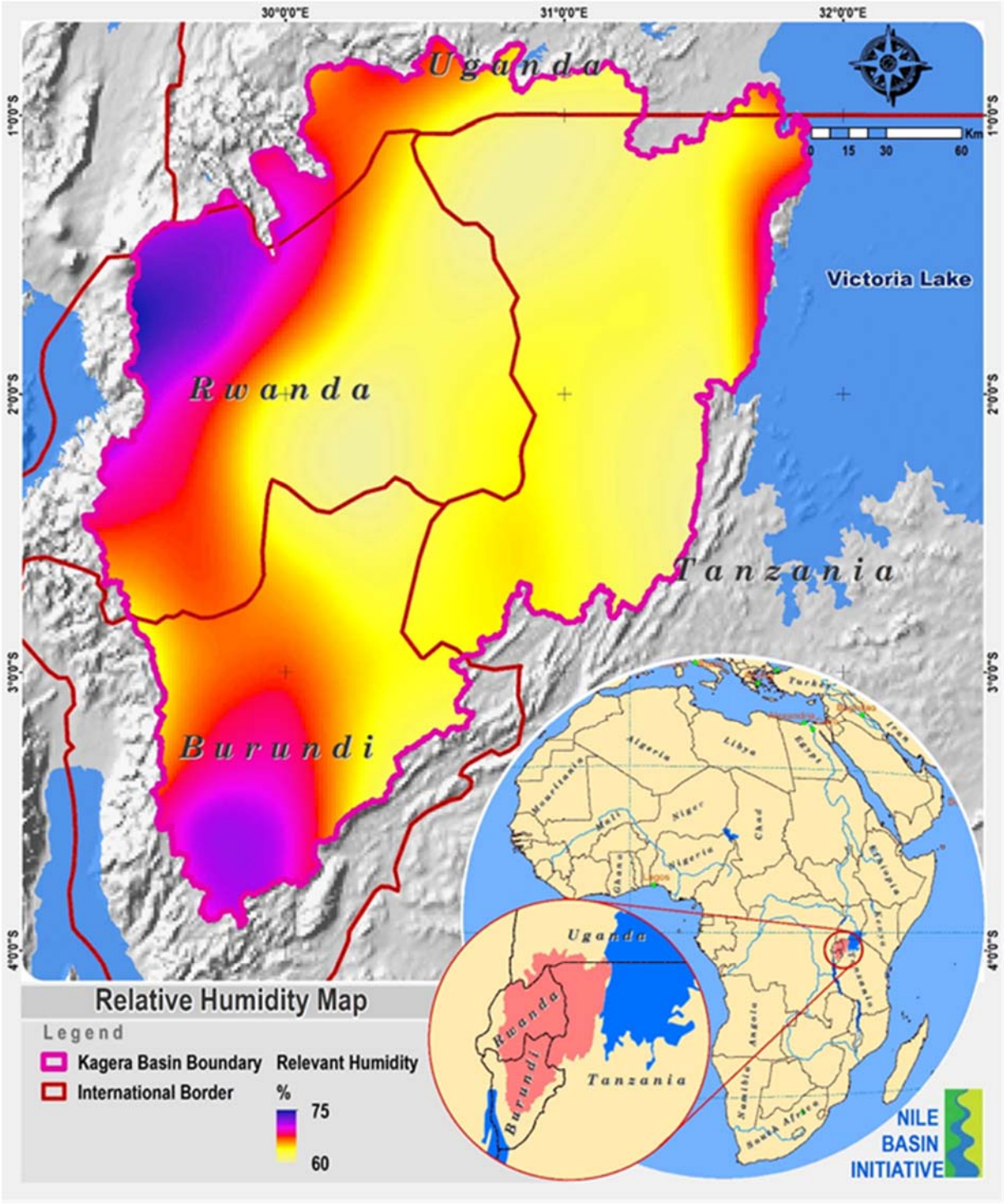


Figure 4-4: Relative Humidity Map

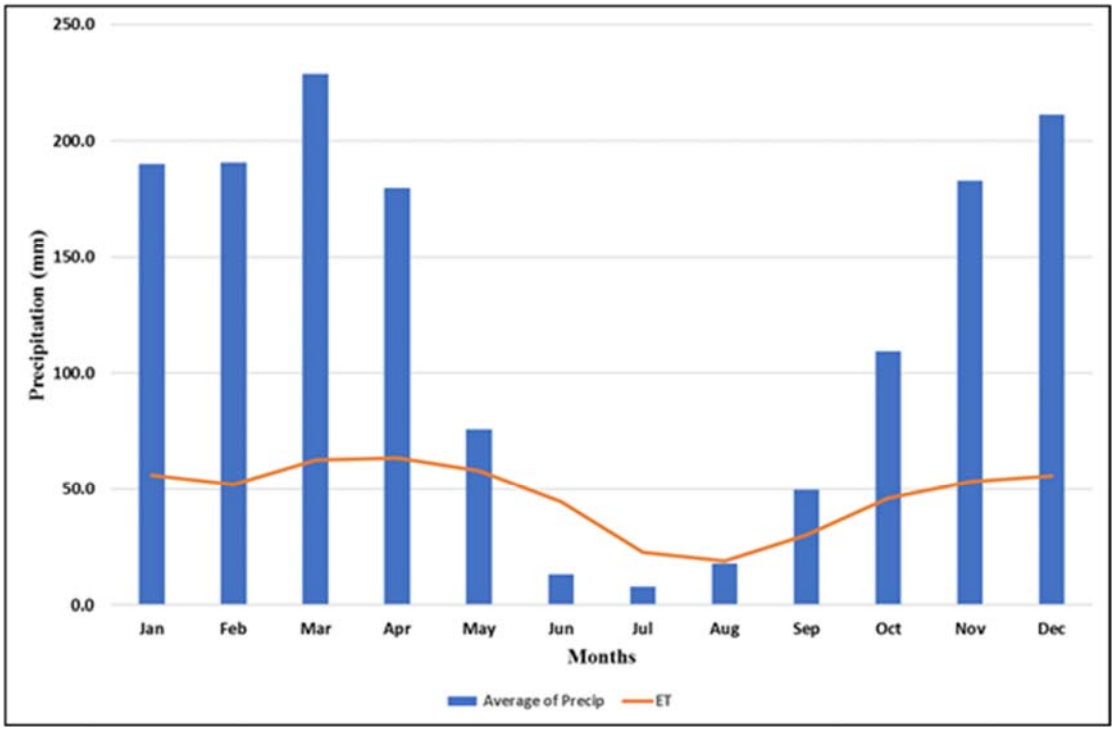


Figure 4-5: Average Precipitation and Evapotranspiration for the Highlands Part

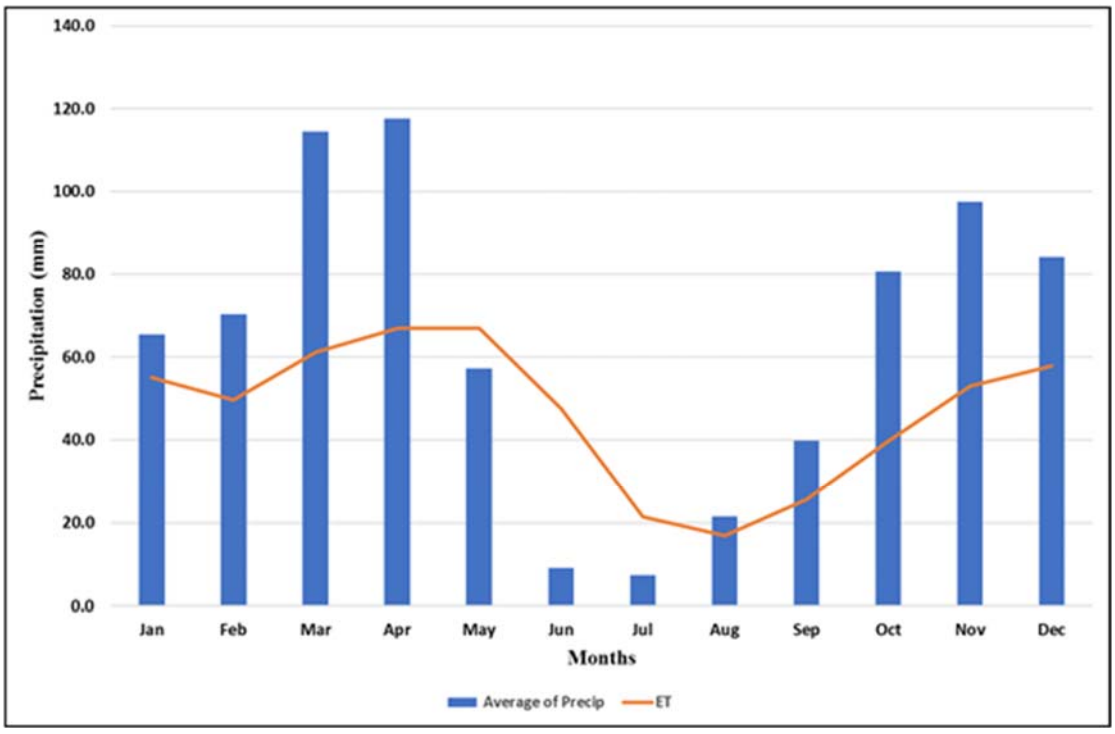


Figure 4-6: Average Precipitation and Evapotranspiration for the Plateau Part

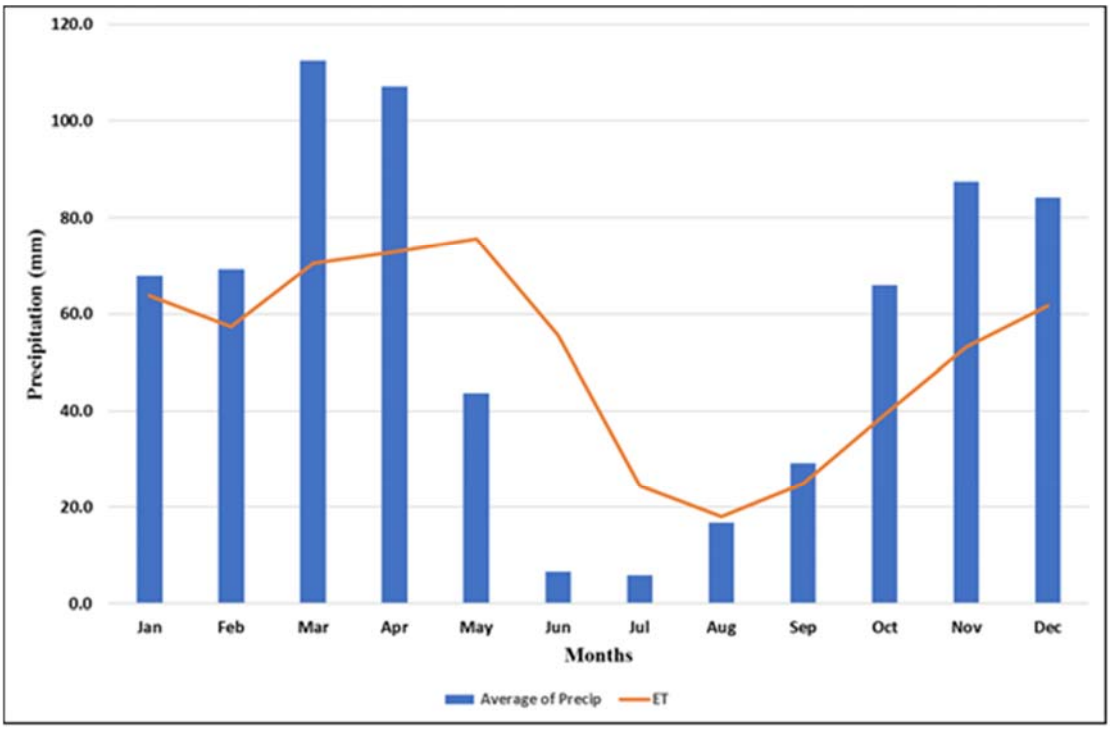


Figure 4-7: Average Precipitation and Evapotranspiration for the Low-lands Part

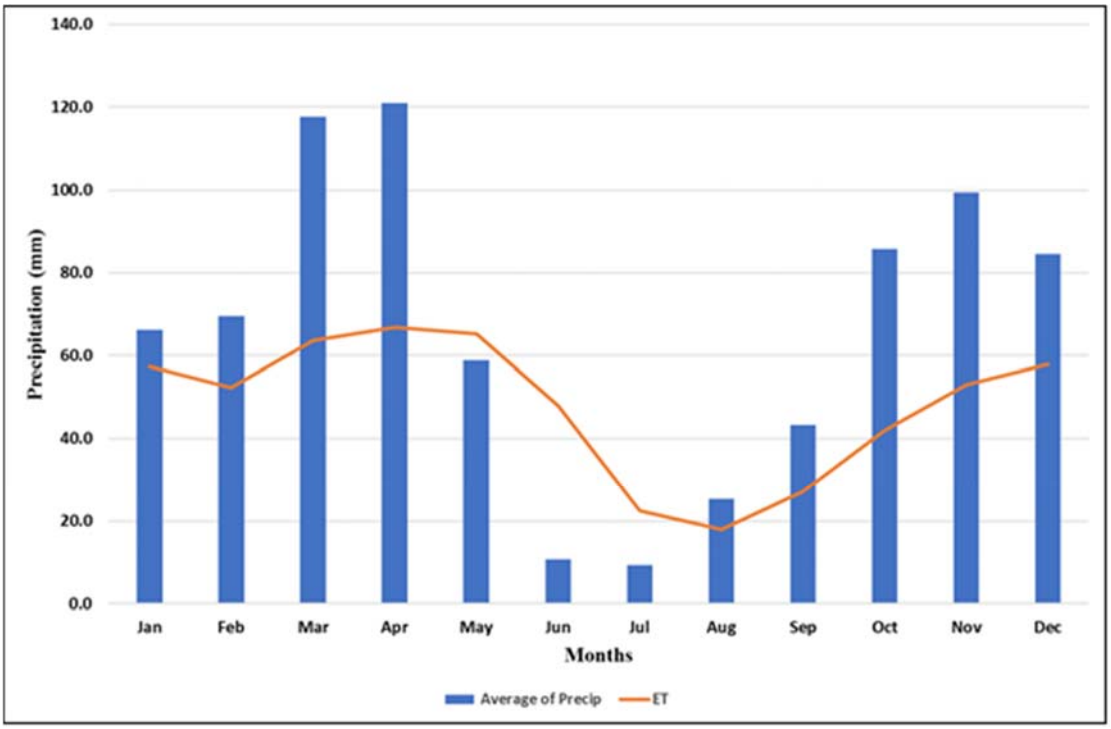


Figure 4-8: Average Precipitation and Evapotranspiration for study Area

The hydrology of the basin is defined by a number of physical conditions namely, its climatic conditions, topography and geology. The surface runoff generated by the significant precipitation which falls over the Kagera basin is drained by a number of Rivers which eventually join the Kagera River that drains into Lake Victoria.

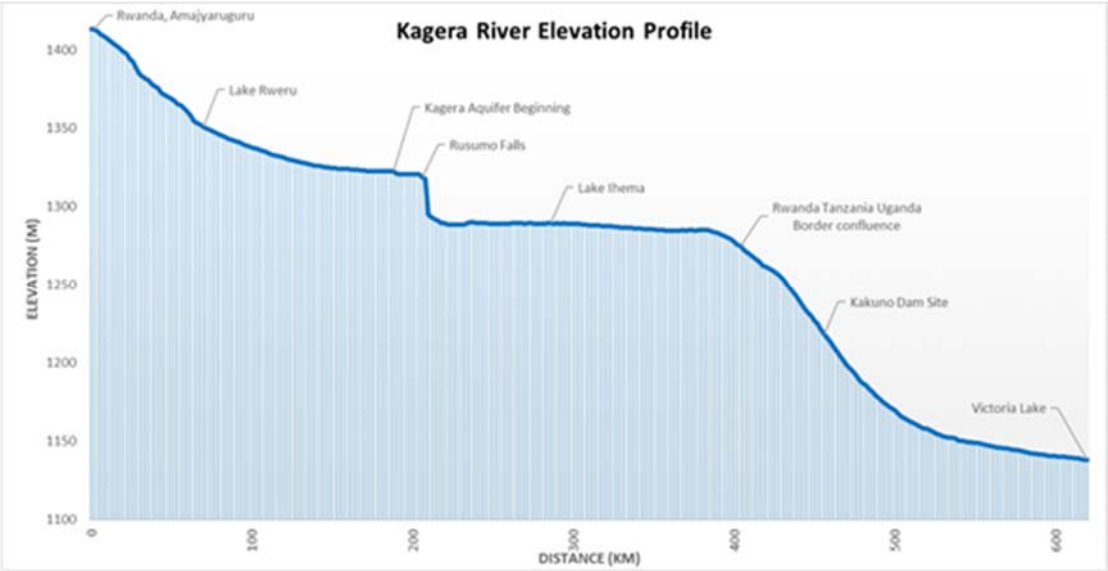


Figure 4-9: Kagera River Elevation Profile

The average annual discharge of the Kagera river at Kyaka (close to the River outlet in Victoria Lake) is 184 m3/sec, which is equivalent to 3.15 km3/year, with a low ratio of maximum, 540 m3/sec to minimum of 101 m3/sec flows caused by large swampy areas upstream, in Karagwe district (Tanzania). A representative sample of Kagera river hydrograph at Nyakanyasi station for 1971-1972 is given in Figure 2 14. The Kagera river is a potential source of recharge to the aquifer, it is also acts as a drain through which excess aquifer water leaks to the river which drains excess flows to the Lake Victoria. The water level of lake Victoria at the eastern end of the basin has seen an progressive rise in recent years (Figure 4-12). The lake is geologically connected to the Kagra aquifer in limited sections through which the water flow is exchanged between the aquifer the lake depending of their stage.

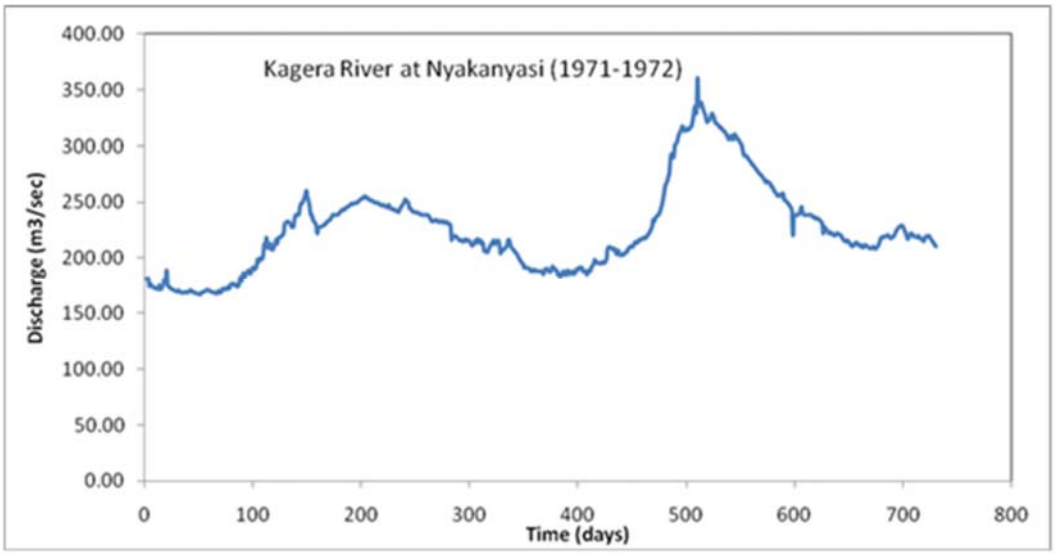


Figure 4-10: Hydrograph for Kagera River at Nyakanyasi station (Tanzania) for 1971-1972

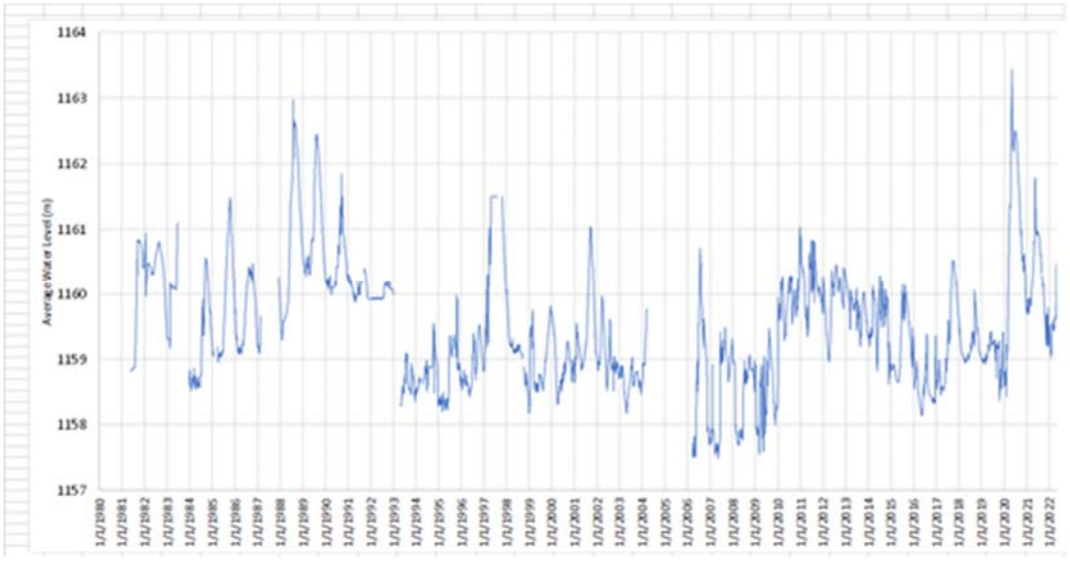


Figure 4-11: Hydrograph of Kagera River at Kyakaferry 1980 – 2022

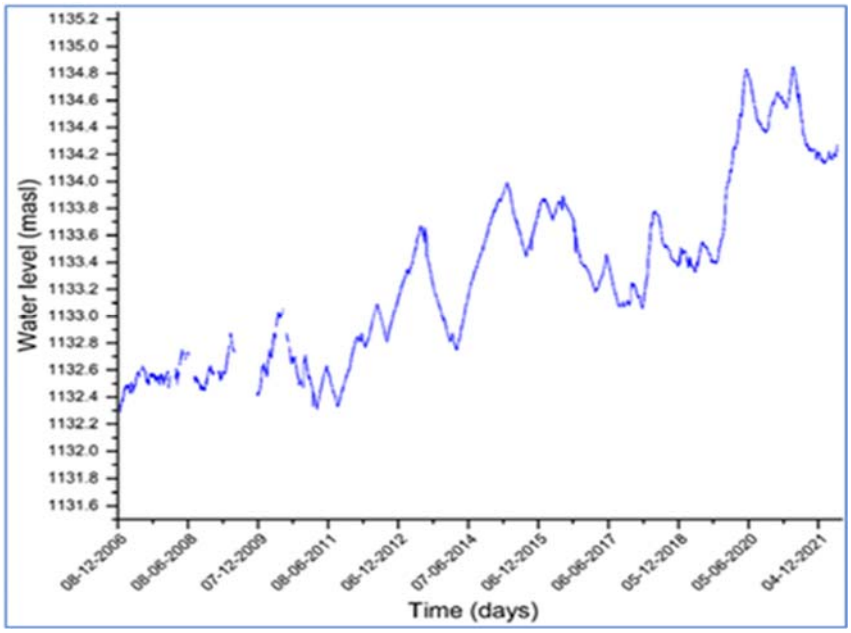


Figure 4-12: Water Level of Victoria Lake @ Bukoba 2008 – 2021

5. Groundwater Flow & Development

The determination of the overall groundwater flow pattern within the study region is reliant on the availability of groundwater level measurement data. Limited number of measurements are however available to conduct a detailed analysis of groundwater flow. The groundwater flow however is governed by the Kagera river with the general direction of flow is in tandem with the that of the river and the groundwater levels in the areas close to the river are equal to river stage. The general groundwater flow in the aquifer ascertained from the limited available data is depicted in Figure 5-1

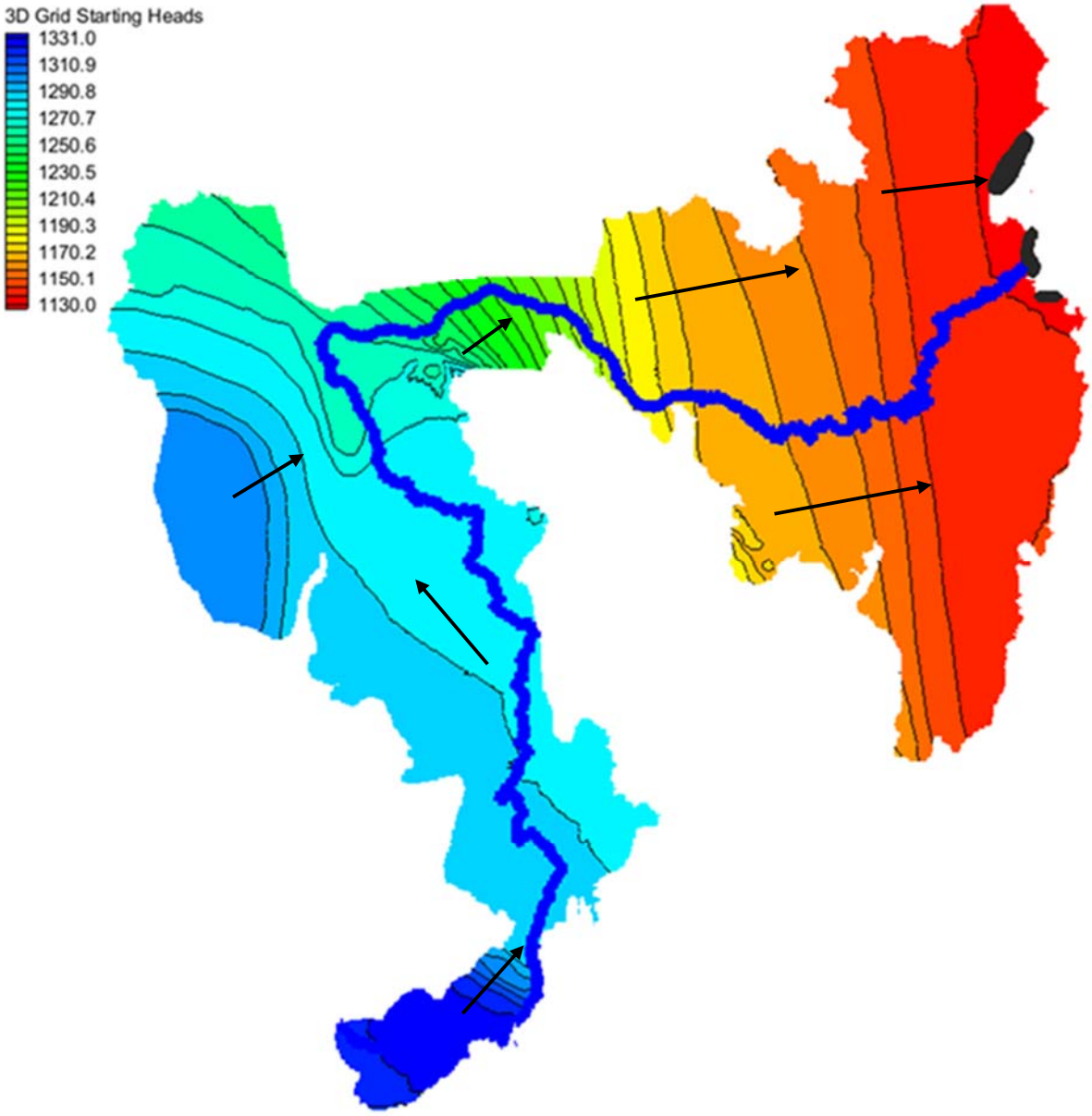


Figure 5-1: Initial Groundwater Level

The total population of the four riparian countries of Kagera is estimated to be more than 120 million with Tanzania being the most populous (~49%) followed by Uganda (~32%), then Rwanda (~10%) and Burundi (~9%). The average annual population growth rate in the four countries is about 3% and about half of the total population is below the age of 15. The population within the Kagera aquifer area is estimated to be about 900,000 distributed between the four countries as follows; Tanzania 59%, Uganda 21%, Rwanda 17% and Burundi 3%

Farming activities are the most dominant livelihood activity in Kagera aquifer area. The main livelihoods structure in the aquifer are dominated by subsistence farming; crop and livestock production. The main food crops include finger millet, maize, beans, bananas, cassava, potatoes, in addition to fruits and vegetables with Coffee being a major cash crop.

Other livelihood activities include small scale fish farming, agroforestry and brick making. Agricultural activities are dominated by women, while the remaining aforementioned activities are dominated by men. The aquifer region is generally one of high poverty, with poverty status varying from one location to another depending on existing opportunities for economic activities. Urban centres within the aquifer serve as regional trade and service centres relying primarily on trade and services and small manufacturing activities.

Precipitation and surface water from rivers and lakes are the source of water for the different livelihood activities in the Kagera region. Groundwater is used primarily as a source of drinking water and for animal watering accounting for about 70% of water supply (springs and boreholes). Women and children are mostly responsible for the collection of water. The average time spent to collect the water ranges between 20-30 minutes. Access to improved safe water sources varies greatly within the project areas and ranges in average from 60% to 80% with average per capita water use of about 25L/day. The development of groundwater resources in the area is increasingly sought by the authorities in the four riparian countries to improve access to safe water in a declared effort by the four countries to achieve universal access by 2030 in line with the sustainable development goals. Groundwater can contribute to the reduction of the risks of waterborne diseases as in general it is of better quality than surface water sources. The

challenge however, is to prevent groundwater contamination from anthropogenic sources. While the development of groundwater can effectively contribute to the enhancement of the domestic water supply, it is generally hampered by a number of technical, financial and/or managerial factors.

Estimation of current and future groundwater abstractions from the Kagera aquifer were estimated based on available population data, the current and projected per capita domestic water consumption. The analysis is based on the assumption that groundwater from the aquifer will be used solely for the provision of domestic water supply and that it will not be used for other activities such as irrigation or industrial uses. The projection did not take into account possible use for animal watering.

Table 5-1: Population and Domestic Water Consumption Estimates 2020 - 2050

Year	2020	2030	2050
Estimated Population	800,000	1,000,000	2,000,000
Consumption (Liter/day)	20	50	100
Percentage of population using Groundwater	50	80	70
Total Abstraction/Day (m3/day)	8,000	40,000	140,000

Current abstraction is estimated to currently take place via 400 to wells discharging at low yields of about 20m3/day. While the pumping of these well may be improved to meet future demand it was assumed that the maximum allowable discharge individual wells will be limited to 100 m3/day and that new wells will be installed to cater for increased groundwater abstractions. Furthermore, it was assumed that a minimum distance of 400 meters between pumping wells will be maintained.

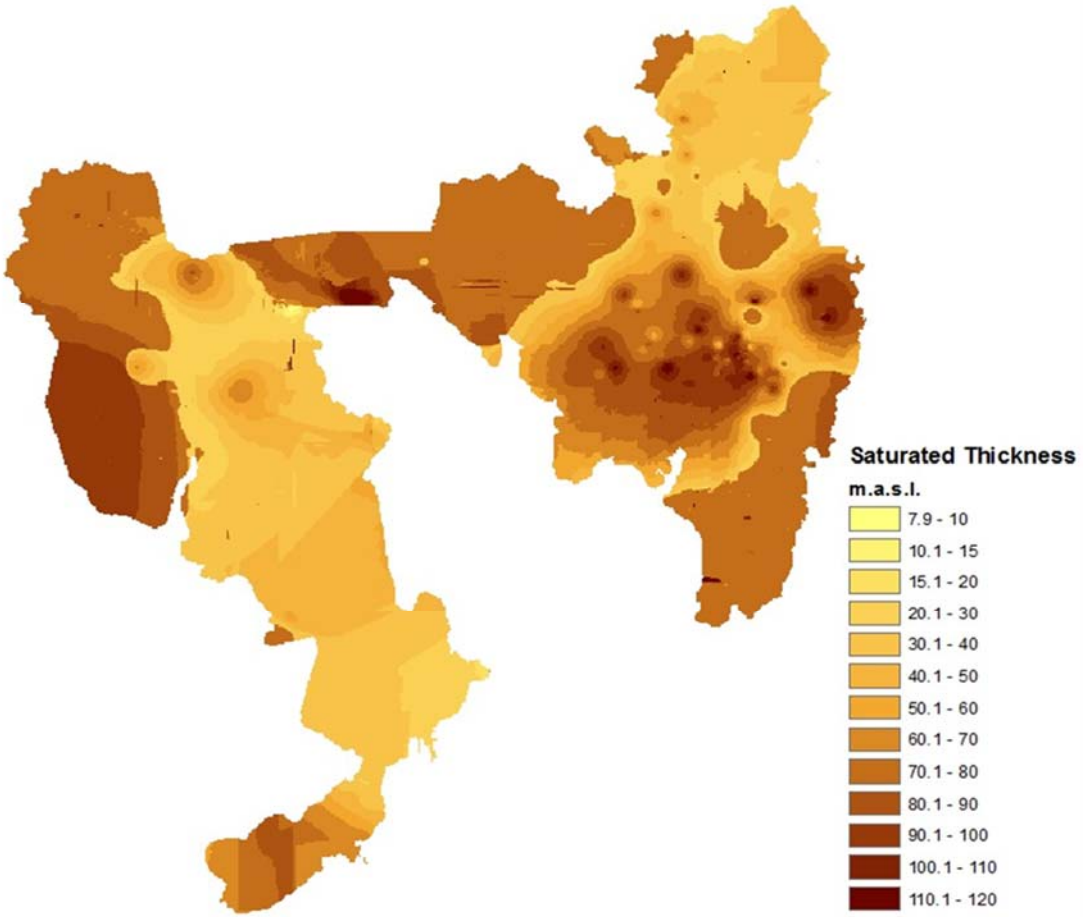


Figure 5-2: Aquifer Saturated Thickness

6. Numerical Modeling

6.1. Introduction

Groundwater numerical models have grown into indispensable tools for the characterization, simulation and management of groundwater resources. Advanced modeling techniques enable the consolidation of different types of local or regional information within the model area, including the complex boundary conditions, their physical and mathematical interaction as well as human influence.

6.1.1. Model Type and Attributes

- The implementation of a groundwater model most appropriate for the Bara Basin involves the consideration of a number of factors, namely:
- The physical characteristics of the study area (both surface and hydrogeological)
- The utilization of all available data, including geological and hydrogeological information as well as historic and recent records of groundwater levels.
- The aim of the investigation, which is defined as the determination of reasonable sustainable groundwater extraction rates for urban and rural domestic use with regard to future groundwater levels and depths to groundwater.
- Based on geological and physical characteristics of the study region, the following factors were adopted to determine the layout and internal structure of the groundwater model:
- The project area comprises a series of discontinuous single layer alluvial aquifers that are hydrogeologically connected via subsurface flow in the underlying fractured basement and hydraulically connected through the Kagera River.
- Future groundwater development for domestic use is most likely to rely on the use of groundwater as it is more sustainable and less prone to contamination.
- The development of the shallow aquifer will be restricted to domestic water supply and will not be extended to livestock watering, irrigation or other industrial uses.

- The package GMS from Aquaveo was applied to develop the numerical model of the Kagera aquifer. GMS is a preprocessor and postprocessor of the modular three-dimensional finite difference groundwater model "MODFLOW" which is developed and published by the U.S. Geological Survey.

6.2. Spatial Discretization

The reliability and accuracy of a groundwater model, as a mathematical-numerical approximation of reality, depends significantly on the appropriate discretization of the model area. This must take into account the specific topographic, geological and hydrogeological boundary of conditions of the study area. In addition, the layout of the finite difference mesh must consider both the characteristics of the project area, its connectivity and the expected interventions in groundwater flow due to variations of the boundary conditions. The model boundary was expanded beyond the alluvium aquifer to include parts of the adjacent fractured metasedimentary basement formation to ensure the aquifer connectivity and model stability.

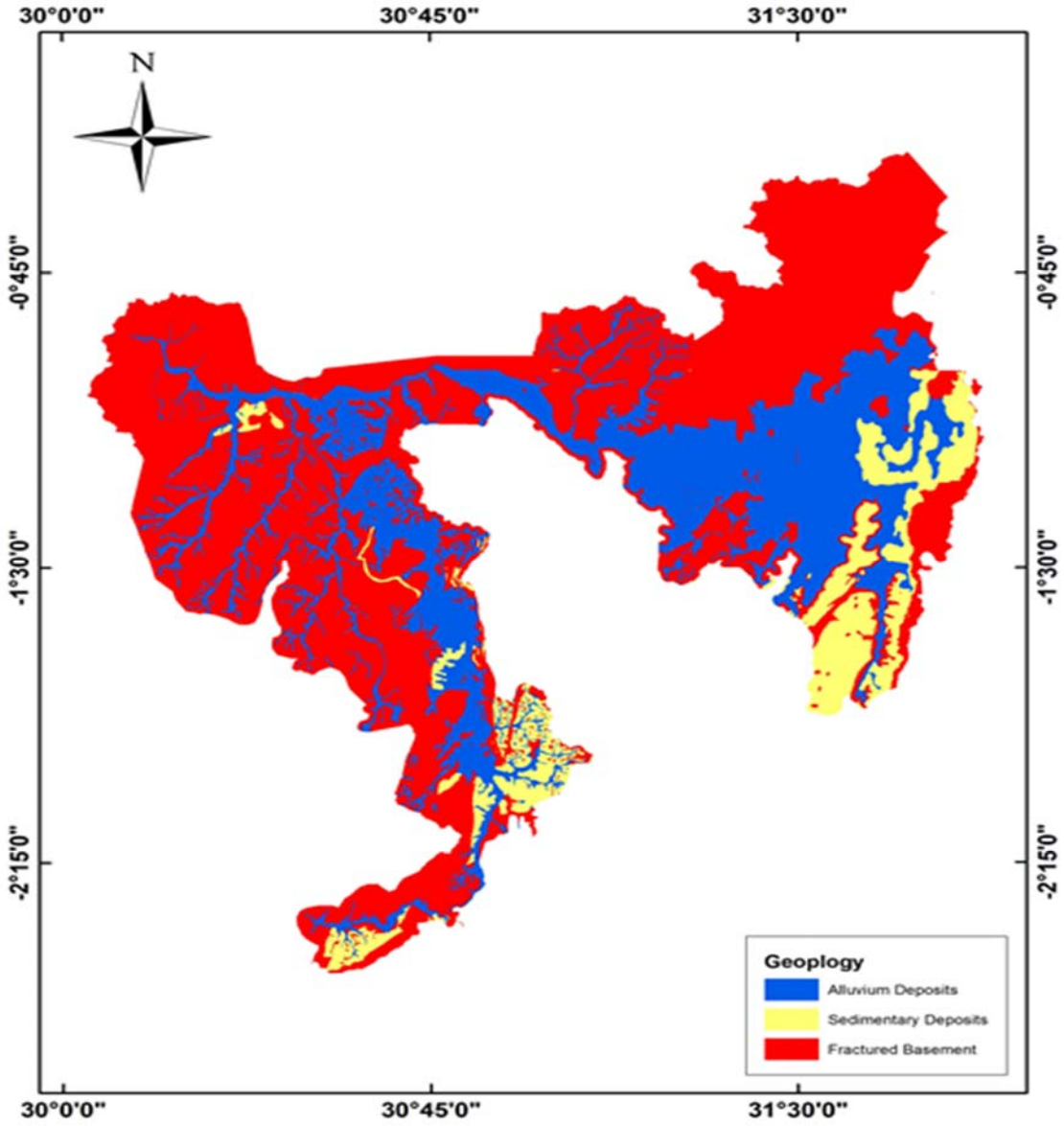


Figure 6-1: Aquifer Geologic Formation

The model includes a very large number of rectangular cells. The groundwater model computes the resulting groundwater level at the center of each cell. The surface created by joining the center of each element describes the three-dimensional orientation of the groundwater surface in the study area and enables a fully three-dimensional interpretation of the available data. This

in turn allows the analysis of the existing depth to groundwater based on present as well as future groundwater conditions.

The aquifer was modeled as a heterogeneous and isotropic unconfined aquifer with varying thickness depending on the available geophysical data using a 400 m grid.

Table 6-1: Spatial Discretization- Statistical Data

Parameter	Data
Number of Cells	300,312
Model Area	17,500 Km^2
No. Inactive cells	109,577
No. Active cells	190,735

6.3. Boundary Conditions

Areas of the aquifer that are bounded by rock outcrops are clearly defined as the end of aquifer and were modeled as no flow boundary conditions.

The specified Head (DIRICHELT) type boundary condition prescribes the piezometric heads at a defined location on the model boundary, this classification was assigned to Lake Victoria.

Head Dependent Flux (Cauchy) type boundary condition was used to model the interaction between the Kagera aquifer and the Kagera River.

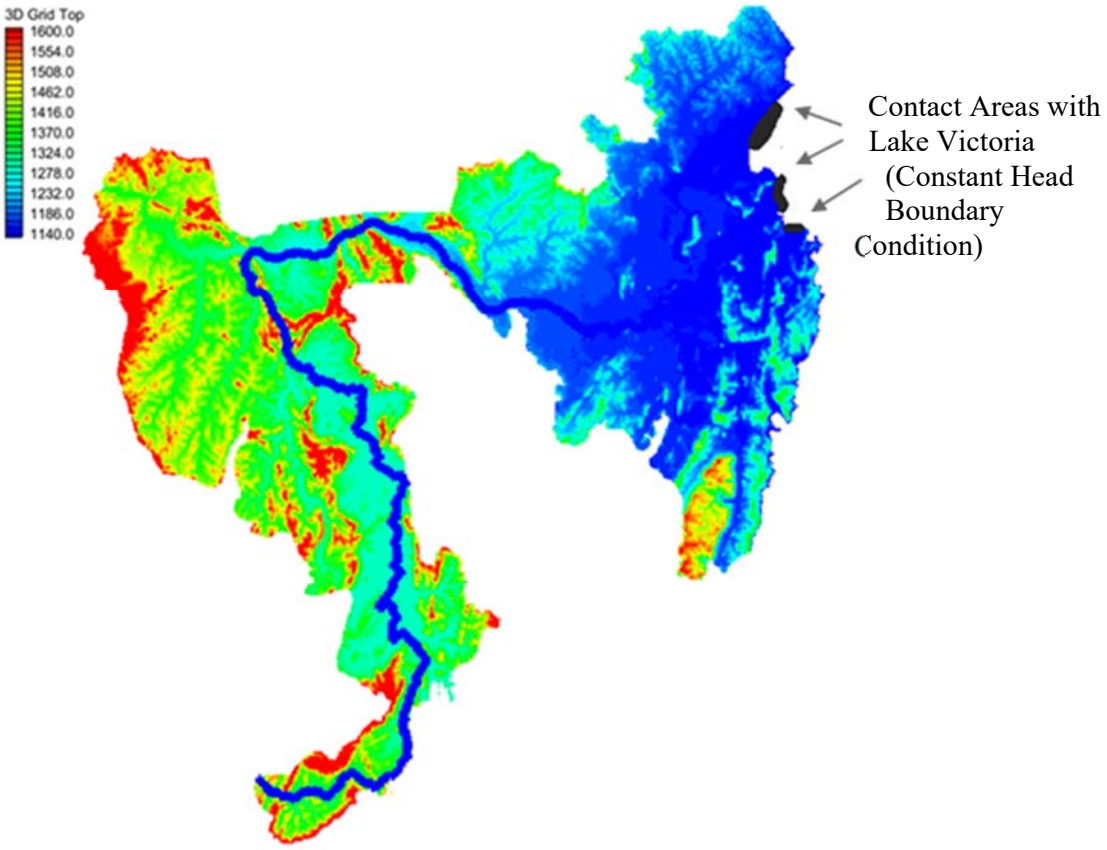


Figure 6-2: Location of Contact Zones with Lake Victoria

6.4. Steady State Simulation

Prior to the performance of reliable simulation runs, the groundwater model's geological or hydrogeological boundary parameter settings (e.g. hydraulic conductivity, storativity, recharge and river conductance) have to be proved for compliance with the actual boundary conditions. Therefore, model calibration against available historical data is to be carried out at the onset of the modeling process as part of the model set up process.

The calibration process requires a sufficient amount of control data such as observed groundwater levels in order to verify the model. However, the necessary data for conducting a full calibration was not available due to the absence of groundwater monitoring data and the fact that most of the available data were used to establish the model initial conditions. Given the fact that the Kagera aquifer system is one that is underdeveloped and is virtually pristine, it was decided to calibrate the model under steady state conditions. The underlying assumption

is that the aquifer has been in state of equilibrium for a very long period of time. The model parameters were changed with the objective that the steady state model simulation will regenerate the initial head observations. Given that the estimation of aquifer recharge was one of the prime objectives of the study, the values of the hydrogeologic parameters were varied within the sought possible ranges to assess their impact on the potential recharge. Recharge rates were linked to precipitation rates (as a percentage of precipitation rates). The input value of precipitation was modified while being maintained as less than 1% of precipitation until the steady state solution generated by the model matched current conditions.

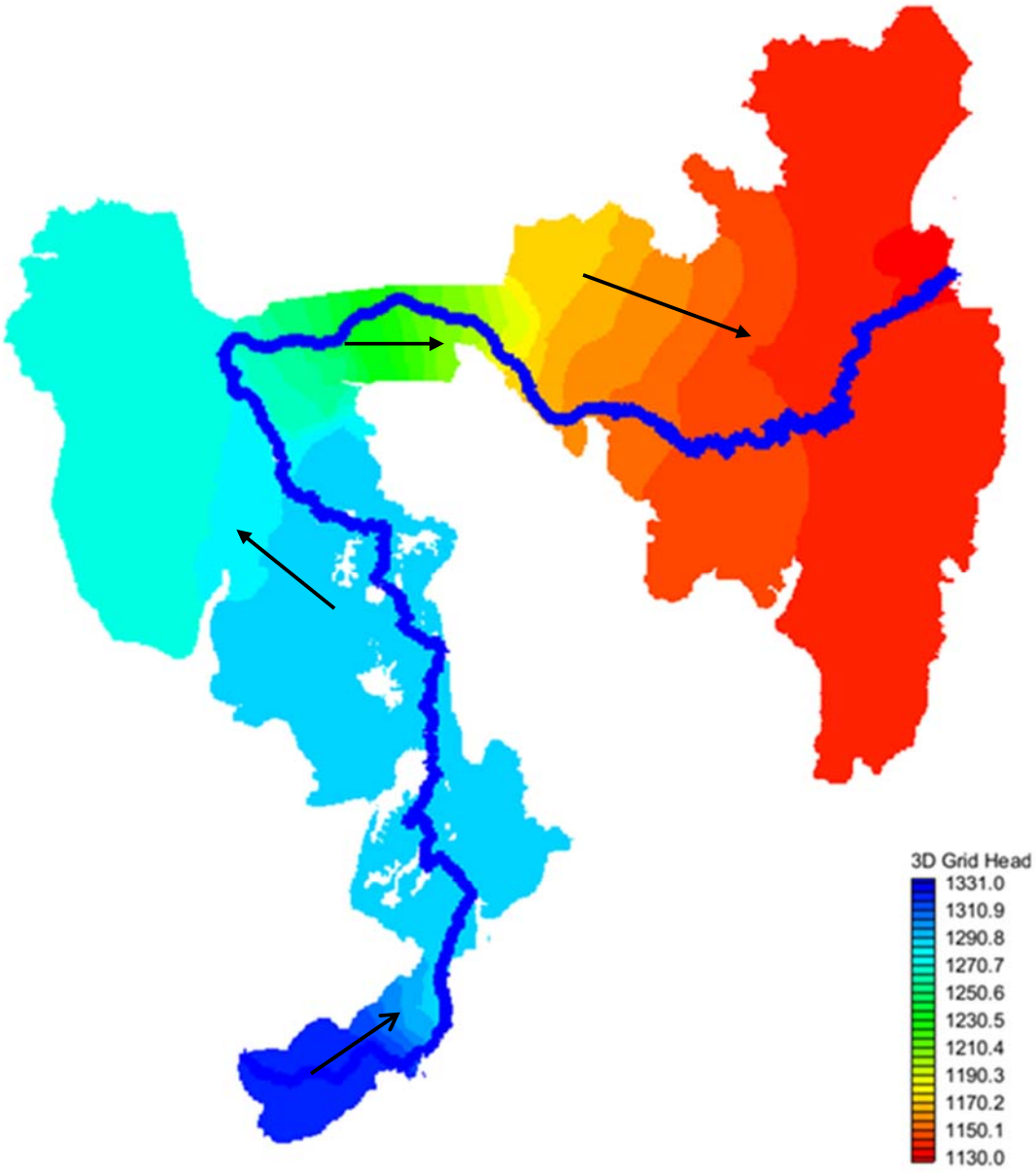


Figure 6-3: Water Level and Groundwater Flow Directios of the Steady State Simulation.

The water balance for the aquifer system can be mathematically represented by the following equation

GWi + R – GWo – GWp

Where :

GWi = Groundwater inflow through the outer boundaries

GWo = Groundwater outflow through the outer boundaries

GWp = Groundwater abstraction by wells

R = Recharge

The boundaries in the case of the full Kagera model are the Kagera River and Lake Victoria and the result returned by the equation represented the amount of abstraction or storage in the aquifer. Estimates of inflows to and from the aquifer under current steady state conditions were ascertained during the modelling process and are reported in the table 6-2

Table 6-2: Aquifer Mass Balance under Steady State Conditions (Upper Bound)

Flow Source	Daily Flow (m^3/day)	Annual Flow (m^3/year)
Lake Victoria	-17,130	-6,252,370
Wells	-8,900	-3,248,500
Kagera River	-118,841	-43,376,998
Recharge	144,329	52,680,260
Net Aquifer Discharge		**-197,608**

The (-ve) sign indicate flow form the aquifer while the (+ve) sign indicates from to the aquifer.

The high-end result shows that the total annual recharge to the aquifer is about 52.7 MCM per year of which about 43.4 MCM is leaks to the Kagera River to be drained Lake Victoria as part of the Kagera River flow system. About 6.3 MCM flow directly from the aquifer into Lake Victoria while current abstraction by wells accounts for about 3.25 MCM/year. It is t be noted

that of the estimated net discharge from the aquifer under current conditions is in the order 200,000 m3/year which indicates that the aquifer is underutilized.

Conducting the analysis using lower bound estimates of hydraulic conductivity and recharge values produced the lower-end mass balance result shown in table 6-3

Table 6-3: Aquifer Mass Balance under Steady State Conditions (Lower Bound)

Flow Source	Daily Flow (m^3/day)	Annual Flow (m^3/year
Lake Victoria	-12,920	-4,715,734
Wells	-8,900	-3,248,500
Kagera River	-87,307	-31,867,202
Recharge	108,246	39,509,885
Net Aquifer Discharge		**-321,551**

In this lower bound case the total annual recharge is in the order of 40 MCM/year of which about 32 MCM leaks to the Kagera River and 4.7 MCM/year flows directly y from the aquifer to the lake. The foot print of pumping 3.25 MCM/year in this case will be annual abstraction of about 320,000 m3/year from the aquifer, which is insignificant compared to the aquifer storage and potential.

The water balance analysis using the aforementioned lower bound case was extended to compute the mass balance for each of the three identified aquifer segments (Upstream, Middle and Delta Segments)

Table 6-4: Aquifer Upstream Segment Mass Balance under Steady State Conditions (Lower Bound)

Flow Source	Daily Flow (m^3/day)	Annual Flow (m^3/year)
Lake Victoria	0	0
Wells	-40	-14,600
Kagera River	-1,876	-684,887
Recharge	3,052	1,113,878
Flow to Middle Segment	-1,129	-412,085
Net Aquifer Discharge		**2,306**

The water balance of upstream segment reveals that the total annual aquifer recharge generated within the segment is about 1.1 MCM/year of which 0.7MCM/year leaks to the Kagera River and about 0.41 MCM/year flows as subsurface flow into the middle segment. Total current abstraction is limited to about 14,600 m3/year. This upstream segment of the aquifer has a small storage and almost all of the aquifer recharge it receives is transmitted downstream to the middle segment. Abstraction from the aquifer is effectively directly withdrawing water from the river.

The mass balance of the middle segment shows that a total recharge in the amount about 15 MCM is annually generated within this zone about 97% of which drains back to the Kagera River. This segment receives about 0.41 MCM/year in subsurface flow from the upstream segment and passes about 0.47 MCM/year to the delta segment. This part of the aquifer has excess flow to the aquifer storage in the amount of about 100,000 m3/year which appears in the form of wetlands, discharge to lakes and springs. Current abstraction is estimated as limited to about 233,600 m3/year.

Table 6-5: Aquifer Middle Segment Mass Balance under Steady State Conditions (Lower Bound)

Flow Source	Daily Flow (m^3/day)	Annual Flow (m^3/year)
Lake Victoria	0	0
Wells	-640	-233,600
Kagera River	-40,007	-14,602,555
Recharge	41,098	15,000,712
Flow to Delta Segment	-1,923	-471,945
Flow from Upstream Segment	1,129	412,085
Net Aquifer Discharge		**104,697**

The mass balance of the Delta segment of the aquifer shows that a total recharge in the amount of about 23.4 MCM is annually generated within the downstream segment of the aquifer of which about 70% (16.6 MCM) drains into the Kagera River under current (2021) steady state conditions. The segment receives about 0.47 MCM of annual subsurface flow from the middle segment while about 4.7 MCM discharges annually from the aquifer to the Lake Victoria.

Current annual abstraction from the delta segment is estimated to be about 3.0 MCM per year resulting in a withdrawal of about 0.43 MCM/year from the aquifer storage.

Table 6-6: Aquifer Delta Segment Mass Balance under Steady State Conditions (Lower Bound)

Flow Source	Daily Flow (m^3/day)	Annual Flow (m^3/year)
Lake Victoria	-12,920	-4,715,734
Wells	-8,220	-3,000,300
Kagera River	-45,424	-16,579,760
Recharge	64,097	23,395,296
Flow from Middle Segment	1,923	471,945
Net Aquifer Discharge		**-428,553**

6.5. Simulation Runs

Following the model establishment and the completion of the steady state run, a transient simulation run from the year 2022 to 2051 was made. The transient run simulated the gradual increase of daily pumping from 8000 m3/day at 2021 to 40,000 m3/day at 2030 and 140,000 m3/day by 2050. The model results showed that the proposed development could be sustained by the system with acceptable local drawdown levels of less than 5 meters in 98% of the aquifer area and maximum local drawdowns of 11 meters in Figure 6-4 . The analysis of the results did show that pumping rates of up to 20 MCM/year could be sustained with virtually no abstraction from the aquifer storage after which additional pumping will be at the expense of aquifer storage.

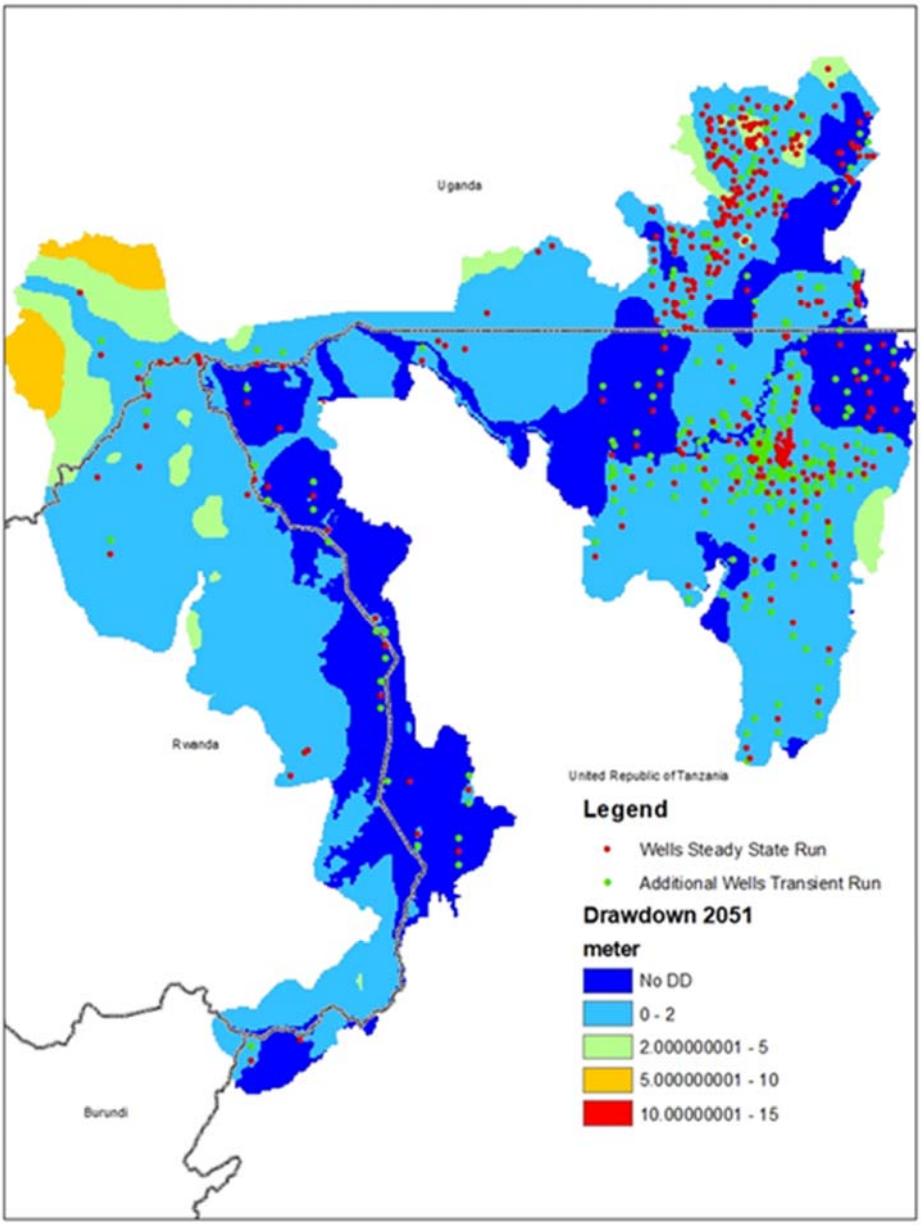


Figure 6-4: Variation of Aquifer Abstraction from Storage Levels with Pumping Rates

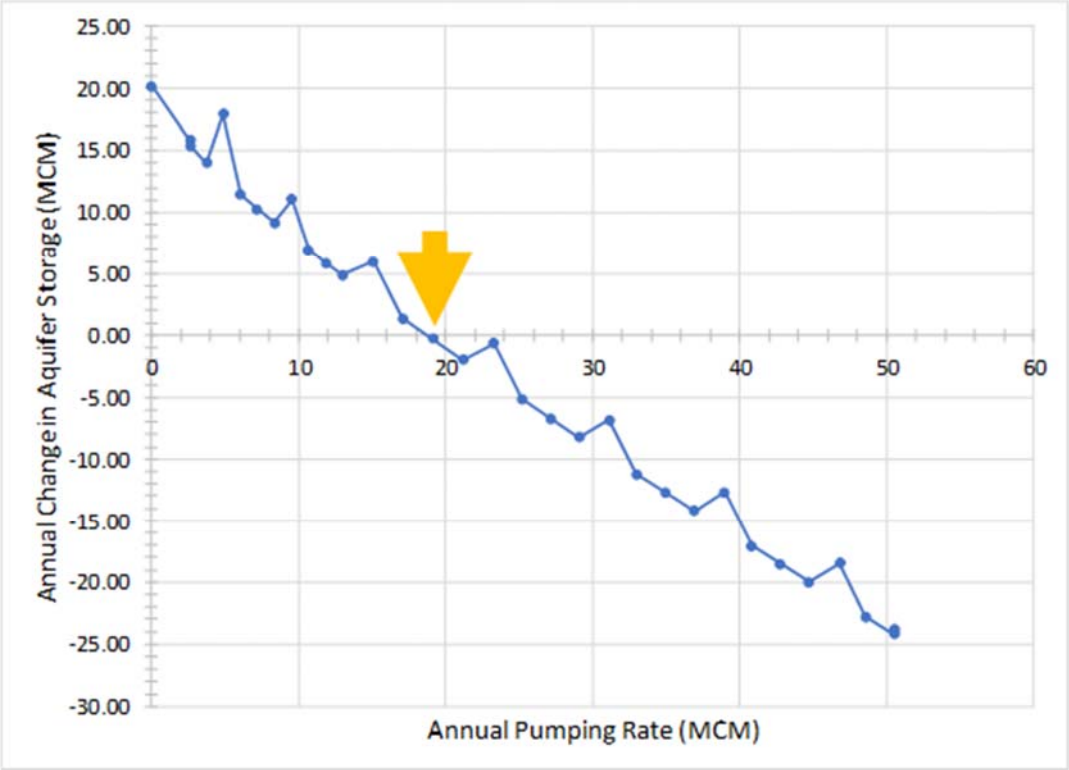


Figure 6-5: Variation of Aquifer Storage Withdrawals with Total Abstraction from Aquifer

6.6. Impact of Climate Change

The analysis of the impact of climate change on the Kagera basin area was conduced conducted through the World Climate Research Program (WCRP) Coupled The analysis projected the changes to three climate parameters; Temperature, Precipitation and Evapotranspiration to the year 2100 under four Representative Concertation Pathways, namely RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The results of the analysis projected that the Kagera Basin Catchment area will witness the following changes:

The average surface temperatures are expected to rise by $1^{O}C$ to $4^{O}C$ by the year 2100 depending on the level of success to reduce CO2 emissions.

The basin is projected to witness an increase in average annual precipitation and the number of effective rainy days per year, with an increase in the frequency of occurrence of serve events.

The rainfall pattern is not projected to significantly change. December is projected to replace November as the month with the highest monthly precipitation rates.

Failure to reduce CO2 emissions to zero by 2100 (RCP2.6) will cause a gradual and marked increase of annual evapotranspiration rates as of 2050. An increase of 70 mm/year can be expected according to the RCP8.5 Scenario.

Indications are that the Kagera basin catchment area is one of the regions that is projected to experience increases in precipitation. In spite of this, surface and groundwater resources may still be negatively impacted. Increased precipitation variability, the inevitable surface temperature rise and potential increase of evapotranspiration may affect hydrological responses within the catchment, reduce the surface runoff and cause drying of the wetlands. The issue of impact of climate change is not trivial and indications of the increase precipitation is not an assurance of an increase in groundwater recharge. Changes of environmental flow and the periodicity of replenishment event may lead to reduction of groundwater recharge in spite of increases in total annual precipitation.

It can be argued however that given the amount annual recharge to the Kagera aquifer (40 to 50 MCM), the fact that climate change is likely to cause more precipitation (an increase of 60 to 150 mm/year) than the net resulting evapotranspiration, that the Kagera aquifer recharge is unlikely to be negatively impacted by climate change.

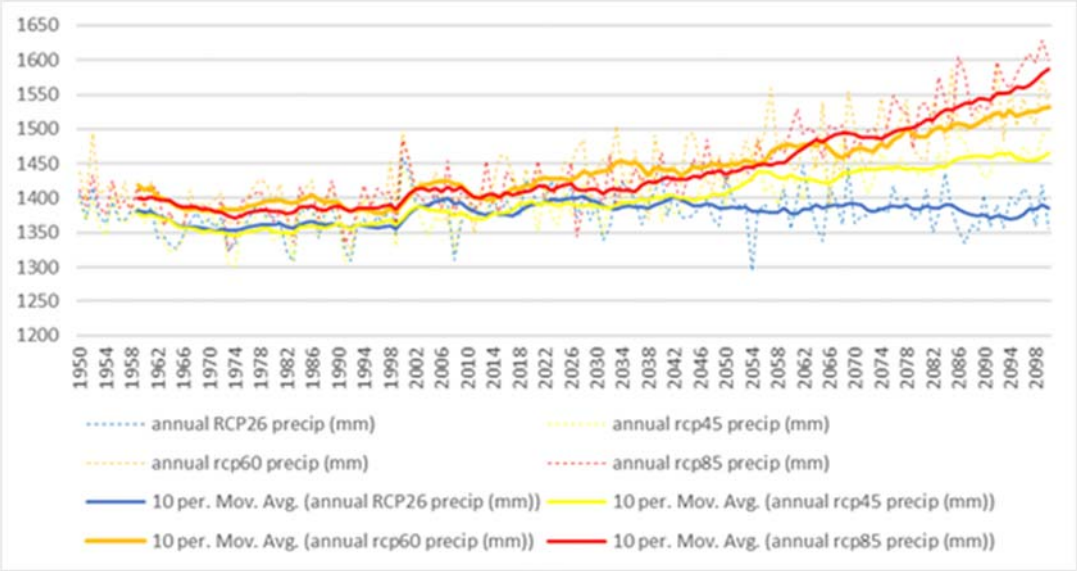


Figure 6-6: Predicted Climate Change Impact on Precipitation

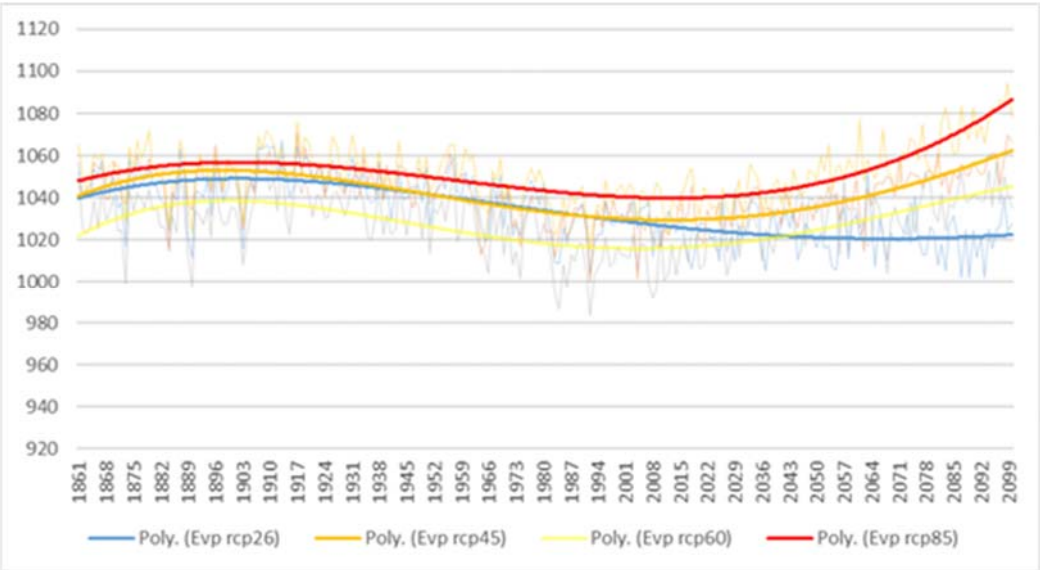


Figure 6-7: Predicted Climate Change Impact on Evapotranspiration (mm/year)

6.7. Aquifer Development Potential Zones

Concerns about the reduced availability of groundwater due to over exploitation has lead to the development and adoption of groundwater management trends that are focused on the enhancement of recharge. The identification, selection and development of sites for the enhancement of natural recharge or generation of artificial recharge is being regarded within many groundwater management authorities as a necessity for the establishment of their aquifer

management plans. The preparation of suitability maps for managed aquifer recharge (MAR) or Potential Aquifer Recharge Zones (PRZ) is one that uses a multi criteria decision making process to analyze multiple data sets representing the aquifer feature to select or the most suitable recharge zones. The required data sets include physical features such as Slope, Drainage Density, Soil Characteristics, Geology, Precipitation, Landuse and Landcover. It is important however to emphasize that the use of MAR or PRZ is only necessary as part of implementing a sustainable aquifer management in aquifer zones that are subject to exploitation leading to excessive drawdowns/depletion or salinization.

The Kagera aquifer is an underutilized aquifer for which there are no current development plans. The management of aquifer must be enhanced via establishing a monitoring system, control of groundwater development activities and the development of long term aquifer development plans the impact of which can be assessed to consider the development of managed recharge plans. MAR plans can be targeted to improve recharge in areas of high stresses rather than be universally implemented.

The upstream and middle segments of the Kargera Aquifer in particular will most probably be excluded from the plans of developing MAR plans for the Kagera Aquifer given the narrow width of the aquifer in these areas, proximity to the the river and other natural surface water bodies and the excess recharge to these zones. The impact of river control, landuse change and land development on groundwater recharge should be however be carefully considered during the preparation and implementation of land development plans in these areas. The delta segment of the Kagera Aquifer on the other hand is one that could potentially require the implementation of MAR plans in some areas if excessive localized aquifer development is implemented.

Identifying and classifying the area of the aquifer according to their yield potential is one that may be more urgent to the aquifer development planners. The aquifer was classified into three potential yield zones based on expected aquifer depth, hydrogeologic properties and recharge potential. The analysis was confined to the extent of the alluvium aquifer and all area beyond which are deemed as low or vey low yield zones. High yield zones can support concentrated

well field developments with high or very high discharge wells to serve large population centers. Medium yield zones may support limited high discharge wells to serve large settlements. Low yield zones are only suitable to support low yield developments to serve small rural communities.

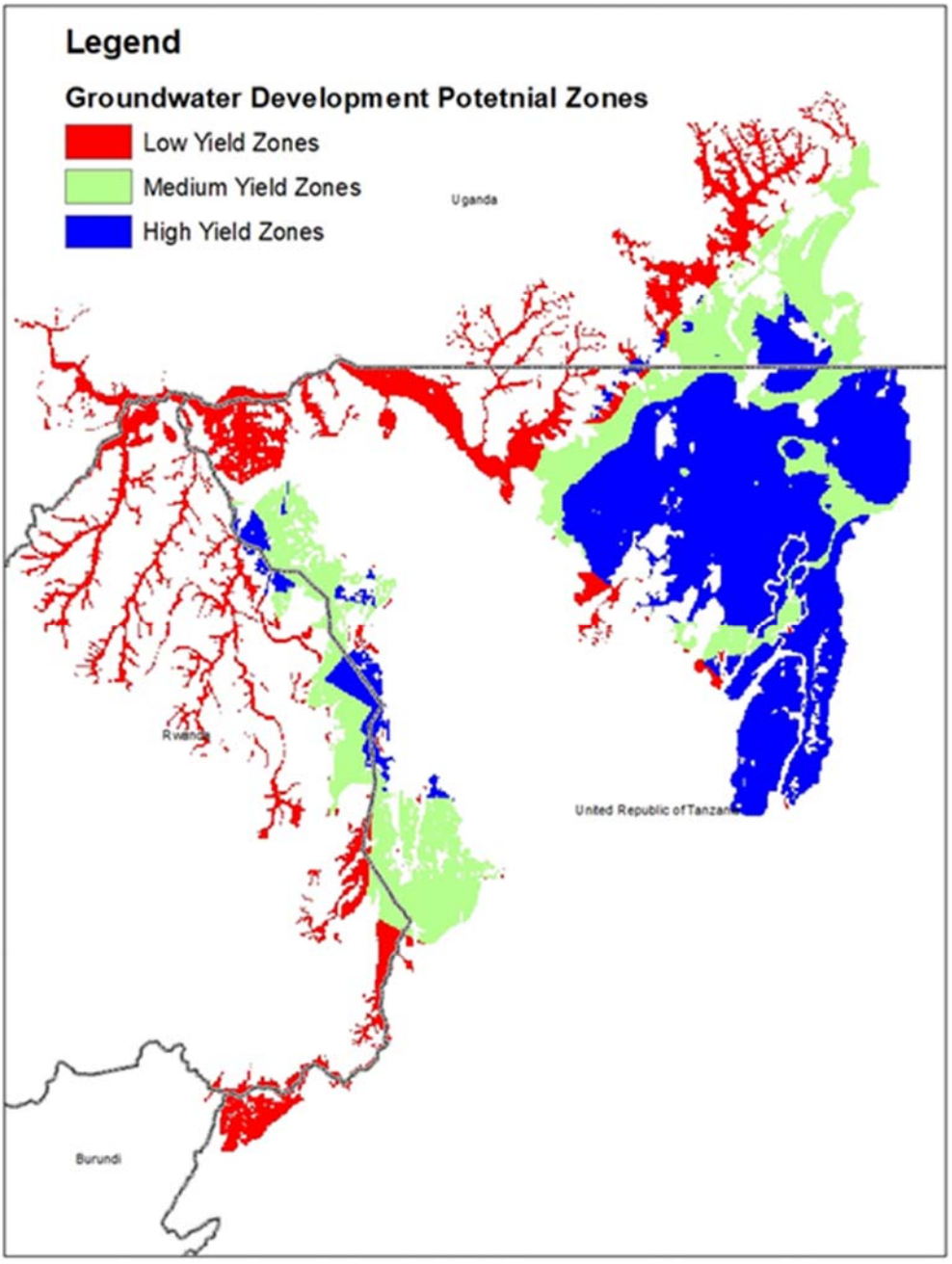


Figure 6-8: Groundwater Development Potential Zones

7. Conclusions

The evaluation of groundwater situation in the Kagera Aquifer conducted in this study shows that the project area possesses a 6,300 Km2 unconfined groundwater reservoir for groundwater resources. The aquifer is currently under utilized with current abstractions estimated to be in the order of 3.25 MCM/year used primarily for the provision of domestic water for rural communities.

The future proposed development of the Kagera aquifer is best envisaged as to be limited to the provision of domestic water supply to the estimated 900,000 who dwell in its extent in accordance with the aquifer potential and stated water resources development priorities of the four riparian countries that share aquifer. The societies living across the borders of the four riparian countries are engaged in similar livelihood activities, live similar socio-economic conditions that are characterized by high poverty rates and lack of access to safe water for a significant portion of their communities. (>30%).

Based on the available data and the results obtained by groundwater modeling the groundwater situation in the study area can be described as follows;

- The Kagera aquifer constitute a groundwater reservoir with an estimated storage of about 50 billion m3. The actual current groundwater abstraction is estimated to be about 3.25 million m3/year, which is utilized for domestic use.
- The aquifer recharge is linked to the precipitation in the Kagera basin which indirectly replenishes the aquifer through contact with the river flow it generates or the wetlands it forms or through preferential fracture flow from the surrounding basement complex formations.
- Groundwater flow in the aquifer flows in the same direction of the Kagera River draining eventually in the direction of Lake Victoria.

- The estimated annual recharge to the aquifer is estimated to be between 40 to 50 MCM/year.
- The aquifer annual safe yield had been estimated to be about 20MCM. Higher annual abstraction are bound to result in abstraction from the aquifer storage.
- The modeling of the aquifer has revealed that it can sustainably support the abstraction of up to 140,000 m3/day (52 MCM/year) estimated as 70% the daily consumption of the population in the aquifer extent by 2050. Controlled drawdowns not exceeding 5 meters are to be expected in about 65% of the aquifer area. Localized drawdowns between 5 to 11 meters may occur in 2% of the aquifer area.
- The development of the Kagera Aquifer is best conducted in a non-concentrated fashion with distances of at least 400 meters between wells

8. Recommendations

This groundwater study is based on all the relevant available groundwater information; however, there are some limitations of the previously conducted geological and hydrogeological investigations. The available geological data is for the most part recent and satisfactory; the available geophysical and lithological data however do not adequately cover the study area. The study was specifically hampered by the absence of groundwater level data due to absence of effective well inventories or groundwater monitoring systems.

The developed model is an interpretive model that was useful in understanding the aquifer dynamics and estimate its potential, further development of the model after obtaining the required missing data and fully calibrating it is strongly recommended.

Additional recommendations for the future data collection and model enhancement include:

- Establishing a Repository of Existing Data: A concerted effort by each of the four riparian countries to compile the available groundwater related information and data within their institutions into a dynamic and easily accessible spatial database will enhance the knowledge about the current state of the aquifer. The repository should consolidate all the existing data & maps obtained from previous studies and development activities within the aquifer and include all the data needed for the aquifer planning whether physical or social.
- Data Sharing Protocols to ease the accessibility to available data and information for the purpose of aquifer development and research will expand and disseminate knowledge about the aquifer and its status. The data sharing should include stakeholders at all levels including the end users and should facilitate the sharing of data and information between the four riparian countries.
- The development of a transboundary groundwater monitoring systems for the Kagera Aquifer is urgently needed. The proposed system should monitor groundwater levels and quality and should be integrated with the climatic and surface water resources

monitoring network in the basin. The monitoring system should be designed and optimized to provide regional and local information about the aquifer.

- A joint exploratory program to assess the aquifer extent, storage and hydrogeologic properties is needed. The program which could be undertaken by each country within its national borders could include detailed geological mapping, exploratory drilling, geophysical investigations, pumping tests and well inventory surveys to determine aquifer abstractions.
- It is paramount to engage and actively include the local communities in the aquifer management and planning. Undertaking community outreach programs to assess the needs of the local communities and enlist their efforts in the aquifer protection and monitoring is highly recommended. Awareness, outreach and training programs should be designed to attain this objective with a focus on sharing the aquifer development plans and engaging local communities' efforts in implementing them.
- Field investigations to identify the sources of recharge to Kagera aquifer and better assess its quantity are highly recommended. This could include isotope studies. Studies to investigate the correlation between precipitation levels and patterns in the Kagera Basin with groundwater recharge should be undertaken.

The objective of future studies should focus on the improvement of the predictions made for the Kagera Aquifer and the investigation of Enhancement of the model to include the interaction between precipitation, surface waters and groundwater as well as the impact of climate change.

9. References

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