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Water Demand Analysis

Drivers and Current status of Domestic and Agricultural Water Use in Lower Akagera.

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Division of Water Resources Engineering
Department of Building and Environmental Technology
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Abstract

The drought prone eastern province of Rwanda has experienced rapid growth in agriculture and population over the past decade. This thesis used the Lower Akagera catchment as a case study to determine the current and historical water demand for domestic and agricultural sectors and identify the factors driving these changes. Based on collected field data, a water use model was trained to estimate domestic water use, extrapolated for the entire catchment using national statistics. The irrigation demand was estimated using a combination of national statistics and the Cropwat 8.0 software.

This thesis found that the population in Lower Akagera has been increasing by 4.2 % annually for the last ten years. In addition, per capita water use has increased due to changes in household sizes, distances, and water sources. Water availability was identified as the main factor limiting households water use. In the agricultural sector, the total cropland in Lower Akagera has increased by 32 %, and the areas allocated for irrigation have increased by around 9,000 hectares. The main risks for the domestic and agriculture sectors are water availability-related factors, where the demand on the already strained system will continue to grow.

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List of Acronyms

cap	capita
CWR	Crop Water Requirements
EICV	Integrated Household Living Conditions Survey
ESA	European Space Agency
ETc	Crop Evapotranspiration Rate
ETo	Reference Evapotranspiration Rate
FAO	Food and Agriculture Organization
FAOLEX	Food, Agriculture and Renewable Natural Resources Legislation Database
GDP	Gross Domestic Product
GEE	Google Earth Engine
GFI	Government Funded Irrigation
IMP	Rwanda Irrigation Master Plan
IRQ	Total Irrigation Demand
IUCN	The International Union for Conservation of Nature
Kc	Crop Coefficient
KWAMP	Kirehe Community-based Watershed Management Project
L	Liter
l/cap/day	Liter per capita per day
LU	Lund University
LULC	Land use and Land Cover
LWH	The Land Husbandry Water Harvesting and Hillside irrigation Project
METEO	Meteorological Institute of Rwanda
MINAGRI	Ministry of Agriculture and Animal Resources
MINIRENA	The Ministry of National Resources of Rwanda
MLR	Multiple Linear Regression
NAKL	Nile Akagera Lower
NAS	National Agricultural Survey

NDVI	Normalized Difference Vegetation Index
NISR	National Institute of Statistics of Rwanda
PPP	Public-Private Partnership
RAB	Rwanda Agricultural Board
RCMRD	The Regional Center of Mapping and Resources for Development
RGB	Red, Green and Blue spectral bands of an image
RH	Relative Humidity
RN	Solar Radiation
RNRA	Rwanda Natural Resources Authority
RPHC	Rwanda Population and Housing Census
RSSP	Rural Sector Support Project
RWB	Rwanda Water Resources Board
SAS	Seasonal Agricultural Survey
T	Temperature
TIN	Triangulated Irregular Network
UNGM	United Nations Global Marketplace
UR	University of Rwanda
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WAPOR	The FAO Water Productivity Open-Access Portal
WASAC	The Water and Sanitation Corporation
WHO	World Health Organization

1. Introduction

In Rwanda, irrigation, followed by domestic water supply, are the main water-consuming sectors. The definition of consumptive water use is water that is abstracted by the supplies without being returned to the source (FAO, u.d.). According to Rwanda's latest water users and uses assessment (RWB, 2020), agriculture contributes to 60 percent of the total water use, and domestic accounts for 39 percent. Today, the country's economy is heavily dependent on agriculture and the sector is considered the main driver of GDP growth and poverty reduction (BIZUHORAHO, 2018; Resiliencebv, 2021). Between 2000 and 2017, Rwanda's overall poverty rate decreased from 60.4% to 28.2%, and agricultural development played a leading role in this reduction (MINAGRI, 2019). Over the past decade, the government has implemented various agriculture development programs, aimed to increase the productivity in the sector and to achieve its GDP target according to the vision 2020. (Resiliencebv, 2021). Given that agricultural productivity depends on water availability, the problems with water shortages and droughts have been identified as the main limiting factor for improved livelihoods in the area (IUCN, 2020). This issue was particularly evident in 2016 when severe droughts in the Eastern Province led to food insecurity for 225,000 people (UNCM, 2021). In the meantime, the population size in the country has increased annually by 2.2% over the last ten years, and about 80% of the population lives in rural areas in the Eastern Province (NISR, 2022a). Although the share of people using improved water sources is 81%, water availability is low in the area, which causes recurrent water shortages (RWB, 2019; NISR, 2022b). Given that the rainfall in the area is far less than in other parts of Rwanda, access to sufficient water remains a challenge for its people.

1.1 Thesis Aim

This thesis aims to estimate the development of water use and demand in the Lower Akagera catchment in Rwanda for the largest water-consuming sectors - agriculture and domestic. By using the Lower Akagera catchment as a case study, the thesis also aims to develop methods for estimates of water use and demand in Rwanda. To achieve this, the following question are addressed:

1. What data are available on water use in agricultural and domestic sectors in the Lower Akagera catchment?

2. How can the available data be included to estimate water demand for 2000-2023?

3. How has water demand changed in the Lower Akagera catchment for 2000-2023?

4. What are the main factors that drive the changes in the water demand?

5. What are the main risks associated with water supply in the area?

2. Background

2.1 Introduction to the Lower Akagera Catchment

The Lower Akagera Catchment is located in the Eastern Province and extends along the Akagera River, internationally known as the Kagera River. This river, flowing from south to north, forms the natural boundary with Tanzania, making it a transboundary catchment within the Nile Basin. As shown in Figure 1 , the catchment comprises the four districts Nyagatare, Gatsibo, Kayonza, and Kirehe, along with a small segment of Ngoma, together standing for an area of 4,288 km², equivalent to 16% of Rwanda's total surface area.

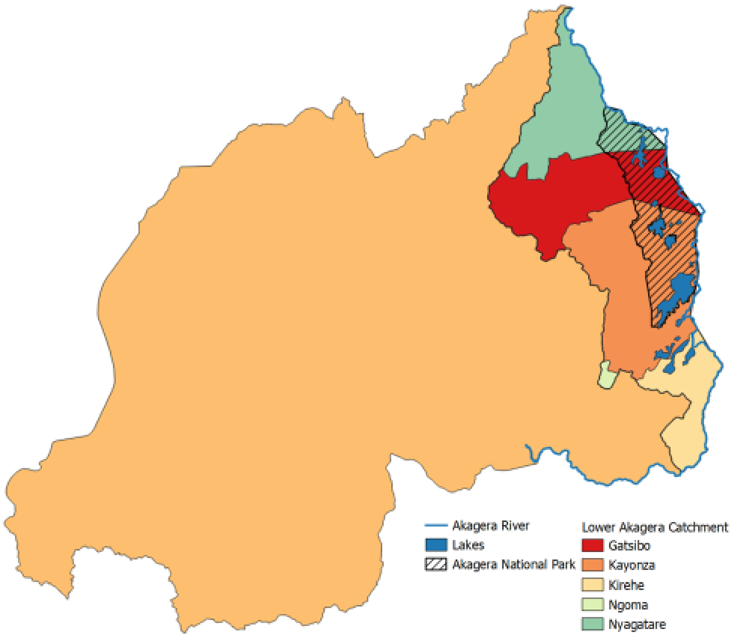

Figure 1 Location of Lower Akagera catchment and districts in the catchment.

The Akagera River originates from Lake Rweru, located in southern Rwanda, where the Nile Akagera Lower (NAKL), also known as Lower Akagera catchment, later commences at the Rusumo Falls in Kirehe. The river meanders through marshlands and lakes before joining the Muvumba River in northern Nyagatare district, marking the downstream limit of the catchment. The catchment is further characterized by various lakes, with the majority located within the protected areas of the Akagera National Park (RWB, n.d.a).

2.2 Administrative Boundaries in Lower Akagera

In Rwanda, the administrative structure is organized from highest to lowest level as Provinces, Districts, Sectors, Cells, and Villages, with each level operating under its own governance (Republic of Rwanda, n.d.). Following a land reform in 2006, the number of districts was reduced from 106 to 30, resulting in the Lower Akagera catchment today consisting of 5 districts, further divided into 37 sectors and 154 cells. Important to note is that not all districts are within the catchment boundaries, with some districts and sectors having their area outside of the Lower Akagera, as demonstrated in Figure 2, Table 1 and Appendix C.

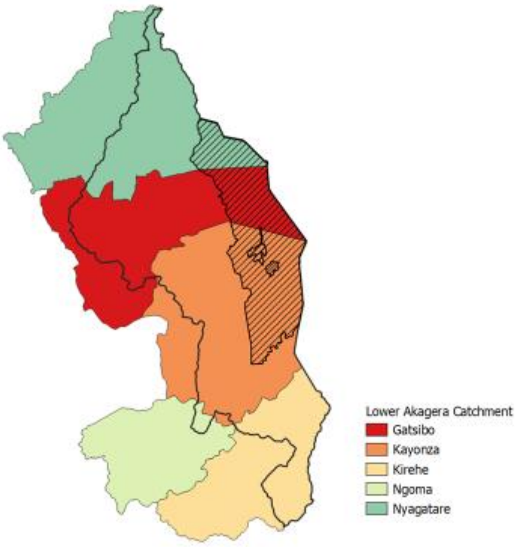

Figure 2 Districts within Lower Akagera.

Table 1 Share of districts covering the Lower Akagera catchment.

District	Nyagatare	Gatsibo	Kayonza	Ngoma	Kirehe
Area within NAKL	51%	72%	84%	4%	44%

In the eastern parts of the catchment, a large area covering 1 120 km^2 consists of the Akagera National Park, one of the country's four national parks and protected areas. This park is the largest protected wetland in Central Africa, known for its diverse wildlife and high biodiversity (African Parks, n.d.). Following the post-war period in 1994, the government reduced the park's size by two-thirds to allow for the resettlement of Rwandan refugees, resulting in changes of land use in the northern parts of Nyagatare over the past 20 years (Akagerea National Park, n.d.)

2.3 Characteristics of The Landscape in Eastern Province

The Eastern Province has a complex mosaic of land covers, including cropland, agroforestry, forest, shrublands, marshlands, and built areas. Forests are mainly located on hillsides and hilltops, while agroforestry and small plots are found in lowlands and rural areas surrounding population centers. In the eastern parts towards Akagera Park, shrublands are dominant on the flat and lower elevations (Gutkin, et al., 2023). The catchment has many agricultural areas, both large-scale (>10 ha), small-scale (<10 ha), and small plots for household farming. As stated in the Rwanda Irrigation Master Plan (IMP), the irrigated areas are recognized as different strata, namely Marshland and Hillside Irrigation (RAB, 2020). The low-lying marshlands, where the water is more abundant, are often used for irrigation (FAO, u.d.).

Compared to Rwanda in general, the Eastern Province is relatively flat. Rwanda's rainfall is characterized by temporal and spatial variations, primarily due to the country's topography and the proximity to the Intertropical Convergence Zone. This results in the Eastern Province having a semi-arid climate, mainly due to its location in relation to the western highlands, making it a drought-prone area characterized by recurrent water shortages (RWB, 2019; Didier, et al., 2019). Rwanda experiences four distinct seasons: a long rainy season from March to May, a short rainy season from September to November, a long dry season from June to August, and a short dry season from December to February (World Bank, n.d.). During the dry months from June to August, rainfall averages around 20 mm per month, while during the rainy season, it increases to approximately 130 mm per month. Similarly, Rwanda has three agricultural seasons that follows the seasonal rainfall: Season A from September to February, Season B from March to June, and Season C from July to September.

2.4 Socioeconomics and Livelihoods in Lower Akagera

In NAKL, most of the area is rural, there is high population density in the inhabited areas, and a considerable amount of the population lives in poverty. Approximately 72% of the population earn their livelihoods from rainfed agriculture and around 80% are involved in agriculture (NISR, 2015). Based on a socioeconomic study in 2021, the primary sources of income in the area are the sale of crops – accounting for 53.4% of income – and livestock products – contributing 20.2% (IUCN, 2020). The study also found that livelihoods are primarily centered around agriculture and livestock and the main challenges includes water scarcity, reliance on forest resources, and inefficient land management. The main source of drinking water in the area comes from public taps, and approximately 65% of have access to clean water. However, a significant portion of the population relies on unimproved sources, with half of the households walk more than 500 meters to fetch water. Farmers and households in the Eastern province are encountering challenges related to insufficient water supply, mainly due to low precipitation and the lack of rainwater harvesting facilities (IUCN, 2020).

2.5 Water management and Stakeholders in Rwanda

Since its establishment in 2020, the Rwanda Water Resources Board (RWB) has operated as an autonomous agency under the Ministry of Environment and collaborates with regional and international institutions with similar missions. As the leading governing agency for Rwanda's water resources, the RWB is responsible for implementing laws, policies, and strategic plans. They also monitor the country's water resources, manage flooding, and ensures sufficient water quality (RWB, n.d.b).

The Water and Sanitation Corporation (WASAC) is the leading stakeholder in Rwanda's urban water supply, distributing piped water, primarily in urban areas. However, in rural areas, water supply is managed through Public-Private Partnerships (PPPs), a collaborative arrangement between the government and private companies. The shift towards PPPs began around 2004 following a World Bank report revealing that half of Rwanda's piped rural water supply systems were nonfunctional due to poor management, resulting in the government adopting the PPP model to enhance rural water services (World Bank, 2010). In many rural areas, the main source of drinking water comes from boreholes and wells, which are still managed and maintained by local communities.

Another important stakeholder is the Rwanda Agriculture Board (RAB), under the Ministry of Agriculture and Animal Resources (MINAGRI). Irrigation investments are led and planned by MINAGRI, while the RAB provides technical support (RAB, n.d) (MINAGRI, 2019). Through the Rwanda Irrigation Master Plan, the government aims to boost agricultural production by promoting efficient and sustainable utilization of Rwanda's soil and water resources through various forms of irrigation (RAB, 2020).

2.6 Previous Water use and demand Assessments

2.6.1 National Master Plans

The National Water Resources master plan (MINIRENA-RNRA, 2015) was developed in 2015 by what today is the Ministry of Environment. This master plan aims to ensure sustainable development of the country's water resources from 2015, when the plan was initiated, until 2040.

In the master plan, a current water consumption assessment was conducted for the reference year of 2012. In this assessment, the plan notes the lack of reliable data for water demand estimations resulting in the domestic water demand estimation was most likely to be overestimated. For the agriculture water use, the plan assumed full exploitation of all irrigated areas, which is not always the case and, the irrigation demand was calculated from a fixed value of 8000 m^3/ha/year for the eastern regions.

The table below shows the output data for NAKL according to the NWRMP.

Table 2 Annual water demand according to the NWRMP.

Sector	Irrigation	Domestic Water
m^3/year	84 400 400	8 800 000

The plan also provides estimation of per capita water demand based on residential area. In 2012, the demand was 60 l/cap/day for urban and 40 l/cap/day for rural households, projected to increase to 70 for urban and 60 for rural households in 2020 based on assumptions related increased living standards.

Similar to the NWRMP, the Rwanda Irrigation Master Plan used a fixed value of 8 000 m^3/ha/year for the water demand estimations. According to the plan, the total area of existing schemes in the catchment was 9 254 ha (In 2020) resulting in an annual irrigation demand of 74.03 Mm^3 (RAB, 2020).

2.6.2 Water Users and Uses Assessment

The water users and uses assessment (WUA) (RWB, 2020) conducted in 2020 was a comprehensive evaluation of water users among the largest water-consuming sectors across Rwanda's all level 2 catchments. The Water Users and Uses Assessment's main goal was to update data collection methods for water users and use, focusing on several key indicators like withdrawal-availability ratio, water use conflicts, and total water use by each major user category.

The assessment lacks details about the methodology used, offering only a general overview of each data source. In the WUA, domestic water use is categorized into Domestic Water Supply, Public Boreholes, and Public Springs. For Domestic Water Supply, it is mentioned that the data on water use was derived from a WASAC database. For Public Boreholes and Springs, water withdrawal was calculated based on known discharge rates from a borehole database for the entire country, assuming the boreholes operate for 4 hours daily.

In the assessment of irrigation water use, irrigation was divided into Small-Scale Irrigation and Large-Scale Irrigation (>10 ha). The WUA mentioned that data was collected from an RAB dataset containing all schemes in the country, combined with existing data from the RWB water permit system. However, it does not specify whether water use was estimated or based on actual water abstraction. Table 3 presents the annual water use in the Lower Akagera according to the assessment.

Table 3 Annual water use according to (RAB, 2020).

Sector	Irrigation	Domestic Water
m3/year	59 924 179	8 006 053

3. Methodology

The overall methodology was a combination of literature review, data collection, statistical analysis, and modeling. The main water use sectors are agriculture and domestic, for which different methods were applied. The overall workflow is presented in Figure 3

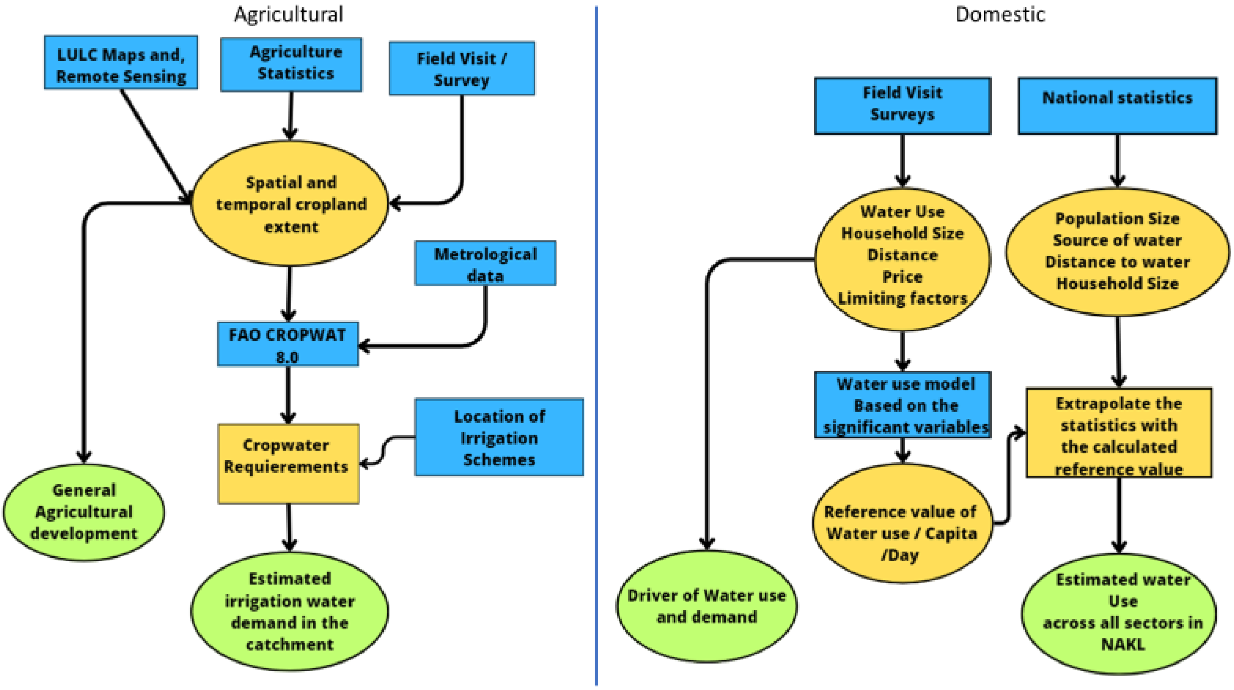

Figure 3 Overview of methodology.

The methodology for agriculture included two parts. The first part involved estimating the irrigation water demand using the Cropwat 8.0 software, by combining national data with field observations and interviews. In the second part, national data combined with a land cover classification was conducted to understand the general agriculture development in the area over the past decade.

The domestic water demand was estimated through a regression model. From the collected field data, this model was trained to provide a baseline value of water demand per capita and extrapolated spatially and temporally over the catchment using national demographic statistics. As a complement to the model, qualitative interviews were conducted to understand the driving factors and the development over the past decade.

3.1 Terminology

In this thesis, domestic water use refers to consumptive water use for domestic purposes, meaning the water fetched and used among households. On the other hand, the household's perceived water use without any limitations will be defined as domestic water demand.

Agricultural water use refers to the amount of water necessary to fulfill crop water requirements through irrigation. Agricultural demand refers to the quantity of water required to make up for losses due to evapotranspiration.

3.2 Field Visit

The Akagera Lower Catchment was visited twice in September 2023. The first visit was carried out in the districts of Kayonza and Kirehe from the 4th to the 7th of September. The second visit in the districts of Gatsibo and Nyagatare between September 23rd and 27th. The field visits aimed to interview the local population, farmers, and district and sector officials about water use and issues in the area. For all districts except Nyagatare, interviews were conducted entirely within the borders of the catchment. However, in Nyagatare, the interviews extended beyond the catchment boundaries because the fieldwork was done in parallel with another researcher whose research focused on the whole of Nyagatare. The team consisted of a Ph.D. student from the University of Rwanda (UR) and Lund University (LU), two undergraduate students from the UR, and the author.

In total, 22 of the catchment's 37 sectors, and 43 cells, were visited, shown in Figure 4. The goal was to conduct at least 30 surveys per district and to include all sectors that have the largest share of their area within the catchment. Following accessibility issues and time constraint, some sectors were left unvisited.

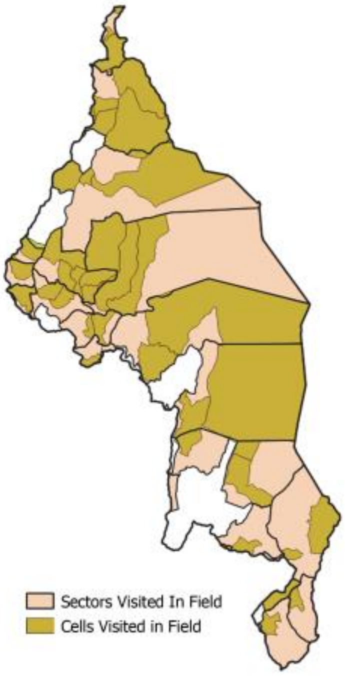

Figure 4 Visited areas during the field visit.

3.2.1 Interviews

To ensure a diverse range of responses, the interviews were conducted randomly in various locations, such as homes, streets, water points, or agricultural areas. A questionnaire was used, which contained quantitative questions – to provide a statistical basis – and open-ended questions – to gain insights into the local situation. The questionnaire is presented in the *Appendix* A, and included questions about daily water use, characteristics of the households, crops grown, and experienced issues related to water. The interviews were done in Kinyarwanda and were carried out by the assistants from University of Rwanda. An initial trial-and-error phase was employed to determine which questions were effective, resulting in the addition or removal of questions. On the first day of interviews, printed copies of the questionnaires were used; however, online Google Forms were later used to facilitate the monitoring and compilation of the responses, although printed copies continued to be used in areas with weak internet connection.

3.3 Methodology for Agricultural Water demand

This section outlines the methodology for assessing water requirements in the agriculture sector. First, the methodology for calculating crop water requirements (CWR) is presented, followed by data collection, and lastly an overview of the Cropwat 8.0 model, which was used for the irrigation demand assessment.

3.4 Irrigation Use and Demand

The total irrigation demand (IRQ) and use of water in agriculture are primarily determined by the size of the cropland, the types of crops grown, and their specific water requirements. The computation of crop water requirements can be done using the KcETo method developed by the Food and Agriculture Organization (FAO) (Allen, et al., 1990). This method involves determining Crop Evapotranspiration (ETc) based on the Reference Evapotranspiration (ETo) of the area, calculated using meteorological data and the Crop Coefficient (Kc). By subtracting the effective rainfall from ETc, the IRQ can be calculated using Equation 1 and Equation 2. Factors like groundwater contribution, soil moisture, slope, leaching requirements, and conveyance losses also influence CWR (Jamal, 2017), but were not included in this method. According to Wallingford (2003), this estimate of irrigation water demand and use should suffice for catchment-level applications.

Equation 1

$$IRQ = \frac{(CWR) * Area_{Cropland}}{Irrigation_{efficency}}$$

Equation 2

$$CWR = (ET_c * K_c) - P_{eff}$$

3.4.1 Evapotranspiration

Evapotranspiration is the process by which water is lost from the Earth's surface to the atmosphere through evaporation and transpiration. It is influenced by location, metrological conditions, and crop type. Hence, a reference evapotranspiration rate (ET$_0$) is calculated, defined as evapotranspiration from a hypothetical reference surface, which usually is grass growing under ideal conditions (Allen, et al., 1990). It is a universal standard, expressing an area's evapotranspiration under a given climate condition, not influenced by crop type or irrigation. Various methods exist to estimate reference evapotranspiration, where FAO recommends using the Penman-Monteith as a standard method. However, this method requires a considerable amount of long-term climatic data, including temperature, wind speed, humidity, and solar radiation, which is not always available (Wallingford, 2003). The factors increasing evapotranspiration include high temperature, radiation, and wind speed, while low humidity reduces it (Abtew & Melesse, 2013).

3.4.2 Crop Coefficient

Knowing the reference evapotranspiration (ET$_0$), the crop evapotranspiration (ET$_C$) can be calculated by adjusting the reference evapotranspiration with a dimensionless crop coefficient, according to Equation 3.

Equation 3

$$ET_c = K_c * ET_o$$

The Kc factor considers differences in crop characteristics and environmental conditions, and varies during the growing period due to changes in vegetation and ground cover, according to Figure 5 (Pokorny, 2019).

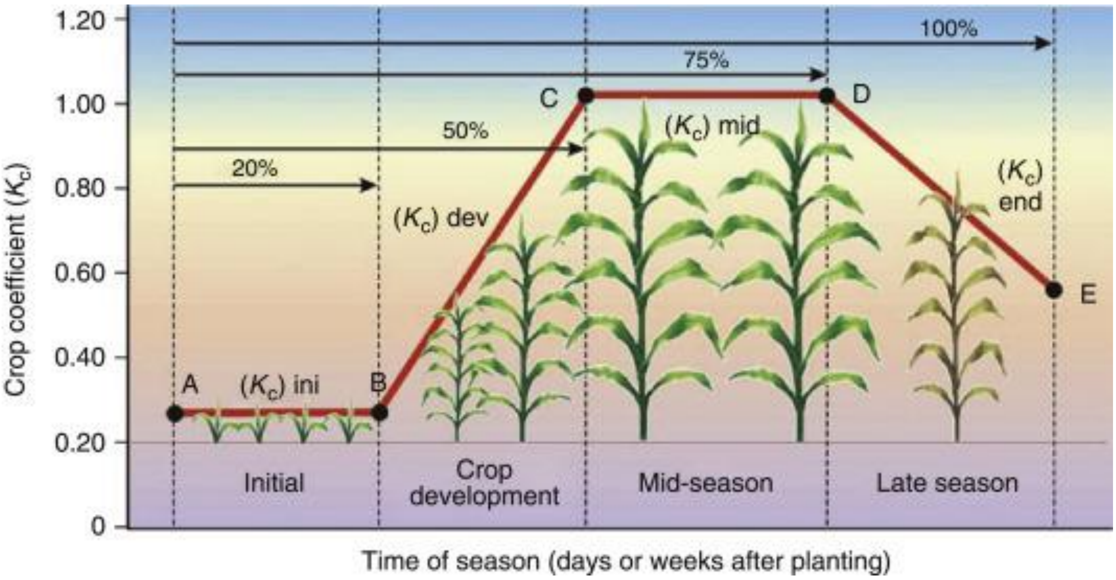

Figure 5 Crop coefficient (Pokorny, 2019).

Three values are required in the crop coefficient curve. The initial stage (Kc_{in}), the mid-season stage (Kc_{mid}), and the end of the growing season (Kc_{end}). Figure 5 illustrates that the crop coefficients follow the increase in vegetation cover, meaning the evapotranspiration rate increases as the crops develop.

3.4.3 Effective Rainfall

The rainfall may fully or partly meet the crop water requirements. However, not all rainfall is effective, as some may become runoff, deep percolation, or evaporation. Effective rainfall in an agricultural context refers to the proportion of the rainfall that contributes to soil moisture and is available for plants (Wallingford, 2003). Various methods can be used to calculate effective rainfall, but studies have found that in areas where water is scarce, like the Lower Akagera, the USDA S.C method is the best option (Bokke & Shoro, 2020). Effective rainfall is calculated according to Equation 4.

Equation 4

for P≤250/3

$$Peff = \frac{P * (125 - 0.2 * 3) * P}{125}$$

For P>250/3

$$Peff = \frac{125}{3} + 0.1 * P$$

3.4.4 Cropwat Model

The Cropwat 8.0 program (FAO, n.d.), a decision support tool created by the FAO, was used to determine the crop water requirements. This program has several functions, including calculating irrigation requirements, reference evapotranspiration, and developing water supply schemes for crops. Cropwat has been used in various studies conducted in Rwanda and is an internationally recognized software in irrigation management.

The Cropwat model estimates reference evapotranspiration using the Penman-Monteith equation based on the factors discussed in section *3.4.1*. It also requires monthly rainfall data, which is converted to effective rainfall using the USDA S.C. method. Additionally, it needs crop-specific information, such as the crop coefficient, which can be taken from a database in the model. Soil data is also required for estimations on detailed irrigation supply scheduling. However, this data can be left outside for general and simple CWR estimates according to the KcEto approach. On the other hand, in the case of rice cultivation, an additional substantial amount of soil data is required, which often requires area-specific field data (Balaghi, 2010)

3.5 Data Collection and Process Agriculture and Irrigation

3.5.1 Climate data

Meteorological data in Rwanda is managed and disseminated by the Metrological Institute of Rwanda (METEO), a government-owned agency established in 1963 (Meteo, n.d.). Through the agency, the climate data needed for the Cropwat model was requested from its web portal.

Rainfall data was received from a dataset containing daily measurements for all stations in Rwanda from 1981 to 2021. The coordinates for each rainfall station were uploaded to QGIS, where all stations located within the catchment area were extracted. In total, 12 stations were identified and one adjacent to the catchment in the northern parts. A gap analysis was conducted, assuming that if zero rainfall was reported for a continuous period of five months or more the station was not working. To remove extremes, all monthly measurements that were +/- 2 standard deviations from the monthly average of all selected stations were excluded. Data from 371 months were identified, resulting in 5% of the data being excluded. It should be noted that the rainfall across the catchment is not normally distributed, leading to the lower bound of the standard deviations being negative in many cases, mainly excluding the upper extremes.

In the final step, the monthly rainfall based on the selected stations from 1981 to 2021 was calculated. The calculated monthly values were uploaded to QGIS, where Voronoi polygons were created for each station according to Thiessen's polygon method, see Figure 6. Using the QGIS built-in tool – TIN-Interpolation – a raster layer was created for each month by interpolating the rainfall linearly within the polygons, resulting in a long-term monthly average of rainfall in the catchment area.

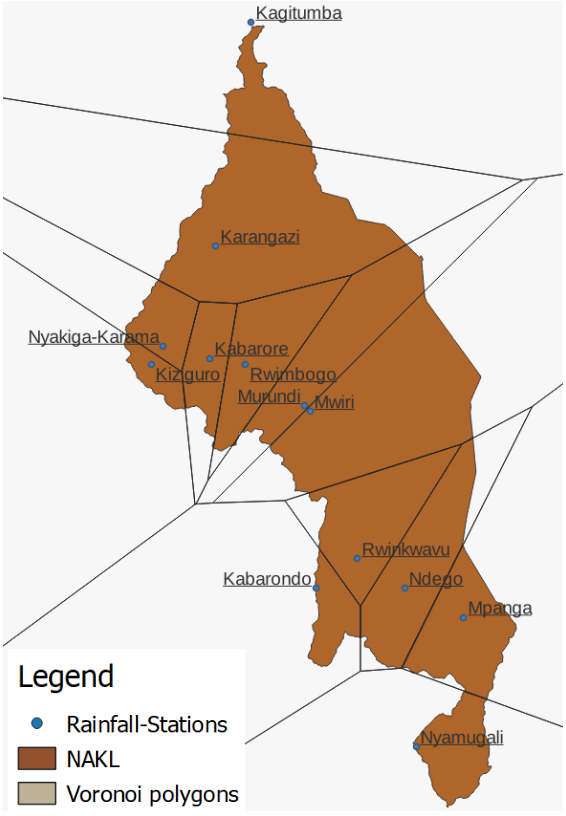

Figure 6 Rainfall stations in the catchment and their contributing area.

Data on relative humidity, solar radiation, and wind speed were also received by the METEO for three stations within the catchment. However, this data was only available from the beginning of 2023 until October, when data was requested. In the Penman-Monteith equation, long-term climatic data is required, making the METEO dataset unsuitable for this purpose. Hence, satellite meteorological data were used.

Satellite data were derived from the WaPOR portal (FAO, n.d.), developed and launched in 2019 by the FAO. WaPOR is a publicly accessible database used to monitor agricultural water productivity at different scales (FAO, n.d.c). This portal provides a global dataset of reference evapotranspiration with the resolution 10 by 10 km, computed according to the Penman-Monteith equation using input from the dataset Agriculture ERA-5 (AgERA-5), an agrometeorological dataset developed by the European Copernicus Programme. The AgERA5- dataset is based on ERA-5 data, tailor-made for most agriculture and agroecological models (ECMWF, n.d.). This dataset contains elements covering temperature, rainfall, humidity, wind speed, cloud cover, and solar radiation.

In the WaPOR portal, a shapefile of NAKL was uploaded and clipped over the layer *Reference evapotranspiration - AgERA5 derived (Global - Monthly - ~10km)* (FAO, 2021), from which a time series from 1981-2021 of the average ETo for the entire area was extracted. Due to the limited data availability from METEO, no cross-validation of the AgERA5 was performed.

3.5.2 Land Use data

The total water demand for the agriculture sector is mainly driven by the cultivated area and land allocated for irrigation. The Regional Center of Mapping and Resources and Development (RCMRD) provides Land Use and Land Cover (LULC) maps for the country for the years 2010 and 2015. However, the latest map available for this purpose was produced in 2015. Therefore, a remote sensing analysis was conducted using Google Earth Engine to determine the current LULC while the RCMRD maps were used for historical land cover. After discussions with an expert from the team that produced the maps, it was advised not to use them to determine the cropland extent. However, since no remote sensing was conducted for years other than 2023, these maps were still included. Therefore, they should only be seen as an indication.

Google Earth Engine (GEE) is a cloud-based image service that provides access to an extensive archive of satellite images where images can be used to classify satellite images through coding. For this purpose, surface reflectance images from the ESA Sentinel-2 were used to produce land cover maps of 2023. Sentinel-2 was launched in 2017 and was chosen due to its high spatial resolution of 10 x 10 meters.

To increase the overall accuracy of the classification, by accounting for local variations across the catchment and comparing the cropland classification's accuracy with the agricultural statistics. Five different maps were therefore produced for each district, except for Ngoma, which was included in the Kayonza classification. An additional classification was also produced for the Akagera National Park.

For the dry season, a median pixel composite of all satellite images was set up between July and August of 2023. The classification was carried out during the dry months because these have been found to have the highest accuracy, and the number of cloud-free images is generally higher during the dry season than the rainy season (Gutkin, et al., 2023). The land cover classification was performed using the Random Forest algorithm, a machine learning technique considered desirable for land cover classification (Gislason, et al., 2006). This classification classifies the satellite images using decision trees based on training points entered manually into the platform.

No ground validation data was collected for this thesis. Instead, training points were selected based on different band combinations, indices, and interpretations of land classes according to RGB images. Figure 7 shows examples of the land classes used in the training process.

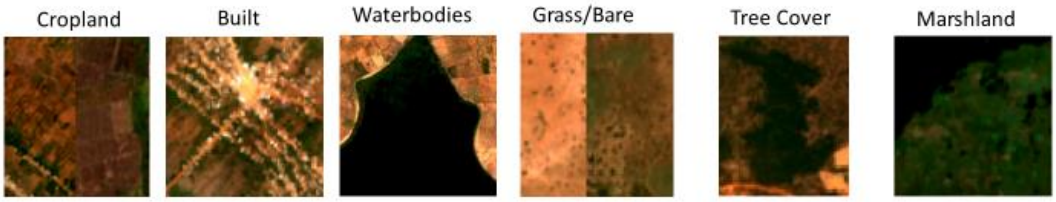

Figure 7 Land classes used in the classifier.

To identify land allocated for irrigation, two different datasets were used – one provided by the RAB and the other by the RWB. These datasets contained shape files of all irrigation schemes in the country, whose locations were then verified using Google Earth satellite images. However, the datasets lacked detailed information about irrigation methods, crops used, planting periods, and other scheme-specific information. Instead, some of this information could be obtained through a literature review of the MINAGRI annual reports from 2009-2023 and other literature.

3.5.3 National Agricultural Statistics

Agriculture data was acquired from the seasonal agriculture survey (SAS) (NISR, 2023), an annual survey conducted since 2014 by the National Institute of Statistics of Rwanda (NISR) in collaboration with the Ministry of Agriculture, to gather information related to agriculture in Rwanda. The survey includes land use, crop use, yields, and agriculture practices during Rwanda's three main agriculture seasons. The resolution of the data is based on a sampling procedure and estimated to a district-level resolution.

Historical agriculture statistics were also collected from the NISR. The first reliable survey available is the National Agriculture Survey (NAS) conducted in 2008. Before this date, agriculture production was based on a projection from an agricultural survey conducted in 1990, meaning that the years between 1990 and 2007 were projected on unreliable data. Additionally, the changes in the administrative boundaries in 2006 makes the statistics before this date not representative on today's administrative borders.
(NISR, 2008)

According to experts at the RAB, the dataset recommended to use is the Seasonal Agricultural Survey (SAS), covering the period from 2014-2023. The methodology used for the survey conducted between 2014-2016 was different, where the statistics were given per agriculture stratum, and not on a district level. The data from 2017-2023 was given on a district level and could still be used. However, between these years of the SAS, there are large variations in the available statistics that require some interpretation to find development logics.

3.5.4 Rwanda Irrigation Master Plan

The Rwanda Irrigation master plan, (RAB, 2020) developed in 2020, is a 10-year strategy aimed at transforming Rwanda's agriculture. As the primary strategic document assessing irrigation in the country, it provides insights into irrigation techniques, crop patterns, and crop water requirements. In the IMP, the RAB utilized the CROPWAT model to estimate gross irrigation water demand for selected crop patterns across Rwanda's agroclimatic zones.

3.5.4.1 Irrigation Efficiencies

The irrigation efficiencies in the IMP are computed according to the FAO guidelines, based on conveyance efficiency in the stratum and field application efficiency. The field application efficiency according to the IMP is presented below:

- *Surface (furrow, basin, border) 60%*

Modern:

- *Overhead (sprinkler, Centre pivot) 75%*
- *Drip 90%*

The overall system efficiencies for the systems are:

- *Marshland surface with lined primary canals and earthen (clay) secondary/tertiary canals: IE = 90% x 60% = 54%*
- *Hillside surface with lined canals/pipes: IE = 95% x 60% = 57%*
- *Hillside overhead with lined canals/pipes IE = 95% x 75% = 71%*
- *Hillside drip with pipes = 95% x 90% = 86%*

3.5.4.2 Crop Water Requirements

The annexes of the master plan were requested and received from the RAB. This annex provides gross irrigation requirements for selected cropping patterns in the agroclimatic zone Eastern Plateau, where the Lower Akagera is located. As previously discussed in Section 3.4.4, field-specific data is required when calculating crop water requirements for Rice. Following the scope and timeframe of this thesis, this data was not collected. As a result, the monthly irrigation requirements for rice were instead derived from the IMP, according to Table 4.

Table 4 Irrigation requirements of rice (RAB, 2020).

Rice	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
m^3/ha	1848	3674	904	339	894	767	2207	4881	1600	1319	689	413

3.5.5 Summation of data used in Agriculture water use and Demand

The available data used is presented in Table 5.

Table 5 Data Availability for agriculture water demand.

National data				
Data Type	**Format**	**Temporal Resolution**	**Spatial Resolution**	**Source**
Rainfall	Measurements	1981-2021	Catchment	Meteo
Eto	Satellite	1981-2021	Catchment	WaPor
Crop use	Statistics	Seasonal 2019-2023	District	SAS
Irrigated Areas in NAKL	Shape	2023	Catchment	RAB/RWB
Irrigation Method	Reports	-	Catchment	-
Irrigation efficiency	-	-	National	RAB
CWR Rice	-	-	Eastern Plateau	RAB
Irrigated Areas SC	Remote Sensing	2023	Catchment	GEE
Rice Fields	Remote Sensing	2023	Catchment	GEE
Current LULC	Remote Sensing	2023	Catchment	GEE
Historic LULC	TIF	2010; 2015	Catchment	RCMRD
Cropland	Statistics	2008; 2017-2023	District	NAS/SAS
Irrigation practices	Statistics	2008;2019-2023	District	NAS/SAS
Field data				
Crop use	-	-	Catchment	Field Survey
Water sufficiency	-	-	Catchment	Field Survey
Irrigation Methods	-	-	Catchment	Field Survey

3.6 Methodology for Domestic Water Demand

This section outlines the methodology for assessing domestic water use and demand. First, the theory and factors influencing water use are presented, followed by data collection, and finally, an overview of the Regression model is presented, including post-processing of collected data.

3.6.1 Introduction to domestic water use estimations

A common way to estimate water use is by using population size and a baseline value of per capita use. The baseline value is often estimated based on an average of urban and rural households, where urban households tend to have higher living standards and service levels, leading to higher water use and rural households generally have lower. Factors such as population growth, economic development, and living standards contribute to increased water use. In Rwanda, the baseline values are 70 for Urban and 60 for Rural households (MINIRENA-RNRA, 2015), based on assumptions related to living standards, economic development, and residential areas. In reality, water demand and use will vary based on local conditions, traditions, and socioeconomic factors (Wallingford, 2003).

Another method to determine water use involves known data from water service providers. Upon request, WASAC provides information on the total water abstracted, losses, and supplies and the RWB maintains a database of boreholes and springs with a known abstraction rate. However, efforts were made to request this data from the agencies and private companies without any success. As a result, this approach will not be included in this study.

3.6.2 Determinants of Water Use

In the Handbook of Assessment of Water Demand in a catchment (Wallingford, 2003), two methods, known as the direct and indirect methods, are described. The indirect method assumes that the amount of water consumed is proportional to the population served and the per capita consumption rate. On the other hand, the direct method involves several factors related to living conditions, such as population size, household size, level of service, tariff levels, local knowledge and indigenous practices, climate, and water quality. Some of these factors are discussed below.

Various studies have shown an inverse relationship between household size and per capita water use. As the number of people in the household increases, per capita water use decreases (Howard, et al., 2020). This is explained by that many households’ water-use activities benefit multiple members, such as washing, cleaning, and cooking (Crouch, et al., 2021).

Numerous studies have been conducted to determine the impact distances between a home and the water source has on water use. (Rhoderick, 2013) compiled 20 studies that investigated the relationship between water accessibility and domestic water use; twelve studies found that as the distance between a home and the water source increased, per capita water use decreased. This is because fetching water over long distances, which is often done by walking, is physically demanding and time-consuming (Howard, et al., 2020).

Water tariffs is a common regulatory instrument to adjust water use, where an increase in price often incentivizes water conservation (Hoehn, 2011). Howard (2020) states that water is a normal good, meaning water demand tends to decrease as the price increases.

In many countries, water availability and domestic water use is highly dependent on the seasons. During the dry season, the primary water source may dry up, resulting in reduced availability, forcing people to use less water or travel longer distances to locate alternative water sources (Howard, et al., 2020). However, in some cases, households practicing rainwater harvesting may experience increased per capita water use; this is because rainwater is free, reducing the household's water bill (Hadjer, et al., 2005).

3.6.3 Multiple Regression Model

Given the interplay of different factors affecting domestic water use, it is not always a single factor that determines water use. To estimate the factors affecting domestic water use, they must be modeled together. This can be achieved through multiple linear regression (MLR), which is a statistical method that predicts the outcome of a dependent variable based on modelling of linear relationships to several independent variables (Taylor, n.d.) (see Equation 5).

Equation 5

$$y = \beta_0 + \beta_1 X_1 + \ldots + \beta_n X_n$$

y = *Dependent variable (Water Use).*
β_0 = *Intercept (Expected value of* y*, when* X_1-X_n *is 0)*
β_n = *Coefficients of the independent variables (Household sizes, Price, etc.)*

The independent variables can be classified as either categorical or continuous. Continuous variables are numerical data that represent quantities (numbers), while categorical variables are non-numerical and are categorized into groups (Wright, 2022). The regression analysis was conducted in MATLAB, with the function *fitlm* (MATHWORKS, 2023).

Based on the field data collected, two regression models were created according to Table 6. The first model evaluated the significance of all variables to create a new extrapolation model that only included the ones found to be significant. This model will evaluate whether national statistics in Rwanda can be used to spatially and temporally extrapolate the model for the entire catchment. As a complement to the Model, an analysis of the open-ended questions was be conducted to identify the determinants and drivers of water uses.

Table 6 Field data used in the regression model.

Dependent Variable	Format	Unit
Y	Water Use	l/cap/day
Independent Variables	**Format**	**Unit**
β_1	Household size	-
β2	Distance	Minutes
β_3	Source of water	-
β_4	Price	Price/Can

The quantitative field data were prepared by the following approach:

- The water use data was collected as the number of jerry cans the household uses. This data was translated to liter/cap.
- Households with a water use greater than 50l day were removed.
- To match the statistical data from the national surveys, all distances greater than 120 minutes were changed to 120 to represent 60 minutes+.
- Some households pay per jerrycan fetched while others pay a monthly price. To include all data in the model, the monthly price was translated to per jerry can price.

3.7 Data Collection and Process Domestic

Demographic data were collected from the NISR, an independent government-owned agency responsible for collecting and disseminating national statistics (NISR, n.d.a). The NISR carries out a Population and Housing Census (RPHC) every ten years. This census involves collecting and recording demographic, economic, and social data for the entire population of the country. The RPHC is divided into one main report and several thematic reports, covering different aspects of the population. Every five years, the NISR also conducts the Integrated Household Living Conditions Survey (EICV), which provides insights into the population's well-being, such as living conditions, housing conditions, household consumptions, and more. Like the RPHC, the EICV is composed of thematic reports (NISR, n.d.b).

The limitations of the RPHC and EICV surveys are in the resolution, as they do not align with the catchment boundaries. In the RPHC, population size and distribution are only available at a sector resolution due to confidentiality reasons, while in the EICV, the statistics are provided at a district or province level. Additionally, for both surveys, the temporal resolution is limited following the changes in the administrative boundaries of January 2006. As a result, no data is available before this date, meaning that only data from 2012 onwards was considered.

3.7.1 Population Size and Distribution

The population size and distribution were derived from the RPHC 2022 and 2012 for each of the 37 sectors within the catchment. To address the differences between administrative and catchment boundaries, population size was recalculated to a catchment level in QGIS by overlaying a layer with population density over the population size according to the RPHC. Assuming that the population density given by WorldPop (Humdata, 2020) is accurate, this layer served as an indicator to determine the spatial distribution of the population by calculating the fraction of the population living inside the catchment of each sector. Using Equation 6, this fraction was later multiplied with the total population of each sector as reported in the RPHC.

Equation 6

$$Populationsize_{NAKL} = Populationsize_{RPHC(n)} \left(\frac{\sum WorldPop_{within\ NAKL\ (n)}}{\sum WorldPop_{Total\ area\ of\ sector\ (n)}} \right)$$

3.7.2 Source of Drinking Water

The main sources of drinking water were obtained from the RPHC surveys of 2022 and 2012, as the percentage of the population using each water source in all sectors within the catchment. However, the 2022 survey did not account for the same sources as the 2012 survey. This was solved by reclassifying the water sources for consistency in both surveys, see *Appendix B*.

During field visits, assumptions were made to simplify data collection on water sources. Firstly, pipe borne water and internal pipe borne water were grouped as in-home water. Secondly, pipe borne water from a neighbor and public tap outside the compound were grouped. Finally, due to limited local knowledge about the condition of boreholes and the difficulty of visually assessing their technical conditions, the categories tube well/borehole and protected spring/well were grouped as protected well. Another assumption was that mineral water and tanker truck were not included, since the number of people relying on these sources was very small. The same classification as described in the RPHC was used for the unimproved sources, resulting in six different groups of water sources.

3.7.3 Distance to Water Source

The distance to the water source was obtained from the EICV survey from 2017 and 2012. In the survey, the distance to the improved water source is given in minutes for each of the five districts within the catchment. The values are given in timesteps from piped water: 0-4 min, 5-14 min 15-29 min, 30-59 min, and 60+ min. These values were reclassified to continuous variables from 0-6 in the MLR model, where 1 indicated the timestep 0-4 and 5 is the timestep 60+. Given that the statistics are for improved sources, it was assumed that the distances also applied to unimproved sources. Additionally, since piped water was not included in the model, distances were recalculated to account for only the time steps 0-60+ min according to Equation 7.

Equation 7

$$D_n = D_n / \sum_{n=0}^{60+} D_n$$

3.7.4 Household Sizes

Household size was collected from the EICV survey. At a provincial level, the statistics are given as the percentage of households with 1, 2-4, 5-7, 8-10, and 11+ persons. Similar to the distance data, the same assumptions and reclassification were used as for the household size in the MLR model.

3.7.5 Summation of Data used in Domestic Water Demand

The available data used for further estimations is presented in Table 7.

Table 7 Data availability for domestic water demand.

National Data				
Data Type	**Format**	**Temporal Resolution**	**Spatial Resolution**	**Source**
Population Size	Statistics	2012;2022	Sector	RPHC
Population Density	TIF	2020;2010	National	WorldPop
Source of Drinking Water	Statistics	2012;2022	Sector	RPHC
Distance to Water Source	Statistics	2011;2017	District	EICV
Household Sizes	Statistics	2011;2017	Province	EICV
Field data				
Data Type	**Format**	**Quantity**	**Spatial Resolution**	**Source**
Water Use	l/cap/day	213	Catchment	Field Survey
Household Sizes	-	213	Catchment	Field Survey
Distance to Water Source	Minutes	213	Catchment	Field Survey
Price	-	213	Catchment	Field Survey
Limiting Factors	Qualitaitve	187	Catchment	Field Survey
Seasonal Water Use	l/cap/day	133	Catchment	Field Survey

4. Results

In this section, the results are provided. Section 4.1 presents the area's general agricultural development, including statistics, land use and land cover. In section 4.2, the results from the irrigation demand are presented, including key statistics, climate data, and crop data. Section. Section 4.3 provides the data for domestic water use, along with the regression model and the extrapolation over the entire catchment. Finally, section 4.4 presents the key field data and identifies drivers and development of domestic water use.

4.1 Changes in cropland extent and Irrigation development in the region

4.1.1 Agriculture Statistics

The statistical agriculture data in Rwanda is fragmented. Compiling agriculture statistics from the NAS and the SAS survey, it is difficult to find any logical development following large variations and inconsistent methodology between the different surveys. Discussed in the following section is the available data and its limitations. The primary limitation related to agricultural data is the spatiotemporal resolution, which is only available on a district level. Therefore, applying the data on a catchment level is not fully representative.

4.1.2 Output from Statistics

The earliest statistics on irrigated areas in the region were obtained from the NAS. From this survey, the total irrigated area was interpreted by summarizing the area for irrigated crops, under drainage, and watered, according to Table 8. No data on irrigation was available between the 2008 NAS and the SAS of 2019 to 2023, which only provides information on the total area under modern irrigation, such as pivot, sprinkler, and drip irrigation, as shown in Figure 8.

Table 8 Irrigated land 2008 within the districts of NAKL (NISR, 2008).

NAS (2008)	Irrigated	Drainage	Watering	Total
Nyagatare	837	233	18	1088
Gatsibo	392	1802	282	2476
Kayonza	17	195	293	505
Ngoma	487	443	26	956
Kirehe	513	538	0	1051
Total	2246	3211	619	6076

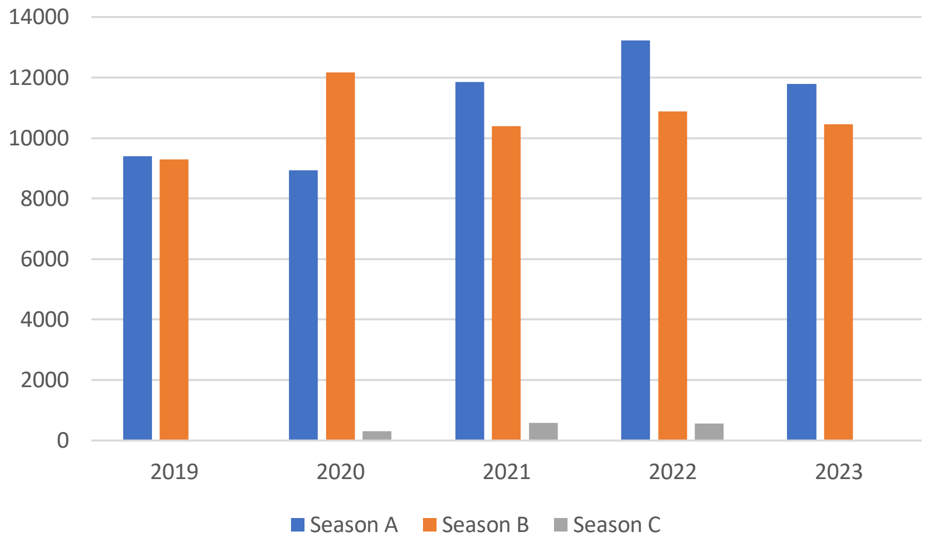

Figure 8 Modern irrigated land within the districts from the SAS 2019-2023.

It is not possible to draw any conclusions about development of total irrigated land from the different surveys, as only modern irrigated land was included in the SAS. However, an overall increase in modern irrigated land over the four years from 2019 to 2023 can be observed. Based on Figure 8, rrigation is mainly practiced during seasons A and B, while the land under irrigation is much smaller during season C.

Looking at the irrigation methods used over recent years, a trend towards improved irrigation efficiency can be observed in the catchment – from 3% in 2018 to 14% in 2023, as seen in Figure 9.

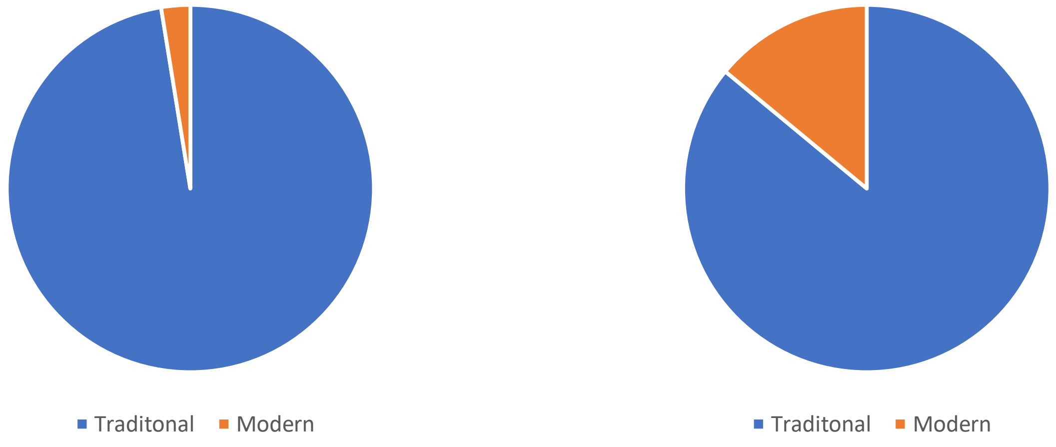

Figure 9 Average irrigation method in 2018 (left) and 2023 (right).

4.1.3 Changes in Cropland According to National data

Since the NAS in 2008, there has been a large expansion of cropland within the districts. The graph in Figure 10, illustrates the total cultivated area in 2008, represented by columns, and the average annual cultivated area for both agriculture seasons, A and B, according to the SAS from 2017-2023. From 2008 to 2023, the total cropland area in the Nyagatare, Gatsibo, Kayonza, Ngoma, and Kirehe districts increased by 42.7%, from 214 258 hectares to 305 800 hectares. Kirehe showed the highest increase in cropland area at 73.0%, followed by Nyagatare and Kayonza districts, which expanded by around 42%. Ngoma had a 39% increase, while Gatsibo showed the smallest increase of 25%.

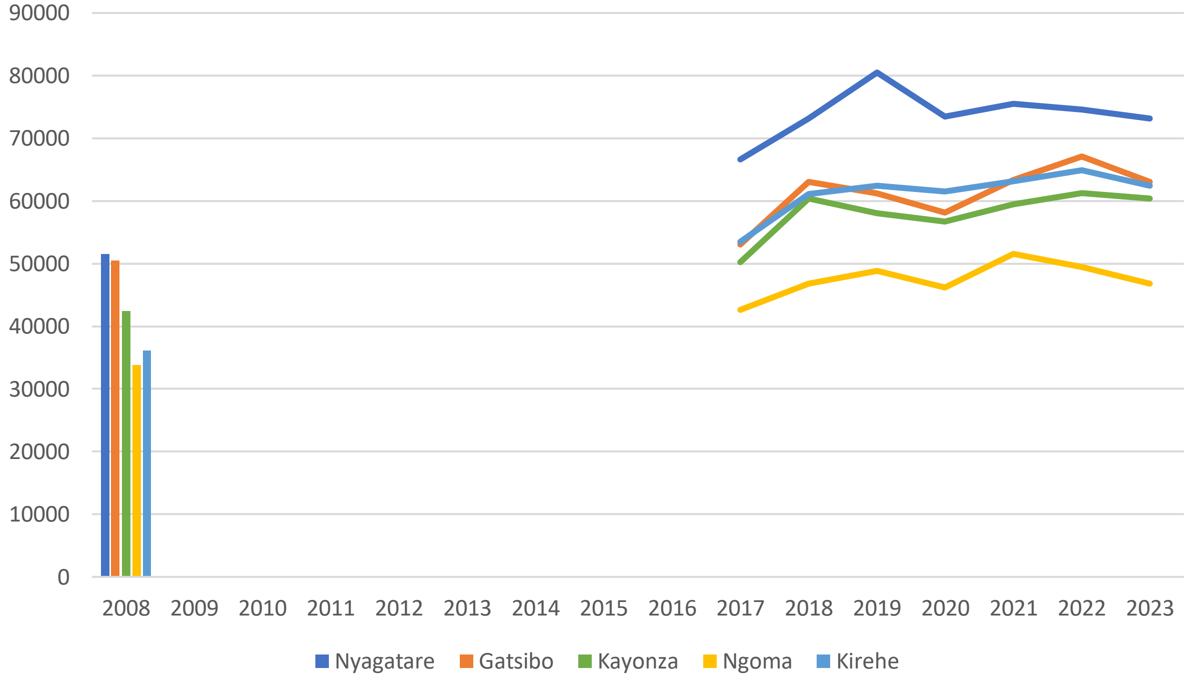

Figure 10 Cropland development 2008 (NAS) and 2017-2023(SAS).

Given that the resolution of the statistics is at district level, there are uncertainties when estimating cropland development for the whole catchment. For instance, only 4% of Ngoma district's area is within the catchment. On the other hand, Kayonza district, with 84% of its area within the catchment and a 42.3% increase in cropland, is probably more representative, see Table 9.

Table 9 Total cropland development between 2008 to 2023.

	Nyagatare	Gatsibo	Kayonza	Ngoma	Kirehe	Total
2008	51 476	50 490	42 450	33 774	36 068	214 258
2023	73 150	63 050	60 400	46 800	62 400	305 800
Increase	42,1%	24,9%	42,3%	38,6%	73,0%	42,7%
Area within NAKL	51%	72%	84%	4%	44%	-

4.1.4 Land Use and Land Cover Changes in Lower Akagera

The land cover maps produced by the RCMRD in 2010 and 2015 are presented in Figure 11 along with a mosaic of the maps created in GEE and the map produced by the ESA for 2021.

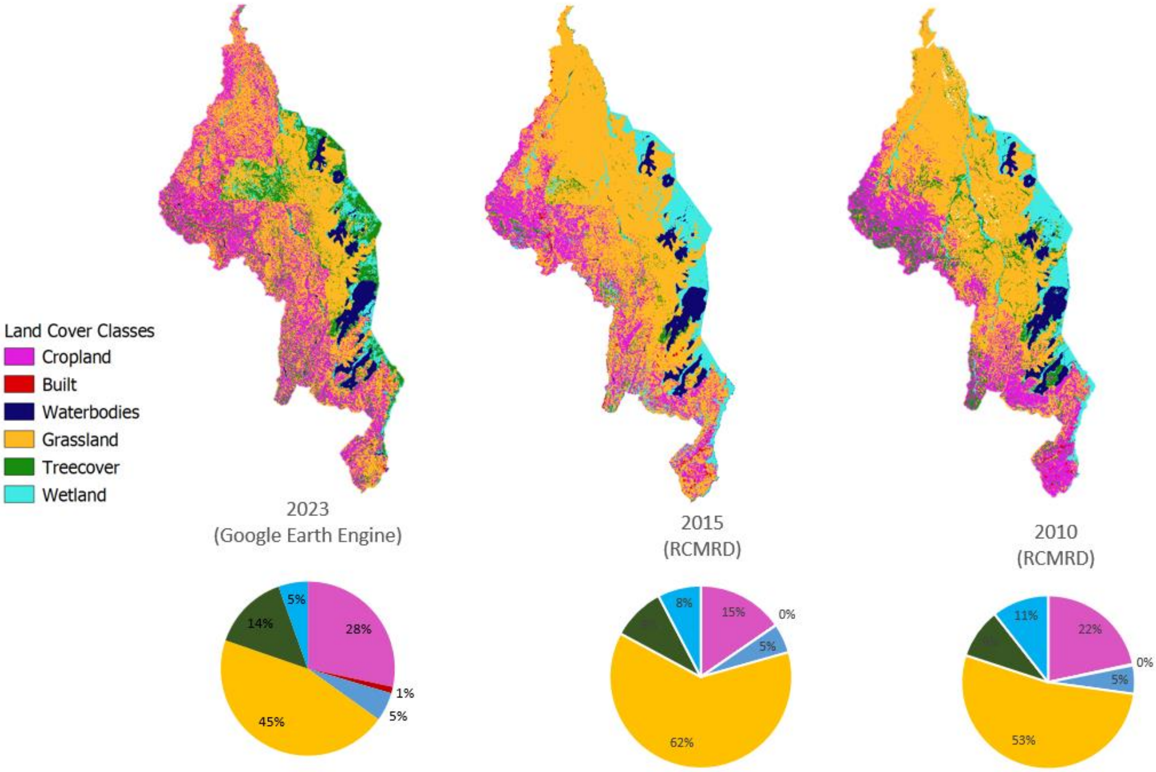

Figure 11 Land use and Land cover in NAKL 2010;2014;2023.

In 2010, the RCMRD estimated the total cropland area to 92 271. During that year, cropland was mainly concentrated in the southern parts of Kirehe and the western regions of Gatsibo. In the northern parts, the land was covered primarily by grassland. However, by 2015, cropland appears to have decreased to approximately 15% compared to 22% in 2010. In the northern parts, grassland still covered most of the land, while cropland seems to have reduced in extent in the southern parts. The most likely reason explaining this is that the RCMRD maps were not created to determine the cropland extent, and these maps rely on less reliable data and serve a different purpose. In the GEE classification, the southern parts of the catchment have a cropland extent similar to 2015, with most of the cropland surrounding the lakes. However, there has been an increase in cropland west of the national park and a notable increase in the northern parts where grassland has turned into cropland. The tree cover has also increased from 9 to 14 percent, which could indicate both an increase in the cultivation of bananas and agroforestry or reforestation.

The total cropland area in 2023 was estimated to be 122 706 hectares, an increase of approximately 30 000 hectares (32%) since 2010. This increase is similar to the overall development in the region, which has seen a increase of 44% according to national statistics.

4.1.5 Comparison between Classification and the SAS

The land cover classification was compared with the reported cropland in the SAS by calculating the relative error, see Table 10 . The classification in Nyagatare was almost similar to the reported area, with a relative error of 0.4%. However, the error ranges from 8-14% in the other districts.

Table 10 Relative error of classification

Districts	GEE 2023	SAS 2023	Relative Error
Nyagatare	73 560	73 300	**0,4%**
Gatsibo	56 868	63 400	**10,3%**
Kayonza	54 897	59 800	**8,2%**
Ngoma	-	47 100	**-**
Kirehe	53 063	61 700	**14,0%**

Several reasons could explain the differences between the land cover classification and the agricultural statistics. No ground validation data were collected to train the land cover classification, resulting in choosing training points based on band combination and a visual interpretation of the land cover. The land cover classification was also performed during the dry season, thus classifying cropland as fallow area. For this reason, irrigated crops were not included due to the differences in the spectral reflectance between fallow land and irrigated crops. Another reason is that in the SAS, the areas covered by bananas are included in the total cultivated area. In the classification performed in Google Earth Engine, bananas were classified as tree cover. As described in section 4.2.1 Crops Cultivated , bananas stand for almost 20% of the cultivated area, which is most likely the main factor explaining the relative error. Additionally, the SAS survey is based on a sampling procedure, and thus has uncertainties itself.

4.1.6 Sufficiency and Irrigation Practices from Field Survey

From the field surveys, it became evident that seasonality influences whether the water availability is adequate for the farmers' needs. Described in Figure 12, 93% percent of the farmers answered that the rain is sufficient for the crops during the rainy season; in contrast, only 20% of the answered that the water availability was adequate during the dry season.

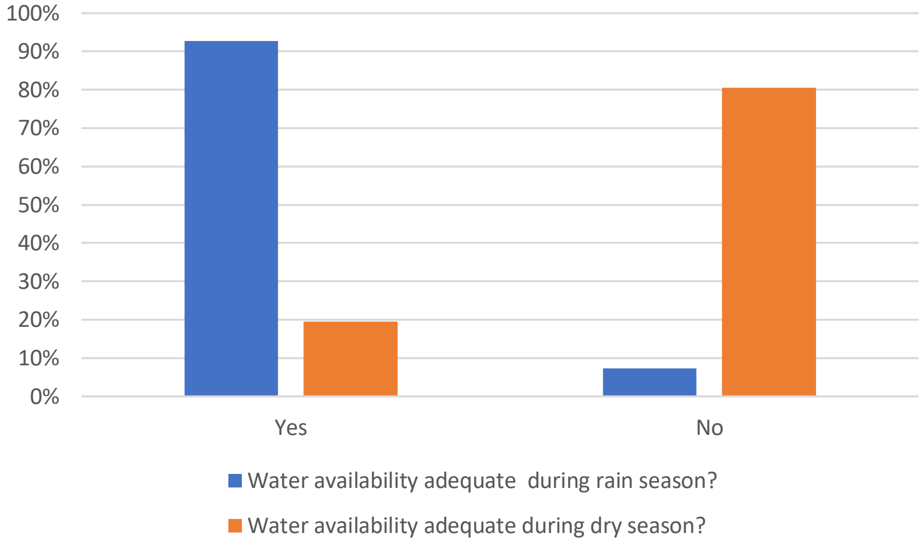

Figure 12 Adequacy based on different season.

During the two rounds of surveying, it was discovered that 61% of the 63 farmers practiced some form of irrigation throughout the year. All of these farmers were either small- or large-scale farmers, and none of the household farmers practiced irrigation. After gaining new insights from the first round, the question was adjusted to include irrigation practices based on different seasons. Out of all the farmers who practiced irrigation during the second round, 73% irrigated during the dry season, while the remaining 27% irrigated all year round.

4.2 Irrigation demand estimations

4.2.1 Crops Cultivated according to the SAS Survey

Figure 13 illustrates the average crops cultivated during each agricultural season according to the SAS from 2019 to 2023. Seasons A and B have a comparable crop pattern, on the other hand, season C is mainly dominated by vegetables, which account for 55% of the total crop area, followed by beans and sweet potatoes. Soybeans have a minimal presence across all seasons.

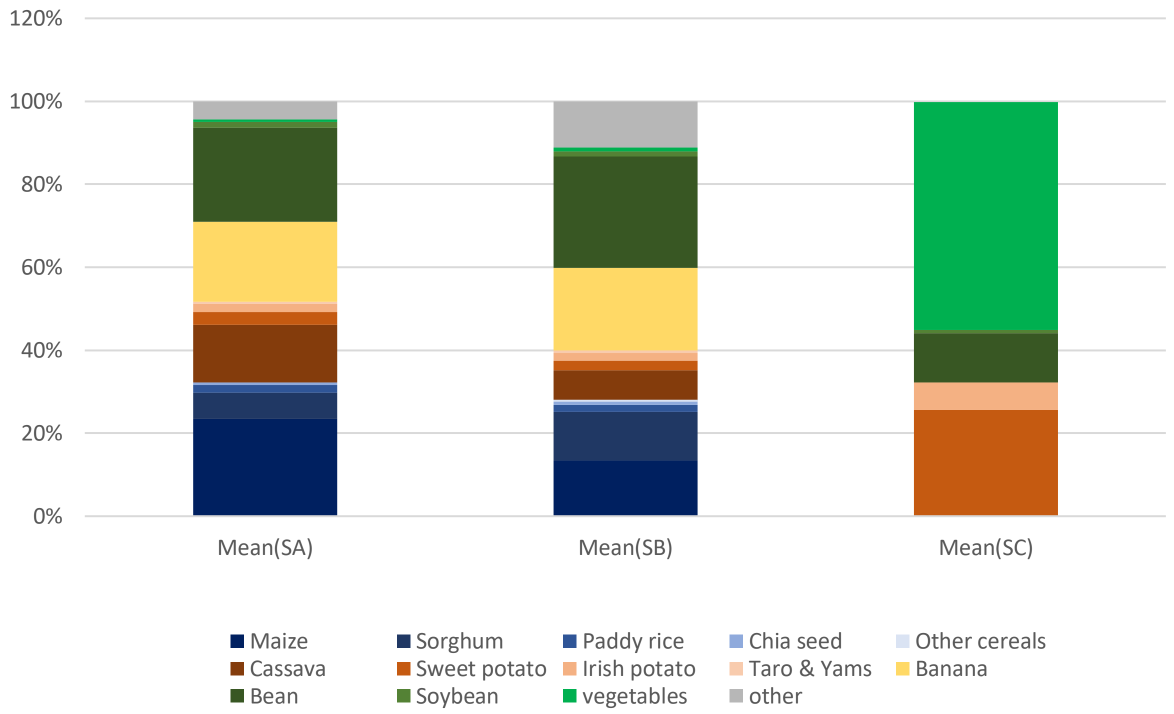

Figure 13 Average crops grown during each agricultural season from 2019 to 2023.

Bananas are only grown in seasons A and B. However, bananas are perennial crops and not under irrigation. Therefore, an adjusted crop distribution was calculated, excluding bananas, sorghum, chia seeds, and the category "other crops" to account only for the irrigated crops see Figure 14.

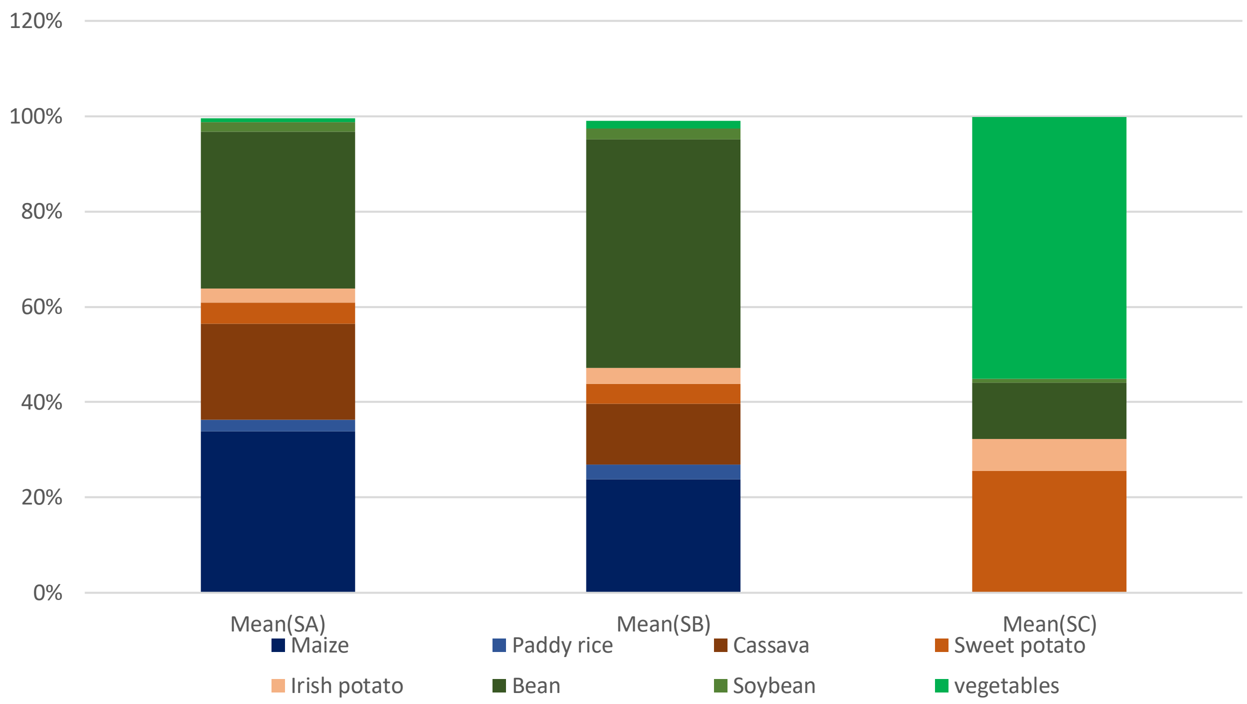

Figure 14 Crop distribution of Irrigated crops during each agricultural season from 2019 to 2023.

4.2.2 Crops Cultivated according to Field Survey

The main crop cultivated by surveyed farmers is maize, accounting for around 80%. The crops used are quite similar between the household and small/large-scale farmers, except for rice and vegetables, which are cultivated more commonly among small/large-scale farmers. This could be explained by the fact that household farmers tend to grow crops for personal consumption, while small and large-scale farmers produce crops that can be sold on the market. The cultivation of beans and soybeans is also slightly higher among small-scale farmers, while household farmers more commonly grow bananas. The field data are presented in Figure 15 below.

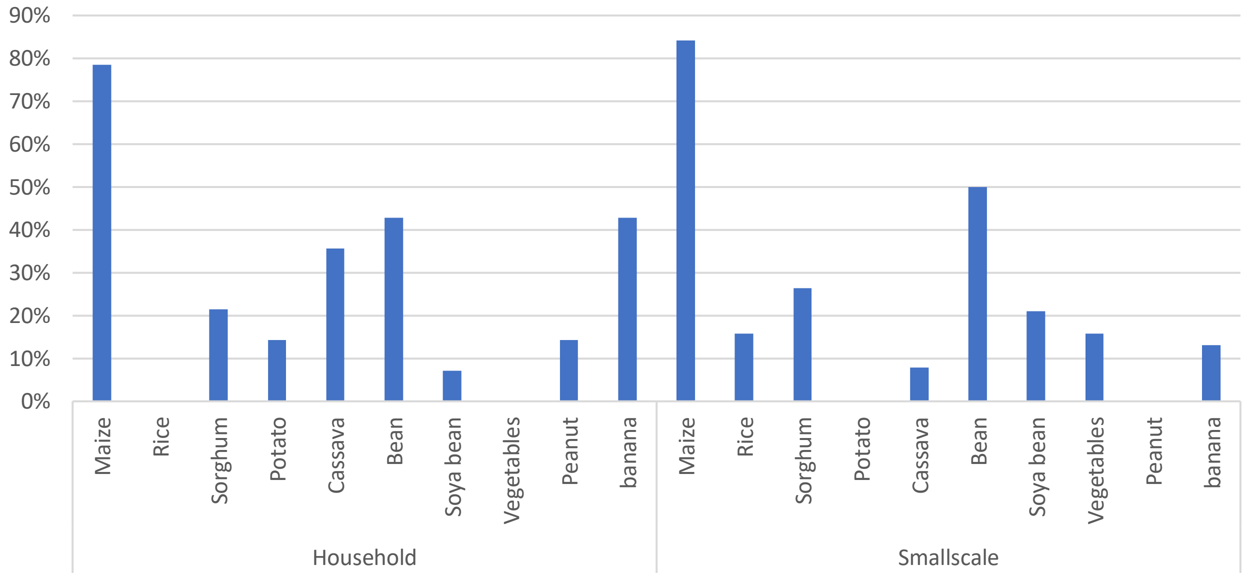

Figure 15 Crops cultivated among surveyed farmers, separated between household farmers and small/large-scale farmers.

4.2.3 Observed Irrigation Method from Field

All farmers, both small and large scale, who practice irrigation were interviewed in marshlands. The irrigation methods reported by these farmers were either watering, surface, or traditional. Figure 16 illustrates the typical irrigation method used in the marshlands, which involves water canals originating from an upstream dam. The water is collected from these canals and later irrigated through a hand pump or cans. Another method observed during the fieldwork was paddy fields used for rice cultivation, as shown in the left Figure.

Figure 16 Canals used for surface irrigation (left) and flooded paddy field used for Rice (right).

4.2.4 Irrigated areas

The dataset received from the RWB and the RAB are shown in Figure 17, where the RWB schemes are depicted by dots and the RAB in orange and yellow areas.

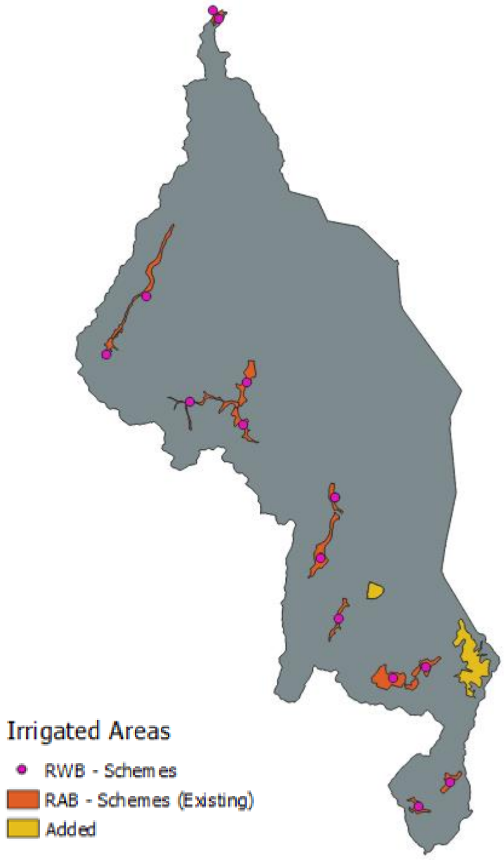

Figure 17 Land allocated for irrigation in NAKL

In the RAB dataset, 14 schemes were identified, while 94 were marked as NULL and 20 were marked as under design. After consulting with experts at the RAB, two schemes, Bramin and Mpanga, highlighted in yellow in Figure 17, were changed from NULL to existing. The RWB dataset included 14 irrigation schemes.

Table 11 presents all registered irrigation schemes, including the areas reported by different sources.

Table 11 Irrigated areas in Lower Akagera.

Name	Type	Area RWB	Area RAB	Litterature	Year	Method	Rice	Source
Kagitumba	Hillside	98	256	500	2015	Modern	No	(MINAGRI, 2014)
Matimba	Hillside	200	75	400	2014	Modern	No	(OAG, 2015)
Rwangingo-Karangazi	Marshland	435	1245	922	2016/ 2017	Surface	Partly	(CDAIS, 2019) (MINAGRI, 2017)
Gatsibo 8	Marshland	45	59	45	2016/ 2017	Surface	No	(MINAGRI, 2017)
Rwagtima Downstream	Marshland	33	923	326	2015/ 2016	Surface	Yes	(MINAGRI, 2016a) (MINAGRI, 2016b)
Gacaca	Marshland	400	582	400	2015/ 2016	Surface	Yes	(MINAGRI, 2016b) (Eco-Excellence, 2012)
Rwagitima-Ntende	Marshland	72	654	608	2010/ 2011	Surface	Yes	(MINAGRI, 2016a) (MINAGRI, 2016b)
Rwinkwavu	Marshland	107	388	462	2018/ 2019	Surface	Yes	(MINAGRI, 2019b) (Nkurunziza, et al., 2022)
Migera	Marshland	60	1272	1233	2015/ 2016	Surface	Yes	(MINAGRI, 2016b) (Nkurunziza, et al., 2022)
Kayonza 4	Marshland	78	414	420	2014/ 2015	Surface	No	(MINAGRI, 2015)
Bramin	Hillside	-	598	500	2013	Pivot	No	(MINAGRI, 2014)
Nasho Phase 2	Hillside	110	1724	1200	2017	Pivot	No	(MINAGRI, 2017) (Water Network Research, 2020)
Nasho Phase 1	Hillside	600	589	600	2013	Sprinkler	No	(MINAGRI, 2013)
Mahama	Marshland	108	442	440	2014/ 2015	Surface	No	(MINAGRI, 2015)
Nyamugali	Marshland	81	334	412	2014/ 2015	Surface	No	(MINAGRI, 2015)
Mpanga	Hillside	-	-	1100	2021	Modern	No	(MIANGRI, 2021)

According to the MINAGRI annual reports, all irrigation schemes in NAKL were introduced between 2010 and 2021 through governmental programs except for Bramin farm, which is a privately-operated farm. Out of the 16 schemes, 7 are hillside that use modern techniques such as pivot, sprinkler, or drip irrigation. For the marshland schemes, it was not possible to find irrigation methods. However, since surface irrigation was reported for some schemes, it was assumed that this method was employed in all schemes, as this was also observed during fieldwork.

There are large differences in reported areas from different sources. The areas according to the RWB is generally lower than the MINAGRI and RAB datasets. However, the RAB dataset matches the reported values except for Matimba, Kagitumba, Rwagtima-downstream, and Nasho phase 2. The area for the Matimba and Kagitumba schemes may differ as they partly are located in the adjacent Muvumba catchment. Additionally, these two schemes, including Nasho Phase 2, are pivot irrigation, which means that the actual irrigated area, depicted in the red circles, is much smaller than the area of the shape file, see example in Figure 18.

Figure 18 Nasho Phase 2 the actual irrigated area shown in circles and the irrigated area according to the shape file from RAB and satellite images from Sentinel-2.

For the Rwagtima downstream, the layer was overlaid over satellite images to confirm its area, and it was found that the actual area was smaller than the shape file. Following the differences in the datasets, the reported value in the MINAGRI reports will be used as the true value for further calculations.

4.2.5 Classification of Irrigated Areas in Season C

In section 4.1.2 found that irrigation was mainly practiced in seasons A and B. Hence, irrigated in season C areas were estimated using Google Earth Engine based on a greenest pixel composite (satellite images with the highest NDVI). Figure 19 shows this classification for Nasho 1 and Nasho 2. The resulting estimate of total irrigated area in season C for all schemes, 916 ha, was found to be much lower than the registered irrigation area of the schemes, indicating that irrigation is mainly practiced during seasons A and B, which are in line with the SAS statistics. Combined with data from Table 11, it could also be found that irrigation was mainly practiced by modern irrigation (650 ha), while the surface irrigated area was 266 ha.

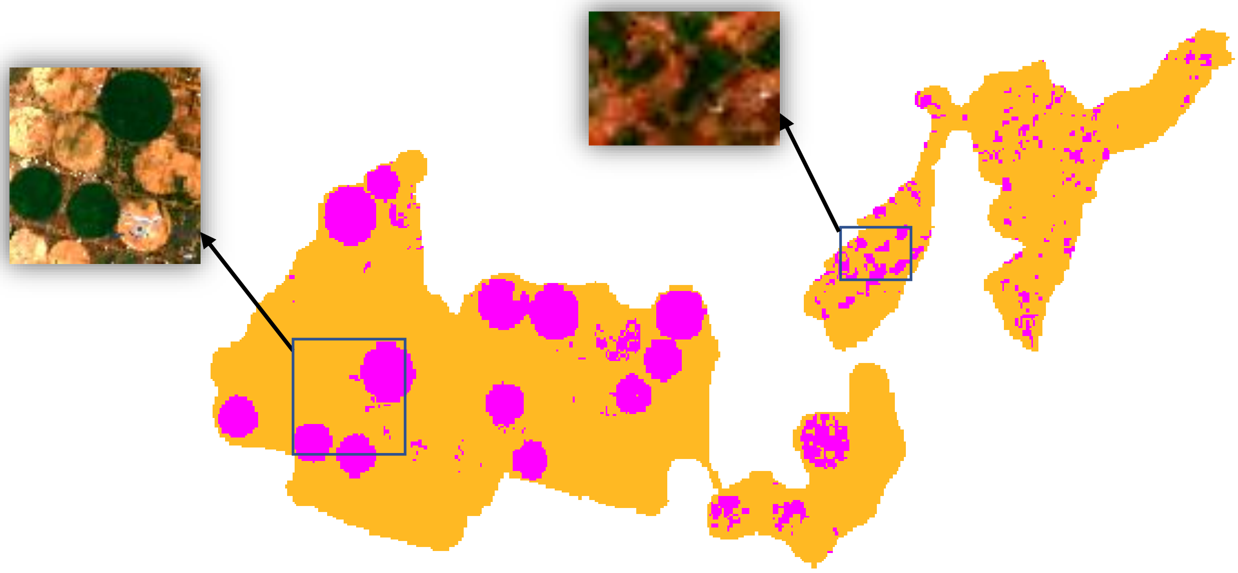

Figure 19 Irrigated land in the Nasho scheme shown in pink, and Fallow areas are in yellow (Season C 2023) from a classification of Sentinel-2 images in GEE.

4.2.6 Classification of Paddy Field

The literature review revealed that the irrigation schemes Rwinkwavu (A) and, Gacaca, Rwagtima (B) are rice fields, while Rwangingo-Karangazi (C) is partly cultivated for rice. A classification was conducted to confirm if the fields (A-B) were paddy and to determine the share of Rwangingo-Karangazi (C) used for rice cultivation, see Figure 20. In (A), a misclassified area was found. However, this area was compared with a high-resolution image from Google Earth (see the right RGB image), which indicated that the area was indeed paddy. Based on the remote sensing results, it was assumed for further calculations that the entire area for all schemes, as reported by MINAGRI according to Table 11, cultivates rice except for Rwangingo-Karangazi, estimated to be 28% paddy.

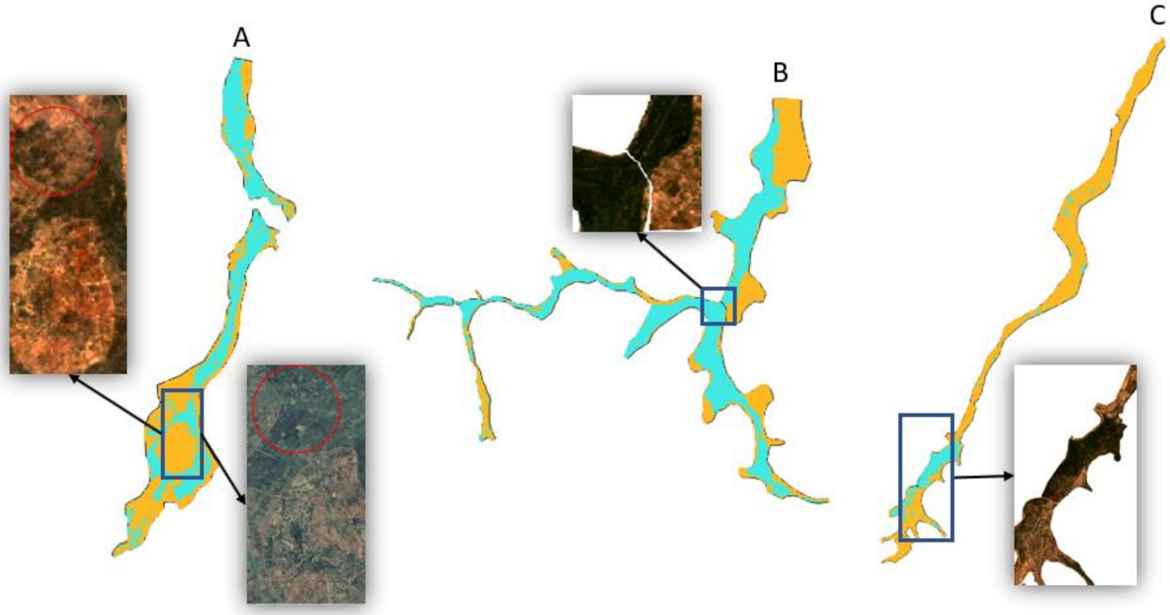

Figure 20 Classification of rice in turquoise compared with RGB images from Sentinel-2 and Google Earth.

4.2.7 Irrigation development in Lower Akagera

Based on the reported areas from the MINAGRI reports, Figure 21 shows the irrigation development in the catchment from 2010 until 2023 including irrigation method for 2023. The total irrigated area today is 9 564, where 20% is irrigated through surface irrigation, 45% uses improved methods, and 35% is allocated for rice.

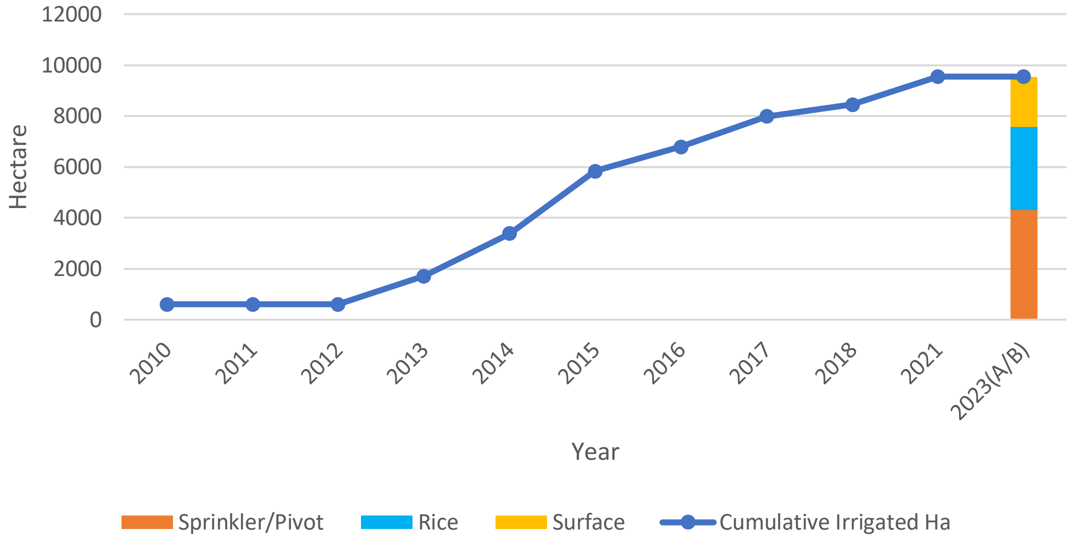

Figure 21 Cumulative irrigated area in NAKL 2010-2023 based on Table 5 and Rice Classification.

4.2.8 Climate data

The interpolated average monthly rainfall for the catchment is presented in Figure 22. The Figure shows a seasonal rainfall pattern, with lower rainfall from June towards August and December to February and a peak rainfall in April for season A and, October and November for season B.

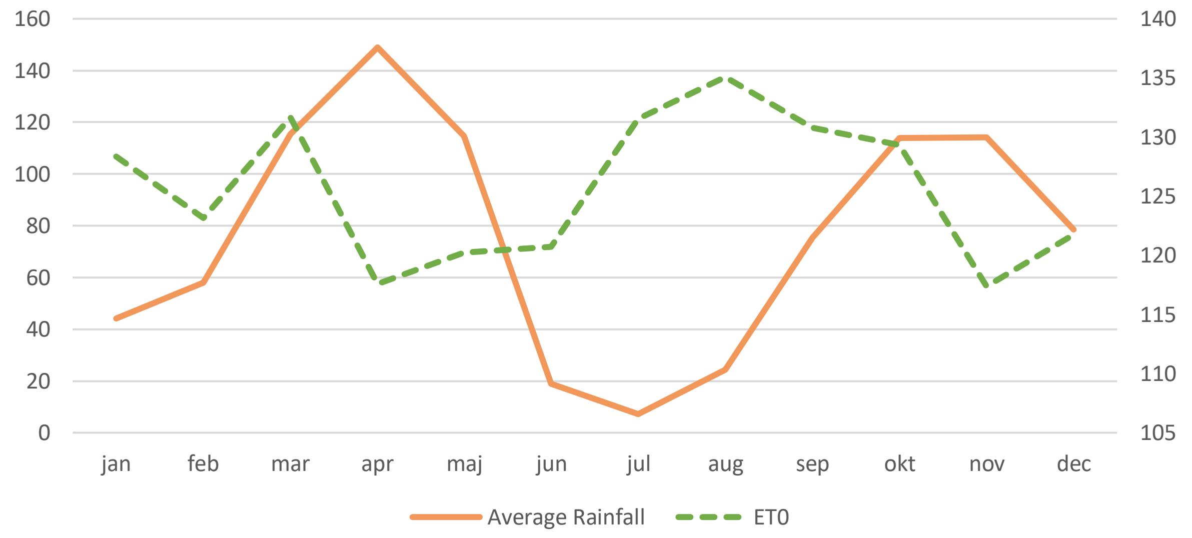

Figure 22 Monthly rainfall and reference evapotranspiration according to AgEra-5 (1981-2021).

In Figure 22, the reference evapotranspiration from AgERA-5 derived from the FAO WaPOR is also depicted. As expected, the ETo is following an inverse seasonal relationship compared to the rainfall, with an increased ETo during the drier months from June to August.

4.2.9 Cropwat Model for Monthly Irrigation Requirements

Based on the field surveys combined with the SAS, it was found that maize, potato, beans, vegetables, and rice are the most commonly grown crops in the area. The Cropwat model was set up for these crops using the monthly climate data and irrigation efficiencies according to the IMP. As previously mentioned, rice estimations require additional data, not collected, which is why the CWRs were extracted from the Irrigation master plan. Figure 23 presents the monthly CWR for the selected crops from the Cropwat model, including irrigation method. The figure shows that maize, potato, and beans grown in seasons A and B, beans in season C, vegetables grown continuously throughout the year, and rice in seasons A and B.

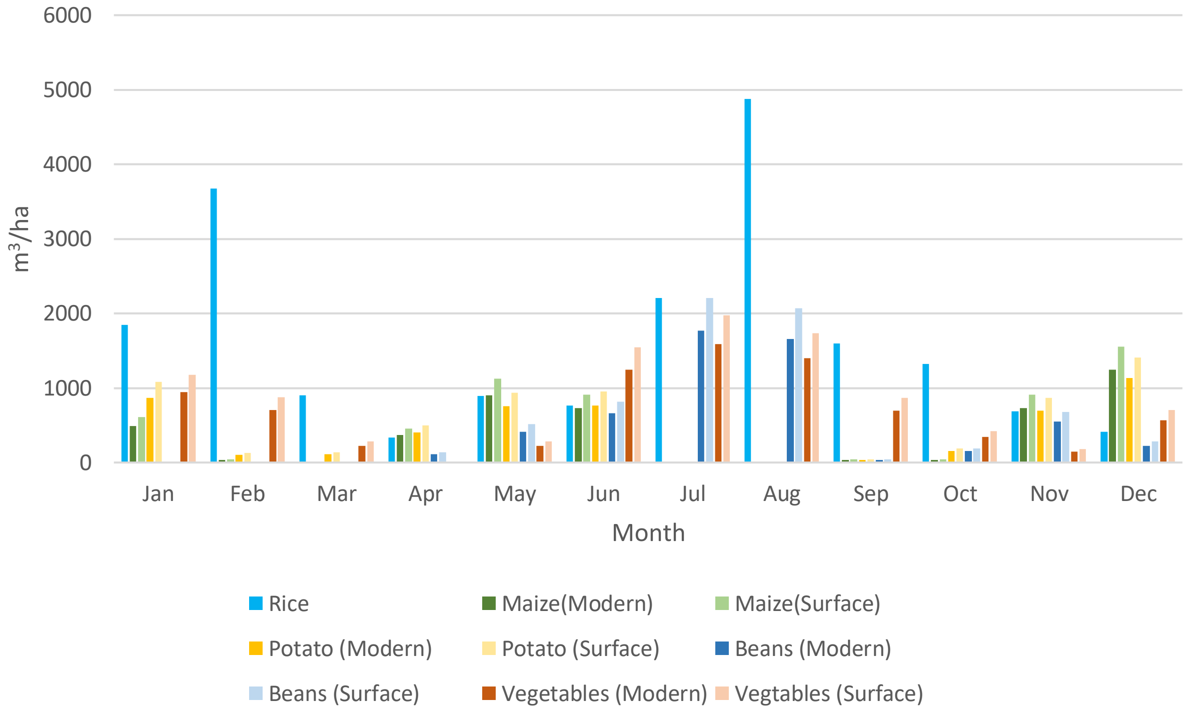

Figure 23 Crop Water Requirements for most common crop cultivated in NAKL.

The annual irrigation demand for the selected crops are summarized in Table 12. Rice is estimated to have around four times higher irrigation demand than the other crops, and seasons A and B have notably high demands for February and July in Figure 23. The high comparative demand for rice is explained by its cultivation method, as it is grown in flooded fields and requires a substantial amount of water. The high extremes before the cultivation of rice are explained by the land preparation, where large amounts of water are lost through percolation from the flooded basins (IMP,2020).

Table 12 Annual irrigation demand of the most common crops grown in NAKL.

Crop	**Annual irrigation demand (m^3/ha/year)**
Rice	19 535
Maize (Modern)	4 576
Maize (Surface)	5 699
Potato (Modern)	5 022
Potato (Surface)	6 256
Beans (Modern)	5 576
Beans (Surface)	6 945
Vegetables (Modern)	8 068
Vegetables (Surface)	10 050

4.2.10 Extrapolation to catchment level of Irrigation water Use

As previously stated, no detailed information regarding crop patterns for the schemes was available. Therefore, in seasons A and B, an evenly distributed crop pattern with 25% maize, 25% potato, 25% beans, and 25% vegetables was assumed for the non-rice schemes. In season C, 50% beans and 50% vegetables were assumed. Using data from Table 13 and Equation 8, the total annual irrigation demand was calculated for the NAKL based on irrigation method, irrigated area and the crops assumed to be cultivated.

Table 13 Irrigated areas, Cropping pattern, and Irrigation Efficiency.

Season	Modern Irrigated area (ha)	Irrigation Efficiency (modern)	Surface irrigated area (ha)	Irrigation Efficiency (surface)	Crop Pattern	Paddy Area (ha)	
A/B	4300	0.71	1968	0.57	25% Maize 25% Potato 25% Beans 25% Vegetables	3278	100% Rice
C	650		266		50% Beans 50% Vegetables	-	-

Equation 8

$$IRQ_{total} = \frac{\left(CWR_{Cropping\ pattern\ (A,B)} * A_{modern\ A,B}\right)}{IRReff_{modern}} +$$

$$\frac{\left(CWR_{Cropping\ pattern\ (A,B)} * A_{Surface\ A,B}\right)}{IRReff_{Surface}} +$$

$$\frac{\left(CWR_{Cropping\ pattern\ (C)} * A_{modern\ C}\right)}{IRReff_{modern}} +$$

$$\frac{\left(CWR_{Cropping\ pattern\ (C)} * A_{Surface\ C}\right)}{IRReff_{surface}} +$$

$$\left(IRQ_{Rice} * A_{Paddy}\right)$$

The total annual irrigation water demand was estimated to be 92 Mm^3. Figure 24 illustrates two distinct peaks in the demand throughout the year, with an increased demand in the dry periods, showing an inverse relationship to the rainfall.

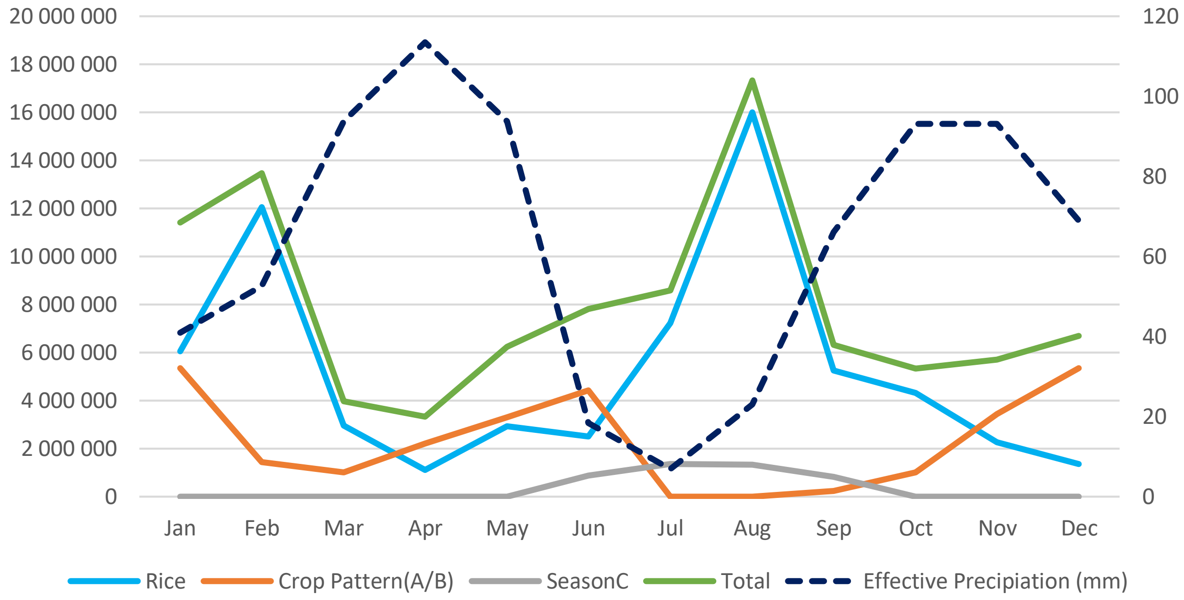

Figure 24 Estimate monthly irrigation demands.

4.3 Domestic Water Demand Estimations

4.3.1 Demographic Data

The total population in the Lower Akagera catchment was estimated to 986 276 people based on the 2022 RPHC, an annual increase of 4.56 percent since the RPHC 2012 survey of 631 721 people (NISR, 2014a; NISR, 2023b). A detailed spatial temporal distribution of the calculated population size is presented in Appendix D .

In 2012, the largest proportion of households relying on improved sources was public tap at 35%, followed by protected wells at 23%, and in-home water at 3%. Of the unimproved sources the main source was river/lake water at 22% followed by unprotected springs at 18%, see Figure 25.

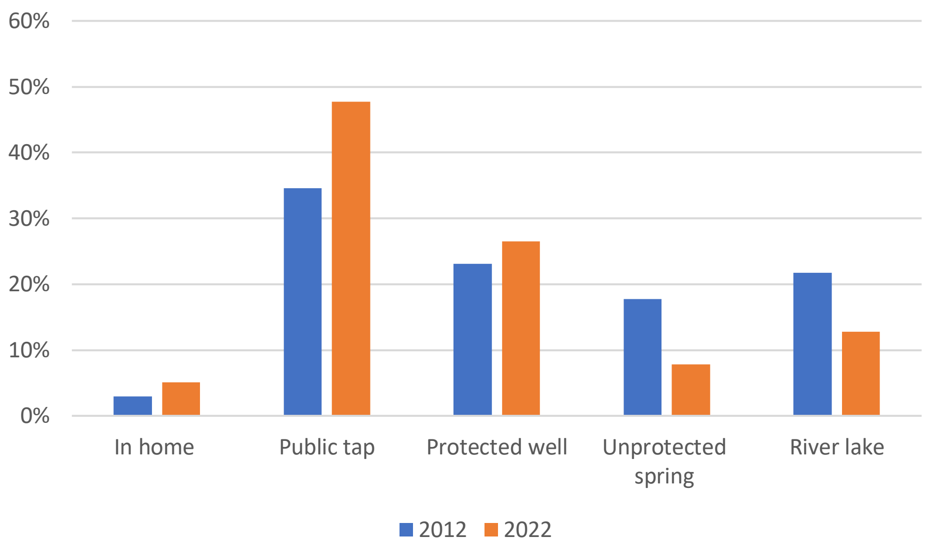

Figure 25 Average source of drinking water across all sectors in NAKL (NISR, 2023c) (NISR, 2014b).

By 2022, an increase in the use of improved sources can be seen with a shift from lake/river and unprotected wells to public taps and protected wells. Public tap water still remained the most common source with an increase to 48% and protected wells to 27%. River and lake water decreased to 13%, while the use of unprotected springs decreased to 8%. There was also an increase in-home water, which increased to 5%. In total, between 2012 and 2022 the share of households in the sectors within the NAKL using improved water sources increased from around 60 to 80 percent.

During the six-year period between the EICV3 and EICV5, the distances to the water source decreased, with an average reduction from 17.4 minutes in 2012 to 11.3 minutes in 2017. In general, there has been a trend towards shorter distances, with an increase for the categories 0-4 minutes and 5-14 minutes, while a reduction of the distances more than 15 minutes, as seen in Figure 26. The average distances to the source of water are presented in Appendix D, which are the values to be used in the extrapolation model.

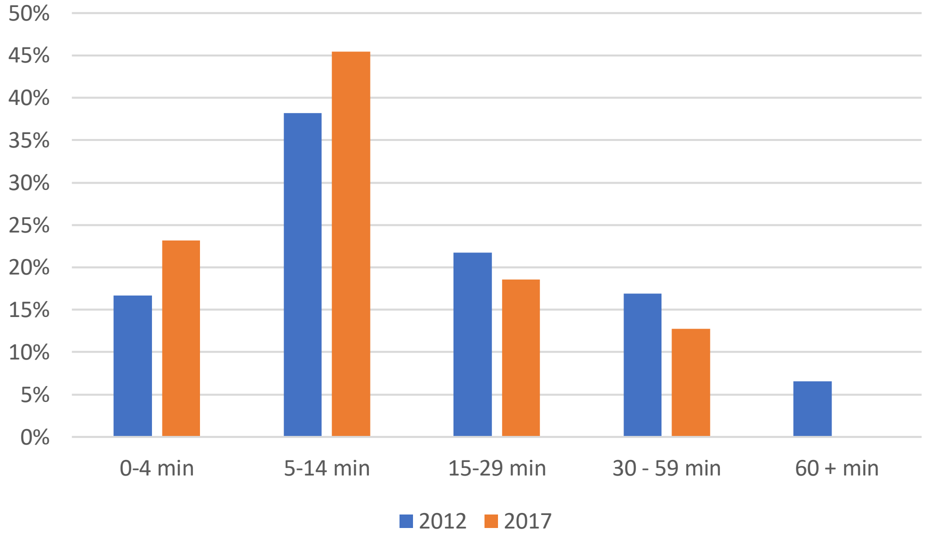

Figure 26 Average distance from home to water point in 2011 and 2017 (NISR, 2012; NISR, 2018).

When comparing the EICV3 with the EICV5 survey in Figure 27, it can be seen that the most common household sizes are those with 2-4 persons, followed by 5-7 persons. From 2011 to 2017, a trend towards smaller household sizes can be seen and the overall average household size has decreased from 4.8 to 4.4 persons. The data extracted from the EICV, used in the extrapolation model is presented in Appendix D.

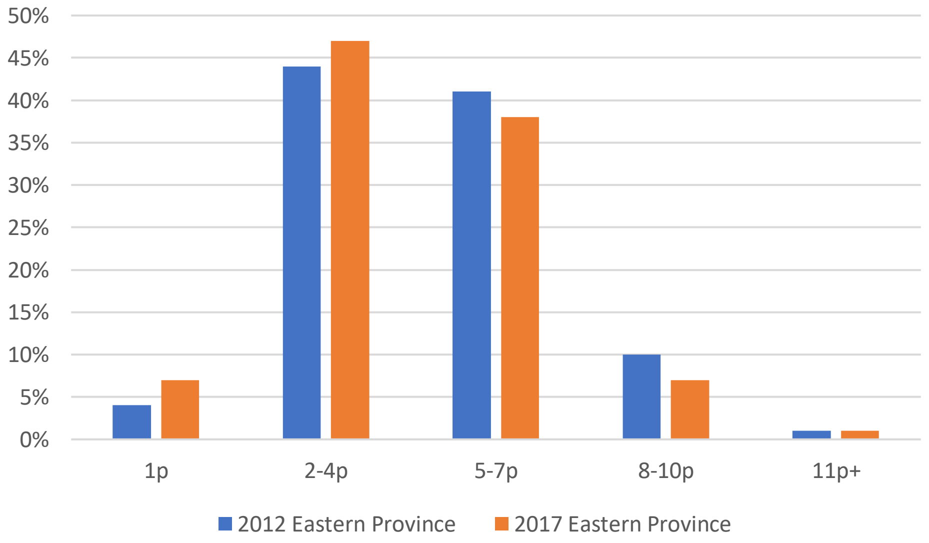

Figure 27 Average Household sizes in Eastern Province 2011 and 2017 (NISR, 2012; NISR, 2018).

4.3.2 Regression Model

The full regression model evaluated all collected variables against the water use to identify those that are significant. Figure 28 displays the scatter plot of all variables and their relation to the per capita water use. The scatter is color-coded according to the source of water. Table 14, shows the output table from the MATLAB-regression.

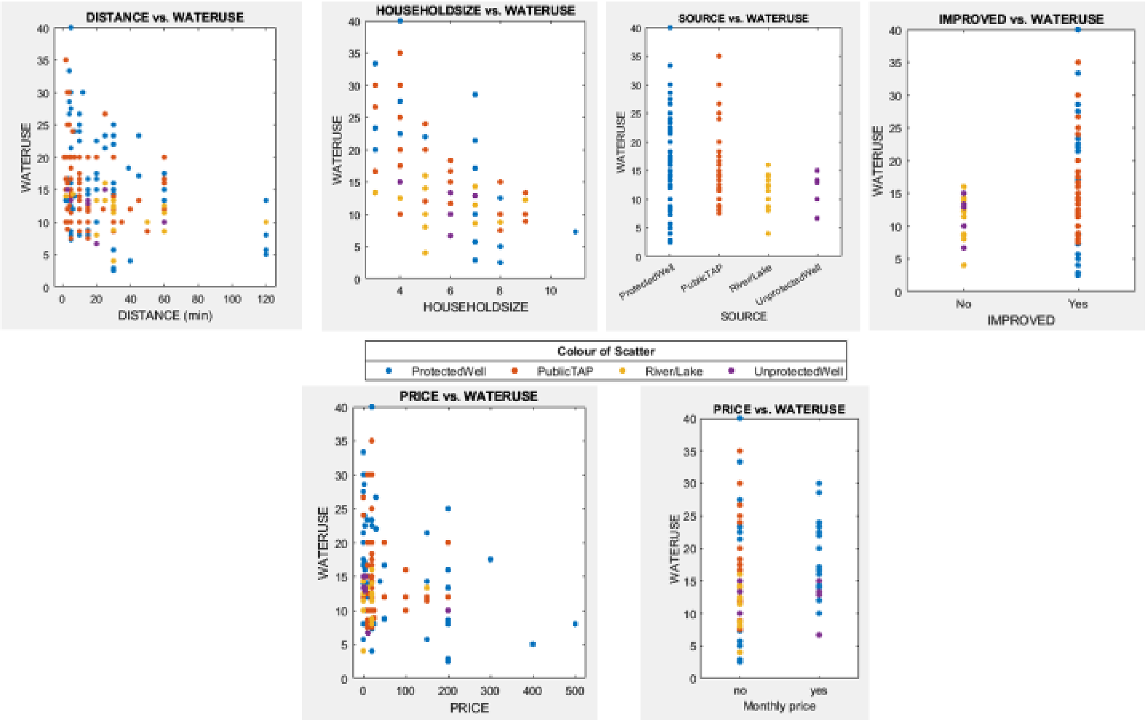

Figure 28 Scatter plot based on the first regression of all variables collected during field.

Table 14 Output from MATLAB (Full regression model).

Variable	Estimate	SE	tStat	pValue
(Intercept)	23.429	2.3445	9.9928	2.1583e-19
DISTANCE	-0.046044	0.017445	-2.6394	0.0089479
HOUSEHOLDSIZE	-1.9962	0.23105	-8.6396	1.6382e-15
SOURCE_PublicTAP	-1.0374	0.79658	-1.3024	0.19427
SOURCE_River/Lake	1.5766	2.2936	0.68741	0.49261
IMPROVED_Yes	3.9739	1.9452	2.043	0.042343
PRICE	-0.0063436	0.0058041	-1.093	0.2757
MonthlyPrice_yes	2.0123	1.1176	1.8006	0.073248

Both the distances and household sizes were highly significant. The negative relationship between distance and water use aligns with the expectation that longer distances may decrease water use due to the increased effort required to transport it. From the scatterplot, it can be seen that public tap is most common for shorter distances of 0-10 min, while unprotected wells are generally further away from households home. Household sizes are also negatively correlated with per capita water use. It should be noted that field data was only collected for households with 3 to 9 persons, with only one survey for households of 11 people. This creates uncertainty in the data, particularly the upper limit of 9+ and lower limit of 3-. No clear relationship between the source of water and household size can be seen.

The source of drinking water among households also has a significant impact on water use, with a notable decrease in water use for unimproved sources such as rivers/lakes and unprotected wells. There is a large variation for protected wells upper limit of 40 l/cap/day to the lower limit of 3 l/cap/day. Most surveys conducted were from improved sources, with protected wells standing for 46% and public taps for 42%, while rivers/lakes 7% and unprotected wells only 3%. Following the large sample size of protected wells, this category may capture more additional factors not included in the model. Comparing the scatter plot of source with household size and distance, it can be seen that the lowest water use for protected wells corresponds to households with large household sizes and long distances, as shown in Figure 29.

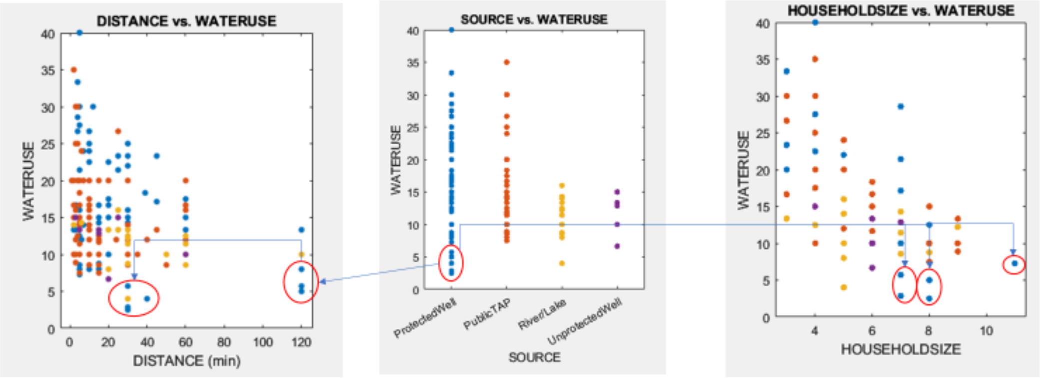

Figure 29 Factors possibly explaining the lowest water uses for households using protected wells.

Lastly, price, and water use showed no clear relationship. However, 30 of the households surveyed paid a fixed monthly price for water, which was then recalculated to price per can, based on stated monthly number of cans, to allow for a comparison with the other households. As a result, an additional variable was introduced to compare the households paying per can with those paying a monthly price. The relationship showed a slightly higher per capita use for households paying a monthly price than those paying per can.

4.3.3 Extrapolation model to catchment level

The variables with statistically significant correlations to water use – Household Size, Distance, and Source – were selected to train a regression model to estimate water use in the whole catchment, through extrapolation with data from the EICV survey. To match the data in the EICV survey, the selected variables were assigned as categorical variables, see Figure 30.

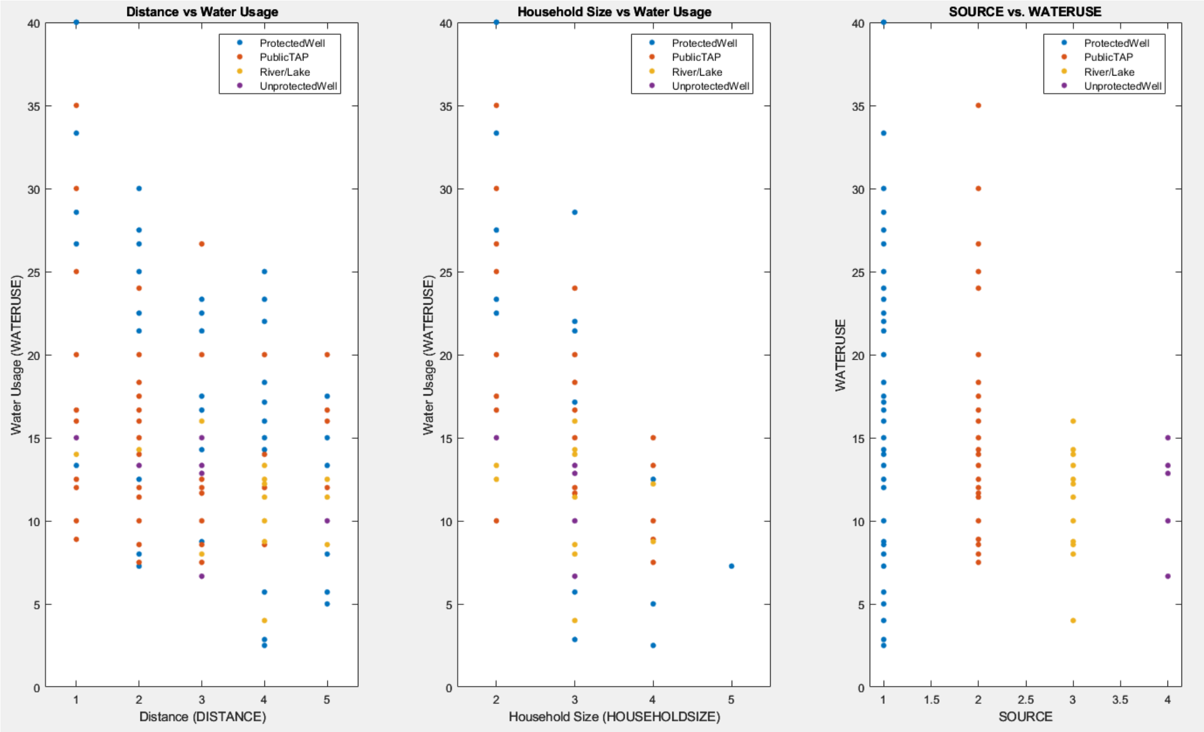

Figure 30 Scatter plot of the selected variables in the Extrapolation Model.

All included variables in the extrapolation model had high statistical significance, and the model had an R^2 value of 40% and an adjusted R^2 of 37.5%, as shown in Table 15.

Table 15 Model output for the Extrapolation model

Variable	Estimate	SE	tStat	pValue
Intercept	23.344	0.94692	24.652	8.0913e-63
DISTANCE_2	-2.331	1.0035	-2.3229	0.021178
DISTANCE_3	-4.1726	1.0914	-3.8232	0.00017544
DISTANCE_4	-4.4446	1.1379	-3.906	0.00012791
DISTANCE_5	-5.0485	1.3368	-3.7765	0.00020917
Public TAP	-1.5738	0.71208	-2.2101	0.028219
River/Lake	-2.4656	1.2241	-2.0142	0.045312
Unprotected Well	-3.4511	1.8803	-1.8354	0.067912
HOUSEHOLDSIZE_3	-5.7975	0.75194	-7.71	5.6044e-13
HOUSEHOLDSIZE_4	-9.0626	1.3421	-6.7524	1.5123e-10
HOUSEHOLDSIZE_5	-13.74	4.8196	-2.8508	0.004813

In the model, the intercept value of 23.3 is based on households using protected wells with a distance of 1 and a household size of 1. Note that the p-value for the unprotected well exceeds the significance threshold of 5%. However, this variable was kept in the final model to account for its potential impact.

4.3.4 Estimated Domestic Water Use

From the MLR model, a baseline value of l/cap/day using the NISR statistics for each sector within the catchment was estimated. The value for 2012 is depicted in blue in , and the orange line represents the per capita value for 2022. However, in field, only limited data was collected on piped water. Therefore, in the extrapolation, the reference value of urban water demand (70l/cap/day) according to the NWRMP was used for this category. The share of households using piped water is presented in colons in Figure 31.

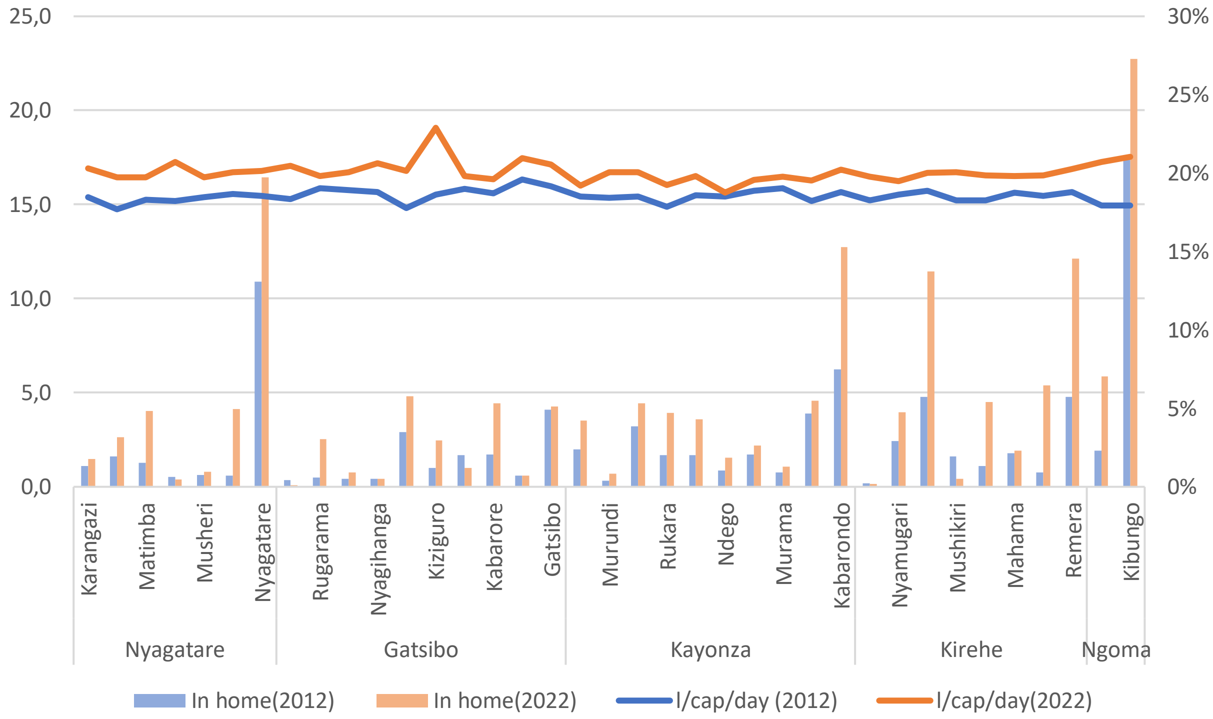

Figure 31 Estimated water use/capita according to the model and share of household using In home water.

In the past decade, changes in household sizes, distances, and source of drinking water have increased water consumption, ranging from 0.2 to 3.6 liters per person per day. On average, there has been an increase of 1.3 liters per person per day. Additionally, there has been an increase in the percentage of households using piped water, ranging from 0 to 10%, with an average increase of 2.2% across all sectors. The demographic data, previously presented in section 0, was extrapolated for the entire catchment using the Equation 9.

Equation 9

$$Water\ use = (\ 23.152 + \left(D_{(5-15)} * EICV_{Distance(5-15)} + \cdots + \ D_{(60+)} * EICV_{Distance(60+)}\right) + \left(HH_{(1)} * EICV_{HH(1)} + \cdots + \ HH_{(11+)} * \ EICV_{HH(11+)}\right) + \left(Source_{(Public\ tap)} * RPHC_{Public\ tap} + \cdots + \ Source_{(Unprotected\ well)} * RPHC_{(Unprotected\ well)}\right)$$

The annual domestic water use in the Lower Akagera was estimated to 7,7 Mm^3 in 2022, which is a total increase of 2.6 Mm^3 from 2012. In Figure 32, the annual water use per sector in the Lower Akagera is presented for 2012 and 2022.

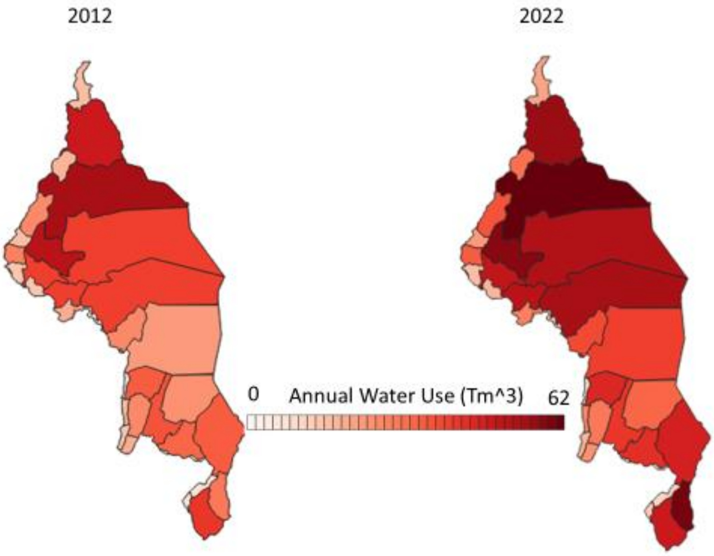

Figure 32 Estimated annual domestic water demand in NAKL for 2012 and 2022.

4.4 Changes in Water use and Limiting factors

As the extrapolation model can explain 40% of the variation in stated water use, there are other factors affecting household water use that were not included in the model. During the field surveys, households were asked why the water was not adequate and the main limiting factor. Figure 33 shows the percentage of households that stated "Yes" and "No" for the most commonly identified limiting factors.

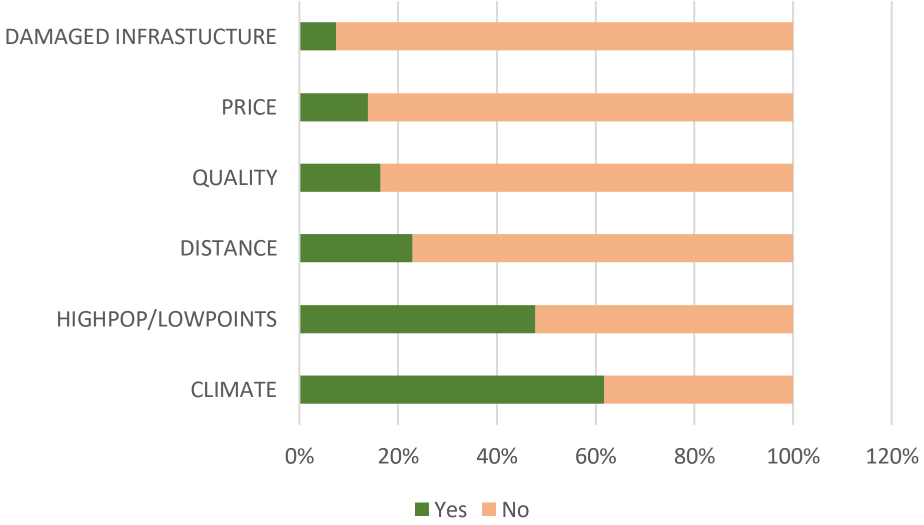

Figure 33 Experienced limiting factor among 187 surveyed households.

Based on these results, it can be concluded that factors related to climate are major limiting factors. Figure 34 shows the share of households stating factors related to availability as the main limiting factor, based from households saying either climate, high pop, or damaged infrastructure. In total, 82% of the surveyed households experienced factors related to water availability as a limiting factor.

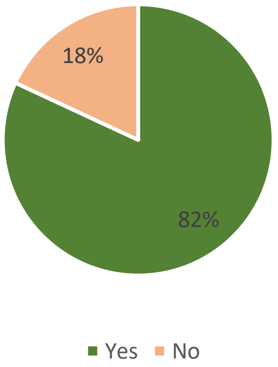

Figure 34 Availability as a limiting factor related to water use.

4.4.1 Recent changes to water availability

No quantitative data on water use and availability over the years was collected. Instead, qualitative interviews were conducted to understand the development. These surveys focused on addressing the following questions:

- Have you noticed any changes in water availability and use over the recent years?
- Have there been any changes to the source your household relies on in the past years? If a Change, how have these changes affected the water use?

The responses to this question varied depending on the location of the survey. Some areas experienced increased water availability, while others experienced a decrease. Climate variability and prolonged droughts are believed to have reduced the overall availability in many areas, although the largest variations are interannual following the different seasons. This is discussed in more detail in the section *4.4.2*.

The factors that increased water availability included the construction of new boreholes, public taps, dams, and infrastructure developments like electric pumps and increased storage capacity. However, in some areas, insufficient maintenance and management have led to damaged boreholes and pipelines, making the water sources less reliable. Another reason for reduced availability is the increase in population, where more people now rely on the same sources.

It can be concluded that there has been a change in the sources of water used by households in the area, which are in line with the findings in the RPHC surveys. In some areas, boreholes and public taps have been introduced, and total number of boreholes and taps have been increased. There has also been a shift from using surface water, such as dams, streams, and swamps, to improved sources, like protected wells and public taps. The observed changes in water use following the shift in sources, aligns with the MLR model, with increased water use for improved sources. The water source itself can partly explain the increased use related to introducing new and improved sources. However, it can also be explained by the other limiting factors described in the previous section 0, like better quality or a decrease in distance, as the new sources are often introduced closer to people's homes. Additionally, new sources also increase the number of water points per capita, accounting for the high population factor.

Out of the 213 households surveyed, only 19% responded that the water availability is adequate for their needs. In contrast, 81% of households experience water scarcity, where the demand is higher than their use. Figure 35 shows box plots of water use in blue and demand in orange. The average water demand calculated is 28 liters per capita per day, which is almost twice the average water use value. The water demand shows large variations, ranging from a lower limit of 11 to an upper limit of 80 liters per capita per day. As discussed in the Terminology section, water demand is defined as the perceived amount of water needed. Therefore, the large variations in demand could be explained by the fact that the perceived amount of water needed is higher for those already having a larger water use, while for households with already low water use, what is considered adequate is much lower. The estimated water demand is much lower than the national reference value of 60l/cap/day in 2020, which is projected from an value of 40 l/cap/day in 2012 (NWRMP, 2015).

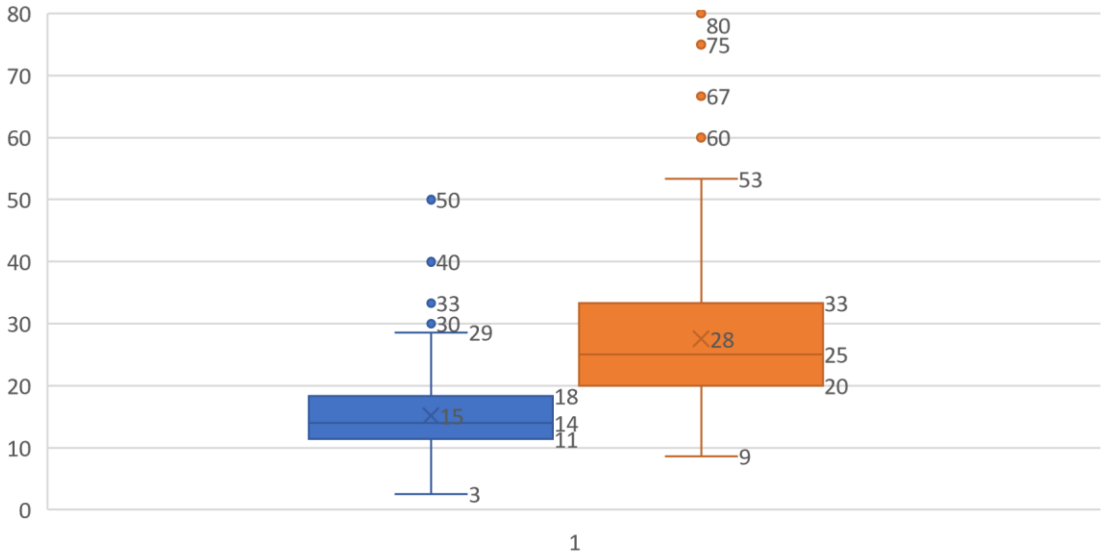

Figure 35 Water Use vs Water Demand.

4.4.2 Seasonal Variations in Water Use

During the second round, water use during the dry and rainy season was added. This question focused on the water fetched at the main water point. In Figure 36, the water use in the dry season is shown in blue colons, where the difference between the dry and rainy seasons is shown in red. The weighted annual average is shown in the dashed green line.

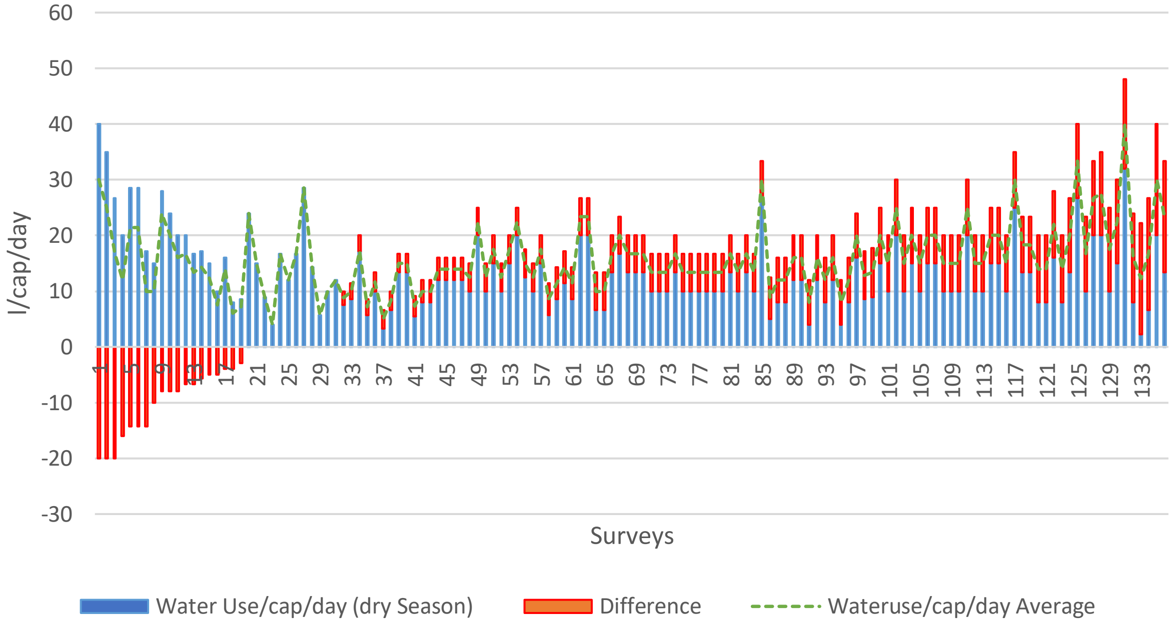

Figure 36 Water Use based on different seasons from field Round 2.

It can be observed that in most cases, there is an increase in overall water use during the rainy season, with a positive difference, se observations 33 to 135. However, there is a negative trend in observations 1 to 19, with a decrease during the rainy season. To better understand the seasonal impact on water, use and availability, qualitative surveys were conducted which aimed to answer the question:

- *Do you experience variation in water availability and use based on different seasons?*

Out of all surveys conducted, all respondents experienced changes in the water availability and use based on different seasons. During the rainy season, water availability increases, resulting to an increase in daily water use. Some households have reported that water availability increases in the rainy season due to rainwater harvesting while others stated that the availability in wells and taps increases, resulting in sufficient water supply throughout the day with fewer disruptions. On the other hand, during the dry season, wells often run dry, and public taps face disruptions with long periods without water. Additionally, the source of water can vary between seasons. For example, in the dry season, some people rely on other sources, often unimproved, and have to walk longer distances to fetch the water.

Below are some selected interviews from the field:

- “*Yes, in the rainy season we practice rain harvesting. This makes the availability higher and the water use is increasing* “
- *“During the rainy season water is available and we use 7 jerrycan per day. But during the dry season water is don’t get enough and we use 4”*
- *“In dry season water is not enough but in rainy season water is available and consumption is on higher level like 5 Jerry Cans per day compared to dry season of 3 jerrycans”*
- *“In the rain season, we can collect rainwater and use it for different activities. This reduces the number of jerry cans we have to fetch or buy from the water point. In the dry season we get all the water we need form the water points. However, due to budget issues/ price, we do not get much water. We can buy about 3“*
- *“In dry season Water is not enough but in rainy season water is available and we use to fetch more water because is available for a whole day”*
- *“During the rainy season water availability increases and it reduces walking longer distances to the water point. But in the dry season water decreases at a high level”*
- *“During the rainy seasons water availability increases while in dry season water decreases at high levels with a conflicts between neighbors”*

5. Discussion and Recommendations

5.1 Evaluation of the Results

5.1.1 Evaluation of Agriculture Results

The Cropwat model is based upon several assumptions and relies on limited data. The model results should therefore be taken as an indication. First, the meteorological data used for estimating crop water requirements as discussed are generalized for the entire catchment based on 12 rainfall stations. The rainfall data analysis showed that the northern parts of the catchment had more outliers, indicating greater rainfall towards these areas. Furthermore, the ET_0 data from the WAPOR and local climate stations were not cross-validated and the WAPOR data were therefore used without knowing their accuracy. To improve the meteorological estimations, a grid-based approach should be considered to account for the spatial variability in climate throughout the catchment.

The estimation of total irrigation demand is based on various assumptions related to total irrigated land. Firstly, the total share of land allocated for irrigation is uncertain. According to MINAGRI reports, the estimated irrigated area in the catchment was 9 564 hectares, which is similar to the total irrigated area reported in the IMP of 9 254 hectares (RAB, 2020). Additionally, the WUA categorizes irrigation schemes in Rwanda as Large Scale and Small Scale. Looking at the reported areas for the schemes in the datasets, it is evident that all areas exceed 10 hectares, meaning that small-scale irrigation may not have been included in these reports. During the field visits, surveys were conducted in locations where irrigation was observed. However, one of these areas visited was not found in any of the datasets, meaning that additional areas, not included in the data sets, may be allocated for irrigation.

Another limitation is that the NISR data related to agriculture does not align with the catchment's boundaries, as the resolution is given on a district level. However, if statistics were provided at a sectoral, catchment, or scheme level, it could provide valuable information for estimating water demand and use, improving water productivity, irrigation management, and agriculture monitoring.

Irrigation requirements vary depending on the type crops being cultivated, and since no scheme-specific data were available, the cropping patterns needed to be assumed. Therefore, detailed information on cropping patterns and other scheme-specific data is necessary to provide accurate estimations.

Lastly, the irrigation requirements are based on the demand, not use. The Cropwat model assumes water availability to be adequate throughout the entire season, however, during the field visit, it became evident that water availability varies between seasons and that the availability is rarely adequate. Thus, the actual water use is most likely lower than the model estimate.

5.1.2 Evaluation of Domestic Results

Similar to the irrigation estimates, the domestic extrapolation model also has limitations. Though the model in itself is not fully representative, the estimated water use was based on a large sample size where the estimated baseline values in section 1.1 reflect the reality, at least for the sources and conditions included in the model. The key limitation related to the extrapolation is the uncertainty of urban households and in-home water uses, since no field data was collected for this category. Therefore, the model is more reliable for the population with similar conditions as the ones included in the model.

In addition, the extrapolation was based on data that did not align with the catchment boundaries. The primary determinant of water use is population size, which was estimated by combining demographic statistics with a population density layer. While this method is more accurate than calculating population size based on only contributing area, it does not provide a true representation of reality. Additionally, the domestic water model assumed that the water sources were homogenous within all sectors, which adds uncertainty, especially in sectors with low contributing areas or with urban centers outside the catchment. For example, in the Nyagatare sector, it was assumed that 23% of the sector used piped water, even though the urban area is located outside the catchment.

Another limitation related to the statistics is that all distances were only provided for improved sources, whereas the model assumed that these distances also applied to the unimproved sources. However, during the field visit, it became evident that improved sources often are located closer to people's homes, meaning that the distances for the unimproved sources could potentially be further away from people's homes, a factor the model did not account for.

The field visit took place in September, at the end of the dry season, when the water availability is at its lowest. The effects of conducting surveys during this time of the year should be considered when evaluating the results, especially for the surveys conducted in the first round. During this round, seasonal factors were not considered, meaning that the reported water use likely reflects the current use at the time of the survey rather than the daily average throughout the year. When questions about seasonal variations were introduced for the second round, the surveys revealed that the use varies depending on the season, with a general increase during the rainy season. This means that the reported use from the first round may have been underestimated, potentially impacting the MLR-model.

5.2 Drivers and Risks of Water Use

Through various governmental programs, the Rwandan government has invested in agriculture to expand irrigated areas over the past decade. In the Lower Akagera, the total irrigated area has grown, increasing from 608 hectares in 2010 to 9 564 hectares by 2023. This expansion of irrigated areas has led to an increase in irrigation demand. However, no temporal extrapolation was made to quantify the increase over the same period. This was because data for ten years back were scarce, making reliable estimations challenging.

The cropping patterns within the schemes also play a role in driving irrigation demand. For instance, rice had approximately four times higher irrigation demand than other crops. The Rwinakwu scheme, developed for rice irrigation in 2014/2015, was previously used by residents grazing and growing other crops (Nkurunziza, et al., 2022). Shifting this area to paddy fields has increased water use remarkably. Additionally, the irrigation method employed within the schemes also impacts irrigation demand. According to the NISR statistics, there has been a trend toward improved irrigation efficiency in the region in recent years, indicating a shift toward less water-demanding methods. However, many schemes in the NAKL still rely on high-demanding methods, such as surface irrigation, which are less effective.

The Lower Akagera has witnessed a remarkable increase in cropland over the past decade, especially in the northern parts, which has increased the water demand in the region. Therefore, the impacts of cropland expansion on the hydrological cycle should be further investigated. During the field visit, it was found that only 20% of the interviewed farmers believed that water availability was sufficient for their agricultural needs and that the availability plays a key role in agriculture productivity, especially during season C. Moreover, the vulnerability to climate variability and droughts is altered following the large increase in cropland.

The main driving factor for domestic water use is the increase in population. Over the past decade, the population in the Lower Akagera has had an annual growth rate of 4.56%. Following reduced distances and household sizes, the per capita water use in the Lower Akagera catchment has also increased over the same period, ranging from 0.2 to 3.6 l/cap/day. Furthermore, a trend towards improved water sources was observed, with a shift towards improved sources, resulting in increased water use. However, the regression model for domestic water use only explained 40% of the variability in water use, meaning that there are other important factors determining the per capita water use.

The field surveys revealed that nearly 80% of the households mentioned factors related to water availability as the main limiting factor for water use. Though there has been a shift towards improved water supply, other factors have emerged in the region that limit water use. The increase in population has put pressure on the existing water supplies, leading to inadequacy because too many people rely on the same sources. Exacerbated by maintenance issues, this has also reduced the availability, constraining water use and forcing households to use other sources. Additionally, climate factors were identified as a major factor related to water availability, where it was found that seasonality influences the household's water use, with a generally lower water use during the dry season. Many households also reported reduced water availability over recent years due to climate variabilities or prolonged droughts. The effect of climate variability should therefore be investigated further.

The main future risks associated with domestic water supply in Lower Akagera are most likely related to water availability. As the population continues to grow, the demand for the already strained water supply system will increase. Combined with the ongoing maintenance issues and the potential impacts of climate change, the Lower Akagera will likely face continued water availability challenges.

6. Conclusions

This thesis aimed to estimate water use and demand in the Lower Akagera catchment in Rwanda, focusing on the agriculture and domestic sectors to develop methods for estimating water use and demand. Through this approach, a complex interplay of different factors was identified, affecting water use. The results revealed that the agricultural demand is mainly influenced by agricultural expansion, irrigation development, and climate factors. Scheme-specific data on irrigation methods and cultivated crops also play a role in the total irrigation demand through irrigation efficiencies and related crop water requirements. Additionally, the total cropland in the region has shown a notable increase over the past decade, altering the region's vulnerability to climate variabilities. Based on the regression model, improved water sources, shorter distances, and reduced household sizes have resulted in increased daily water use among households. While the model only explained 40% of the variability in water use, the field data identified factors related to water availability as the main factor constraining water use.

Estimating agricultural water demand via the KcETo approach in Cropwat is an effective method to estimate irrigation requirements. However, this model can be refined using more scheme-specific and detailed agro-climatic data. Furthermore, the impact of water availability must be accounted for, to estimate the actual irrigation water use accurately. Using the regression model for domestic water use estimates was satisfactory. National statistics allowed the model to be spatially and temporally extrapolated for the entire catchment. However, this model can be further refined to include additional variables and consider interannual variations. The insights from the field surveys on limiting factors, indicated that incorporating factors like price, quality, and availability could improve the model's accuracy. Additionally, the model should be trained with a larger sample of unimproved sources and piped water to be more comprehensive, and the regression model accuracy should be validated against national data from water service providers.

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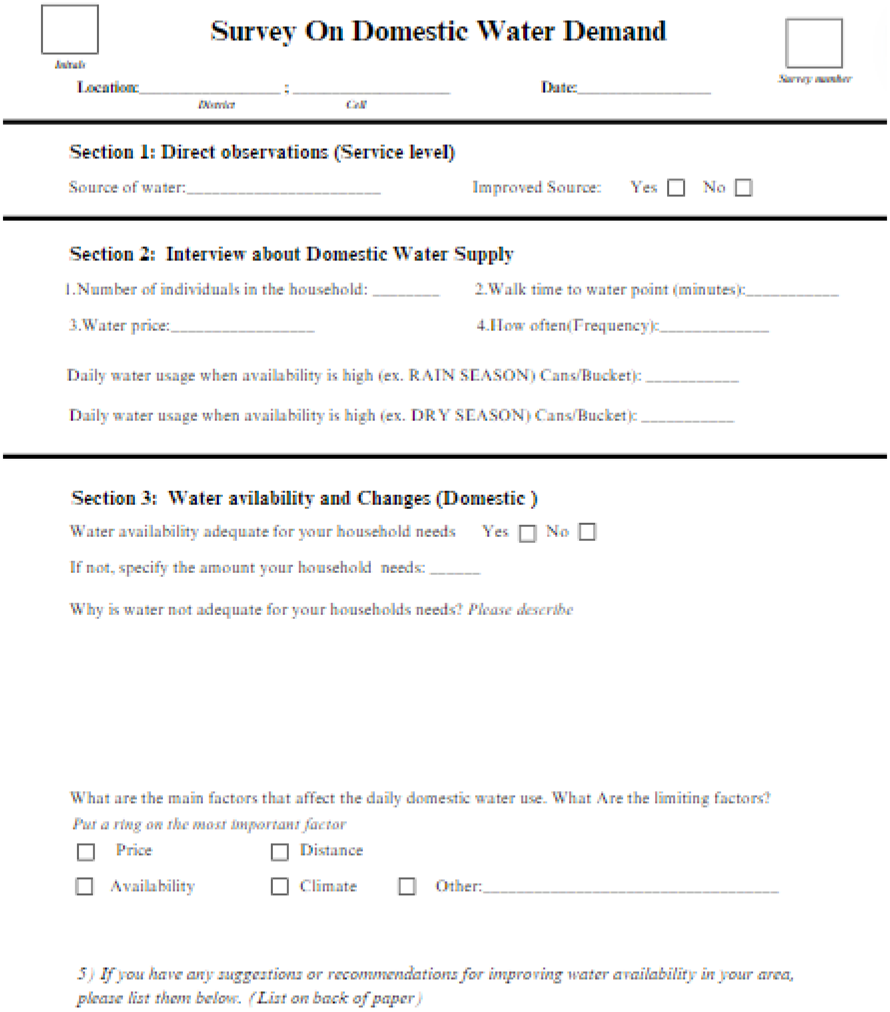
Appendices

A. Questionnaire

Online Survey Round 1:
Water Demand (google.com)

Online Survey Round 2:
Water Demand (google.com)

Solid copy:



☐
Initials

Survey On Domestic Water Demand

☐
Survey number

Location:_______________ : _______________ **Date:**_______________
District Cell

Section 1: Direct observations (Service level)

Source of water:______________________ Improved Source: Yes ☐ No ☐

Section 2: Interview about Domestic Water Supply

1.Number of individuals in the household: ________ 2.Walk time to water point (minutes):___________

3.Water price:_________________ 4.How often(Frequency):_____________

Daily water usage when availability is high (ex. RAIN SEASON) Cans/Bucket): ___________

Daily water usage when availability is high (ex. DRY SEASON) Cans/Bucket): ___________

Section 3: Water avilability and Changes (Domestic)

Water availability adequate for your household needs Yes ☐ No ☐

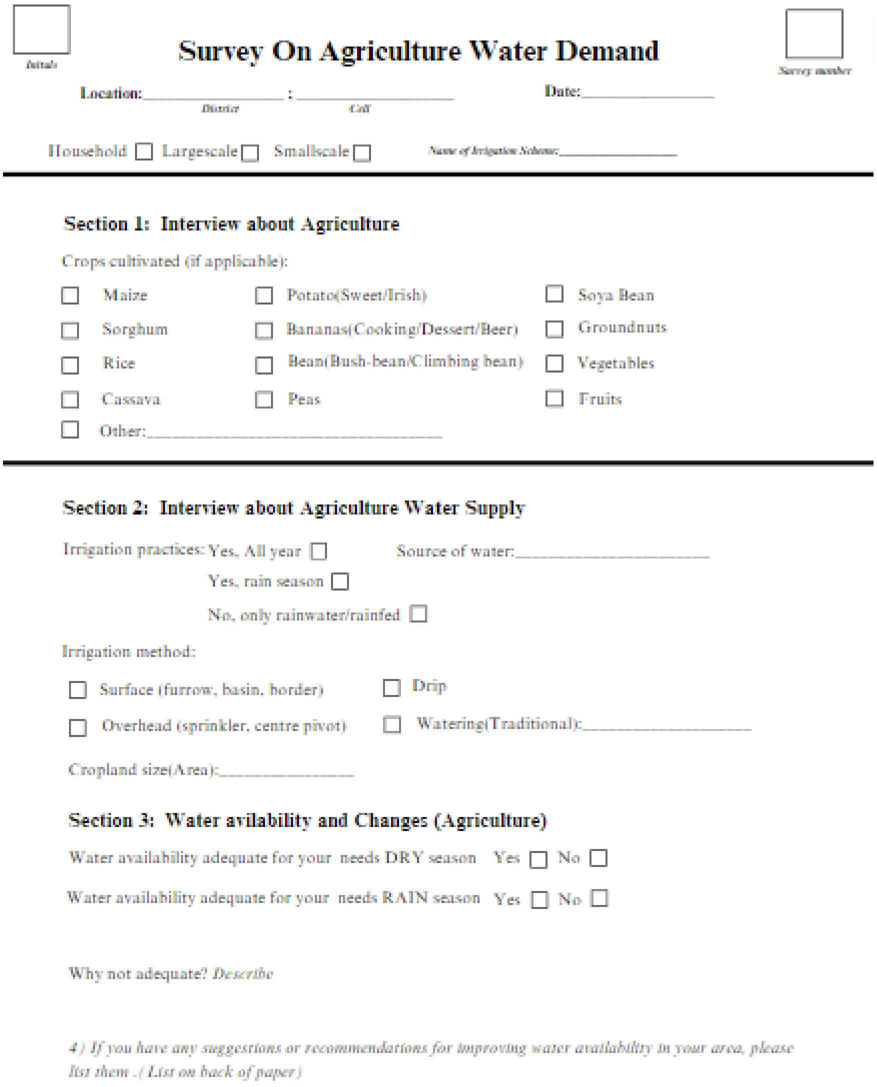
If not, specify the amount your household needs: ______

Why is water not adequate for your households needs? *Please describe*

What are the main factors that affect the daily domestic water use. What Are the limiting factors?
Put a ring on the most important factor

☐ Price ☐ Distance
☐ Availability ☐ Climate ☐ Other:_________________________________

5) If you have any suggestions or recommendations for improving water availability in your area, please list them below. (List on back of paper)



☐ *Initials*

Survey On Agriculture Water Demand

☐ *Survey number*

Location:________________ : ________________ **Date:**______________
District *Cell*

Household ☐ Largescale ☐ Smallscale ☐ *Name of Irrigation Scheme:*______________

Section 1: Interview about Agriculture

Crops cultivated (if applicable):

☐ Maize
☐ Sorghum
☐ Rice
☐ Cassava
☐ Other:______________________________

☐ Potato(Sweet/Irish)
☐ Bananas(Cooking/Dessert/Beer)
☐ Bean(Bush-bean/Climbing bean)
☐ Peas

☐ Soya Bean
☐ Groundnuts
☐ Vegetables
☐ Fruits

Section 2: Interview about Agriculture Water Supply

Irrigation practices: Yes, All year ☐ Source of water:____________________
Yes, rain season ☐
No, only rainwater/rainfed ☐

Irrigation method:

☐ Surface (furrow, basin, border) ☐ Drip
☐ Overhead (sprinkler, centre pivot) ☐ Watering(Traditional):__________________

Cropland size(Area):______________

Section 3: Water avilability and Changes (Agriculture)

Water availability adequate for your needs DRY season Yes ☐ No ☐

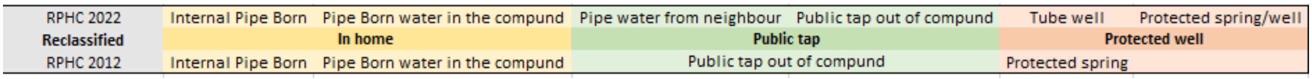
Water availability adequate for your needs RAIN season Yes ☐ No ☐

Why not adequate? *Describe*

4) If you have any suggestions or recommendations for improving water availability in your area, please list them .(List on back of paper)

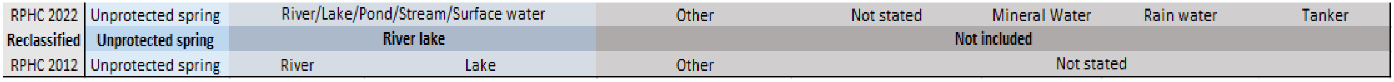
B. Reclassification of Source

Improved Sources:



RPHC 2022	Internal Pipe Born	Pipe Born water in the compund	Pipe water from neighbour	Public tap out of compund	Tube well	Protected spring/well
Reclassified	**In home**		**Public tap**		**Protected well**	
RPHC 2012	Internal Pipe Born	Pipe Born water in the compund	Public tap out of compund		Protected spring	

Unimproved:



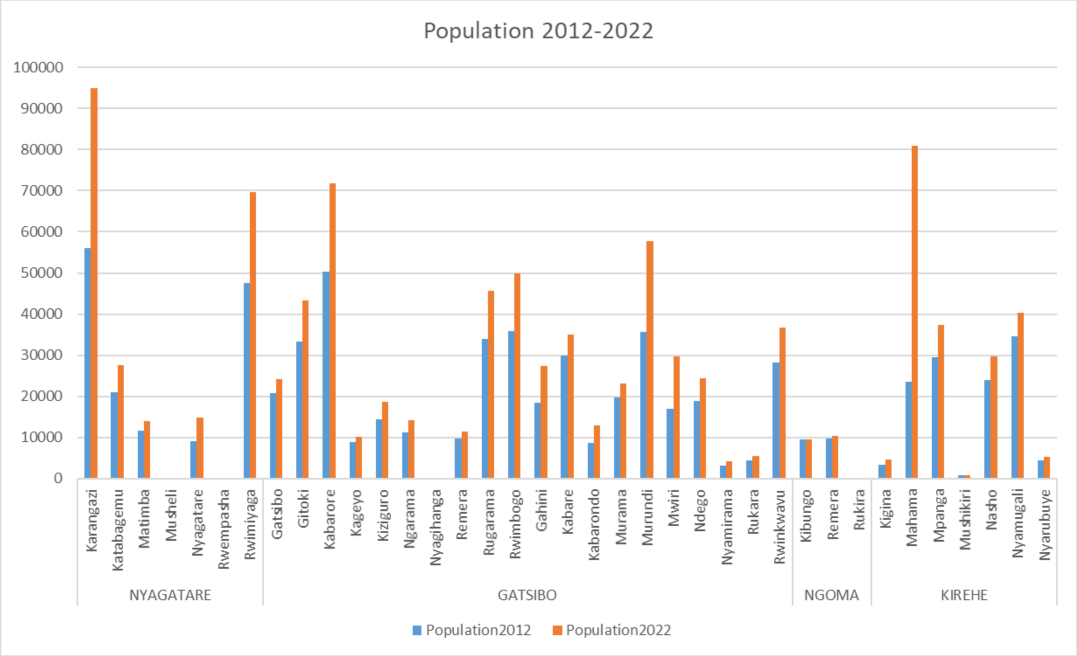
RPHC 2022	Unprotected spring	River/Lake/Pond/Stream/Surface water		Other	Not stated	Mineral Water	Rain water	Tanker
Reclassified	**Unprotected spring**	**River lake**		**Not included**				
RPHC 2012	Unprotected spring	River	Lake	Other	Not stated			

C. Share of Catchment covered by sectors

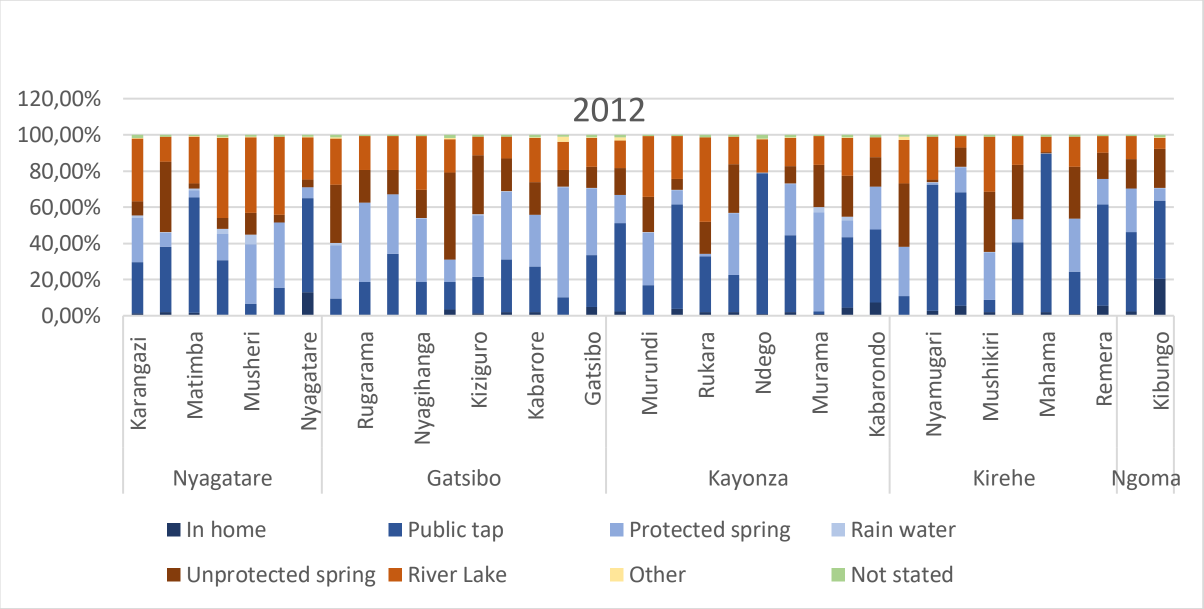
SECT_NAME	**Area_NAKL (SQKM)**	**%AreaNAKL**
Kabarore	126.371719	100.015856
Gitoki	75.379061	100.008897
Rwinkwavu	89.475396	100.008178
Murundi	530.992246	99.999244
Ndego	197.91681	99.983367
Rwimbogo	732.951064	99.978452
Karangazi	551.32104	99.20111
Murama	69.771486	98.775837
Mahama	66.463594	98.360549
Nyamugali	91.248701	95.870788
Mwiri	517.692947	95.864561
Mpanga	234.623852	94.694353
Rugarama	70.784518	93.441563
Nasho	90.103631	90.06171
Rwimiyaga	267.895923	89.457257
Kabare	100.885932	88.85258
Gahini	87.481386	74.367417
Katabagemu	69.153988	68.538474
Matimba	49.504434	62.570678
Gatsibo	32.76083	53.218058
Kiziguro	28.765151	46.771141
Kageyo	24.846062	44.725665
Ngarama	23.520506	42.582155
Kibungo	17.964806	42.207721
Remera	20.474165	38.513531
Remera	14.158827	28.381104
Nyagatare	41.592921	26.470841
Nyarubuye	22.557537	26.044701
Kabarondo	13.39991	24.348964
Rukara	8.722741	13.653308
Nyamirama	8.107659	13.572824
Kigina	8.191681	11.883576
Mushikiri	1.618396	1.704641
Nyagihanga	0.24413	*0.342795*
Musheli	0.212494	*0.215194*
Rukira	0.02592	*0.037751*
Rwempasha	0.012606	*0.007496*
Kigarama	3.4e-05	*0,00003*

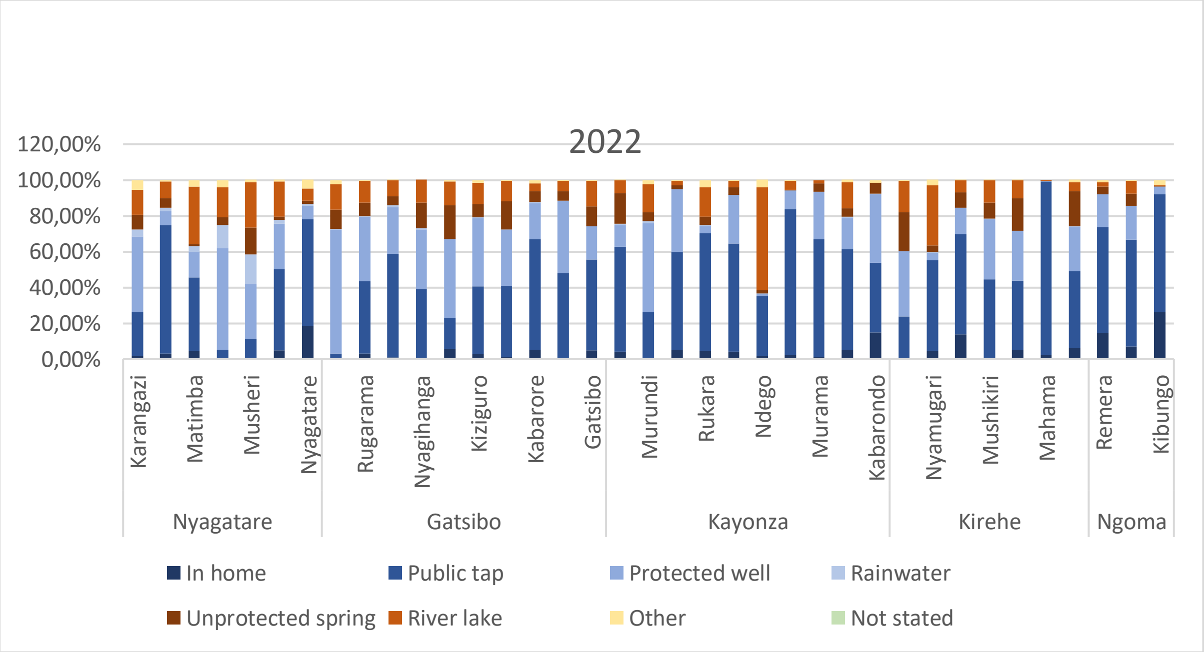
D. Data used in the MLR model

Population Size and Distribution:



Source of Drinking water:





Distance:

Survey	Year	0-4 min	5-14 min	15-29 min	30 - 59 min	60 + min
EICV3	Nyagatare	19%	32%	26%	18%	5%
	Gatsibo	19%	41%	26%	11%	3%
	Kayonza	14%	48%	21%	13%	4%
	Ngoma	20%	42%	17%	15%	6%
	Kirehe	12%	28%	18%	26%	16%
	Average	**17%**	**38%**	**22%**	**17%**	**7%**
EICV5	Nyagatare	25%	42%	21%	13%	0%
	Gatsibo	14%	54%	22%	10%	0%
	Kayonza	17%	42%	22%	19%	0%
	Ngoma	21%	49%	16%	14%	0%
	Kirehe	39%	41%	13%	7%	0%
	Average	**23%**	**45%**	**19%**	**13%**	**0%**

Household Sizes:

Survey	Area	1p	2-4p	5-7p	8-10p	11p+
EICV5	Eastern Province	4%	44%	41%	10%	1%
EICV3	Eastern Province	7%	47%	38%	7%	1%

E. Accuracy of land use classification

The producers, consumers, and overall accuracies for each classification in GEE.

District	Land cover	Producer Accuracy	Consumer Accuracy	Overall Accuracy
Nyagatare	Cropland	0.83	0.88	0.83
	Built	0.8	1	
	Water	0	0	
	Grass/Bare	0.96	0.73	
	Treecover	0.77	0.823	
	Wetland	0.71	0.833	
Gatsibo	Cropland	0.9	0.96	0.86
	Built	0.88	0.78	
	Water	1	0.8	
	Grass/Bare	0.8	0.81	
	Treecover	0.9	0.82	
	Wetland	0	0	
Kayonza	Cropland	0.88	0.83	0.9
	Built	1	1	
	Water	1	1	
	Grass/Bare	0.82	1	
	Treecover	0.85	1	
	Wetland	1	0.78	
Kirehe	Cropland	0.92	0.85	0.85
	Built	0.83	0.55	
	Water	1	1	
	Grass/Bare	0.79	0.95	
	Treecover	0.85	1	
	Wetland	1	0.67	
National park	Cropland	-	-	1
	Built	-	-	
	Water	1	1	
	Grass/Bare	1	1	
	Treecover	1	1	
	Wetland	1	1	
Rice Fields	Rice	1	1	1
	Not rice	1	1	
Cropland SC	Cultivated	0.9	0.9	0.9
	Fallow	0.9	0.9	