FINAL REPORT

Integrated Strategic Water Resources Planning and Management for Rwanda

REPORT

259

CLIENT **FONERWA**

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FutureWater Report 259

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Authors
Brecht D'Haeyer
Peter Droogers
Johannes Hunink
Corjan Nolet
Bruce Uwonkunda
Placide Nshuti-Kanyabujinja
Aussi Sayinzoga
Simon Thuo
Jean Ntivunwa
Devaraj de Condappa

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FutureWater

ADDRESS
FutureWater B.V.
Costerweg 1V
6702 AA Wageningen
The Netherlands

TELEPHONE **+31 317 460 050**
WEBSITE **www.futurewater.eu**

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List of Acronyms

Acronym	Definition
ADB	Asian Development Bank
AWD	Alternate Wetting-Drying
BCM	Billion cubic meter
BOO	Build-Operate-Own
BOT	Build-Operate-Transfer
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CKIV	Lake Kivu catchment
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
CROM	Catchment Restoration Opportunity Mapping
CRUS	Rusizi catchment
DEM	Digital Elevation Model
DO	Dissolved oxygen
DSS	Decision Support System
EAC	East African Community
EDCL	Energy Development Corporation Limited
EDPRS	Economic Development and Poverty Reduction Strategy
ENACTS	Enhancing National Climate Services
ENSO	El-Nino-Southern Oscillation
EPI	Enterprise Partnership Initiative
ERT	Electrical resistivity Tomography
ET	Evapotranspiration
FAO	Food and Agriculture Organization
FONERWA	Rwanda National Fund for Environment
GCM	Global Climate Models
GIS	Geographic Information System
GPS	Global Positionning System
GW	Ground Water
HEA	Hydro-Economic Analysis
HP	Hydropower
IDW	Inverse Distance Weighting
ISRIC	World Soil Information
IUCN	International Union for Conservation of Nature
KPI	Key Performance Indicators
LTA	Long-Term Average
LULC	Land Use Land Cover
LWI	Living Water International
MAI	Mean Annual Inflow
MINECOFIN	Ministry of Finance and Economic Planning
MINEFRA	Ministry of Infrastructure
NAKL	Lower Akagera catchment
NAKN	Akanyaru catchment
NAKU	Upper Akagera catchment

Acronym	Definition
NELSAP	Nile Equatorial Lakes Subsidiary Action Program
NGO	Non-Governmental Organisation
NISR	National Institute of Statistics of Rwanda
NMUK	Mukungwa catchment
NMUV	Muvumba catchment
NNYL	Lower Nyabarongo catchment
NNYU	Upper Nyabarongo catchment
NPV	Net-Present Value
NRW	Non-Revenue Water
NST1	National Strategy for Transformation
NWRMP	National Water Resources Master Plan
OYASF	Over-Year Active Storage Factor
PES	Payment for Ecosystem Services
PPP	Public-Private Partnership
PV	Photovoltaic
RAB	Rwanda Agriculture Board
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RDB	Rwanda Development Board
REMA	Rwanda Environment Management Authority
RFFP	Returning Farmland to Forests Program
RURA	Rwanda Utilities Regulatory Authority
RWB	Rwanda Water Board
RWFA	Rwanda Water and Forestry Authority
SDG	Sustainable Development Goals
SEI	Stockholm Envronment Institute
SPCR	Strategic Program for Climate Resilience
SSIT	Small-Scale Irrigation Technology
SSP	Shared Socioeconomic Pathways
SWOT	Strengths Weaknesses Opportunities Threats
TSS	Total Suspended Solids
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNICEF	United Nations International Children's Emergency Fund
USA	United States of America
WAPOR	Water Productivity through Open access of Remotely sensed derived data
WASAC	Water and Sanitation Corporation
WASH	Water Sanitation and Hygiene
WEAP	Water Evaluation And Planning
WHO	World Health Organization
WRM	Water Resources Management
WRMP	Water Resources Management Policy

Executive Summary

Highlights of the Report

Assessment of water resources under a changing climate

- Results of a Regional Climate Model (RCM), provided by Meteo-Rwanda for the Representative Concentration Pathways (RCP) 4.5 and RCP 8.5, indicate that while temperature is expected to increase, no significant trend is expected for rainfall.
- The hydrological water balance of all 2.5 catchment levels has been produced for the baseline period (2000 to 2019) and the future period under climate change conditions, representing 2050 (years 2040 to 2059).
- In general, projections show a mild decrease in runoff and groundwater recharge under RCP 4.5 compared to the baseline. The situation gets more contrasted under RCP 8.5, with a clear spatial contrast between the western part of the country (significant decrease) and its eastern part (mild increase). This implies that, under RCP 8.5, wet regions under the baseline (west of Rwanda) are most impacted by climate change and will face lower water availability and increased stress. The availability of renewable groundwater supply will significantly diminish under RCP 8.5.

Detailed Water Allocation

- The total storage capacity of groundwater resources is 81 BCM.
- Water balances, comparing available water resources under climate change with future sectoral water demands, have been produced for all catchments classified between level 1 and level 2.5 for 2050 (years 2040 to 2059).
- The water balances for 2050 pick out level 2.5 sub-catchments with the highest unmet demand, by definition, the amount of water demand which cannot be satisfied by available water resources.

Strategic Water Resources Conservation and Development:

- A list of 39 prioritised new dams, with a total storage of 781 MCM, has been identified to reduce the volume of unmet demand by 2050. This includes four regulatory dams, expected to reduce turbidity in rivers with high sediment loads. The key features (e.g., storage capacity, dam height, catchment area, inundated area, soil erosion risk, and cost) have been assessed.
- A series of guidelines for water resources development covering the supply-side (e.g., increase in surface storage, avail groundwater, implement Payment for Ecosystem Services) and the demand side (e.g., Public-Private Partnerships for domestic water supply, further irrigation development, reuse of treated domestic wastewater, a clear policy framework for water financing) have been proposed towards 2050.
- Nature-based solutions are suggested, combined with the 39 prioritised new dams, to mitigate the dam siltation and contribute to the sustainability of the new dams.

Strategic Water Resources Management Options:

- A Strategic Water Storage Plan is elaborated to schedule the construction of the 39 prioritised dams and implement most of the water resources development guidelines. The plan is scheduled along the three implementation stages 2030, 2035 and 2050.
- The Cost Benefit Analysis of the Strategic Water Storage Plan shows the benefit of associating the construction of the 39 new dams with the Integrated Sediments Management Plan (NbS measures upstream of the dam, regular desilting of the new dam). However, additional implementation of regulatory dams, to clear sediments from the system, leads to smaller benefits due to the high maintenance costs associated with these regulatory dams.
- Three transformative flagship projects are identified in consultation with stakeholders to contribute to implementing Vision 2050, the Strategic Water Storage Plan and the Water Resources Development Guidelines. The first is a multi-purpose dam of 14.2 MCM in Rulindo, to supply domestic water to Kigali, provide irrigation along the Yanze and generate electricity with the association of hydro and solar powers. The second is a dam of 147.8 MCM in Kayonza, mainly for irrigating 9,795 ha and generating electricity with the association of hydro and solar powers. The third aims to study the groundwater potential in the Kirehe district for supplying domestic water and, if the potential is deemed enough, to provide water for livestock and irrigation.

Revised National Policy for Water Resources Management:

- The 2011 National Policy for Water Resources Management was ambitious and innovative at its time. Despite significant gains, it faced implementation challenges due to urbanisation, economic growth, high level of sedimentation in rivers, lack of sufficient sectoral coordination and inadequate human and financial resources.
- The updated policy merging Water Supply, Sanitation and Water Resources sectoral policies should ensure that the institutional gains made for water resources management since 2010 are sustained. Such gains refer particularly to the creation of the Rwanda Water Resources Board (RWB), answerable to the Government directly through the Prime Minister, strengthening district authorities for management, and implementing Vision 2050 and LTS1.
- This assignment included support for the Inter-Ministerial Task Force in charge of drafting the new merged policy, with iterative recommendations for improvement in successive drafts.

Background and Context of the Study

Rwanda's 2011 National Water Resources Policy was founded on the principle of catchment-based water resources management. The 2015 National Water Resources Master Plan (NWRMP) was developed within this framework. The NWRMP quantified available water resources and demand under current and projected situations. It also formulated management options for the rational use of available water resources, with a time horizon of 25 years (up to 2040). The NWRMP revealed that even though Rwanda receives relatively high amounts of rainfall, the country is still classified as economically water-scarce, with declining renewable water availability per capita. Water scarcity in Rwanda is mainly considered economically driven, due to the inability to invest in infrastructures needed to store and distribute water.

In 2020, Rwanda published Vision 2050, its national long-term development strategy, stating new and ambitious objectives for urbanisation, energy production, irrigation and water resources development. This would vastly increase water demand and, more importantly, large water deficits by 2050. There is, therefore, a need to review and update the NWRMP to facilitate the implementation of water-dependent components of Vision 2050.

In this regard, the Rwanda Green Fund (FONERWA), in collaboration with the Rwanda Water Resources Board (RWB) and with financial support from the World Bank, has undertaken the **"Integrated strategic water resources planning and management in line with Rwanda's Vision 2050"**. The assignment essentially builds on the 2011 National Water Resources Management Policy, the 2015 NWRMP, Vision 2050, different sectoral master plans and the Hydro-Economic Analysis recently completed by the World Bank. The assignment is organised along the following five topics:

- Detailed Hydrological Assessment, with a groundwater resources assessment, the development of a semi-distributed hydrological model to assess the hydrological budget for the current situation and under climate change.
- Detailed Water Allocation Assessment, with the development of a water allocation plan, the analysis of the water surplus and deficits in space and time and the identification of prioritised strategic water resources development infrastructures.
- Strategic Water Resources Conservation and Development, with a technical appraisal of each prioritised strategic water resources development infrastructure, an assessment of contribution from Natural based Solutions to protect new infrastructures and the update of water resources development guidelines.
- Strategic Water Resources Management Option, with stakeholder engagements to finalise the strategic water storage plan for Rwanda and to identify flagship projects, the cost-benefits analysis of the strategic water storage plan and the drafting of a series of flagship project concept notes.
- Revised National Policy for Water Resources Management to revise the 2011 National Water Policy based on the latest policies, particularly Vision 2050.

Detailed hydrological assessment

Assessment of groundwater resources

The assignment focused on assessing the storage capacity of the main aquifer systems in Rwanda. The assessment considered the following information:

- The principal lithologies of Rwanda, in particular its main aquifers systems.
- A physiographic zoning identifies areas with strong similarities, such as soil characteristics, altitude and ecological environment.
- Values of the effective porosity found in the literature,
- Inventory of existing boreholes, to approximate the thickness, interpolated over the respective aquifer areas in each physiographic zone.
- A resistivity study was conducted during the assignment to characterise the groundwater locally. In addition, it was used to complete the thickness data from the boreholes database.

It eventually led to a total groundwater storage of about 81 BCM. This magnitude result is in line with the range of values found in the literature, such as the 2015 NWRMP, which estimated a total groundwater storage of about 61 BCM.

Hydrological assessment at level 2.5 catchment

The Water Evaluation And Planning (WEAP) model, developed for the Hydro Economic Analysis (HEA), was further refined for this study's hydrological assessment. The timestep in the model was monthly, and its calibration was validated against the evapotranspiration data from the remote sensing-based evapotranspiration dataset WaPOR (source:FAO).

The fundamental spatial units of the model are the level 2.5 catchments, containing 86 sub-catchments (Figure 1). The level 2.5, intermediate between catchment levels 2 and 3, was introduced by the Rwanda Water Board (RWB) to facilitate strategic planning at the national level. They were created by clustering level 3 catchments with similar characteristics in terms of land use and hydrological behaviour.

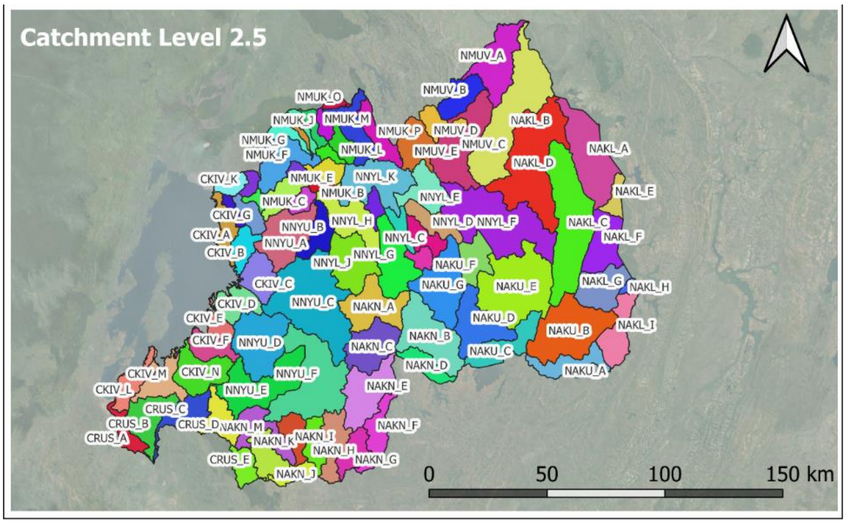
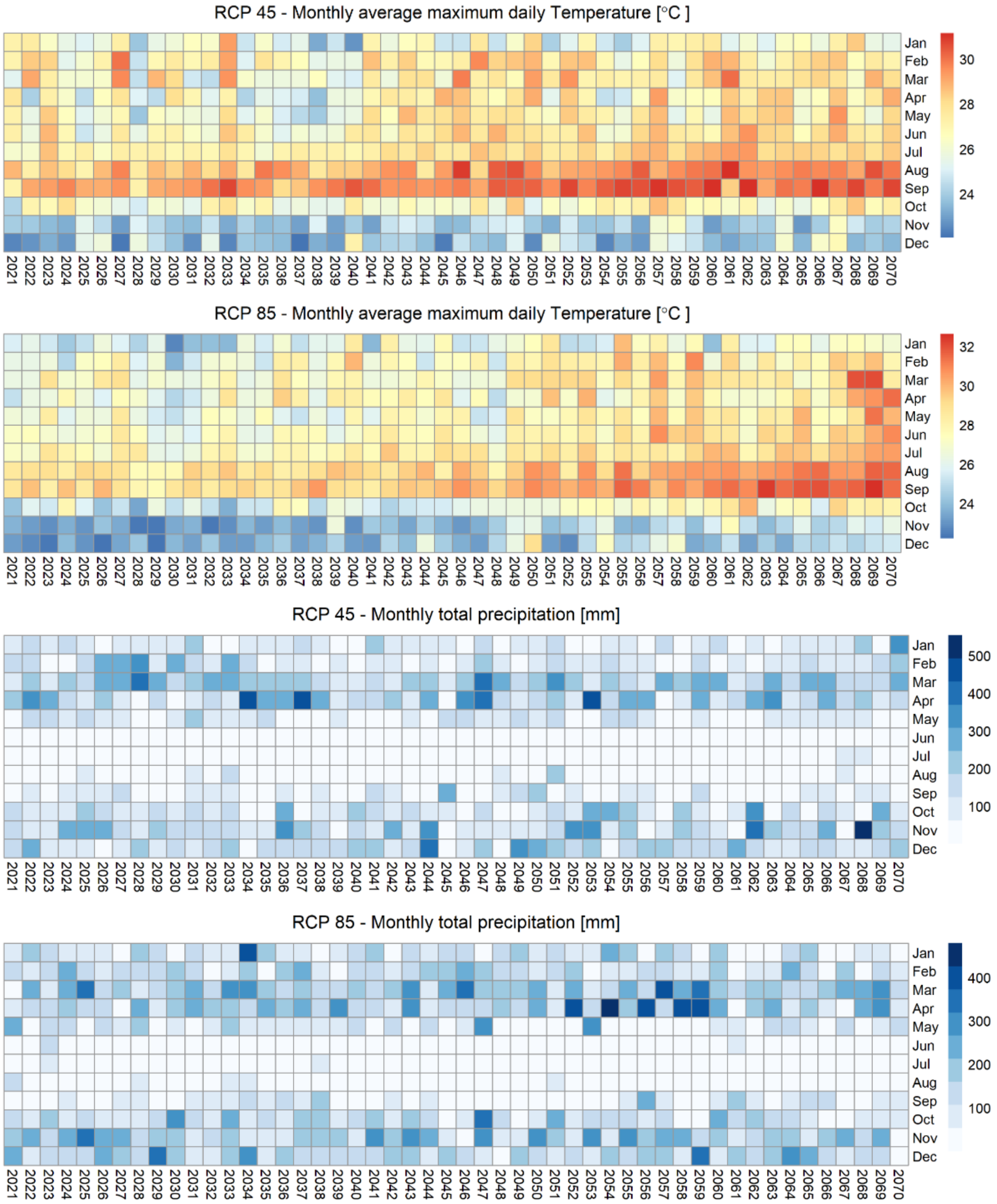


Figure 1: 86 level 2.5 sub-catchments of Rwanda

The hydrological assessment was derived for:

- The current conditions, i.e., the baseline climate period (2000 to 2019), rely on historical data from Meteo-Rwanda.
- The future period incorporates climate change conditions and represents 2050 (2040 to 2059). Results of a Regional Climate Model (RCM) were provided by Meteo-Rwanda for the Representative Concentration Pathways (RCP) 4.5 and RCP 8.5. An illustration of temperature and precipitation change for Lower Nyabarongo is shown below (Figure 2), with a visible increase in temperature but no particular and significant trend noted for rainfall.


RCP 45 - Monthly average maximum daily Temperature [°C]

RCP 85 - Monthly average maximum daily Temperature [°C]

RCP 45 - Monthly total precipitation [mm]

RCP 85 - Monthly total precipitation [mm]

Figure 2: Projection of temperature (up) and precipitation (down) for RCP 4.5 and RCP 8.5. Based on Regional Climate Models provided by Meteo-Rwanda

The two climate scenarios are used in WEAP to determine the hydrological impact of climate change. The hydrological assessment is produced for every 2.5 sub-catchment, compared with baseline results. An example is shown below for a 2.5 sub-catchment (Figure 3).

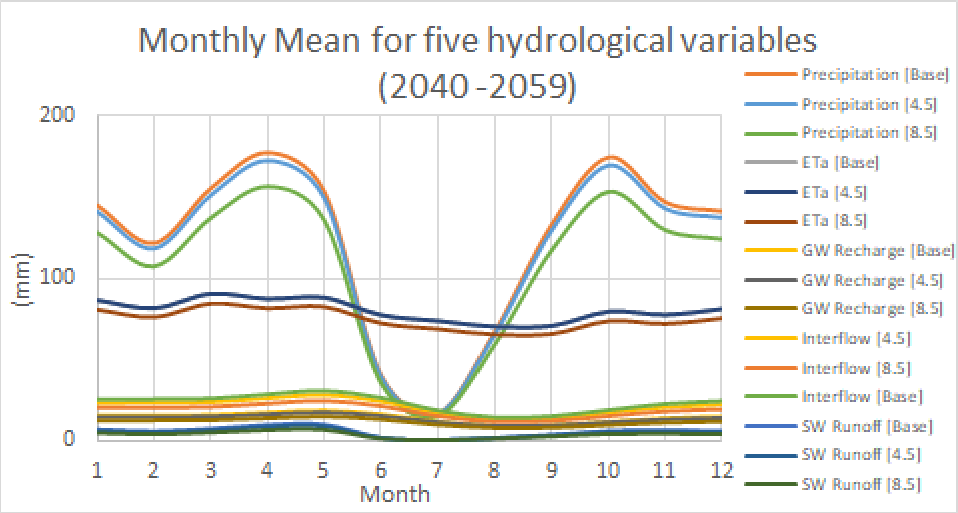
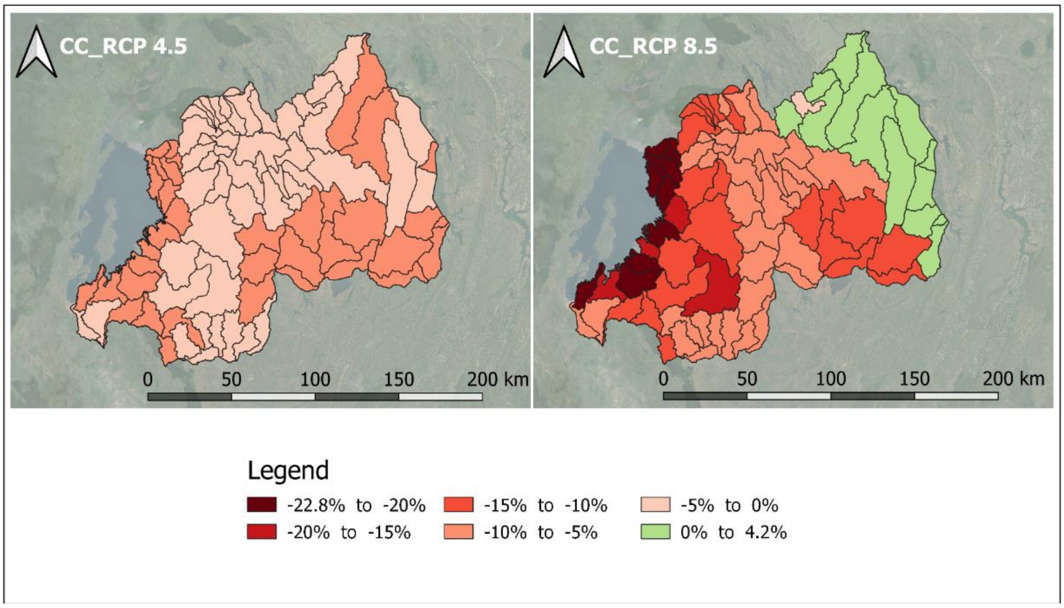


Figure 3: Example of a hydrological assessment for a 2.5 sub-catchment of the Kivu catchment.

In general, projections show a mild decrease in runoff and groundwater recharge under RCP 4.5, compared to the baseline (Figure 4). The situation gets more contrasted under RCP 8.5, with a clear spatial contrast between the western part of the country (more significant decrease) and its eastern part (mild increase). This implies that, under RCP 8.5, wet regions under the baseline (west of Rwanda) are most impacted by climate change and will face lower water availability and increased stress. The availability of renewable groundwater supply will significantly diminish under RCP 8.5.



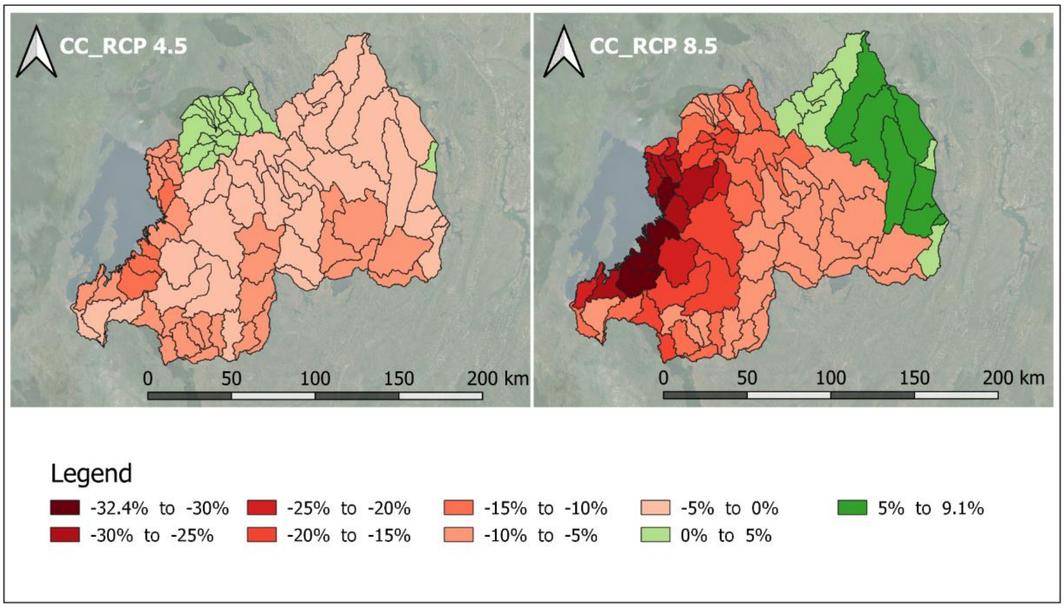


Figure 4: Change in surface Runoff (top) and groundwater recharge (bottom) between the baseline period (years 2000 – 2019) and the horizon 2050 (years 2040 – 2059) for each level 2.5 sub-catchment, for RCP 4.5 and RCP 8.5.

Detailed Water Allocation

Water allocation plan

Water demands up to 2050 were computed from the various sectoral master plans. Dams under construction or with secured implementation (Nyabarongo II, Akanyaru, Warufu and Muvumba) were added to the WEAP model. Allocation rules were according to the Water Law, i.e. priority to supply domestic water, then environmental flow and last to economic uses of water (agriculture and industries).

The Water Resilient scenario introduced by the Hydro-Economic Analysis was used. The scenario supposes the implementation of Vision 2050, with increased water demands, particularly large-scale irrigation, better irrigation efficiency through climate-smart technologies, and reduced dependence on hydropower. This scenario was combined with two additional scenarios: (i) the most likely climate scenario, i.e., the RCP 4.5 (as compared to RCP 8.5) and (ii) the implementation of planned/secured projects (new dams, irrigation schemes), such as Nyabarongo II, Akanyaru, Muvumba, and Warufu.

Different results are presented for all catchment level 2.5, including the following:

- Hydrological Water Balance,
- And the monthly water availability where the monthly available water (runoff and groundwater recharge) is compared to the total monthly water demands from all sectors, to identify months of surplus and potential deficits (which can be regulated by natural and artificial storage).

Level 1 water balances are also produced for all the nine level 1 catchments, such as (Figure 5):

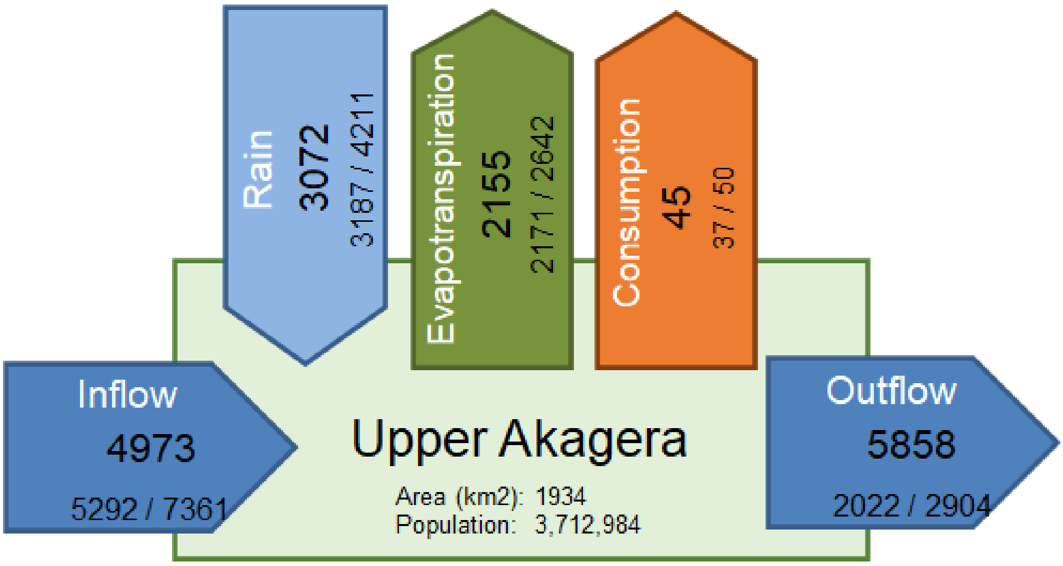


Figure 5: Example of a water balance produced for the Upper Akagera level 1 catchment.

Strategic water resources infrastructures to address water deficit by 2050

In this study, the unmet demand calculated with the WEAP model is used to define the water deficit:

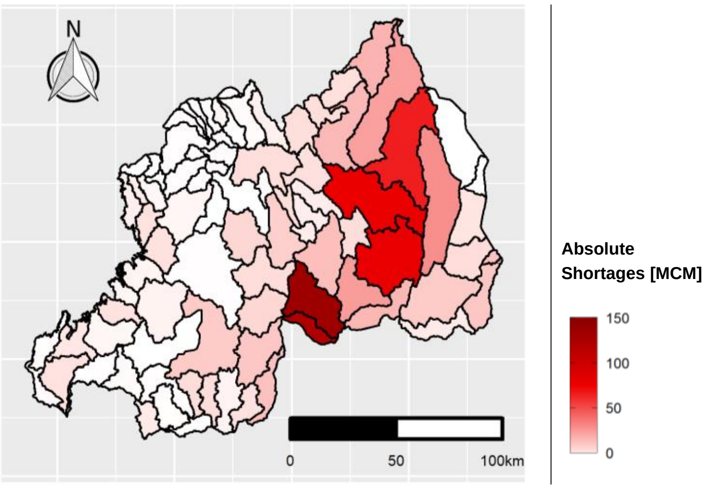


Figure 6: Unmet demand, at level 2.5 catchments, representative of horizon 2050 (2040 to 2059) under an RCP 4.5 climate.

The model was then employed to address these deficits by selecting dams among the list of 132 potential new dams proposed by the 2015 NWRMP. Without adequate technical data and information on the technical characteristics of these potential new dams, their storages were approximated by the mean annual inflow of the river they would impound if constructed, to avoid under or over-sizing the dam. The model also took into account the proposed water transfer from the Akagera river to the Kayonza district.

Assessment of the potential 132 dams was based on their capacity to improve the satisfaction of water demands (or to reduce the unmet demand). It resulted in prioritising 69 dams (Figure 7), ranked by their capacity to reduce unmet demand.

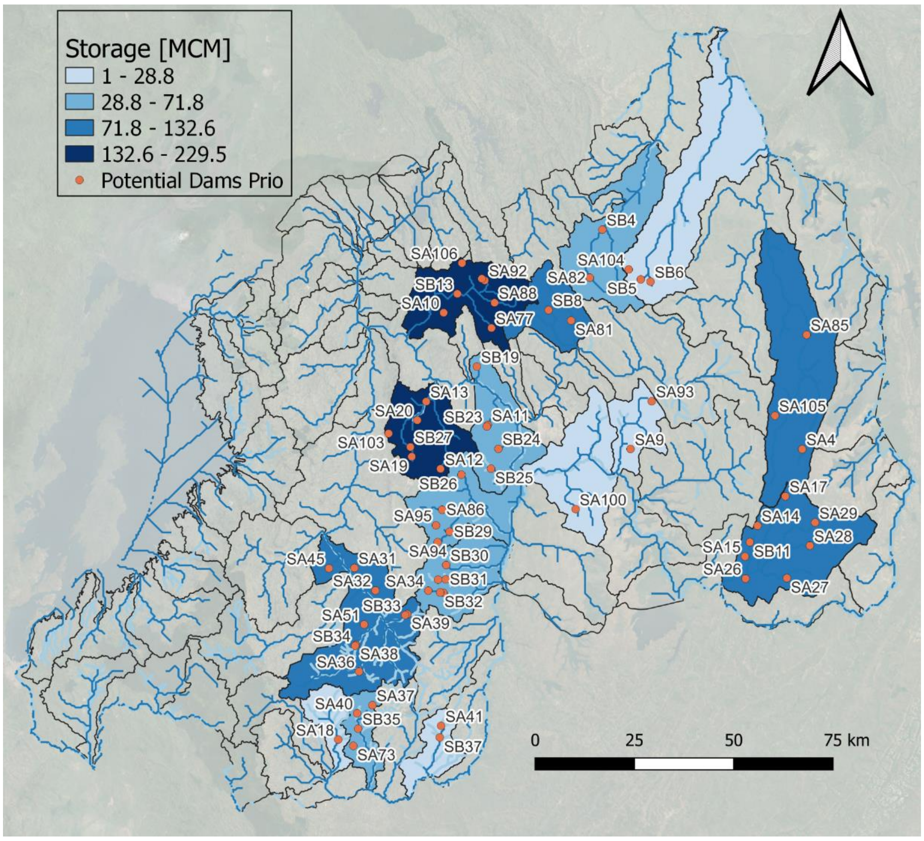


Figure 7: Overview of the 69 first prioritised storage locations as identified in the model (RCP 4.5, 2040 - 2059).

A second and final prioritisation was conducted, validated with stakeholders, that considered complementary ground parameters, such as topographical characteristics, geology, erosion potential, site accessibility, strategic use, catchment size and proximity with other prioritised dams. Four regulatory dams were added to reduce turbidity in rivers with high sediment loads. Thirty-nine dams were selected at the end of the second prioritisation (Figure 8).

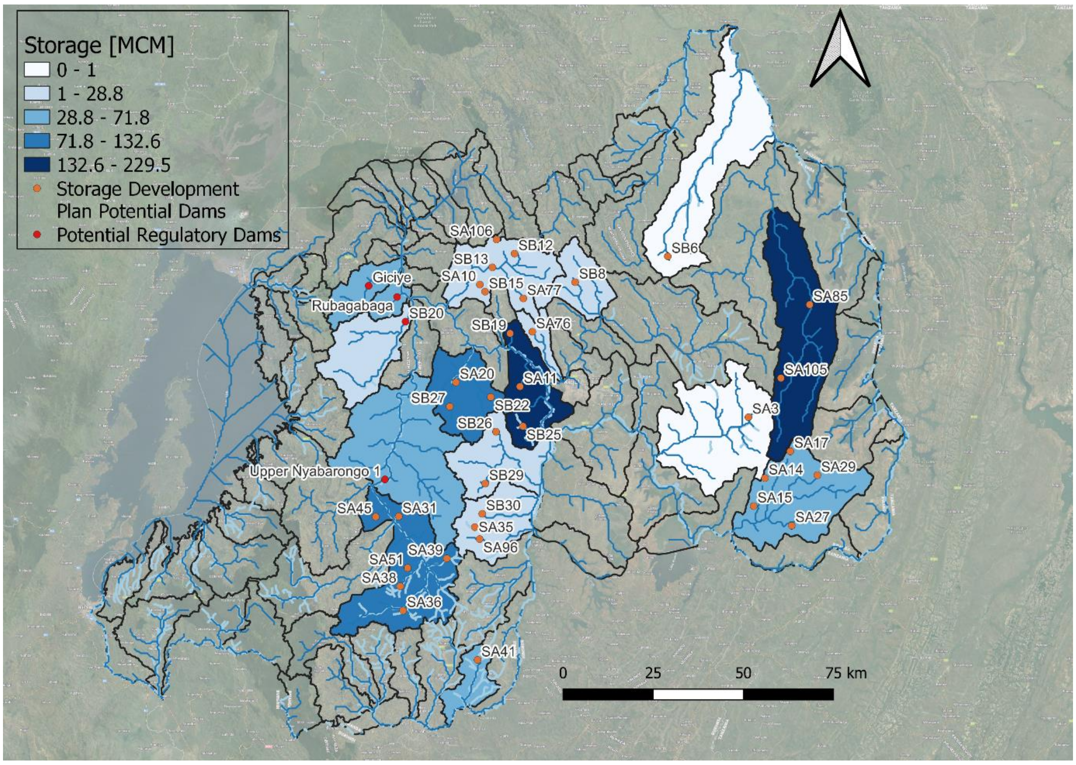


Figure 8: Overview of the 39 final prioritised storage locations as identified with ground parameters

Strategic Water Resources Conservation and Development

Technical appraisal of prioritised strategic water resources development infrastructures

A technical appraisal was conducted for the 39 prioritised dams, to assess the following salient features:

- Storage capacity, which ranged from less than 1 MCM to a maximum of 168 MCM, results in total storage of 812 MCM. The small reservoirs are the regulatory dams, whose purpose is not to store water but trap sediments.
- Dam height, ranges from 5 to 76 m, with the regulatory dams having the smallest heights.
- Catchment areas, range from approximately 170,000 ha, for a regulatory dam located on the Nyabarongo river, to less than 20,000 ha for most of the dams, located on smaller rivers.
- Inundated areas, ranging from 1,900 ha to less than 200 ha for most of the dams.
- Soil erosion risk, with most of the catchment areas under moderate and high erosion risk, and few sites located under very high and extremely high risk of soil erosion by design during the prioritisation.
- Costs, range from US dollars 3 to 138 million

Update the Water Resources Development National Guidelines

The Water Resources Development National Guidelines of the 2015 NWRMP have now been updated, based on the outcomes of the Hydro-Economic Analysis, the assessment of this assignment and stakeholder consultations. The guidelines are for the long-term, towards 2050 and are organised into two categories « Supply side » and « Demand side ».

Supply-side guidelines pertain to :

- **Surface storage**, with the upgrade of existing dams – especially those being highly sedimented, building the prioritised dams proposed in this study and the use of natural lakes. Any new dams, or upgrade of existing dams, should be associated with an integrated plan to manage sediments, to extend the lifetime of new projects. This plan should cover: (i) soil and water conservation measures (NbS) in the upstream catchment, (ii) regular maintenance to remove sediments from the reservoir and (iii) economic utilisation of collected sediments for civil engineering structures and to replenish agricultural soils. The integrated sediments management plan should be accounted for in the CAPEX and O&M costs. New dams should be multi-purpose, addressing several sectoral development goals simultaneously. As a form of multi-purpose use, developing recreational and eco-tourism activities along the dam and reservoir (e.g., boating, site seeing, hotels) can build a sense of cultural heritage and generate additional revenue streams for the maintenance.
- **Groundwater**, with the need to conduct surveys to understand the groundwater systems and their availability, before developing groundwater exploitation for domestic water supply and possibly use for irrigation in case of sufficient productivity. The use of satellite-based technologies to monitor groundwater is emerging. Its application to Rwanda should be investigated, like in the casestudy from UNICEF. A strict licensing (water and drilling permits) and monitoring system should be implemented for groundwater abstractions, given the decentralised nature of groundwater exploitation, taking lessons from experiences elsewhere (e.g., groundwater user associations). Solar groundwater pumping has great potential for decentralised and community exploitation of groundwater; however, existing implementations elsewhere have shown that solar pumping has to be strictly licenced and monitored. Due to the extended nature of the groundwater resource, local communities and the private sector can contribute to understanding and tracking groundwater resources, alongside the government.
- **Payment for Ecosystem Services (PES)** programs should be integrated with other rural development initiatives to increase incomes with particular emphasis on restoring, or preserving, ecosystems and raising awareness of the importance of ecosystem services. Going beyond a specific sector, a synergetic approach to funding for PES should involve all sectors and development partners. FONERWA would logically be the appropriate government body in Rwanda to receive funds from different streams and sectors to finance PES schemes.
- **Flood protection control**, to mitigate events with grey infrastructures and Nbs, but also for adequate reactivity with early warning systems.
- **Smart association of hydropower and solar energy for electricity production**, to reduce the burden on hydropower by increasing the use of solar energy and its synergies with hydropower. The use of floating PV should be investigated in particular.

Demand-side guidelines pertain to:

- **Domestic water supply**, with Public-Private Partnerships (PPP) for capital-intensive domestic water infrastructure projects in cities and other water-related infrastructure and service delivery.
- **Irrigation**, with rainwater harvesting for supplementary irrigation and the continued support of Small-Scale Irrigation Technology (SSIT) for smallholder farmers. SSIT should be accompanied by regulatory, monitoring and enforcing mechanisms to ensure that SSIT does not increase water consumption but water efficiency. More generally, enhancing irrigation water productivity should consider a systemic perspective: instead of solely focusing on increasing water efficiency at the farmer level, a systemic perspective should be embraced to include the dependencies between water users and the role of return flows.

- **Reused treated domestic wastewater** for irrigation, industries and non-potable domestic uses.
- **A clear policy framework for water financing** is needed to ensure integrated water resources management's sustainability and long-term financial viability. The polluter pays principle needs to be enforced in Rwanda, as this principle is fundamental to many environmental policies worldwide, including in Europe and the USA. Similarly, the users' pay principle should be adopted in Rwanda to provide a basis for water pricing and allocating scarce water resources among different users.
- **Develop and implement a consistent water quality monitoring program** to track any positive impacts arising from the efforts in soil erosion control and wastewater treatment and reuse.

These guidelines require effective legal, regulatory, and institutional mechanisms. Without the supporting governance structures, infrastructure will degenerate over time, and any allocation decisions will be undermined, leading to a less secure water future for Rwanda. Investment in governance is as critical as any other aspect of water planning.

Barriers need to be removed at several levels, including inadequate enforcement mechanisms to guide water use and management. The lack of established regulatory norms and standards, and their inconsistent enforcement, has increased the risk for private sector actors to engage in the sector and beyond. This is the case, for instance, in implementing PPP, where regulatory gaps mostly include: (i) more explicit regulations and requirements for private operators; and (ii) developing actual regulatory institutions (such as the inclusion of an independent regulator). Two principal models of intervention exist in Rwanda:

- The decentralised approach, which places responsibility at the regional level and within the concerned line Ministries.
- A more centralised approach, which is based on establishing one dedicated national PPP unit (RDB for Rwanda).

Contribution of Nature-based Solutions

Nature-based Solutions (NbS) have been proposed within each dam site catchment area to mitigate the dam siltation once constructed and ensure the sustainability of the 39 prioritised water storage infrastructures. Implementing the recommended nature-based interventions will largely contribute to the sustainability of the prioritised dams through the prevention of their sedimentation and therefore ensuring their full water storage potential. Proposed measures include mainly afforestation, agroforestry, hedgerows, bench terraces, contour bank terraces, reforestation, grassed waterways, riverside bamboo and savannah restoration.

Some NbS measures will also provide storage benefits due to increased infiltration and groundwater recharge.

Strategic Water Resources Management Options

Strategic water storage plan

The Strategic Water Storage Plan has been prepared to facilitate phasing the construction of the 39 prioritised dams, with a total storage of 781 MCM. The plan is a portfolio of investments to implement the Water Resources Development Guidelines and results in the following outputs:

- Augmentation of surface storage capacity through the construction of new storage dams.
- Adoption of the Integrated Sediments Management Plan, with measures:
    - at-source: erosion control measures through NbS,
    - in the reservoir: to desilt and value collected sediments.
- Adoption of the other recommendations in the guidelines related to water and land management in Rwanda (e.g., promotion of PES to fund NbS, multi-purpose dams, and PPPs).

The Strategic Water Storage Plan phases the potential investments in three stages 2030, 2035 and 2050. The time sequencing for construction is based on the prioritisation, with dams having the greatest reduction of unmet demand being built first. The first three prioritised dams are advised to be commissioned by 2030, then the following eight prioritised dams by 2035 and lastly, the remaining dams are to be finalised by 2050. The impact of reducing the unmet demand is shown (Figure 9) and is most significant during dry years.

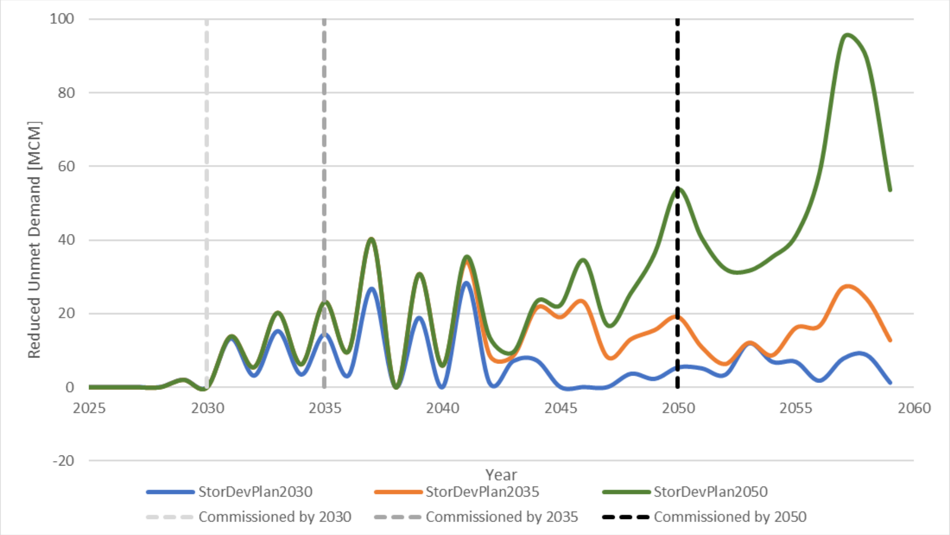


Figure 9: Reduced Unmet Demand for Water Storage by 2030, 2035 and 2050 on the national level.

Cost benefits analysis of the Strategic Water Storage Plan

A Cost Benefit Analysis (CBA) was performed to get insight into how cost-effective the phased Strategic Water Storage Plan is. The benefits included in this CBA are:

- Reduced unmet demand, and thus increased economic water productivity.
- Increased land productivity from reduced loss of fertile soil.

The main cost items that were considered in the CBA are:

- Newly built storage infrastructure.

- Costs of erosion control measures (NbS).
- Capital/maintenance of regulatory dams, especially for the integrated sediment management plan.

Other relevant assumptions for the analysis are:

- The storage plan was analysed for investments up to 2030 and 2035. The potential investments beyond 2035 were not included, as requested by the client, given the highly uncertain socio-economic conditions on that time horizon.
- The return on investment analysis horizon is 30 years.

The analysis was done for the following five scenarios, so the marginal impact of different measures and options can be explored (each scenario includes all previous ones):

- A. Storage Dams up to 2030, without implementation of Integrated Sediments Management Plan.
- B. Storage Dams up to 2035, without implementation of Integrated Sediments Management Plan.
- C. Erosion control measures with a 50% adoption rate, meaning the NbS or erosion control measures (part of the Integrated Sediments Management Plan) are effective by 50%.
- D. Erosion control measures with a 90% adoption rate, meaning NbS measures are effective by 100%.
- E. Regulatory dams in the main reaches, to control sediment transport and use sinks to clear sediments from the system.

From the key cost-benefit indicators presented in Table 77 1, the following conclusions can be drawn:

- *Scenario B vs A:* Phase 2 (investments up to 2035) of the Strategic Storage Water Plan provides substantial additional economic benefits compared to Phase 1 (up to 2030 only). The return on investment for the 2035 horizon is more favourable due to the reduced investment costs, but in the long run (2050), the return on investment is much higher if Phase 2 is included. At the same time, the benefits will reduce significantly towards 2050 due to the increased sedimentation and the consequently reduced benefits progressively over time.
- *Scenario C and D*: accompanying new grey infrastructure (dams) with investments in green infrastructure (NbS for erosion control) leads to substantial additional land and water productivity benefits. The returns, however, depend to a large degree on the successful adoption of the NbS investments. The return on investment of a high adoption scenario (100% - Scenario D) is significantly higher than a moderate adoption scenario (Scenario C).
- *Scenario E: c*omplementing the investments with regulatory dams, to trap sediments and clear sediments from the system, leads to slightly higher water productivity benefits. The return on investment for the 2050 horizon is positive, but to a lesser extent than a scenario in which these dams are not built due to their high maintenance costs. Also, the Present Net Value is lower, suggesting that this complementary investment in regulatory dams is less favourable from an economic point of view.

Table 1: Cost-benefit indicators of the five scenarios

Cost-benefit indicator		Scenario				
	Unit	A	B	C	D	E
Mean annual water productivity benefits	*M US$/yr*	69	139	155	188	187
Mean annual land productivity benefits	*M US$/yr*	3	1	4	7	6
Return on investment in year 2035	*%*	-106%	-139%	-133%	-124%	-135%
Return on investment in year 2050	*%*	8%	-3%	25%	78%	8%
Disc. rate 6%: NPV in 2050	*M US$*	204	285	412	650	462
Disc. rate 12%: NPV year 2050	*M US$*	2	-22	32	131	38
Disc. rate 6%: year positive NPV	*yr*	13	16	15	14	16
Disc. rate 12%: year positive NPV	*yr*	19	>30	22	17	22

Overall, the proposed Strategic Water Storage Plan will lead to considerable benefits for the 2050 horizon due to a portfolio of investments in grey and green (NbS).

Flagship projects

The assignment identified three flagship projects expected to be transformative and contribute to implementing Vision 2050, the Strategic Water Storage Plan and the Water Resources Development Guidelines. The following three flagship projects were identified in consultation with stakeholders:

- Multi-purpose Dam in Rulindo.
- Irrigation Dam in Kayonza.
- Groundwater for improving water security in Kirehe.

Multi-purpose Dam in Rulindo:

Outcome: Improved water use efficiency and optimised water allocation for urban water supply in Kigali, rural irrigation and electric generation in Rulindo.

Outputs:

- Development of a multi-purpose storage reservoir for water supply to Kimisagara WTP, climate smart irrigation development in Yanze catchment, recreation and eco-tourism, and smart association of renewables for electricity generation (solar and hydro).
- Integrated plan to sustainably manage sedimentation, including upstream landscape restoration for soil erosion control using NbS and reservoir dredging.
- Development of the project business case and investment plan.

Rationale:

The multi-purpose dam is located on the Yanze river, in Rulindo District. The major water uses observed in the Yanze catchment are upstream agriculture by the local communities and water supply to Kigali. Yanze river is one of the water supply sources for the City of Kigali through the Kimisagara WTP, which produces 22,000 cubic meters per day of treated water. Over the years, the river has been facing growing challenges affecting the catchment's water availability. This reduction in water availability has led to increasing water conflict between the local communities and WASAC.

A multi-purpose storage reservoir is proposed for water supply, irrigation and electricity generation associated with upstream landscape restoration. The dam would be on the Cyonyonyo stream, a tributary of Yanze River, with a dam height of 37 m and storage of 14.2 MCM, and inundate a total area of 90 ha.

The reservoir will optimise domestic water supply, by storing water during periods of water scarcity and improving the river's water quality due to the integrated sediment management plan. The plan will reduce soil erosion and sedimentation, by treating the sediment source from the degraded upstream landscapes and removing sediment from the reservoir. The first sub-component of the sediment management plan will focus on upstream landscape restoration with NbS to minimise soil erosion. The second sub-component will deal with the reservoir's de-siltation by removing sediment using innovative and low-cost technologies for suction, dredging and sediment storage.

The irrigation component will cover 913 ha, designed to be climate resilient, with optimum crop water productivity. To generate additional revenue and build heritage from the project, recreational and eco-tourism activities (e.g., boating, site seeing, hotels) will also be developed. The proximity of Kigali is an advantage in this respect. Another component of the project will be related to energy generation, mainly to satisfy the need of the communities in the catchment. A mixture of hydro and solar energy will be assessed in this project. For solar energy, the less accessible side of the reservoir will be used to install floating PV panels.

Payment for Ecosystem Services (PES) will be developed to ensure the self-maintenance of the upstream NbS interventions, supporting and encouraging upstream farmers to conserve their lands. This scheme will be designed as a fund, to be hosted in FONERWA for the benefit of upstream farmers (also the local landowners). Revenue will be collected from those directly benefitting from the reservoir's water resources, mainly WASAC, REG, RAB and the eco-businesses using the reservoir.

To optimise the project management and ensure it generates high income at the macro level, the project will incorporate a PPP framework specifically designed to attract an investor that will develop the reservoir and all those components, and be allowed to use it for 25 years.

Irrigation Dam in Kayonza

Outcome: Improved water use efficiency and optimised water productivity through climate-resilient irrigation in Kayonza District.

Outputs:

- Development of a single-purpose storage reservoir for climate-smart large-scale irrigation development in Kayonza District, with recreational and eco-tourism activities around the reservoir .
- Integrated plan to sustainably manage sedimentation, including upstream landscape restoration for soil erosion control using NbS and reservoir dredging.
- Development of the project business case and investment plan.

Rationale:

The Eastern Province of Rwanda, including the Kayonza district, has faced a prolonged drought that has increased water scarcity in the region. This region receives the lowest rainfall amount per year in Rwanda. At the same time, Kayonza district is among the country's most suitable agricultural land, which is why there are many irrigation projects in the area.

The flagship project consists of developing an irrigation reservoir in the sub-catchment of Kadiridimba. The dam would supply water for irrigation and cattle farming systems. The dam will be 16m in height, store 147.8 MCM and inundate 1,870 ha.

The irrigation component of this project will be a scheme of 9,795 ha. The area will be designed to be climate resilient, with a supplemental irrigation system. Optimum crop water productivity will be achieved with capacity building based on FAO's "Real Water Savings" concept to understand how to optimise their water efficiency practically.

Similar to the first flagship project in Rulindo, the project will contain the following:

- additional revenue, with eco-tourism activities;
- the integrated sediment management plan, with NbS for soil erosion control upstream and regular desilting from the reservoir;
- energy generation with a mixture of hydro and floating PV for solar energy, mainly to satisfy the need of the communities in the catchment;
- PES to ensure the self-maintenance of the NbS interventions, with a fund to be hosted in FONERWA and fed from those directly benefitting from the reservoir's water resources, mainly REG and RAB and the eco-businesses using the reservoir;
- a PPP framework specifically designed to attract an investor that will develop the reservoir and all those components, and be allowed to use it for 25 years.

Lastly, RWB is considering a water transfer project in the lower Akagera. Suppose this transfer project would be technically feasible and acceptable from an environmental and social standpoint, it could be relevant that the receiving point of the transfer would be the new dam, bringing the potential to produce more benefits (irrigation and hydropower).

Groundwater for improving water security in Kirehe

Outcome: Improved water security for rural domestic water supply, livestock and small-scale agriculture through sustainable groundwater exploitation.

Outputs:

- Development of multipurpose groundwater exploitation for rural domestic water supply, livestock and possibly climate-smart small-scale irrigation.
- Integrated plan to sustainably manage groundwater recharge through landscape restoration, of the recharge catchment, for increased infiltration using NbS.
- Development of the project business case and investment plan.

Rationale:

Groundwater is relatively unexploited in Rwanda, while it can be a supplementary water source in areas with scarce surface water resources. A recent from UNICEF has identified zones of high potential in the southeastern region of Rwanda, particularly in the Kirehe district. As is generally the case for the Eastern Province, this district has been facing a prolonged drought that has increased water scarcity in the region. Since the district has been included in secondary cities, the urban population is planned to increase to 650,000 people, with an additional 100,000 in rural settlements. This means water supply demand will increase rapidly in the area. At the same time, Kirehe District is among the country's most suitable agricultural land, which is why there are many irrigation projects in the area. There has also been growing conflict between the refugee camp and the hosting communities cultivating around, who associate land degradation with excess runoff generated within the camp.

Therefore, the flagship project is about a detailed analysis of groundwater in the district and exploiting it, primarily to supply domestic water and secondarily to livestock and irrigation, if groundwater potential is sufficient. In addition, the prospect of solar pumps should be studied to withdraw groundwater.

Experience in other countries where groundwater is extensively exploited calls for caution to avoid depletion. The project should therefore be carefully framed to avoid uncontrolled groundwater exploitation, especially if solar pumps are used. Furthermore, groundwater use for irrigation should be associated with climate-smart agriculture and efficient irrigation systems to best use extracted water. Finally, sustainable groundwater management, including financial sustainability, should be explored by associating government organisations (e.g., WASAC, RAB, RWB), private players and local communities.

Revised National Policy for Water Resources Management

Implementation of the 2011 National Policy for Water Resources Management

The objectives of Rwanda's 2011 National Water Resources Management Policy were designed for direct translation into implementation activities, with indicators and associated responsibilities. The Policy reflected Rwanda's intentions on institutional coordination while supporting the devolution of decision-making and management to district authorities, enhancing the sustainability of service provision, regulation, and management through use-based fees. The 2011 Policy recognised water as a cross-cutting natural resource with applications across all sectors, including domestic consumption, agriculture, commerce, and industry, as well as ecological functions for environmental conservation and providing essential ecosystem services for the sustainability of nature-based resources, including forests, fisheries, and animals.

Despite a sound and well-articulated basis, discussions with stakeholders identified several policy implementation challenges. These include growth in population, land use, agriculture, mining and urbanisation. The continuous high level of sedimentation of rivers, dams and other storage systems also poses a challenge. Other challenges were the extent of interagency coordination required to meet the policy goals, adequacy of human, technical and financial resources, mobilisation and deployment, and the challenges of devolution given low technical capacities at district levels and the inherent misalignment between a catchment-based approach to managing water given empowerment of district authorities.

Revision of 2011 policy and incorporation of latest targets

The Revision of the 2011 policy is to lead to a new policy merging Water Supply, Sanitation and Water Resources sectoral policies. Consultations with key officials from lead Ministries, State Agencies responsible for implementation and development partners suggest the following as areas of interest in the emerging new Policy:

- **Sustaining the gains made for water resources management since 2010**. At the institutional level, The Rwanda Natural Resources Authority gave rise to Rwanda Forest and Water Authority under the Ministry of Environment. Finally, in 2020, the Rwanda Water Resources Board (RWB), independent of any Ministry, was formed with broad powers to manage and coordinate all Ministries, agencies and sector actors, answerable to Government directly through the Prime Minister. The establishment of the RWB was recognised as a good first step in providing a cross-sectoral governance arrangement that now needs to be institutionalised in policy, law and regulations.
- **Sector practitioners worry that merging the WRM Policy with the more visible water supply may jeopardise the gains made**, particularly if a similar amalgamation of the legal and regulatory framework follows this. Decision-makers, particularly at district and local levels, frequently favour water supply due to its direct impact and support from residents.
- **On the other hand, there is an opportunity to strengthen awareness of catchment protection,** as water quality is a key concern for users and managers, who are likely to take direct roles in watershed conservation to enhance the security and quality of the water sources.
- **Actors involved in the human right to water advocacy would like to include direct mention of hygiene** in the new policy title to give effect to findings of the recent Demographic and Health Survey that indicates the issue of hygiene is lagging behind and thus needs high-level visibility to gain more attention and funding.

- **Strengthening the capacity of District Authorities for management and implementation** has to be core to enhanced water security and preventing degradation of landscapes essential to water quality and safety while integrating the service delivery to resource sustainability.

Recent targets to include in the new policy include the NST1 and Vision 2050, with ambitious objectives for individual access to domestic water and sanitation.

Implementation Plan for the revised 2011 National Policy for Water Resources Management

The first version of the new policy, drafted by the Inter-Ministerial Task Force, was reviewed during the assignment. The first draft placed a premium on the external environment in which services are delivered. The following was suggested to the task force:

- Strengthen the internal capacities of the implementing agencies.
- Define institutional roles and responsibilities (including trade-offs, for instance, between economically important initiatives like agro-industry or mining that may compromise water quality).
- Effective communication and engagement, beyond raising awareness towards effective and substantive public engagement.
- Community action in water resources management, such as flood control, drought management and soil and water conservation.

The Task Force produced afterwards a second draft, reviewed during the assignment and the following areas for further strengthening were emphasised:

1. Major water resource user sectors (e.g., hydropower, mining, irrigation, hygiene, health) should update their master plans.
2. The international agreements Rwanda has committed to should be accounted for since these commitments will imply significant demand for water resources.
3. Following WHO's Water Safety Plan roadmap, Water Safety Plans should be instituted to enhance risk management for domestic water supply.
4. WASAC needs to extend its support for self-supply domestic water (technology, finance) for rural households.

0 Introduction

0.1 Context

Rwanda's 2011 National Water Resources Policy was founded on the principle of catchment-based water resources management. In 2015, within this framework, the National Water Resources Master Plan (NWRMP) was developed, which divided the country into nine Level 1 catchments and twenty Level 2 catchments. The NWRMP quantified, at catchment Level 1, available water resources, water demand, under current and projected situations, and formulated management options for the rational use of available water resources. The Master Plan had a time horizon of 25 years (up to 2040).

In 2017, Rwanda developed a Strategic Program for Climate Resilience (SPCR) as an investment vehicle for Rwanda to meet its climate change goals and to ensure the country is well-equipped to face climatic uncertainties. Among its different sub-programs, the SPCR has "Water Security for All" with three themes:(1) integrated strategic water resource planning and management; (2) catchment restoration; and (3) climate-resilient water infrastructure.

Rwanda has also dedicated commensurable efforts to plan its water resources better. Principal achievements include the 2017 National Strategy for Transformation (NST1), the 2019 Natural Capital Accounting, and the 2020 Irrigation Master Plan and National Land Use and Development Master Plan. It has also developed catchment management plans for most of its catchments.

In 2020 and in continuation of its Vision 2020 and NTS1, Rwanda published Vision 2050, its national long-term development strategy and the adaptation priorities set out in the Enhanced National Determined Contributions (2020), stating new objectives for urbanisation, energy production, irrigation and water resources development. According to the preliminary analysis of a number of catchments (Sebeya, Muvumba, Upper Nyabarongo and Nyabugogo), the consequence of this ambitious vision on demand for water resources is large water deficits by 2050.

Recently (2022) the World Bank published the Rwanda Country Climate and Development Reportwhich highlights key interventions that are needed in Rwanda to strengthen climate resilience in the context of country's development priorities and its commitments under the Paris Agreement. The CCDR finds that additional climate investments in water resources infrastructure could accelerate the pace of structural transformation.

From the 'available water', a limited share can actually be used (technically and economically), as the availability timing is not always aligned with the demand. This suggests a potential for increasing the utilisable water by investing in grey and green infrastructures that increase water storage and promote groundwater recharge through water conservation measures. The 2015 National Water Resources Master Plan identified 143 potential dam sites across all the nine Level 1 catchments with estimates of storage capacity at each site as illustrated in Figure 1.

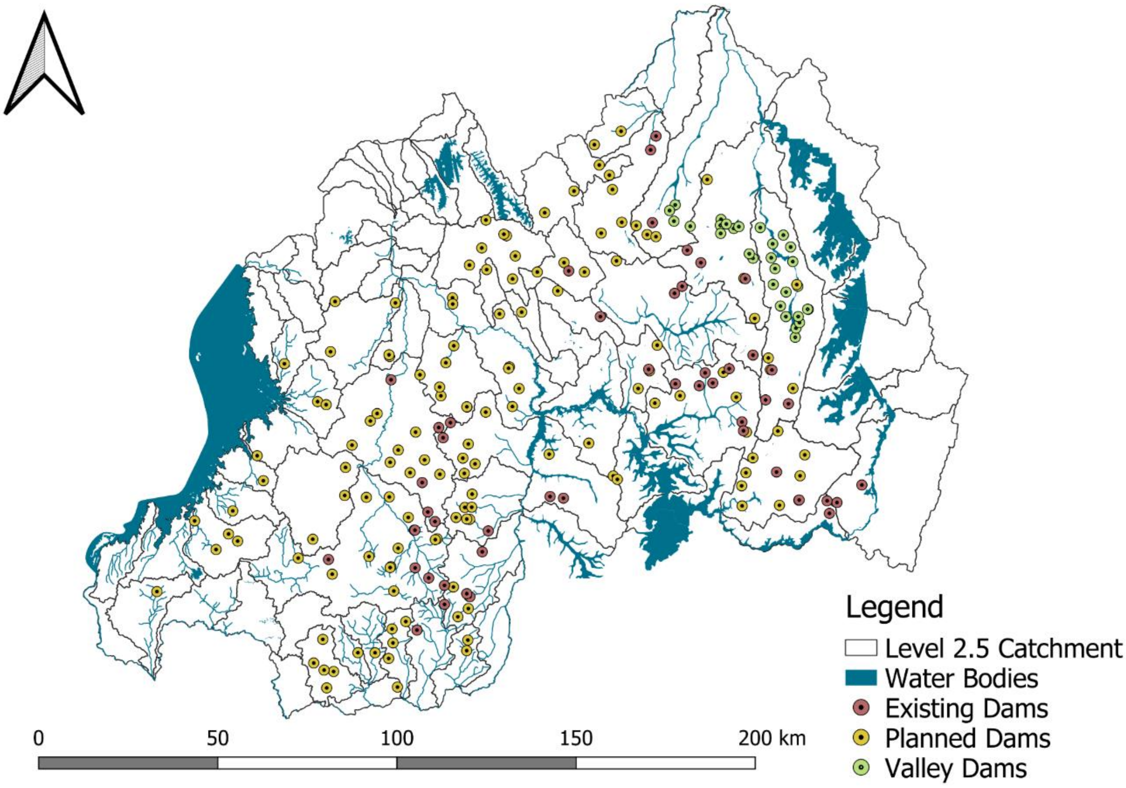


Figure 1. Map showing existing and potential dam sites, on top of the 2.5 catchment delineation (source: HEA)

There is a need to review and update the National Water Resources Master Plan, considering the Vision 2050 covering the period up to 2050. Specifically, there is a need to adjust the current planning to the country's ambitions expressed in Vision 2050 and to Rwanda's Strategic Programme for Climate Change (2017) sub-investment programme #2 'Water Security for All'. It is critical to clarify the roles that catchment restoration, storage and water resources development will play in the trajectory of economic development toward a high-income country, while detailing the actions needed and flagship projects that may catalyze the required transformation.

In this context and to implement the SPCR's "Water Security for All" sub-program, the Rwanda Green Fund (FONERWA), in collaboration with the Rwanda Water Resources Board (RWB) and with financial support from the World Bank, has undertaken the **"Integrated strategic water resources planning and management in line with the Rwanda's Vision 2050"**. This planning will essentially build on the 2011 National Water Resources Management Policy, the 2015 Water Resources Master Plan, developed catchments plans, water accounts, water resources development plans such as Water supply and Sanitation Plans for Kigali and Rwanda (2021), Irrigation Master Plan (2020), and Energy sector strategic plan (2021).

In parallel, the World Bank's 2030 Water Resources Group (WRG2030) has conducted a Hydro-Economic Analysis (HEA) of water resources in Rwanda. This assignment builds on the national water allocation model and the recommendations produced by the HEA study.

0.2 Objectives of the study

The general objective of the study is to develop integrated strategic water resources plans and management guidelines to meet National Strategy for Transformation (NST1) and Vision 2050 targets. Specifically, the assignment is organised along the following five main topics:

- Detailed Hydrological Assessment, with a groundwater resources assessment, the development of a semi-distributed hydrological model to assess the hydrological budget for the current situation and under climate change.
- Detailed Water Allocation Assessment, with the development of a water allocation plan, the analysis of the water surplus and deficits in space and time and the identification of prioritised strategic water resources development infrastructures.
- Strategic Water Resources Conservation and Development, with a technical appraisal of each prioritised strategic water resources development infrastructure, an assessment of contribution from Natural based Solutions to protect new infrastructures, the update of water resources development guidelines and the requirement to set Private Public Partnership and Payment for Ecosystems services.
- Strategic Water Resources Management Option, with stakeholder engagements to finalise the strategic water storage plan for Rwanda and to identify flagship projects, the cost-benefits analysis of the strategic water storage plan and the drafting of a series of flagship project concept notes.
- Revised National Policy for Water Resources Management, to revise the 2011 National Water Policy based on latest policies, in particular the Vision 2050 and NST 1.

0.3 Content of the Final Report

The Final Report contains the final results of the study and is organised into five main chapters reflecting the following five main topics:

- Chapter 1: Detailed Hydrological Assessment.
- Chapter 2: Detailed Water Allocation Assessment.
- Chapter 3: Strategic Water Resources Conservation and Development
- Chapter 4: Strategic Water Resources Management Options
- Chapter 5: Revised National Policy for Water Resources Management

It is also accompanied by the following 18 annexes:

- Annexe 1: Status of data collection and review
- Annexe 2: Boreholes data
- Annexe 3: Groundwater monitoring wells in Rwanda
- Annexe 4: Results of the ERT- 2D resistivity
- Annexe 5: WEAP Model set-up
- Annexe 6: Level 2.5 catchment spatio-temporal hydrological assessment for the baseline situation
- Annexe 7: Level 1 Climate Change Analysis for Meteo-Rwanda data
- Annexe 8: Level 2.5 catchment spatio-temporal hydrological assessment for the Baseline vs RCP 4.5 vs RCP 8.5 climate change scenarios.
- Annexe 9: Water Allocation Plan.
- Annexe 10: Overview of Potential Dams.
- Annexe 11: List of prioritised dams.
- Annexe 12: Field report (technical appraisal of prioritised dams).
- Annexe 13: List of Nature-based solutions for the prioritised dams.

- Annexe 14: Blue water availability and artificial storage per capita, for StorDevPlan2050 scenario
- Annexe 15: List of primary and secondary stakeholders for water resources management in Rwanda.
- Annexe 16: National agencies and stakeholders consulted on Policy Review.
- Annexe 17: Draft Policy Implementation Plan.
- Annexe 18: Updates on the second draft of the new water Policy based on stakeholder inputs.

1 Detailed Hydrological Assessment

1.1 Development of a level 2.5 catchment semi-distributed hydrological model

For the development of the semi-distributed hydrological model at catchment Level 2.5 the following key inputs were required and collected:

- The WEAP model developed for the Hydro Economic Analysis (HEA) – afterwards referred to as WEAP_HEA.
- The input data of WEAP_HEA.
- Climate data from Meteo-Rwanda and other datasets from the respective national agencies.
- Other datasets, satellite-based or in the public domain.

These datasets are summarized in section 1.1.3.

The HEA study, onto which this assessment builds, subdivided the L2 catchments further into 86 level 2.5 catchments (Figure 2), which is the level of detail in the WEAP model adopted in this study as well. The calibrated model established during this preceding study, and its initial set-up have been acquired from SEI and served as the basis for this continuation study. To guarantee that outcomes of this study are as consistent as possible with the HEA work, only necessary adjustments have been made, making the model better fit for this assessment (see section 1.1.2). As a reference, the catchment delineations for level 2.5 and level 1 are presented below (Figure 2).

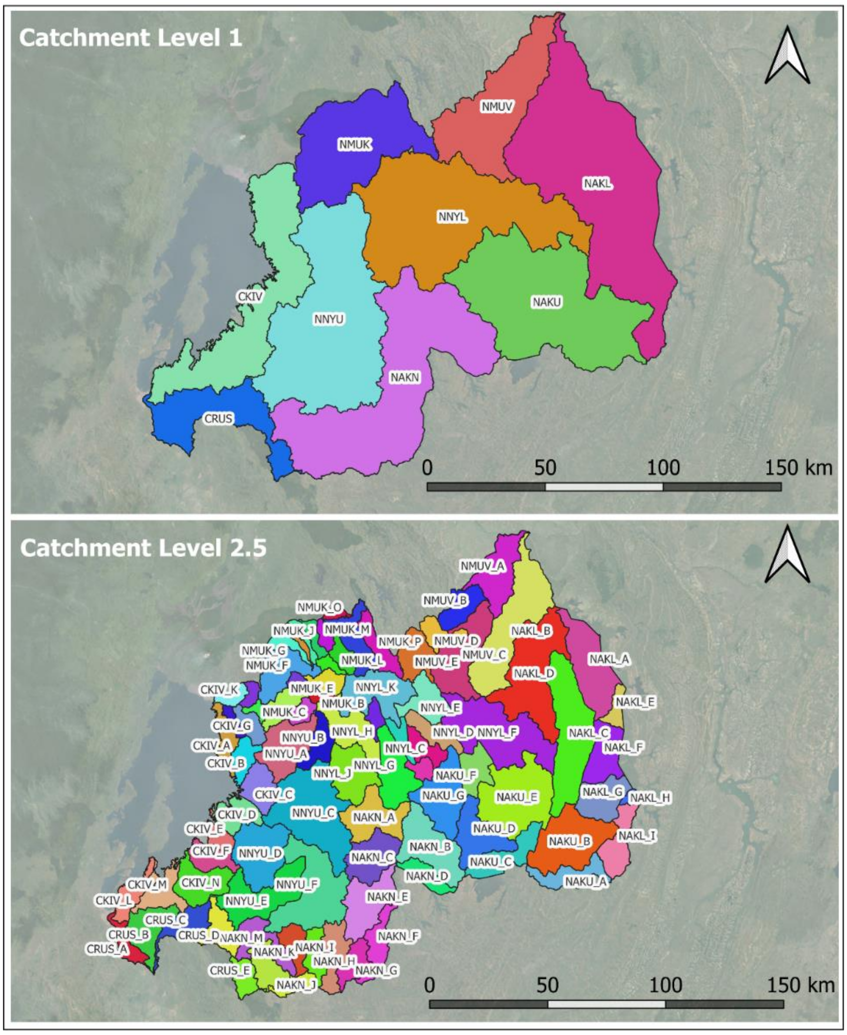


Figure 2. The 9 level 1 catchments and 86 level 2.5 subcatchments as represented in the WEAP model.

1.1.1 Modelling approach

The WEAP_HEA model was received and checked for the assumptions, parameters and model setup. Some interaction with the developers was deemed necessary, and these responded swiftly to resolve a few issues around delineation, among others. Initially, a draft version of the model was received, which was useful for evaluating and testing the model. Later, the final version of WEAP_HEA was received for being used in this study (received on May 23, 2022).

The WEAP_HEA model has 86 sub-catchments (Figure 3). A typical schematic of a sub-catchment is shown in Figure 4. This schematic is implemented for all sub-catchments, although some have small variations. A few minor modifications were made in the schematic for this study, besides other changes and improvements (see section 1.1.2).

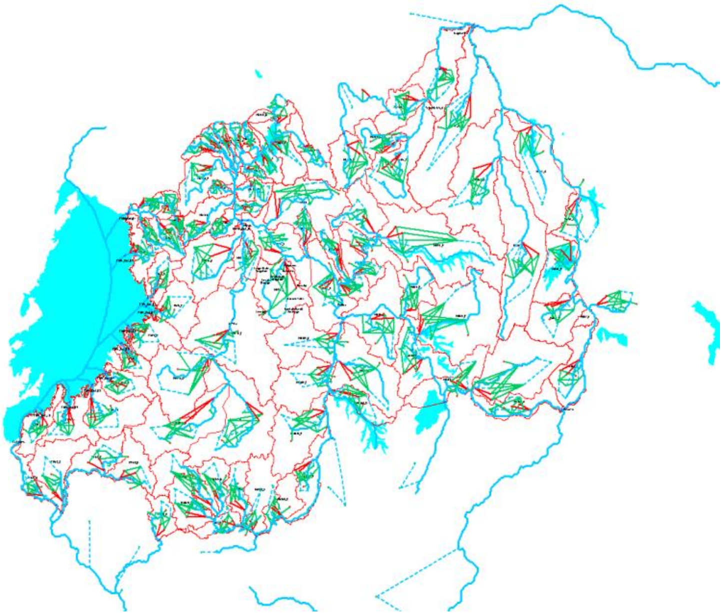


Figure 3. Screenshot of the schematic of the full extent of the WEAP_HEA model

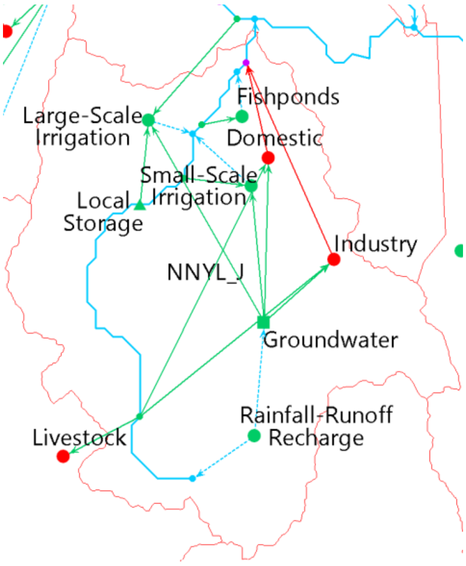


Figure 4. Schematic of a typical sub-catchment in the WEAP_HEA model

One of the core outputs of Task 1 is characterising the hydrology of the Rwandese landscape at catchment level 2.5, for current and future conditions considering the impact of climate change. Thus, the modelling approach needs to cover:

- A baseline climate period (2000 – 2019), as a reference to compare future conditions.
- A future period, incorporating climate change conditions and representative for 2050 (2040 – 2059).

Two climate change scenarios have been established next to a baseline scenario, which relies on historical Meteo-Rwanda data (1981 – 2019). The two climate scenarios are extracted from an RCM provided by Meteo-Rwanda, which has projections for 2021 – 2070 for Precipitation and Temperature for two Representative Concentration Pathways (RCP) 4.5 (RCP 4.5) and 8.5 (RCP 8.5). A detailed overview of the climate data and the three scenarios is provided in section 1.4.1.

Each of these two climate scenarios is then used to determine the mean change, using the Baseline for reference, indicating the change for the period 2050 (averaged for 2040 – 2059) vs 2010 (average 2000

– 2019). The change that will be examined is the variation in each of the five hydrological variables of interest for the hydrological assessment, using a weighted absolute/ percentual average. The five hydrological variables of interest are Precipitation, Evapotranspiration, Surface Runoff, Interflow and Groundwater Recharge. The analyses will not only focus on significant trends within each of the three climate scenarios but also among the three scenarios.

1.1.2 Improvement of the WEAP_HEA model setup

The WEAP_HEA model established by SEI for the HEA was found to be well established for this assessment. This was observed by analysing the model set-up and cross-checking the model output with data received and scrutinised during inception phase (ETa, precipitation, and discharge, detailed afterwards). Annexe 5 outlines the various important components of the WEAP model and provides some of the assumptions made during parameterisation.

As mentioned before, the WEAP_HEA has been the starting point for the model setup of this study. Although the calibrated model showed to be set-up accurately, and satisfying results were obtained, some improvements to the model setup and input data have been implemented, with the following criteria:

- Update of the historical and future climate data, based on data provided by Meteo-Rwanda.
- Consistency of the topology of the sub-catchments and components of the hydrological system.
- Consistency with estimates in the National Water Resources Master Plan (NWRMP, 2015).

Based on these three criteria, the following improvements were made:

1. The historical and projected climate input was replaced with data provided by the Meteo-Rwanda (see Annexe 7).
2. Some clarifications have been applied within the model schematisation, so the naming of the various L2.5 catchments is straightforward. A general description of the WEAP model set-up is presented in Annexe 5.
3. The areas accounted for in the WEAP_HEA model were adjusted to align with those reported in the NWRMP (2015) (see Annexe 5). Also whereas initially the WEAP_HEA model considered 88 catchments, the final version included 86. Areas were adjusted to be representative for these 86 catchments as explained in Annexe 5.
4. The areas of large irrigation, irrigation and/ or fishpond expansion are subtracted from the catchment areas to keep the total land area equal.
5. Lake volumes were corrected to account for active storage. In addition Precipitation and Temperature data were assigned to the lake nodes to account for evapotranspiration.
6. The original model accounted for additional storage based on projected large irrigation expansion. As the aim of this study is to prioritize potential storage reservoirs, the former was replaced with the latter within all the Water Resilient scenarios. In addition, storage reservoirs that are already planned but not yet constructed were implemented through individual storage nodes. Lastly, storage of existing reservoirs was updated using the annual water storage status report (RWB, 2021)[1].

To understand how to move forward with the WEAP_HEA model, the reported areas at level 2.5 and L1 were analysed. Given that the output of this study will serve as a baseline for the updated water resources masterplan, the areas obtained from the existing WEAP model were crosschecked with those (in km^2) reported in the NWRMP (2015). Aggregated at level 1, the analysis showed that some areas accounted for in the WEAP_HEA model did not conform to those reported in the National Water Resources Master Plan (2015), which showed slightly higher areas for some of the sub-catchments. An adjustment through a correction factor determined based on the identified gaps was applied for sub-catchments CKIV and NMUK so that the areas obtained in the NWRMP (2015) are maintained throughout this study. For the

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[1] ANNUAL WATER STORAGE STATUS REPORT FOR 2020 -2021, Rwanda Water Resources Board. June 2021.

cross-border catchments NAKL and NMUV, a clip to the national (level 0) border was applied so that the areas are consistent with the NWRMP (2015).

Table 1. Updated Areas in WEAP model following the discussed methodology (see Annexe 5).

Level 1	Areas NWRMP 2015 (km2)	WEAP Model Input (HEA) (km2)	Adjusted Areas WEAP (km2)	NWRMP 2015 - Adjusted WEAP (km2)	Difference NWRMP 2015 / WEAP (%)
CKIV	2425	2152	2425	0	0%
CRUS	1005	1010	1005	0	0%
NNYU	3348	3378	3350	2	0%
NMUK	1887	1635	1887	0	0%
NNYL	3305	3278	3307	2	0%
NAKN	3402	3390	3405	3	0%
NAKU	3053	2704	3058	5	0%
NAKL	4288	3659	4288	0	0%
NMUV	1565	1583	1569	4	0%
TOTAL	24278	22788	24294		(km2)

Regarding the historical and projected climate data, Meteo-Rwanda data replaces the Princeton dataset used in the WEAP_HEA model, which only had time-series data till 2010. In doing so, the model improved as it better captures the baseline with time-series data from 1981 till December 2019. For one catchment (CRUS), the Princeton dataset was kept as the Meteo-Rwanda dataset showed to be significantly beyond the values obtained within the NWRMP (2015) and the average annual precipitation from the Princeton time-series dataset. As the data for CRUS was copied from the Princeton dataset, it needed to be lengthened to cover the period 2011 – 2019; a monthly average of the last thirty years (1980 -2010) was used to do so.

Table 2 shows how the Meteo-Rwanda data compares to the Princeton dataset and the precipitation averages presented in NWRMP (2015). It is pivotal to note that the Meteo-Rwanda data was analysed for 1981-2019, whereas the Princeton dataset for 1980-2010. For the NWRMP estimates, it is not known over which timespan these estimates were obtained. A detailed analysis is presented in Annexe 7.

Table 2. Precipitation data for the input Princeton dataset, the Meteo-Rwanda dataset and the estimates provided in the NWRMP (2015).

SC	Meteo-Rwanda [mm/year] (1981 - 2010)	Princeton [mm/year] (1980 – 2010)	Princeton /Meteo-Rwanda %change	NWRMP (2015) [mm/year]	NWRMP/ Princeton %change	NWRMP/ Meteo-Rwanda %change
CKIV	1475	1404	105%	1240	88%	84%
CRUS	1995	1396	143%	1295	93%	65%
NNYU	1426	1272	112%	1365	107%	96%
NMUK	1438	1263	114%	1315	104%	91%
NNYL	1292	1084	119%	1191	110%	92%
NAKN	1301	1161	112%	1225	106%	94%
NAKU	1033	954	108%	925	97%	90%
NAKL	895	951	94%	835	88%	93%
NMUV	1068	997	107%	995	100%	93%

Following these findings, the WEAP input files for the baseline scenario (i.e. year 0) were adjusted with Meteo-Rwanda data to represent both the historical precipitation and average temperature. Subsequently, with the modified Meteo-Rwanda historical climate data, the output was cross-checked with the Meteo-Rwanda dataset (Figure 5). As indicated in the figure, major differences are obtained for the southern region (CRUS) where the Princeton dataset was used rather than the Meteo-Rwanda data. Other differences are minor and are attributed to the two different time-series ranges.

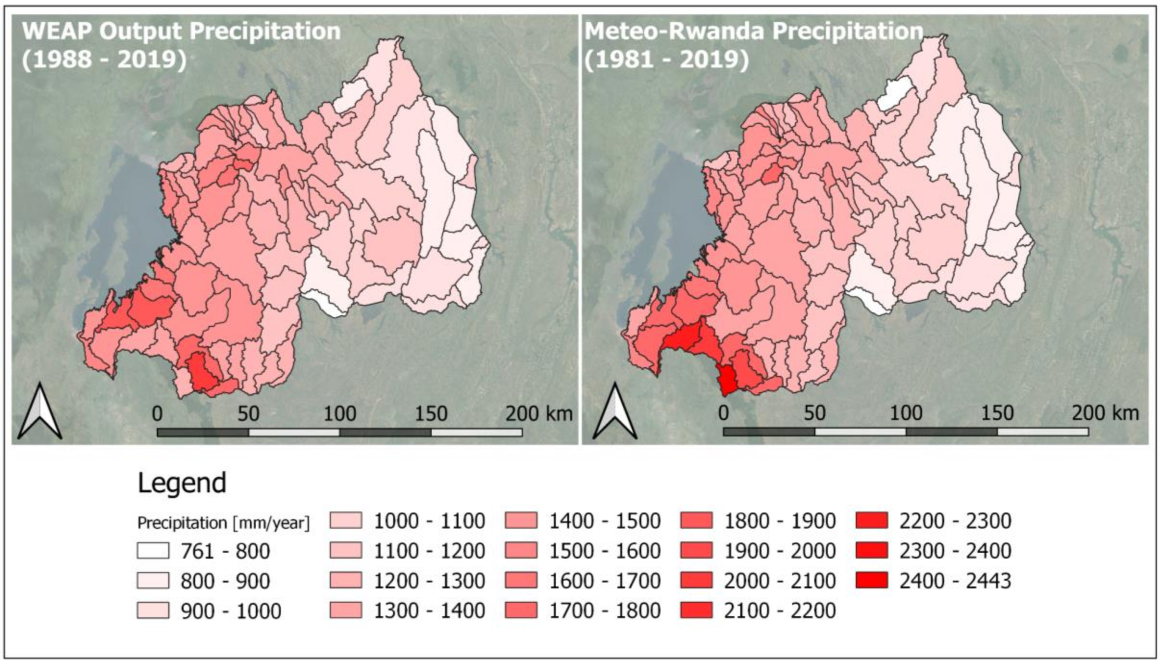

Figure 5. On the left, precipitation data as obtained from the WEAP results section (output for 1988-2019) and on the right, Meteo-Rwanda precipitation data statistically analysed for the period (1981 - 2019).

1.1.3 Hydrological data

Each of the relevant datasets to be considered for the hydrological analysis is presented below. Summarizing maps display the analysed data at catchment level 2, for which tables are also provided, and catchment level 2.5. The precipitation and evapotranspiration data were used to update and evaluate the WEAP_HEA model (see previous section). The other hydrological datasets presented here have been analysed to evaluate the WEAP_HEA model. Also, some of the datasets (e.g. erosion risk) presented here will become more relevant in the next phase of the study when the potential for improved catchment management has to be considered; those datasets are presented here already for completeness.

1.1.3.1 Precipitation

Precipitation data was collected from the Meteo-Rwanda, based on an extraction of 980 data points from the national ENACTS dataset (Figure 6). The “Enhancing National Climate Services-Initative” (ENACTS) reconstructed rainfall and temperature data by combining station data with satellite rainfall estimates, and with reanalysis products for temperature. Bias correction factors were applied to the satellite and reanalysis data and the merged final product is spatiotemporally complete from the early 1980s to the present at a high spatial resolution (4–5 km)[1]. Data was analysed for the available period 1981 – 2019.

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[1] Siebert, A., Dinku, T., Vuguziga, F., Twahirwa, A., Kagabo, D. M., delCorral, J., & Robertson, A. W. (2019). Evaluation of ENACTS-Rwanda: A new multi-decade, high-resolution rainfall and temperature data set—Climatology. International Journal of Climatology, 39(6), 3104-3120.

For each Level 1, 2 and Level 2.5 sub catchment, the extracted data points were averaged to obtain one single precipitation value per catchment level 2.5, as depicted in Figure 7.

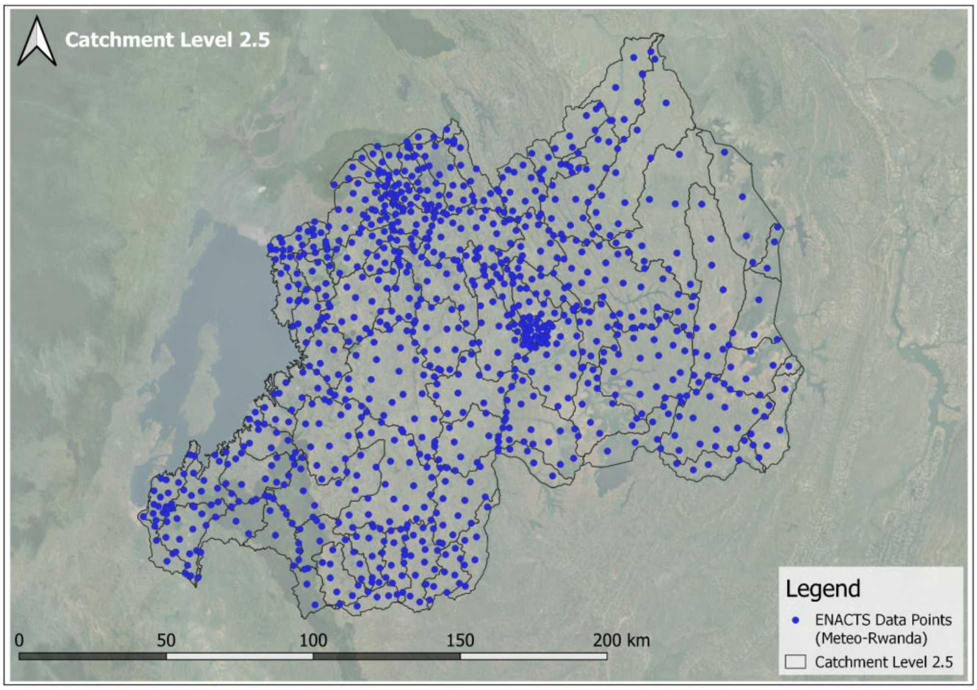

Figure 6. ENACTS Data Points (Meteo-Rwanda, 2022)

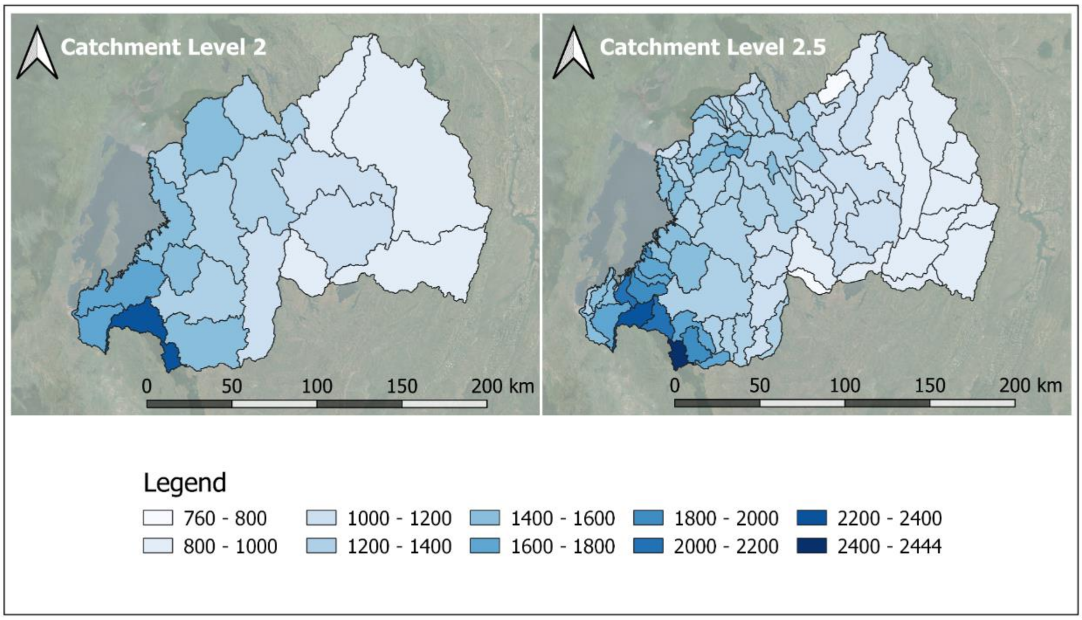

Figure 7. Annual Averaged Monthly Precipitation derived from 980 ENACTS virtual station data (Meteo-Rwanda, 2022).

Figure 8 shows for Level 2 the obtained results from the rainfall analysis. Catchment CRUS_2 (Western province) shows the highest annual precipitation, NAKL_1 in the Eastern province the lowest. From June to September, there is limited rainfall in most of the level 2 catchments. In general, the more eastwards, the less rainfall a region receives.

This dataset was used in the model on the request of Meteo-Rwanda, as the original model developed under the preceding study relied on the Princeton dataset. Meteo-Rwanda's dataset is based on satellite-based CHIRPS in combination with local weather station data. As explained earlier, the original Princeton dataset was exceptionally kept for CRUS.

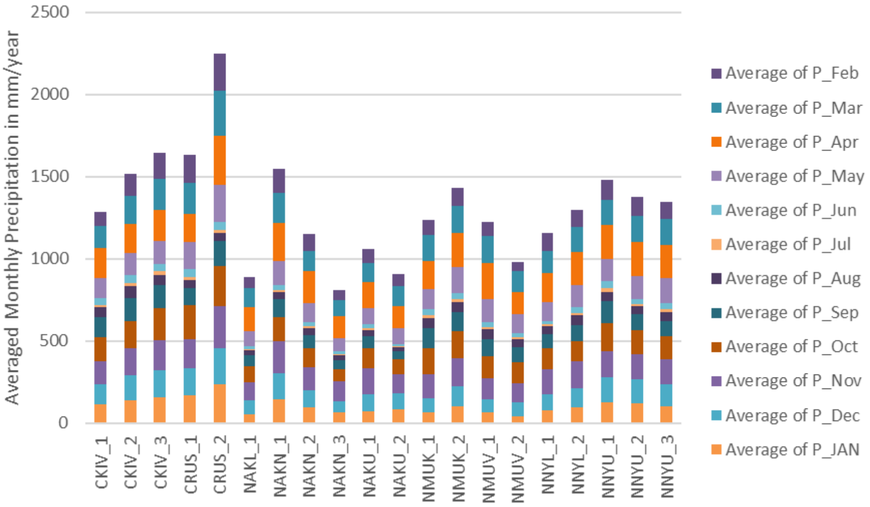

Figure 8. Summary of the monthly precipitation analyses for L2 catchment (1981 – 2020).

1.1.3.2 Evapotranspiration

The WaPOR data for the entire Rwanda (reference and actual evapotranspiration) has been collected to compare the WEAP model results with remote sensing data (see 1.1.4). The collected dataset contains GIS data at country-level for monthly reference evapotranspiration (ETref), actual evapotranspiration (ETa) and Crop Coefficient K_c (avg), from 01-2009 till 12-2021 (Figure 9). Although a 30m product is also available for Lower Akagera, it was decided to use the 100m resolution product for the sake of consistency at the national level (more than 2.5 million pixels).

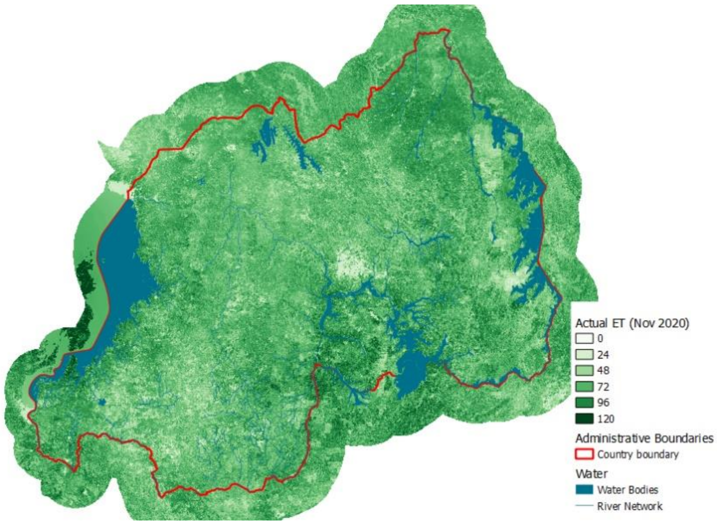

Figure 9. Example of WaPOR data: the monthly ETa in November 2020 in Rwanda

The WaPOR actual evapotranspiration (ETa) is calculated using a surface energy balance algorithm based on the equations of the ET_{Look} model. It uses a satellite platform with both multi-spectral and thermal imagery acquisition. In addition, meteorological data from remote sensing data products is used as input. The energy balance components are calculated with the specified algorithm: net radiation, soil heat flux, and sensible heat flux. The latent heat flux is calculated as residual to the energy balance and represents the evapotranspiration (ET) component of the energy balance. The ETa dataset used in this project is from Level II (100 meters) for each decadal period (10 days). Several publications assess the potential of over- or under-estimation for calculating seasonal ETa, which are available in the WaPOR portal[1] and peer-reviewed journals[2]. Figure 10 shows ETa for each land use class from the LULC-dataset (Esri Rwanda, 2018[3]). The highest absolute ETa is in CKIV_2, the lowest is in the Northern NMUV_1.

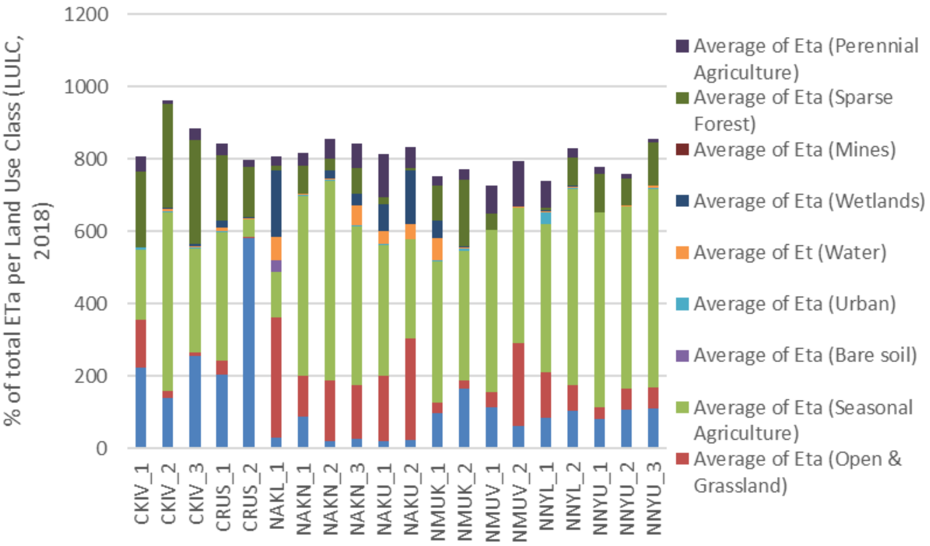

Figure 10. Averaged Annual ETa for each Land Use class (from LULC, 2018) using the WAPOR dataset (WAPOR, 2022).

As shown in Figure 11, there is no clear spatial trend in the ETa-dataset, as ETa mostly depends on land use rather than topography. CKIV_2 and _3 are in the highest ETa classes and both have a relatively high amount of Sparse Forests, which indicates that this class has a higher than average evapotranspiration rate (expressed in mm/year).

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[1] FAO and IHE Delft. 2019. WaPOR quality assessment. Technical report on the data quality of the WaPOR FAO database version 1.0. Rome. 134 pp. http://www.fao.org/3/ca4895en/CA4895EN.pdf

[2] Blatchford, M.L. ; Mannaerts, C.M. ; Njuki, S.M. ; Nouri, Hamideh ; Zeng, Yijian ; Pelgrum, Henk ; Wonink, Steven ; Karimi, Poolad. / Evaluation of WaPOR V2 evapotranspiration products across Africa. In: Hydrological processes. 2020 ; Vol. 34, No. 15. pp. 3200-3221.

[3] Esri Rwanda Ltd., ‘Land Use / Land Cover Map for Rwanda’ (Kigali, Rwanda: Esri Rwanda Ltd., 26 June 2018).

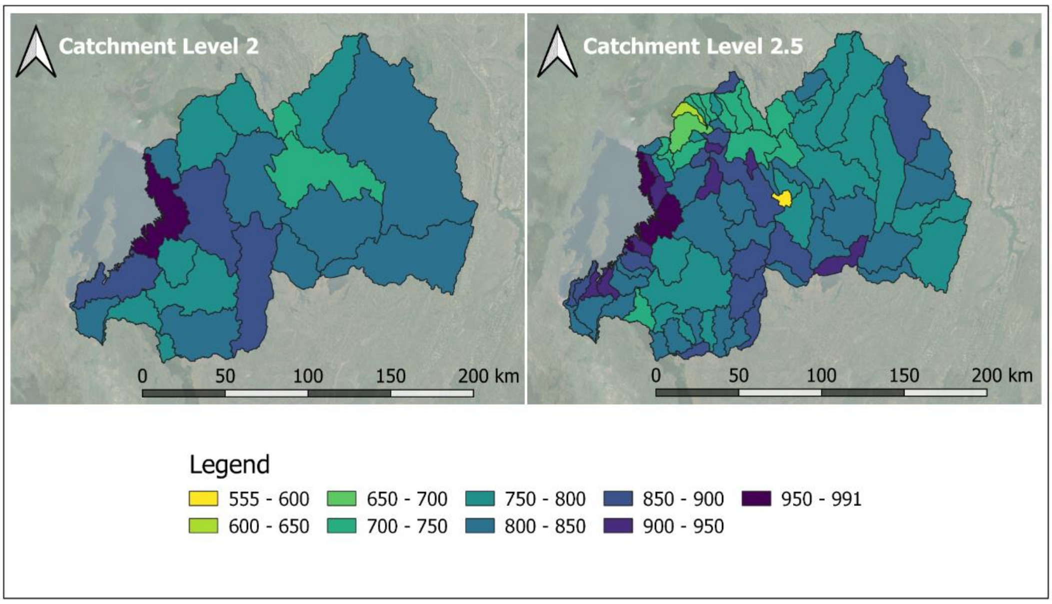

Figure 11. Annual Averaged Actual Evapotranspiration for Rwanda (Eta in mm/year) for both Catchment Level 2 (left) and 2.5 (right). Data retrieved from WAPOR dataset (years 2009-2021).

The average Eta across Rwanda varies between 555 mm/yr and 950 mm/yr. This is consistent with the values that were estimated for 2015 Water Resourses Master Plan, which indicated values ranging between 624 mm/yr and 980 mm/yr. These values are only slightly different which can be attributed to the different methods for estimation and the different time periods considered. A more detailed review of evapotranspiration obtained from different datasets is presented in section 1.3.2.

1.1.3.3 Soil characteristics

Three soil properties, important for the WEAP model, have been analysed: the saturated hydraulic conductivity (expressed in cm/day), the topsoil bulk density (in cg/cm3) and soil depth (in cm). Conductivity values of the topsoil take slightly higher values in the eastern province (Figure 12). The only exception is NMUK_1 in the Northern Province which shows a significantly larger saturated hydraulic conductivity, with values reaching up to 190 cm/day. The data source used for this analysis is HiHydrosoil developed by FutureWater in 2020 (Simons et al., 2020[1]), which has an original resolution of 250 m.

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[1] Gijs Simons, Reinier Koster, and Peter Droogers, ‘Hihydrosoil v2. 0-High Resolution Soil Maps of Global Hydraulic Properties’, 2020.

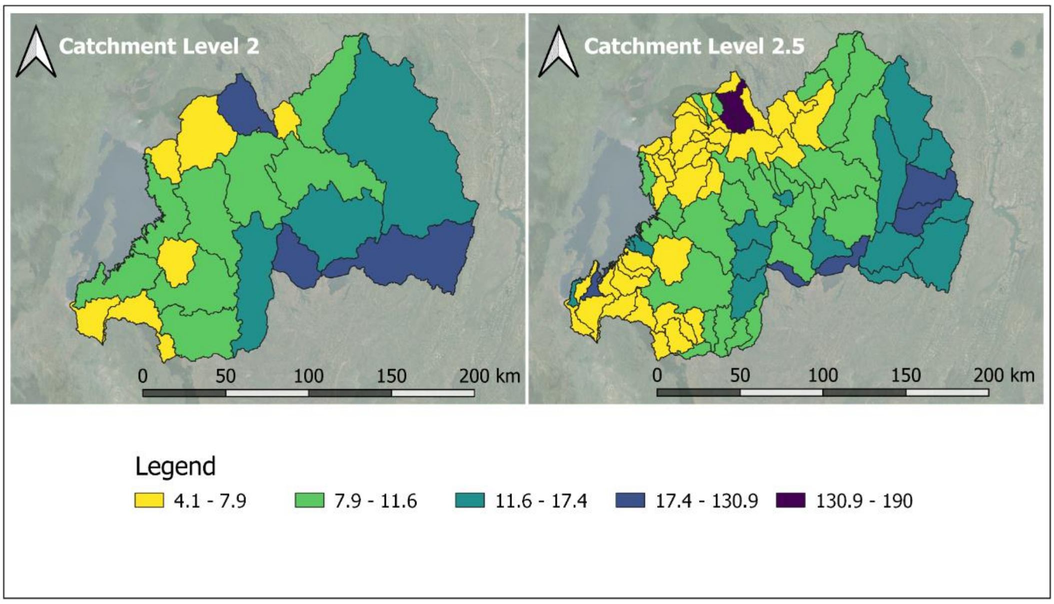

Figure 12. Saturated Hydraulic Conductivity (Ksat) in cm/day (topsoil) from HiHydrosoil (FW, 2020).

Soil bulk density estimates were obtained from the Soilgrids.com dataset developed by ISRIC (Poggio et al., 2021[1]), see Figure 13. The Eastern Province shows relatively higher bulk densities, especially when compared to the Western Province. The Central Province, at Kigali, has the lowest Bulk Density.

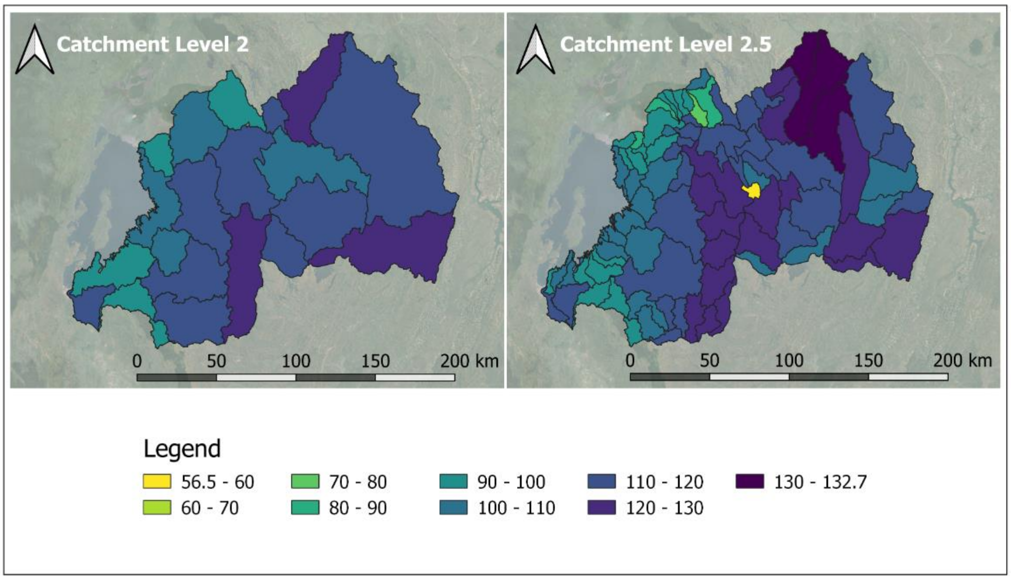

Figure 13. Bulk Density Map retrieved from SoilGrids.com (expressed in cg/cm3).

Soil depth is essential to understanding soil storage potential. The NISR report (2019)[2] documented the soil layer depths as depicted in Figure 14.

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[1] Laura Poggio et al., 'SoilGrids 2.0: Producing Soil Information for the Globe with Quantified Spatial Uncertainty', *Soil* 7, no. 1 (2021): 217–40.

[2] NISR, Government of Rwanda, and RMB, 'Natural Capital Accounts for Mineral Resource Flows' (Kigali, Rwanda: NISR, December 2019).

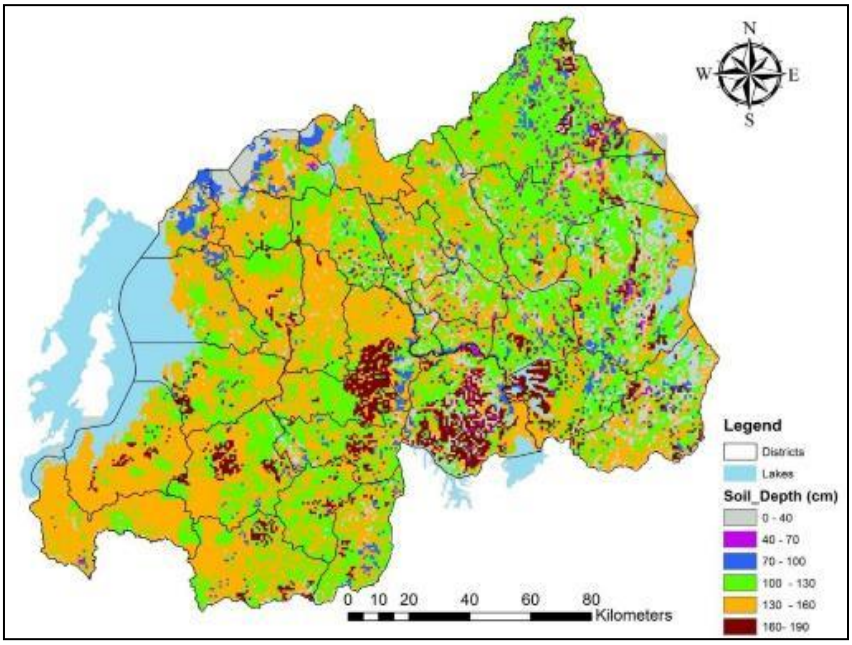
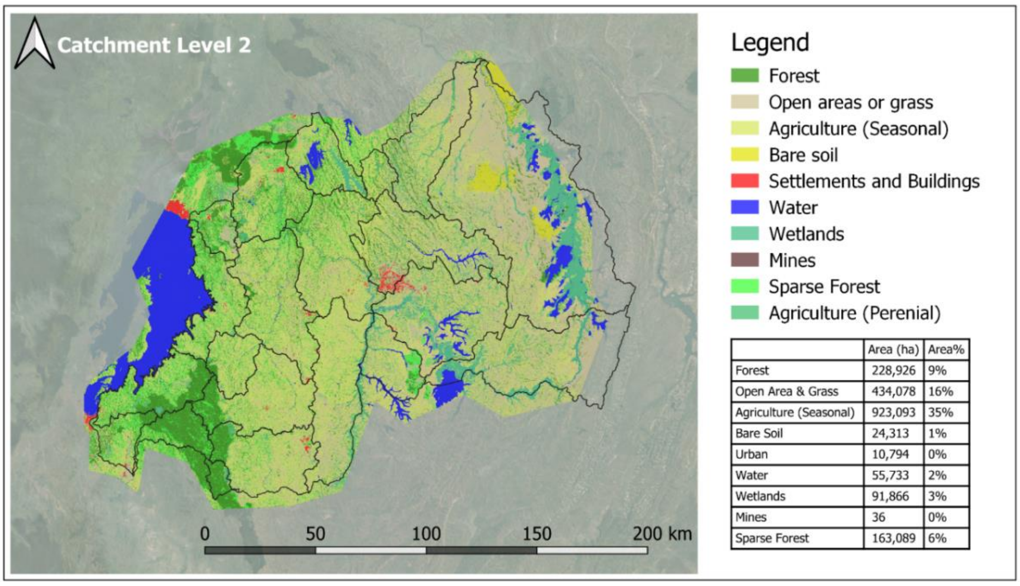


Figure 14. Soil layer Depths (NISR, 2019).

1.1.3.4 Land-use

As for landcover, the WEAP model established in the HEA study subdivided the catchments using the 2018 Land Use and Land Cover study (ESRI Rwanda, 2018[1]). The same dataset is used here as it is the most appropriate to represent the Rwandese landscape (Figure 15). The dataset has ten distinct classes, of which Seasonal Agriculture forms the largest (35%). The main wetlands are predominant in the Eastern and Southern Province, whereas forests are more dominant in the Western Province. Mining and Urban settlements (<1%) are relatively small compared to the other classes and are therefore not shown in the summarising graph (Figure 15).



	Area (ha)	Area%
Forest	228,926	9%
Open Area & Grass	434,078	16%
Agriculture (Seasonal)	923,093	35%
Bare Soil	24,313	1%
Urban	10,794	0%
Water	55,733	2%
Wetlands	91,866	3%
Mines	36	0%
Sparse Forest	163,089	6%

Figure 15. Land Use and Land Cover Map with an indication of the absolute (ha) and relative (%) areas for each LU type, based on the LULC (Esri Rwanda, 2018[2]).

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[1] Esri Rwanda Ltd., ‘Land Use / Land Cover Map for Rwanda’.

[2] Ibid.

Table 3 shows the distribution of land use classes for each of the Level 2 catchments. It should be noted that the LULC map fully covers the extent of the study region as the cross-border catchments in the Eastern province have been clipped to the national border so that only water generated on, and thus available for Rwandese demand are represented in this assessment.

Table 3: Area (in ha) for each land use class across the 20 Level 2 catchments, based on the LULC (Esri Rwanda, 2018[1]).

	Forest (ha)	*Open Area & Grass (ha)*	*Agriculture (Seasonal) (ha)*	*Bare Soil (ha)*	*Urban (ha)*	*Water (ha)*	*Wetlands (ha)*	*Mines (ha)*	*Sparse Forest (ha)*	*Agriculture (Perennial) (ha)*
CKIV_2	10380	2032	38185	0	277	619	66	0	19901	994
CKIV_3	26064	680	22286	0	144	456	645	0	21995	2479
CRUS_1	8792	1764	13577	0	233	263	534	27	7975	1137
CRUS_2	34698	297	2736	0	2	223	174	0	8696	881
CKIV_1	7621	5349	7723	0	301	1	0	0	7231	1320
NAKL_1	14996	182219	76555	24311	179	24422	53538	0	3528	14573
NAKU_2	4278	57133	48024	0	106	5865	15032	0	778	10718
NAKN_2	2870	20944	87889	0	282	599	2710	1	4593	6993
NAKN_3	2229	10445	26139	0	116	2238	2361	0	6299	3995
NAKN_1	12911	13598	55275	0	709	253	0	0	9541	3927
NAKU_1	3455	37676	68985	0	1919	7865	9758	4	3130	20719
NMUK_2	21136	4310	44183	0	823	548	278	5	17854	4116
NMUK_1	8081	2083	28132	0	48	6774	5296	0	7826	1497
NMUV_2	6854	33950	50169	3	125	50	54	0	226	14888
NMUV_1	3196	1214	13310	0	41	0	1	0	1296	2068
NNYL_1	11440	27967	72567	0	3652	3209	300	0	514	15454
NNYL_2	16797	12132	86046	0	626	695	989	0	11977	4407
NNYU_3	12970	10240	85408	0	975	1222	64	0	13730	1658
NNYU_1	4350	1934	28761	0	7	123	0	0	5497	924
NNYU_2	15864	8332	67365	0	232	317	73	0	10524	1661

1.1.3.5 Soil erosion risk

Soil erosion and sediment yield are intertwined processes in the Rwandese landscape. Scouring of riverbeds is not the sole reason for high sediment loads in the rivers. Land degradation also significantly contributes to erosion, and thus sediment loading of the river network. The RWB has established a dataset on Catchment Restoration Opportunity Mapping (CROM-DSS)[2] (Figure 16) (Rwanda Water Board, 2022). The dataset subdivides the landscape into four classes of decreasing erosion risk (Extremely High, Very High, High and Moderate Erosion Risk). This data has been summarised for both catchment level 2 and level 2.5 (Figure 17 to Figure 20). A clear link with topography is noticeable as the Western part of the country, with a higher elevation and a mountainous landscape, shows a higher erosion risk, compared to the eastern part of the country, which only shows catchments with a moderate erosion risk.

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[1] Ibid.

[2] Esri Rwanda Ltd., ‘Catchment Restoration Opportunities Mapping for Rwanda’ (Kigali, Rwanda: Esri Rwanda Ltd., 1 July 2018).

Soil erosion estimates and the linked recommendations for sustainable land management practices will be used for developing guidance on the catchment interventions in the flagship projects to be developed in the next phase.

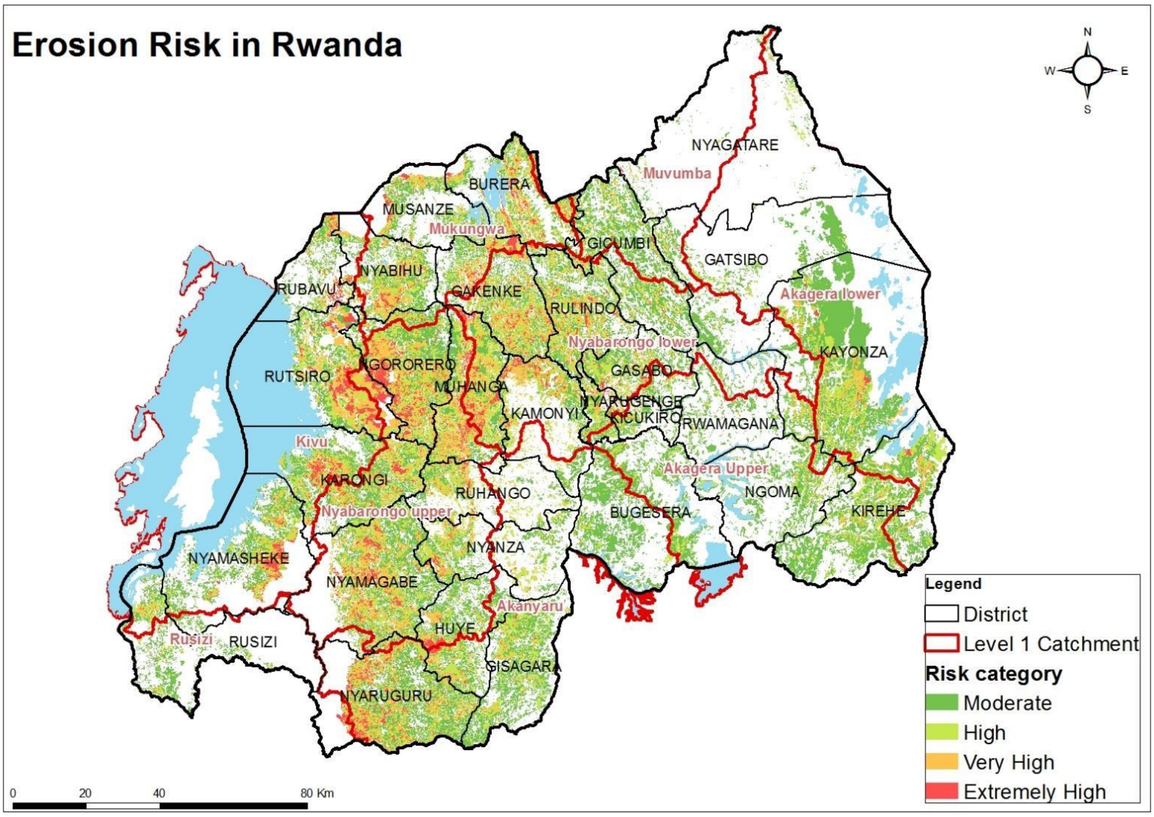

Figure 16. Catchment restoration Opportunity Mapping (CROM-DSS) from the RWB

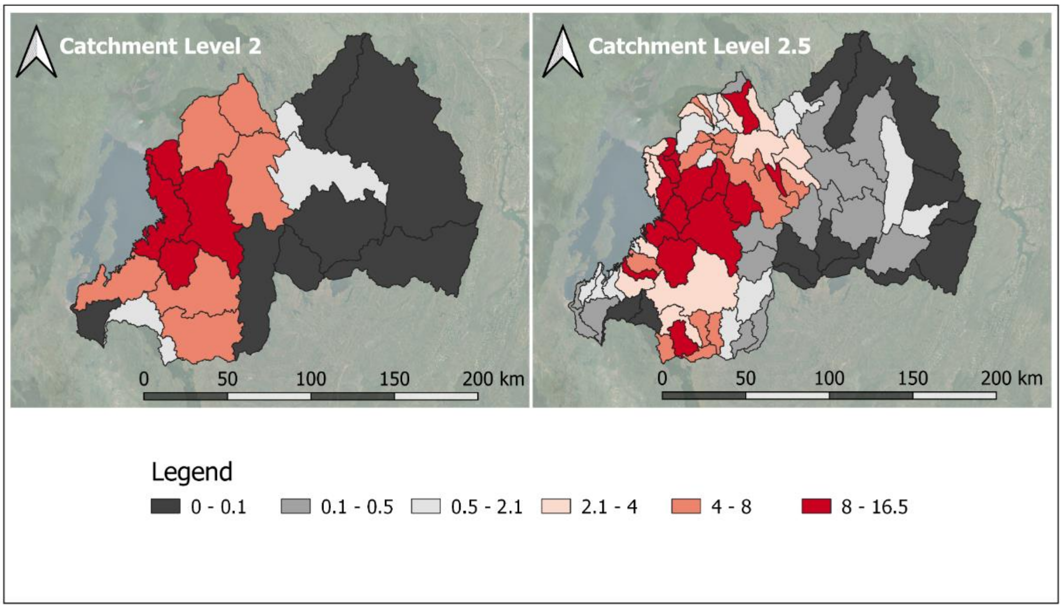

Figure 17: Erosion Risk Map indicating for Catchment Level 2 (left) and 2.5 (right) the percentage area observed at Extremely High Risk. Data source: CROM DSS (Rwanda Water Board, 2022).

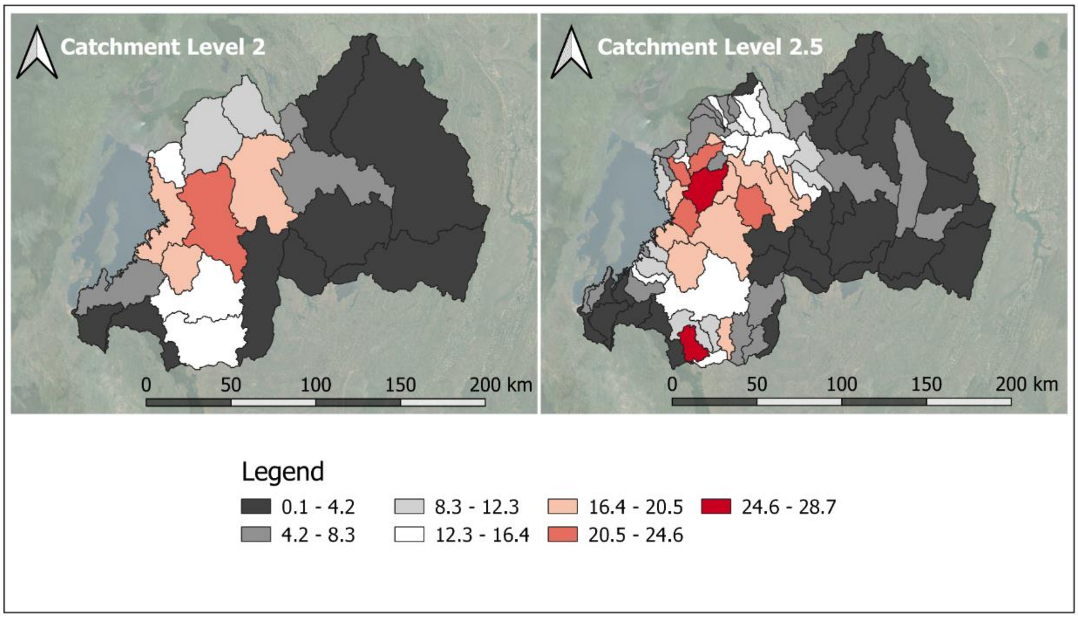

Figure 18: Erosion Risk Map indicating for Catchment Level 2 (left) and 2.5 (right) the percentage area observed at Very High Risk. Data source: CROM DSS (Rwanda Water Board, 2022).

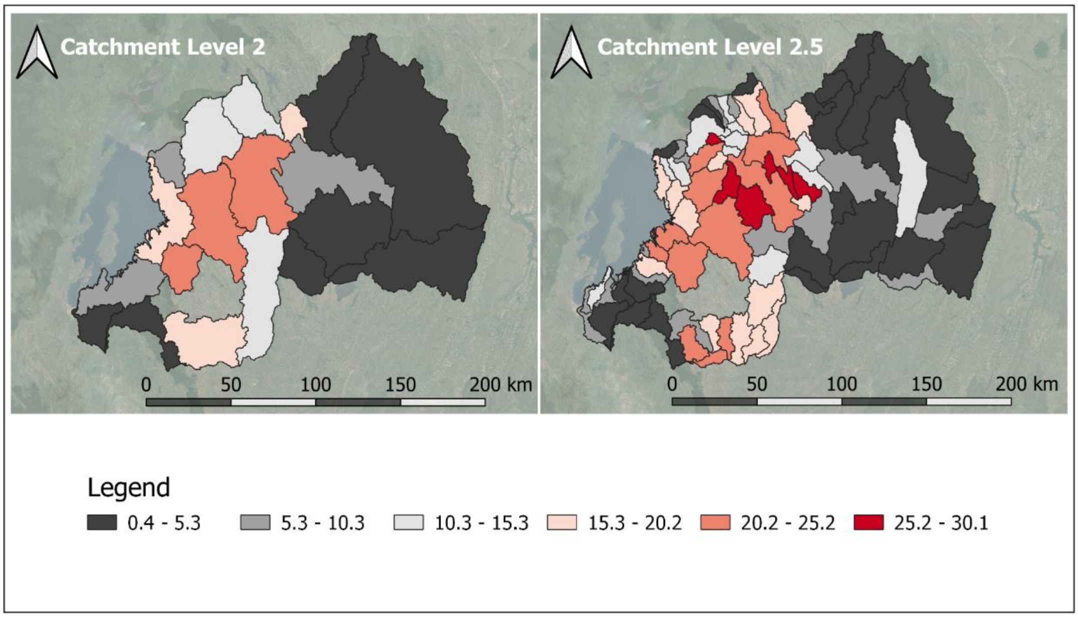

Figure 19: Erosion Risk Map indicating for Catchment Level 2 (left) and 2.5 (right) the percentage area observed at High Risk. Data source: CROM DSS (Rwanda Water Board, 2022).

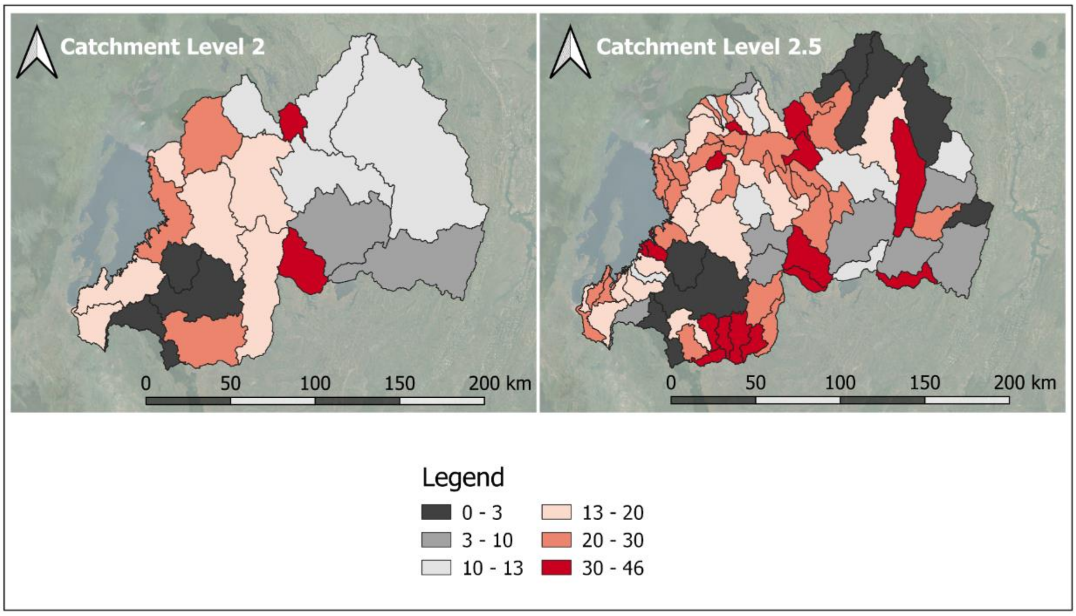

Figure 20: Erosion Risk Map indicating for Catchment Level 2 (left) and 2.5 (right) the percentage area observed at Moderate Risk. Data source: CROM DSS (Rwanda Water Board, 2022).

1.1.4 Model validation

The WEAP_HEA model received by SEI (SEI, 2022)[1] was considered to be well-parameterised, and calibrated for the purpose of this assignment. However, some modifications to the model setup and underlying data have been adopted (see section 1.1.2). Therefore, it was needed to re-validate the model output for ETa, Precipitation and Surface Runoff.

1.1.4.1 Evapotranspiration

Evapotranspiration (ETa) is calculated in the model as a function of a crop-dependent coefficient (abbreviated typically as kc) and dynamic temperature input data. The simulated data was examined and compared with the WAPOR dataset presented under 1.1.3. The goal of this comparison is to check the level of consistency of both datasets. Differences can be expected as the two datasets are derived by very distinct methods, parameters and underlying data. For the purpose of this study, this comparison is done at the national level.

Figure 21 shows the monthly mean ETa values for the modelled data and the remote sensing-based data. The figure indicates that there is a generally good relationship between both ETa datasets at national level. It can also be seen that there is low variability in ETa across the year, in both datasets, which gives confidence in their consistency. It is worth noting that the WAPOR dataset was analysed for 2009-2021 whereas the WEAP Baseline was established for the 2000 – 2019 timespan.

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[1] Swedish Environment Institute. 2022. A Water Resilient Economy: Hydro-Economic and Climate Change Analysis for Rwanda.

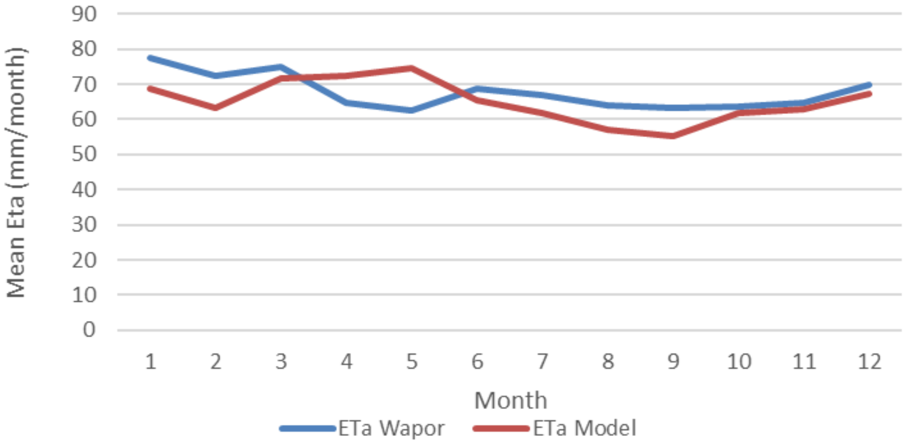

Figure 21. Mean national monthly ETa comparison for WEAP Baseline model output and WAPOR dataset.

1.1.4.2 Precipitation

As the Precipitation data was replaced with Meteo-Rwanda data, a verification on spatio-temporal patterns was performed to ensure that it would not affect the model calibration significantly. The results of this analysis were introduced earlier in section 1.1.2 and details are presented in Annexe 7. Generally, as Figure 22 shows, the differences between the Princeton dataset (used in the original SEI model) and the Meteo-Rwanda dataset (provided during inception phase) were minimal, and on average they showed a consistent monthly trend. One exception to this observation was for level 1 catchment CRUS, for which both the Princeton dataset and the estimates provided in the NWRMP (2015) showed much lower precipitation amounts. Therefore, the Princeton data was exceptionally retained only for this single catchment.

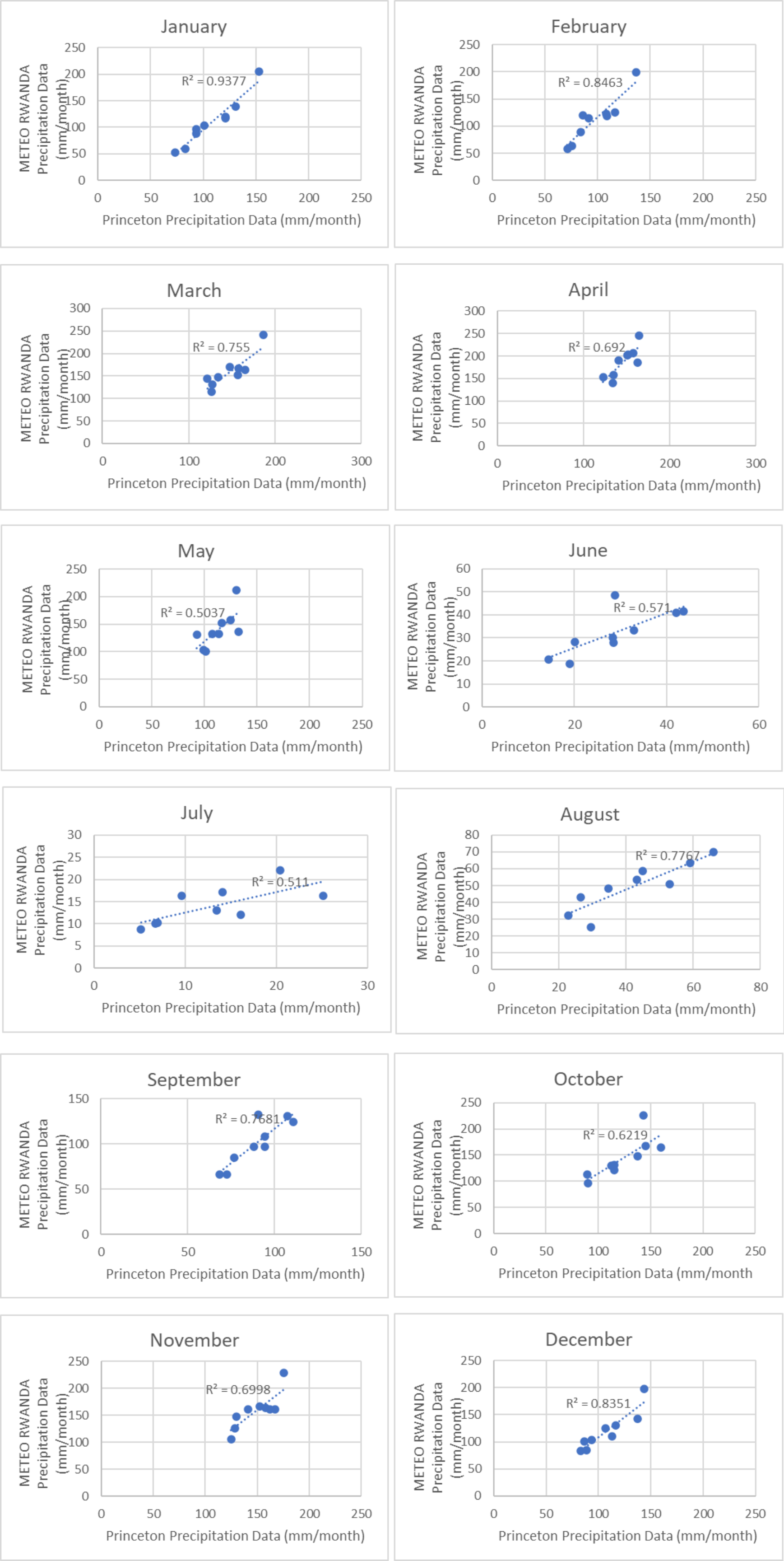

Figure 22. Monthly averaged Precipitation from Meteo-Rwanda (1981 – 2010) and Princeton dataset for 1980 -2010.

1.1.4.3 Water balance

Another check conducted during model validation was to compare the observed flow estimates with the modelled flows. It is hypothesised that observd flows should be close to the sum of the simulated surface runoff, groundwater recharge, and interflow (in the long term) for catchments situated upstream where abstractions are relatively small.

In total, 74 gauge and flow monitoring stations are established in Rwanda. However, only few are functional (Figure 23); therefore, few streamflow data points are available at the RWB water portal (Table 4). Consequently, only two stations (Ruliba and Nyundo) had time series long enough to determine the flows. For the water balance check, flows are expressed here in mm/year, sometimes also called “specific discharge”. This obtained by dividing the mean annual flow by the the contributing catchment. As the contributing catchment of Ruliba is very large, the specific discharge cannot be determined with sufficient confidence given alterations and abstractions; therefore, the water balance check was examined for the Nyundo Gauge Station.

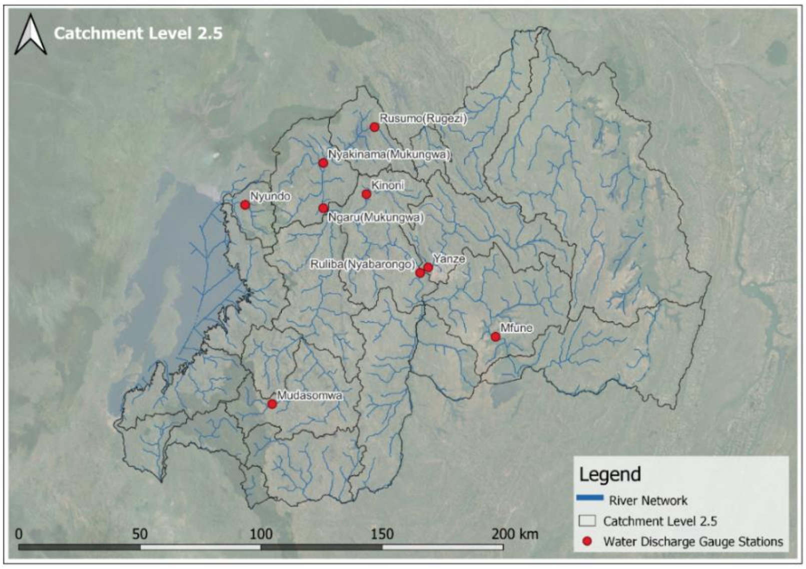

Figure 23. Functioning streamflow gauge station (RWB, 2022).

Table 4. Summary of the available Gauge Stations from the RWB Water Portal (RWB, 2022).

ID	*Location name*	*parameter*	*Unit*	*Start*	*End*	*Continuous (Yes or No)*	*Avg (m3/s)*	*Max (m3/s)*	*Min (m3/s)*
SW5	Akanyaru-upper	discharge	m3/sec	02/03/2016	31/03/2017	No	11.6	135.1	0.01
292001	Kinoni	discharge	m3/sec	01/03/2016	30/04/2016	No	15.4	271.6	1.76
255501	Mfune	velocity	m/sec	30/04/2019	24/03/2022	Yes	6.5	8.3	5.45
298001	Mudasomwa	discharge	m3/sec	01/03/2016	28/02/2017	No	3.9	59.9	1.59
70012	Ngaru (Mukungwa)	discharge	m3/sec	01/03/2016	31/03/2017	No	52.0	89.5	15.08
294701	Nyakinama (Mukungwa)	discharge	m3/sec	01/03/2016	28/02/2017	No	9.3	46.0	0.16
2E+05	Nyundo	discharge	m3/sec	01/01/1974	11/08/2014	No	3.6	99.5	0.04
		discharge	m3/sec	01/08/2020	29/11/2021	No	5.8	49.5	2.92

		velocity	m/sec	21/04/2017	29/11/2021	No	1.3	5.8	0.16
3E+05	Ruliba (Nyabarongo)	discharge	m3/sec	01/01/1961	31/12/2016	No	97.3	352.8	4.59
		velocity	m/sec	03/10/2018	18/03/2022	Yes	1.2	2.3	0.22
294901	Rusumo (Rugezi)	discharge	m3/sec	01/03/2016	31/01/2017	No	2.8	26.8	0.49
282001	Yanze	discharge	m3/sec	01/03/2016	31/01/2017	No	1.2	41.4	0.25

For the Nyundo gauge station, the specific discharge was determined using four methods, of which two relied on WEAP output.

1. The first method looked into the water balance and determined the specific discharge as the rest product after subtracting evapotranspiration (ETa from WAPOR) from the Precipitation (mm/year) (see Equation 1).
2. The second method determined the specific discharge by dividing the average discharge at the Nyundo gauge station by its contributing catchment area (Figure 24).
3. The third method is similar to the first but the ETa modelled by WEAP is used in the water balance calculation instead of WAPOR data.
4. Lastly, the fourth method looks into the modelled specific discharge, hypothesised as the sum of interflow, groundwater recharge and surface runoff (Equation 1) but with results obtained from the WEAP model.

$$P = ETa + Groundwater\ Recharge + Surface\ Runoff + Interflow\ (long\ term) \qquad [Equation\ 1]$$

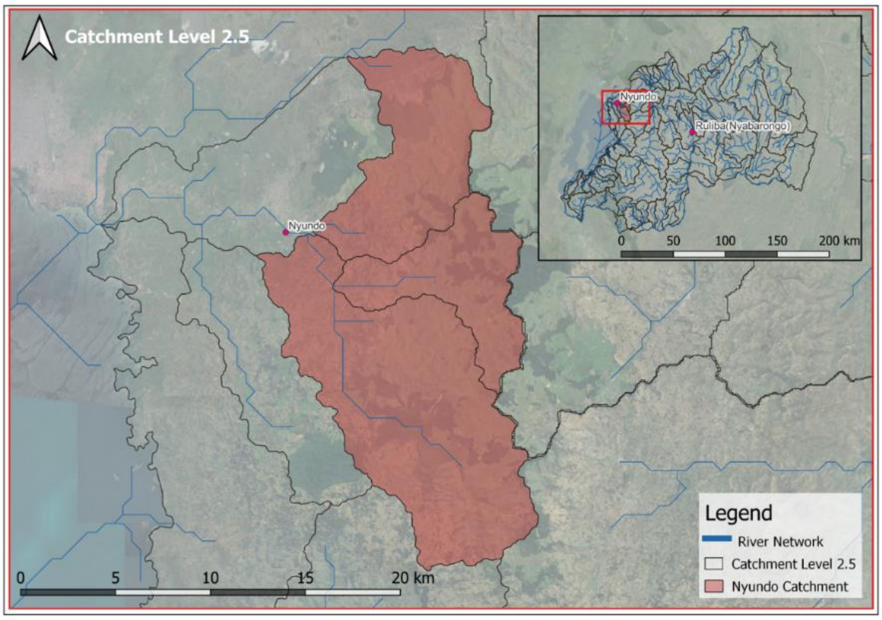

Figure 24: Catchment area upstream of the Nyundo gauge station.

As shown in Table 5, the specific discharge obtained from the second method (507 mm/year) differs by about 17 mm/year from the first method (524 mm/year), which indicates a very good match (3% difference). In contrast, the WEAP model results, i.e. the third and fourth methods, show a marginal deviation from the former. Respectively for the third and fourth methods, an estimate of 437 mm/year and 441 mm/year is obtained (approx. 13% difference). Given that both are in the same range as obtained with the first two methods, it is assumed that both methods work as a proxy for specific discharge. Reasons for the obtained differences for the WEAP estimates (method 3 and 4) include (i) the different time-periods used in the water balance methodology (precipitation data is for 1981 – 2021, evapotranspiration data is for 2009 – 2020, and WEAP modelled data is for 2000 - 2019), (ii) the limited understanding of the exact drainage pattern and the groundwater flow paths and/or (iii) the low data quality.

Table 5. Nyundo Specific Discharge determination using two methods.

Method	*Output*	*Unit*
Specific Discharge (Water Balance)	524	mm/year
Specific Discharge (Observed) [3.64 m3/s]	507	mm/year
Specific Discharge (Water Balance, WEAP)	437	mm/year
Specific Discharge (WEAP recharge + Surface Runoff)	441	mm/year

1.2 Groundwater resources assessment

1.2.1 Available literature

Rwanda is characterised by nine main types of groundwater aquifers (Figure 25):

- Alluvial aquifer, mostly concentrated in the Eastern province.
- Complex aquifer, mostly in a volcanic area in the North of the country and a little a bit in the West province.
- Fractured aquifer (granite and gneiss), covering the whole country except the North and Kigali City.
- Lake aquifers, in the West, North, and East[1].
- Low permeable fractured aquifer (Schist and Mica schist), the East, North,and West.
- Organo-sedimentary alluvial aquifer (clay base), only in the West.
- Peat aquifer, in the North and South.
- Permeable aquifer (quartzite on Schist base), in East and North.
- Semi-permeable aquifer (Schist, mica, and quartzite), quite similar to the previous one, mostly concentrated between the Northern and Western provinces.

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[1] Even though the Lake aquifer (which includes rivers and lakes) is listed among the list of groundwater aquifers in Rwanda, the calculations made under this assignment to estimate the volume of groundwater did not consider lake aquifers due to their direct linkage with surface water.

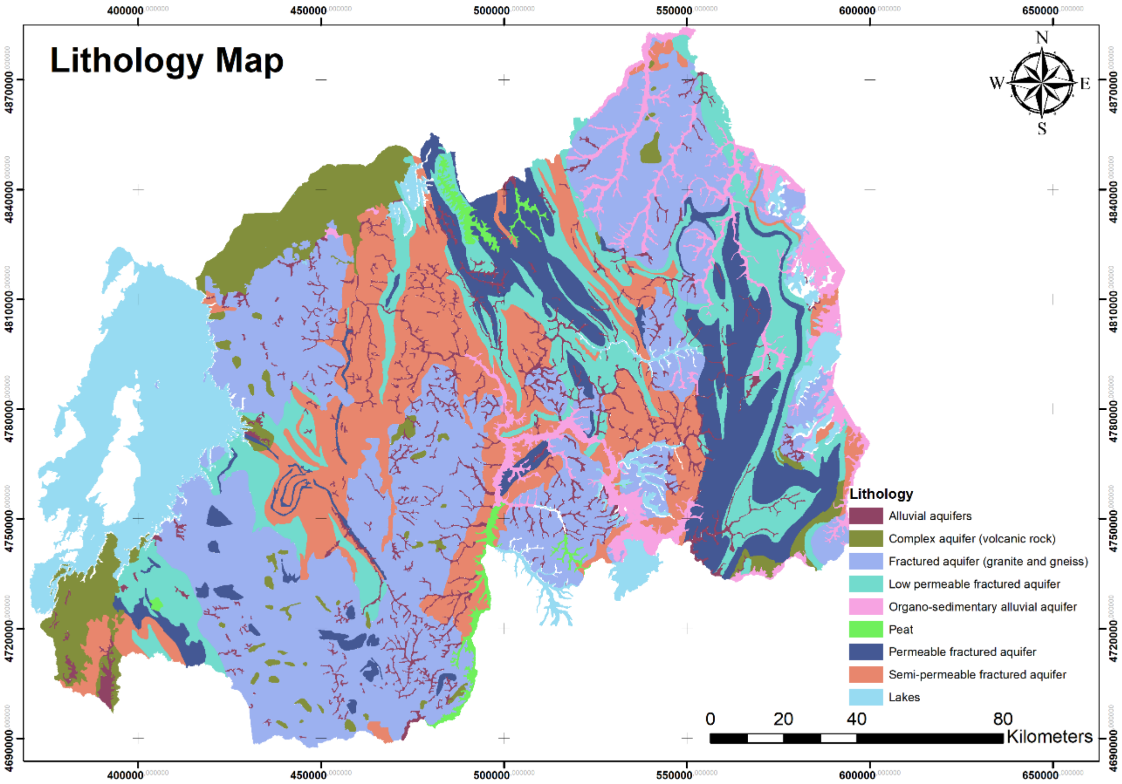

Figure 25: Lithological map of Rwanda (Source: Shapefiles provided by RWB).

The spatial characterisation of the geological formation in Rwanda, is such that the eastern province is characterised by granitic rocks, which are widely distributed. Metamorphic rocks are distributed along the western province border in a narrow belt shape. In the central and south-eastern parts of the country, metamorphic rocks of quartzite and schist sedimentary rocks of mudstone and sandstone are distributed in the north-south direction. The general characteristics of these aquifers are summarised in Table 6.

Table 6: The main characteristics of the types of aquifers.

Type of Aquifer	General description
Alluvial aquifer	Alluvial aquifers are shallow (between 10 and 50 meters), very permeable, and conductive, making them vulnerable. They are usually well connected to streams and rivers and store tiny volumes of water. They are ideal exploration prospects, but over-abstraction could harm stream ecology and aquifer structure. Because the storage capacity of these aquifers is limited, they must be effectively managed in terms of quality and quantity.
Organo-sedimentary aquifers	The organic matter level in organo-sedimentary aquifers ranges from 5 to 15%. Their structure contains peat, which causes decomposition and, in certain circumstances, ignites due to over-abstraction and drying. Their structure (collapse, shrinkage) may vary, affecting their storage qualities. The storage capacity is enormous (up to 75 percent of volume). They must be handled with extreme caution. The water in these aquifers is frequently acidic (pH 4.5) and decreased. The lack of oxygen causes iron and metals to mobilize. This may result in poor quality. High levels of dissolved organic matter because of hygienic, aesthetic, and indirect water quality issues (high mobility of heavy metals).

Type of Aquifer	General description
Permeable fractured aquifers	The majority of the country's permeable fracture aquifers are found in the east as said above. Quartzite is the type of rock found here. They can be very permeable, have little storage capacity, and provide a good to adequate recharge. In terms of wells going dry during the summer season, the combination of high permeability and limited storage can be a problem. These aquifers can generally be targeted for long-term groundwater management, but recharge and water levels must be monitored during abstraction. Quartzite bands straddle surface basins and cause an inter-basin transfer, which is rather fascinating. These transfers have been estimated and found to be insignificant when compared to the basin balances.
Low permeable fractured aquifers	Schist dominates low permeable fractured aquifers. Their recharge is lower, but their storage can be greater than that of quartzite aquifers due to secondary storage (or remaining primary porosity as they are meta-sediments). They are dominant in central region of the country.

The area of the different units is summarised in Table 7.

Table 7: Total area of the different aquifers.

Sr	Aquifers	Area sq.km
1	Semi-permeable fractured aquifer (schist, mica and quartzite)	4,258
2	Permeable fractured aquifer (quartzite on schist base)	2,820
3	Peat	269
4	Organo-sedimentary alluvial aquifer (low permeability, clay base)	1,333
6	Low permeable fractured aquifer (schist and mica schist)	3,549
8	Fractured aquifer (granite and gneiss)	8,555
9	Complex aquifer (volcanic rock)	1,743
10	Alluvial aquifers	1,213

In the absence of specific hydraulic data for Rwanda, generic hydraulic information (Table 8) is used to describe the hydraulic properties of aquifers found in Rwanda (Table 9).

Table 8: Generic hydraulic characteristics of aquifers.

Material	Porosity (%)	Specific Yield (%)	Hydraulic conductivity (m/s)
Unconsolidated deposits			
Gravel	25 - 35	25 - 35	1 - 100
Sand	30 - 45	25 - 40	10^{-4} – 10^{-1}
Silt	35 - 45	20 - 35	10^{-6} – 10^{-4}
Clay	40 - 55	2 - 10	10^{-9} – 10^{-6}
Rocks			
Karst limestone	15 - 40	10 - 35	10^{-4} – 10^{-1}
Limestone, non-Karst	5 - 15	2 - 10	10^{-6} – 10^{-4}
Sandstone	10 - 25	5 - 10	10^{-7} – 10^{-6}
Shale	0 - 10	0 - 5	10^{-11} – 10^{-7}
Crystalline rock (fractured)	1 - 10	1 - 10	10^{-6} – 10^{-4}
Crystalline rock (unfractured)	0 - 2	0 - 1	10^{-11} – 10^{-9}

Table 9: Hydraulic characteristics of Rwanda's aquifers

Permeability in decreasing order	Porosity in decreasing order	Productivity
Alluvial aquifer	Alluvial aquifer	Very permeable, highly conductive, and are usually well connected to streams and rivers, they are good exploration targets
Organo-sedimentary alluvial aquifer (clay base).	Peat aquifer	Highly permeable, Permeability decrease after during the exploration and the microspore space, bulk density and consolidation increase, very easily contaminated but surfaces sediments and during the decomposition process.
Permeable aquifer (quartzite on Schiste base)	Organo-sedimentary alluvial aquifer (clay base)	Very permeable, highly conductive, and are usually well connected to streams and rivers, they are good exploration targets
Fractured aquifer (granite and gneiss)	Complex aquifer	High transmissivity, Very good targets for sustainable groundwater development
Complex aquifer	Fractured aquifer (granite and gneiss)	Moderately permeable, good target for groundwater resource.
Low permeable fractured aquifer (schist and mica-schist)	Permeable aquifer (quartzite on Schist base)	Low permeable, Recharge is very low, Not good for mass supply of groundwater, Drill targets should be much distanced from one to another.
Peat aquifer	Low permeable fractured aquifer (schist and mica schist)	Permeability decrease during exploration and the microspore space, bulk density, and consolidation increase, easily contaminated during the decomposition process. not good for healthy groundwater supply

The effective porosity, the portion of the total void space of a porous material capable of transmitting a fluid, is used to determine the capacity of a material to store groundwater. It can be determined at the laboratory scale when sediment and rock samples of a given volume are dried, and then the pore spaces are filled with water. This measurement was not planned for this assignment and, therefore, available values in the literature will be used. As per Adelana and MacDonald (2008[1]), direct transmissivity measurements and effective porosity are scarce for much of Africa. Therefore, the ranges of values presented in Table 10 will be used in this study:

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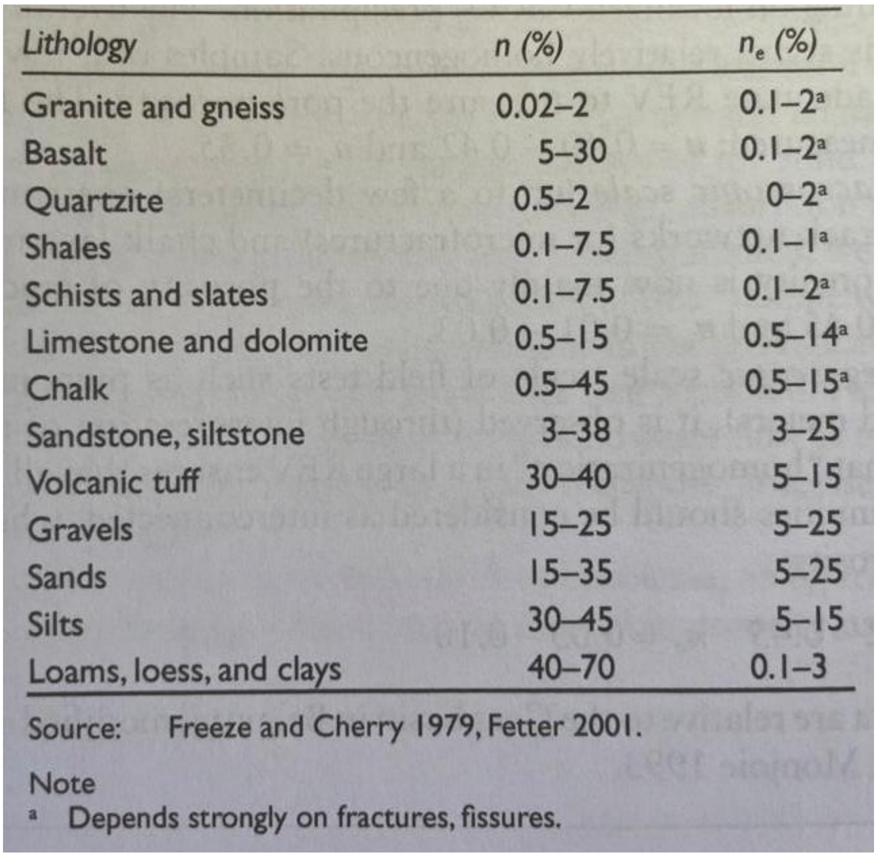
[1] Segun Adelana and Alan M. MacDonald, eds., *Applied Groundwater Studies in Africa*, IAH Selected Papers on Hydrogeology, vol. 13 (Boca Raton: CRC Press, 2008).

Table 10: Typical porosity and effectivity porosity for common lithologies (Source: Dassargues, 2020[1]).



Lithology	*n (%)*	*n_e (%)*
Granite and gneiss	0.02–2	0.1–2[a]
Basalt	5–30	0.1–2[a]
Quartzite	0.5–2	0–2[a]
Shales	0.1–7.5	0.1–1[a]
Schists and slates	0.1–7.5	0.1–2[a]
Limestone and dolomite	0.5–15	0.5–14[a]
Chalk	0.5–45	0.5–15[a]
Sandstone, siltstone	3–38	3–25
Volcanic tuff	30–40	5–15
Gravels	15–25	5–25
Sands	15–35	5–25
Silts	30–45	5–15
Loams, loess, and clays	40–70	0.1–3

Source: Freeze and Cherry 1979, Fetter 2001.

Note

[a] Depends strongly on fractures, fissures.

MacDonald (2012)[2] produced a map that estimates Africa's groundwater reserves (Figure 26), which was based on a synthesis of 283 studies, only two of which included an estimation of porosity obtained through pumping test analysis. This information is used later to compare the groundwater recharge computed by the model WEAP (see section 1.3.3, p86). For the case of Rwanda, the estimation of groundwater storage was in the range of 6 to 198 km^3.

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[1] Alain Dassargues, *Hydrogeology: Groundwater Science and Engineering*, First issued in paperback (Boca Raton London New York: CRC Press, Taylor & Francis Group, 2020).

[2] A M MacDonald et al., 'Quantitative Maps of Groundwater Resources in Africa', *Environmental Research Letters* 7, no. 2 (1 June 2012): 024009, https://doi.org/10.1088/1748-9326/7/2/024009.

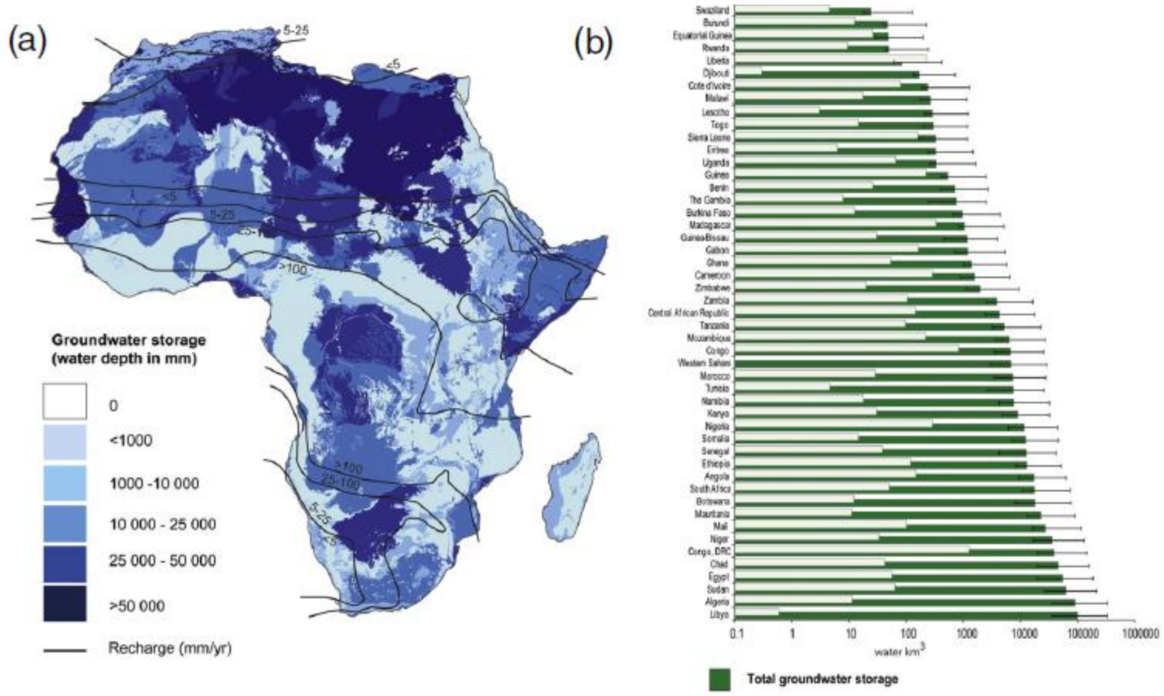

Figure 26: Groundwater storage in Africa (MacDonald et al., 2012)[1]

1.2.2 Effective porosity

The effective porosity will be a central parameter in assessing groundwater storage (see section 1.2.8). Values for Rwandan aquifers were derived assuming likely values based on the information presented above (Table 10):

Table 11: Representative values for effective porosity chosen in this assignment.

Aquifer	Aquifer characteristics	Effective porosity range	Effective porosity
Alluvial	Sandstone-Siltstone	0.03-0.25	0.14
Complex aquifer	Volcanic tuff	0.05 - 0.15	0.10
Fractured aquifer	Granite and gnesis	0.001 - 0.02	0.01
Low permeable fractured aquifer	Schistes and slates	0.001 - 0.02	0.01
Organo-sedimentary alluvial aquifer	Chalk	0.005 - 0.15	0.08
Peat	Sandstone-Siltstone	0.03-0.25	0.14
Permeable fractured aquifer	Schistes and slates	0.001 - 0.02	0.01
Semi-permeable fractured aquifer	Schistes and slates	0.001 - 0.02	0.01

1.2.3 Physiographic zones

Physiographic zoning is a technique that can facilitate the extrapolation of aquifer depths from the available borehole data to zones with strong similarities, such as soil characteristics, altitude and ecology.

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[1] Ibid.

The physiography of Rwanda was estimated using certain variables that can be spatially represented to estimate the degree of similarity in the natural characteristic of areas. The physiographic zonification was done as follows (Figure 27):

- The reclassification of the available topographic data based on altitude and ecological similarities. These were defined based on temperature lapse rate in relation to altitude increment. On average 1 degree Celsius lapse rate occurs each 153 m of increment in altitude. The reclassification of the topographical data was done considering 3 degree Celsius lapse rate (in general a 3 degree lapse rate can be considered as a zone of ecological similarities). The following provided altitude zones of similar ecological conditions based on temperature lapse rate.
- The reclassification of the available Land use land cover (LULC) map was done based on developing LULC clusters that generally have a dominating pattern in their cover and use. For example, annual cropland and perennial cropland were clustered into croplands, or open grassland and closed grassland was clustered into grassland, etc. The following steps provided the LULC clusters.
- An annual average rainfall distribution was interpolated from the existing rainfall database from Meteo-Rwanda. The approach used to interpolate the rainfall distribution is the Inverse Distance Weighting (IDW). The following provided an annual average rainfall distribution map.
- All the information above were with the existing agro-ecological zones to generate the physiographic entities. Figure 28 shows the generated physiographic zones. In total, 13 zones were generated from this process.

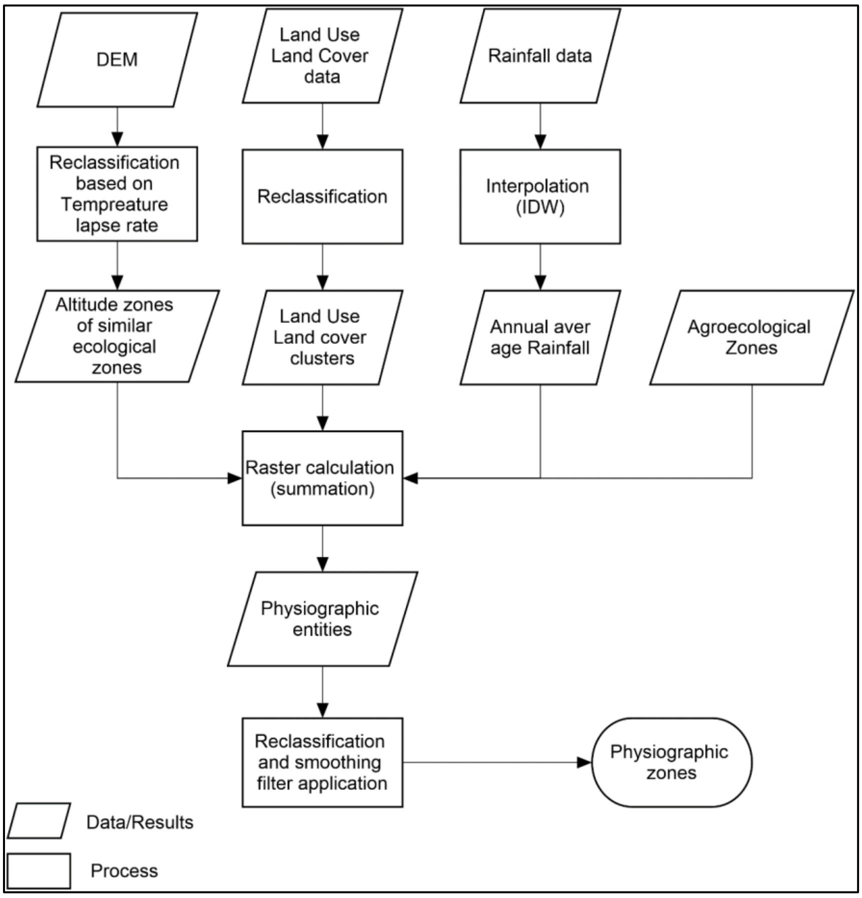


Figure 27: Physiographic zones development process

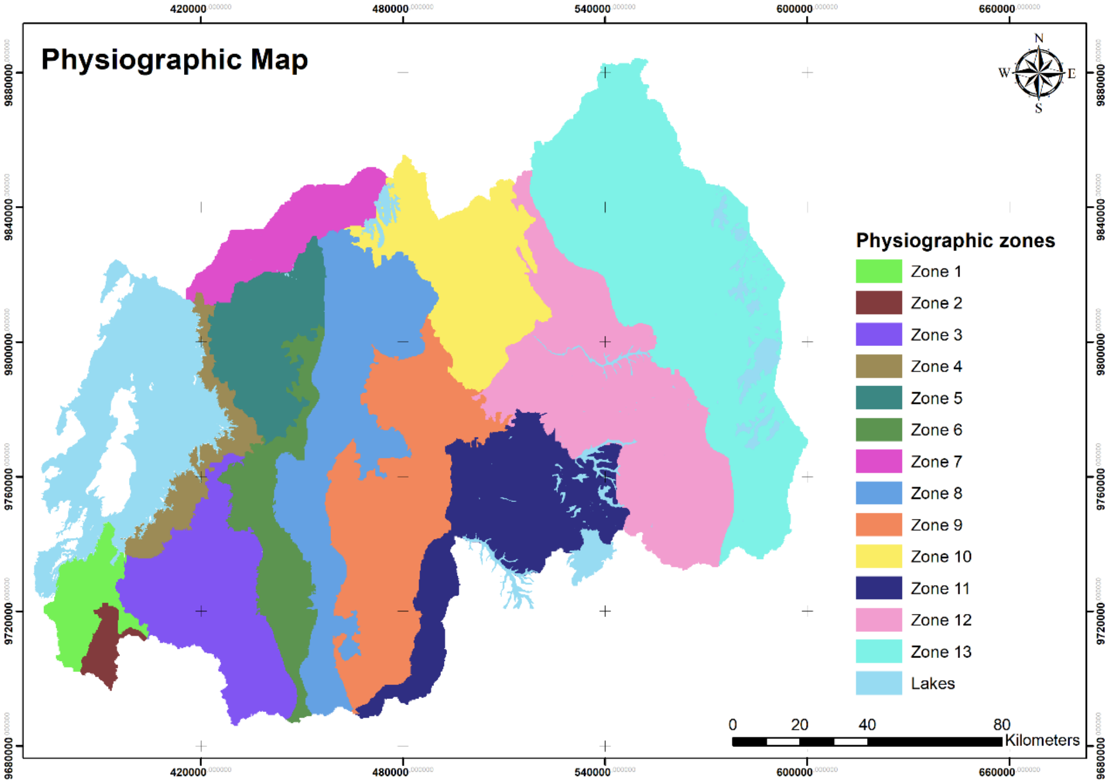


Figure 28: Physiographic map of Rwanda

The aerial distribution of the physiographic units is provided in Table 12.

Table 12: Physiography aerial distribution

Sr	Zones	Area (km²)
1	Zone 1	565,72
2	Zone 2	192,96
3	Zone 3	1.856,88
4	Zone 4	615,35
5	Zone 5	1.210,81
6	Zone 6	1.142,94
7	Zone 7	873,86
8	Zone 8	2.522,87
9	Zone 9	2.729,27
10	Zone 10	1.933,31
11	Zone 11	2.271,62
12	Zone 12	3.418,57
13	Zone 13	5.159,78

1.2.4 Inventory of existing boreholes

Many boreholes have been drilled in Rwanda to provide clean water for domestic use, irrigation, and animal use (in private farms). The highest density is found in the eastern part of Rwanda since this region is vulnerable to drought. Drilling activities have been conducted by private companies or international

NGOs under the supervision of government agencies, mainly the Rwanda Water Resources Board, the Water and Sanitation Corporation or the Rwanda Agriculture Board.

In 2007, Living Water International (LWI) Rwanda began operations to bring safe water to Rwanda, focusing primarily on operations. Their programs are located in areas with high WASH needs. Based on the data received from RWB, LWI Rwanda drilled around 483 boreholes countrywide, with the following characteristics:

- The drilling data covers the period from 2012 to 2020.
- All 483 boreholes are located in three provinces (67 in East, 405 in South, and 11 in West).
- GPS coordinates are provided except 18 boreholes.
- No water level (Static Water Level-SWL) are provided.
- There is no information on aquifer thickness.
- It has few drilling logs.
- There is no information on specific yield.

China Cooperation started in 2019 constructing 200 boreholes in 11 districts of the Eastern and Southern provinces to increase water access in Rwanda. A summary is placed in Annexe 2.

It is important to point out that the database missed some critical information that could have been very useful in determining the volume of groundwater, with a certain level of accuracy that is more satisfactory. From the boreholes database, an emphasis was made on the information on static water level and total depth drilled. Some boreholes had both data and others were missing information on the static water level. This is illustrated in Figure 29 below.

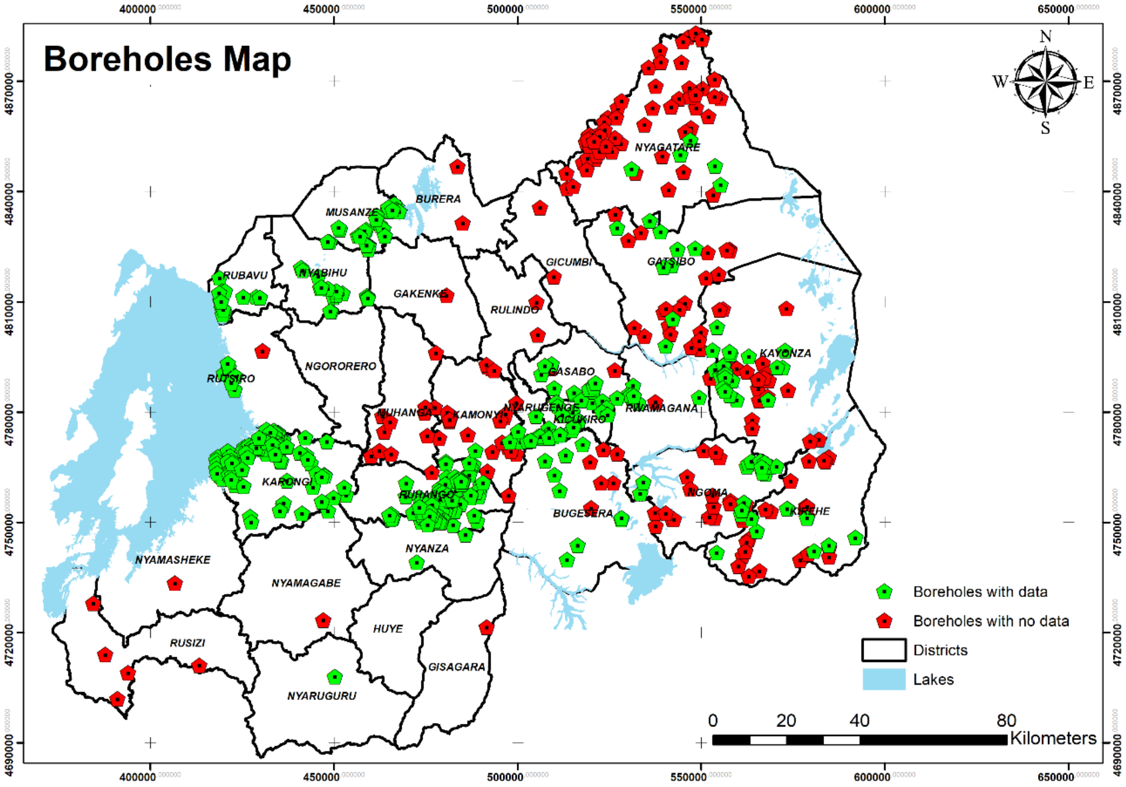


Figure 29: Location of existing boreholes.

Using the coordinates of the drilled boreholes as per the data base provided by RWB, these boreholes have been located within Level 2 catchments under various aquifers (Figure 29). Boreholes are mainly found in fractured aquifers (92), semi-permeable fractured aquifers (47) and alluvial aquifers (36). Data extracted per aquifers are placed in Annexe 2.

The summary of information derived from these borewells, in terms of drilled depth and volume of water extracted, is placed per aquifer in Table 13. The yearly productivity of the aquifer is assessed by assuming that the depth and extracted water volume remain the same throughout the year.

Table 13: Summary table on the productivity for the main types of aquifers

Type of aquifer	Productivity of aquifer					
	in m3/h			in m3/year		
	Maximum	Minimum	Average	Maximum	Minimum	Average
Alluvial	3.0	0.8	1.9	26,280	7,008	17,033
Complex aquifer	1.0	0.6	0.9	8,760	5,256	7,592
Fractured	3.0	0.5	1.7	26,280	4,380	14,569
Lac	2.5	1.5	2.0	21,900	13,140	17,812
Low permeable	3.8	0.6	1.9	33,288	5,256	16,946
Organo sedimentary	2.5	0.6	1.6	21,900	4,818	13,762
Permeable fractured	3.0	0.6	1.8	26,280	5,256	15,407
Semi-permeable	2.5	0.7	1.7	21,900	6,132	14,946

1.2.5 Groundwater monitoring

Contrary to surface water monitoring, initiated before the 1980s, groundwater monitoring only started in 2016. The network currently comprises 11 groundwater monitoring stations equipped with sensors for automatic data collection and eight piezometers for manual data collection during field visits. The data used in this study covers the period up to September 2021. Usually, data collection is done in three periods based on rainy and dry seasons (Table 14).

Table 14: Data collection campaigns

Campaign	Targeted period	Data collection campaign dates
1	Long dry season	End August/beginning of September
2	Short rainy season	End December/beginning of January
3	Long rainy season	Mid-April/beginning of May

The location of existing monitoring wells is shown in Figure 30. These wells are equipped to monitor water level variations as well as other parameters, such as water temperature and electro-conductivity, as summarised in Annexe 3. The map below illustrates the location of the groundwater monitoring wells but some of them are currently not yet operational.

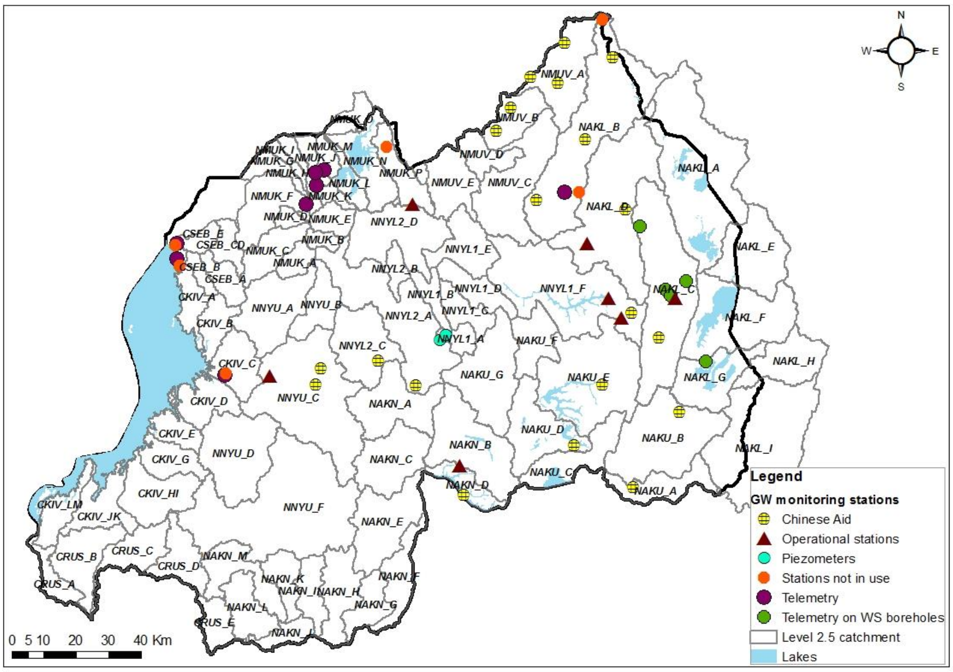


Figure 30: Location of groundwater monitoring wells at Level 2.5 catchments.

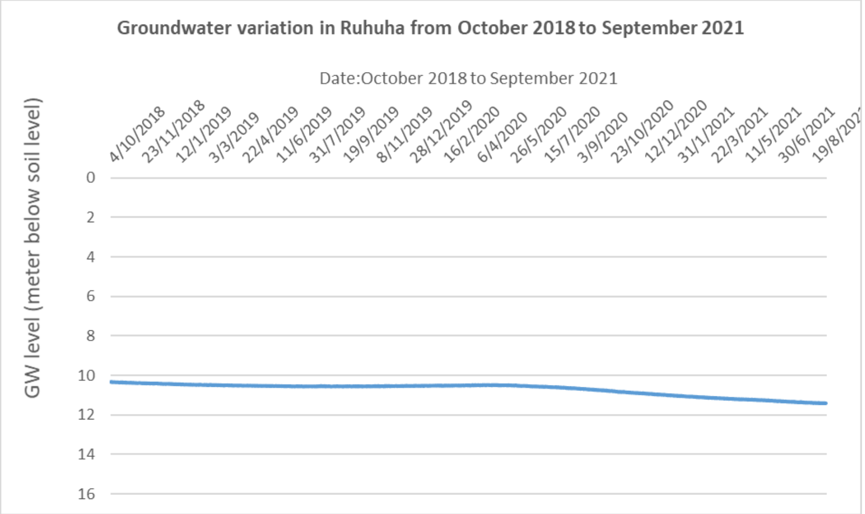
The following table summariSes the characteristics of piezometers per geographical location (provinces). The aquifer thickness in the East province ranges between 33 m and 41 m, while the groundwater level varies between 0.53 m and 90m. The one located at Muhazi was drilled near Lake Muhazi and is very shallow. The average aquifer thickness is 38.25 m. For the Northern province, the average aquifer thickness is 28 m and the average groundwater level is 14 m. In the Western province, the average aquifer thickness is 48 m and the average groundwater level is 14m. However, it should be noted that all these data were collected when installing monitoring stations and are no longer the same currently.

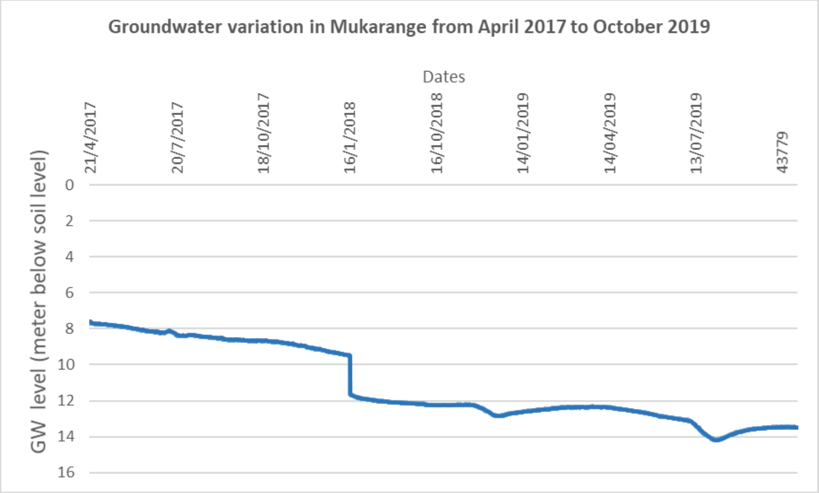
Figure 31 summarises the measurement of groundwater levels. For most piezometers, the levels logically fluctuate according to the rainy seasons. The trend in some wells is an increase in level, since groundwater is not used. Muhazi and Butaro are very shallow where high fluctuation is visible, highly influenced by rainfall. Cyuve is an aquifer in the volcanic rock region, with high transmitivity, causing quick recharge and discharge; this also applies to Rugabano, located nearby.

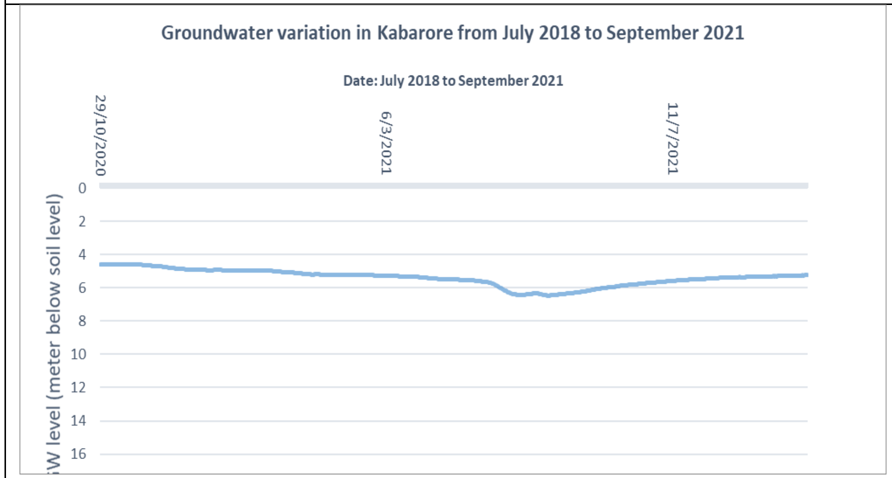
Table 15: Summary of the piezometers installed

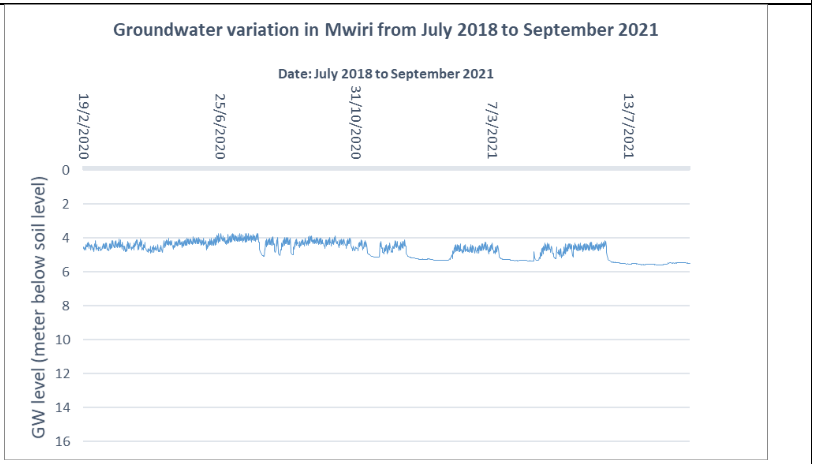
S/N	Name of GW monitoring station	Location	Type of aquifer	Static water level+top part(m)	Top part(m)	Real water level (m)	Total depth (m)	Aquifer thickness(m)
1	Ruhuha	East province	fractured aquifer	50.40	1.05	49.35	86.00	36.65
2	Mukarange		Fractured aquifer	92.38	1.00	91.38	132.00	40.62
3	Rugarama		low permeable fractured aquifer	4.08	0.30	3.78	37.00	33.22
4	Kabarore		fracture aquifer	42.84	0.52	42.32	77.00	34.68
5	Mwiri		Permeable fractured aquifer	25.48	0.60	24.88		
6	Muhazi		Fractured aquifer	1.13	0.60	0.53	47.00	46.47
7	Butaro	North Province	semi-permeable Fractured Aquifer	3.37	0.60	2.77	34.00	31.23
8	Cyuve		complex aquifer (volcanic rock).	16.36	0.60	15.76	41	25.24
9	Ruhunde		semi-permeable Fractured Aquifer	25.48	0.60	24.88		
10	Rubengera	West Province	low permeable fractured aquifer	9.17	0.63	8.54	91.70	83.16
11	Rugabano		low permeable fractured aquifer	24.00	0.74	23.26	36.25	12.99

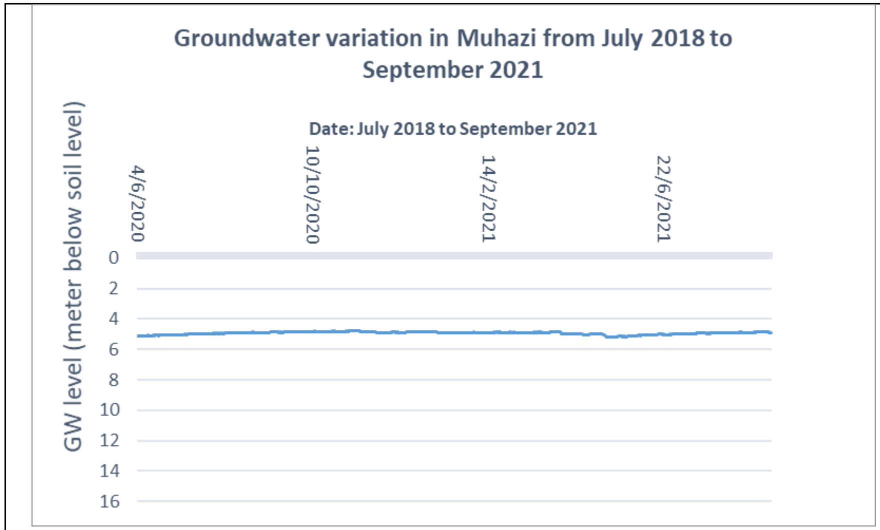
East Province


Groundwater variation in Ruhuha from October 2018 to September 2021

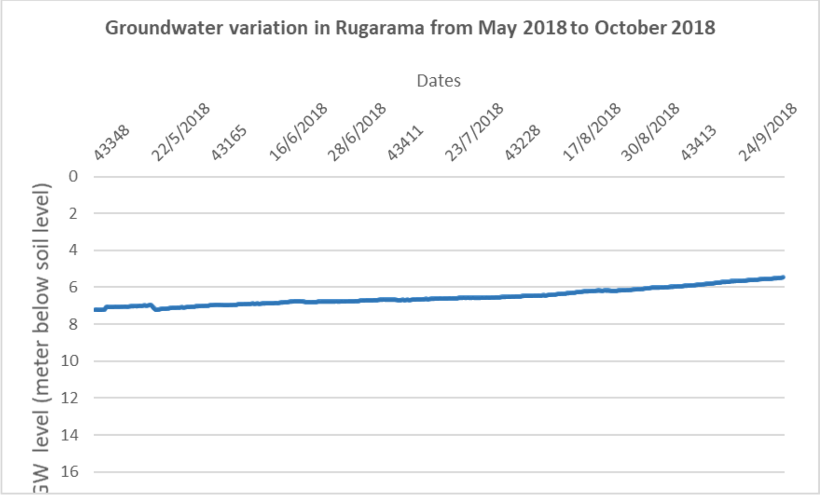

Groundwater variation in Mukarange from April 2017 to October 2019


Groundwater variation in Kabarore from July 2018 to September 2021


Groundwater variation in Mwiri from July 2018 to September 2021

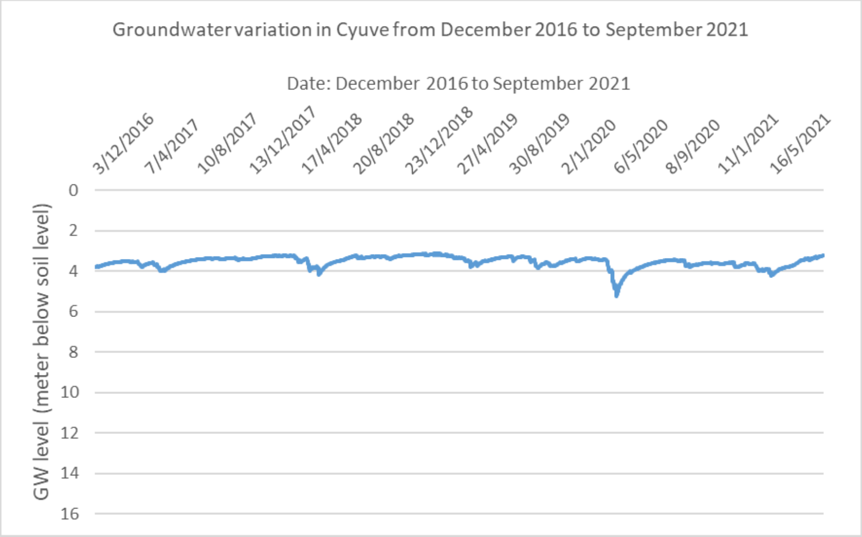


Groundwater variation in Muhazi from July 2018 to September 2021

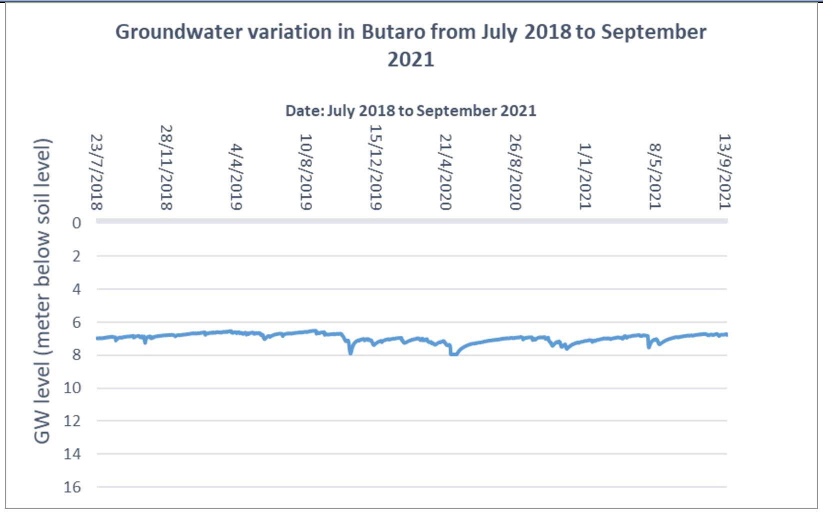


Groundwater variation in Rugarama from May 2018 to October 2018

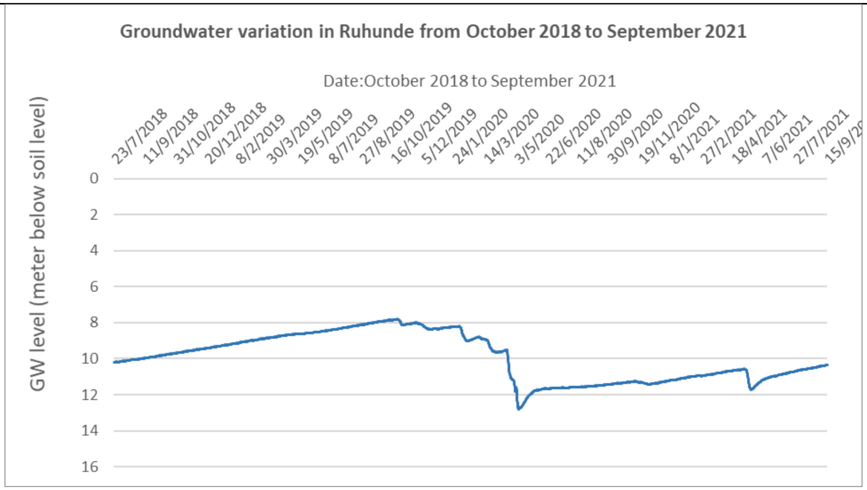
North province



Groundwater variation in Cyuve from December 2016 to September 2021



Groundwater variation in Butaro from July 2018 to September 2021



West Province

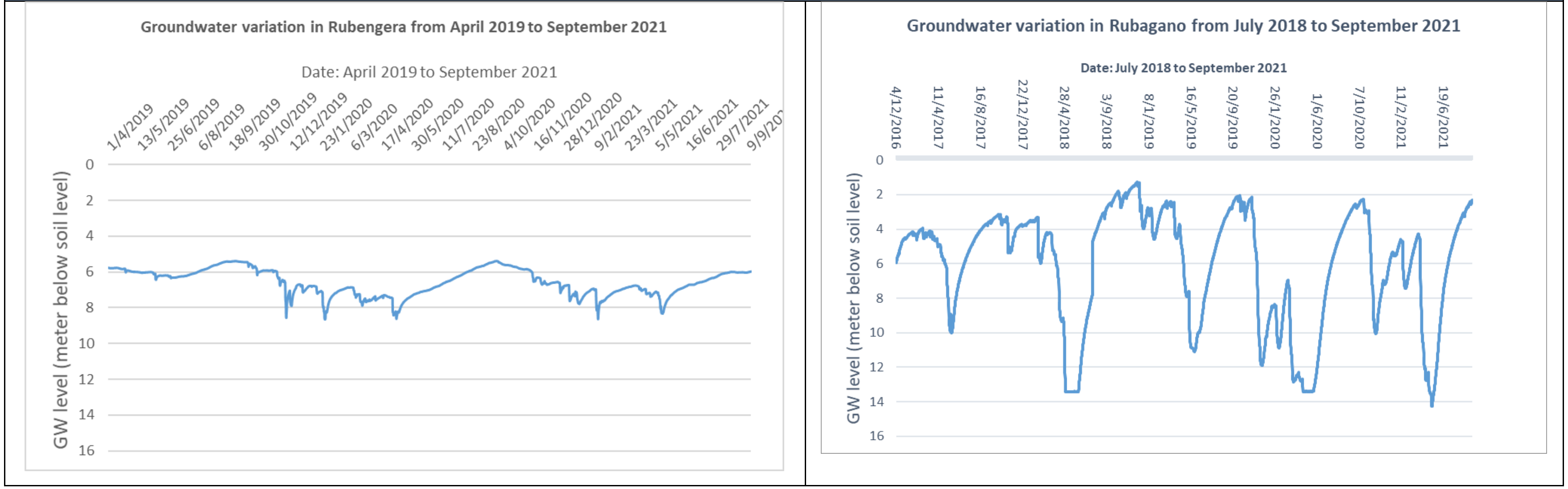


Figure 31: Summary of the groundwater level measurements.

1.2.6 Design of ERT-2D resistivity field survey

In the case of long-term investments in groundwater, it is necessary to know (1) the instantaneous flow, which is controlled by the aquifer's productivity (its transmissivity), (2) the annual sustainability of the instantaneous flow, which is controlled by the available reserves, and (3) the long-term sustainability of the abstraction, which is dependent on reserve renewal (the groundwater recharge). These terms will be assessed by two means:

- Measurements with ERT-2D resistivity, to describe (i) groundwater recharge, to be used to compare with the one from the WEAP Model, (ii) groundwater storage capacity on aquifer level, (iii) the geometry of aquifer to understand if aquifers are connected or overlapping, (iv) hydraulic properties (transmissivity, porosity, hydraulic conductivity and permeability) and their correlation in terms of aquifer productivity and (iv) hydro-geological formation (thickness in meter and which type of rocks before reaching water level).
- The WEAP modelling.

The ERT-2D resistivity survey covered at least 24 sites representing all the types of aquifers, focusing on areas with no existing boreholes. The methodology for selecting the 24 sites is as follows:

- The biggest three aquifers (in terms of surface) were chosen for each of the eight aquifer types (excluding lacs).
- Only one central point was chosen for each of the 24 aquifers to be surveyed.
- The site should be accessible.

The details on the selected 24 sampling sites are presented in Table 16 and Figure 32. The first activity in the field was to determine the exact location of the area to be surveyed. The interpretation of the measurements is based on the difference in conductivity; the higher the conductivity, the harder the rock), and the lower the conductivity, the greater presence of water.

Table 16: Details on the 24 selected survey sites.

S/N	Type_Acquifer	District	Sector	Cell	Village	X	Y	rea of the Acquifer (ha
1	Alluvial aquifers	Gakenke	Ruli	Gikingo	Karango	29.79996874	-1.845081021	6665.115465
2	Alluvial aquifers	Gasabo	Nduba	Gasanze	Nyakabungo	30.08083328	-1.882638508	6605.039094
3	Alluvial aquifers	Rusizi	Bugarama	Pera	Ituze	29.01997508	-2.695944626	4148.557444
4	Complex aquifer (volcanic rock)	Nyagatare	Nyagatare	Rutaraka	Ryabega	30.35311614	-1.360750256	3108.354526
5	Complex aquifer (volcanic rock)	Rusizi	Giheke	Cyendajuru	Murinzi	28.96522812	-2.461120989	41319.4429
6	Complex aquifer (volcanic rock)	Rusizi	Gikundamvura	Mpinga	Bushenge	29.04997645	-2.631600992	3174.937768
7	Fractured aquifer (granite and gneiss)	Bugesera	Mayange	Mbyo	Rugarama	30.1776398	-2.227657457	31784.75877
8	Fractured aquifer (granite and gneiss)	Nyamgabe	Tare	Nyamigina	Uwinyana	29.52381	-2.502422	432533.3876
9	Fractured aquifer (granite and gneiss)	Rutsiro	Ruhango	Rundoyi	Kaziga	29.375617	-1.840419	120015.6877
10	Low permeable fractured aquifer (schist and micaschist)	Gasabo	Gikomero	Munini	Munini	30.23751528	-1.887134043	23709.36
11	Low permeable fractured aquifer (schist and micaschist)	Nyamasheke	Rangiro	Murambi	Nyakabingo	29.16089	-2.411566	32802.869
12	Low permeable fractured aquifer (schist and micaschist)	Rulindo	Burega	Karengeri	Gashinge	30.04638551	-1.720601221	24702.584
13	Organo-sedimentary alluvial aquifer (low permeability, clay base)	Gatsibo	Rwimbogo	Munini	Nyamwiza	30.511088	-1.591656	13129.24322
14	Organo-sedimentary alluvial aquifer (low permeability, clay base)	Nyagatare	Rwimiyaga	Kirebe	Kirebe	30.466714	-1.262764	7142.443371
15	Organo-sedimentary alluvial aquifer (low permeability, clay base)	Nyagatare	Nyagatare	Gakirage	Nkongi	30.287872	-1.401636	18192.43916
16	Peat	Burera	Butaro	Nyamicucu	Murwa	29.852906	-1.385926	8272.959072
17	Peat	Gicumbi	Mukarange	Rusambya	Nyagakizi	30.05441053	-1.48716419	2707.103275
18	Peat	Gisagara	Mamba	Muyaga	Butezi	29.92419919	-2.520639673	12275.95228
19	Permeable fractured aquifer (quarzite on schist base)	Burera	Rwerere	Rugari	Gatovu	29.86351922	-1.52515672	8315.045095
20	Permeable fractured aquifer (quarzite on schist base)	Gicumbi	Kageyo	Kabuga	Gicumbi	30.08891	-1.657086	56474.05655
21	Permeable fractured aquifer (quarzite on schist base)	Rusizi	Bweyeye	Gikungu	Rwamagare	29.220497	-2.614511	11383.36553
22	Semi-permeable fractured aquifer (schist, mica and quartzite)	Gakenke	Rushashi	Shyombwe	Gihororo	29.825748	-1.703356	48390.6276
23	Semi-permeable fractured aquifer (schist, mica and quartzite)	Rulindo	Masoro	Kivugiza	Nyarurembo	30.04832892	-1.801681093	13898.60846
24	Semi-permeable fractured aquifer (schist, mica and quartzite)	Rusizi	Gitambi	Mashesha	Ruvuruga	28.99138451	-2.587106849	10909.34085

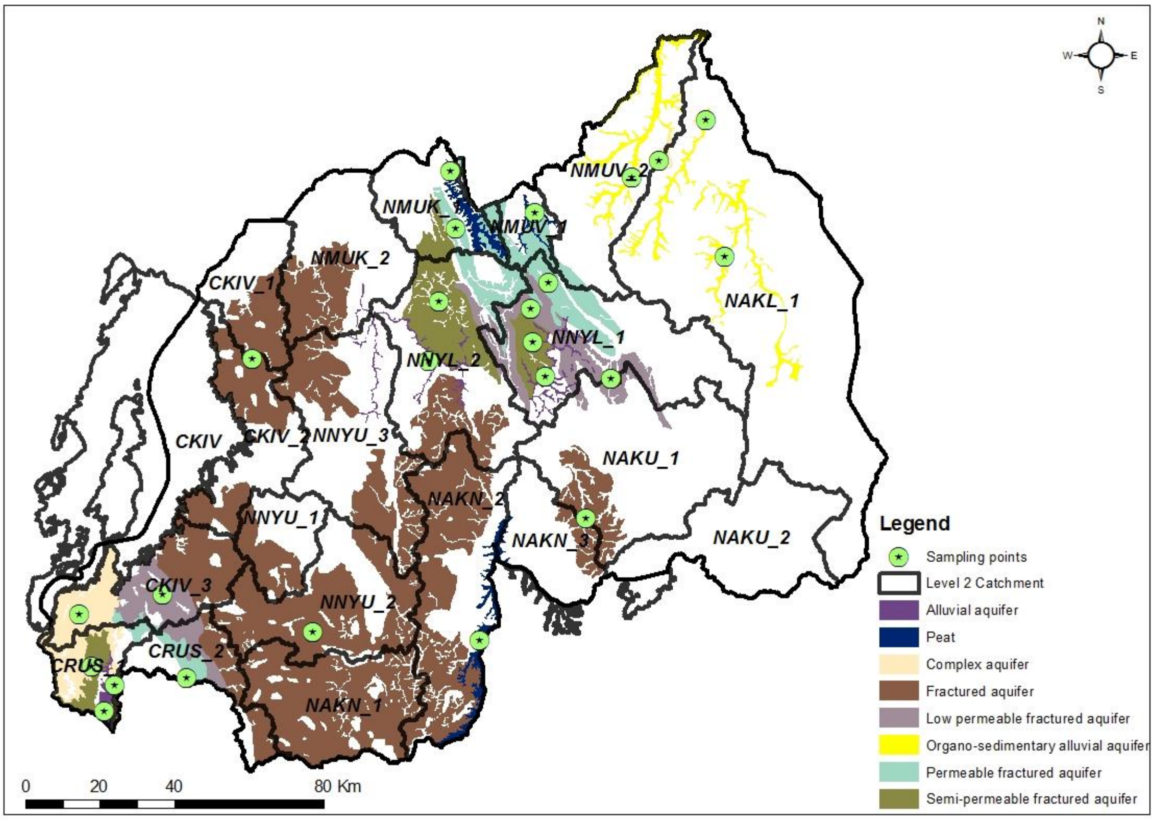


Figure 32: Location of the 24 selected sites for geophysical survey using ERT-2D resistivity.

Traverses will be surveyed using the Wenner-Schlumberger hybrid protocol to overcome individual limitations of Wenner and Schlumberger and optimize probing depth. Traverses will be surveyed with a standard minimum electrode spacing of 1 m, resulting in a mean average probing depth of about 300 m.

1.2.7 Results of the ERT-2D resistivity field survey

For the 24 sites surveyed, the following were assessed (i) surveyed area, (ii) void ratio of the surveyed area, (iii) soil profile and (iv) the theoretical storage capacity. After obtaining the survey soil profile map, we interpret the difference in conductivity, higher the conductivity representing hard rock and lower the conductivity for liquid/groundwater.

The following table summarises the findings from the conducted survey. The aquifer storage was estiamted as a product of [sampled area in m²] x [aquifer thickness in m] x [porosity], leading to a total theoretical storage capacity for surveyed aquifers (541,999 m²) of 36.7 Mm^3. The only dry aquifer was found in Bugesera district (East Province). The aquifer thickness is laying between 170 to 70m.

An example of the soil profile from the survey is in Figure 33. The soil profile in this example is dry due to (1) a sandy layers down to 300 m which allows water to percolate towards deeper layers and (2) high evapotranspiration in this area.

Table 17: Summary of the ERT-2D resistivity field survey

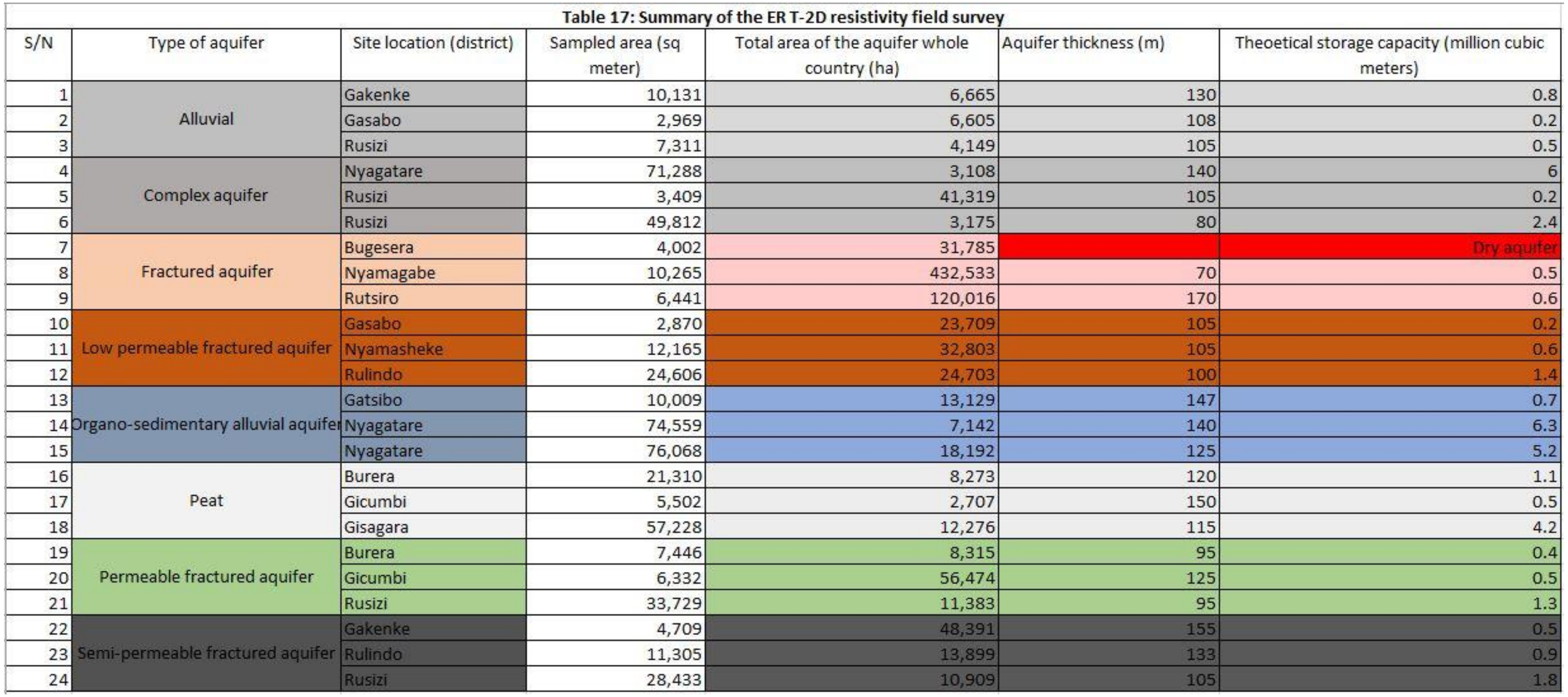
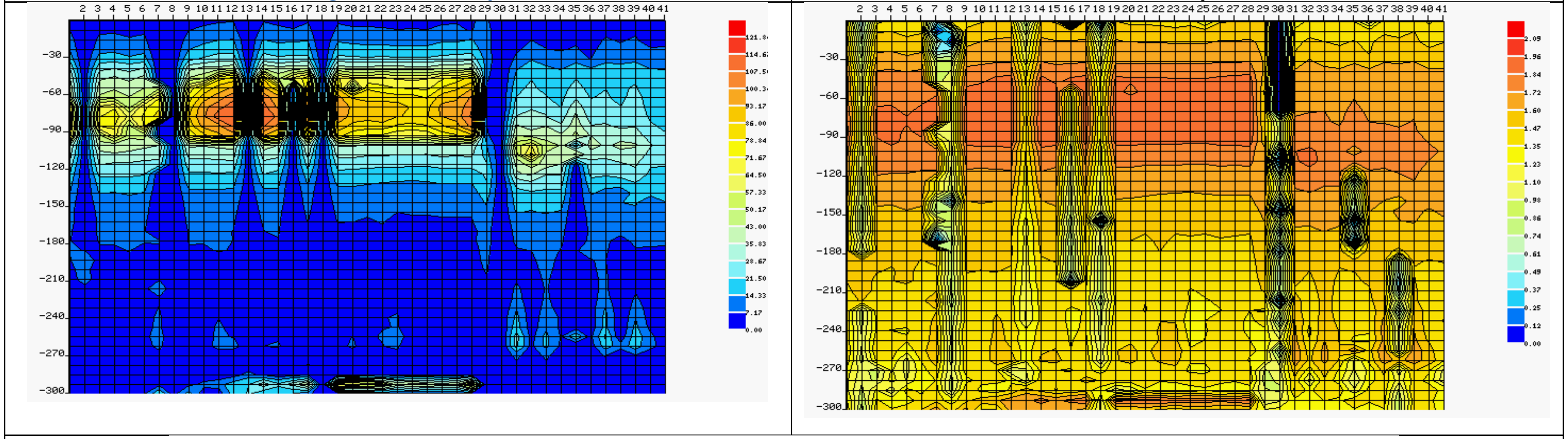


Table 17: Summary of the ER T-2D resistivity field survey

S/N	Type of aquifer	Site location (district)	Sampled area (sq meter)	Total area of the aquifer whole country (ha)	Aquifer thickness (m)	Theoetical storage capacity (million cubic meters)
1	Alluvial	Gakenke	10,131	6,665	130	0.8
2		Gasabo	2,969	6,605	108	0.2
3		Rusizi	7,311	4,149	105	0.5
4	Complex aquifer	Nyagatare	71,288	3,108	140	6
5		Rusizi	3,409	41,319	105	0.2
6		Rusizi	49,812	3,175	80	2.4
7	Fractured aquifer	Bugesera	4,002	31,785		Dry aquifer
8		Nyamagabe	10,265	432,533	70	0.5
9		Rutsiro	6,441	120,016	170	0.6
10	Low permeable fractured aquifer	Gasabo	2,870	23,709	105	0.2
11		Nyamasheke	12,165	32,803	105	0.6
12		Rulindo	24,606	24,703	100	1.4
13	Organo-sedimentary alluvial aquifer	Gatsibo	10,009	13,129	147	0.7
14		Nyagatare	74,559	7,142	140	6.3
15		Nyagatare	76,068	18,192	125	5.2
16	Peat	Burera	21,310	8,273	120	1.1
17		Gicumbi	5,502	2,707	150	0.5
18		Gisagara	57,228	12,276	115	4.2
19	Permeable fractured aquifer	Burera	7,446	8,315	95	0.4
20		Gicumbi	6,332	56,474	125	0.5
21		Rusizi	33,729	11,383	95	1.3
22	Semi-permeable fractured aquifer	Gakenke	4,709	48,391	155	0.5
23		Rulindo	11,305	13,899	133	0.9
24		Rusizi	28,433	10,909	105	1.8

Site: **Rugarama Village, Mbyo Cell, Mayange Sector, Bugesera District**

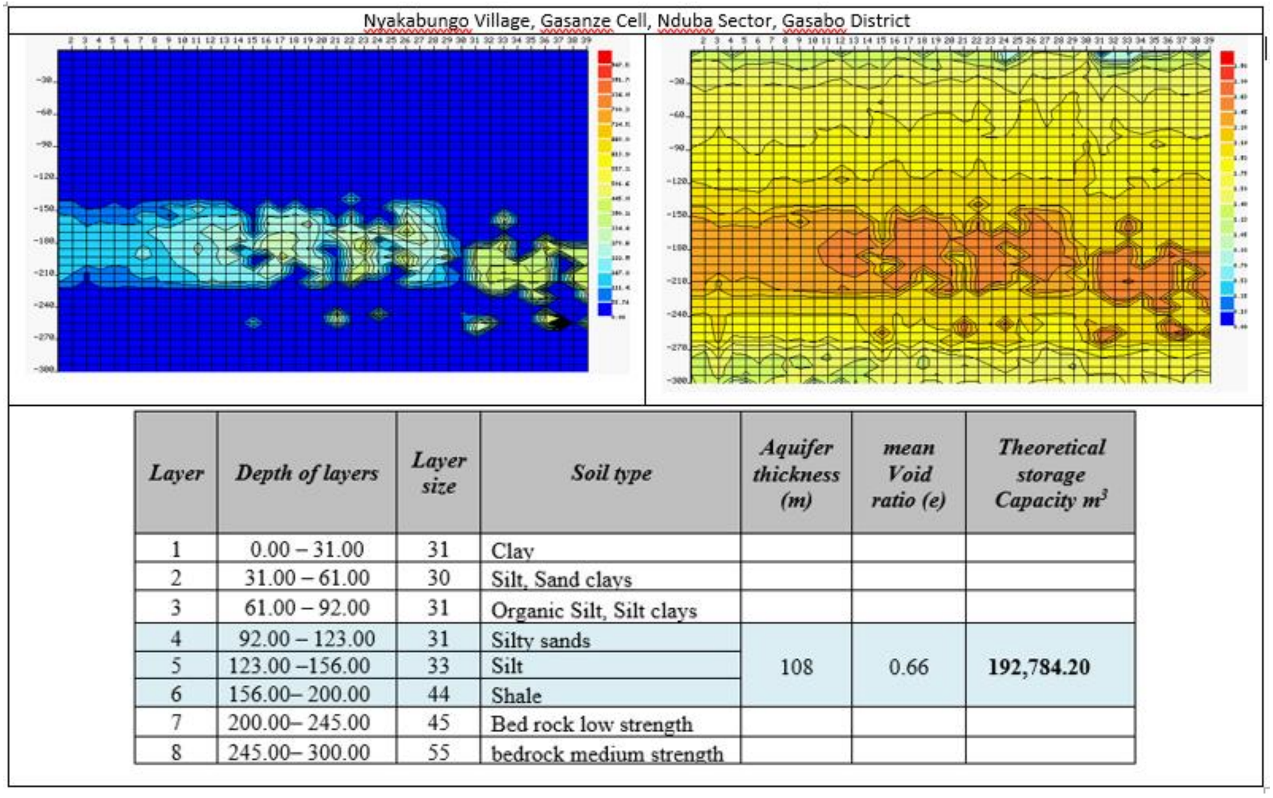

Original Profile map

Processed profile

Layer	*Depth of layers*	*Layer size*	*Soil type*	*mean Void ratio €*	*Theoretical storage capacity m^3*
1	0.00 – 20.00	20	Clay	-	
2	20.00 – 37.00	17	Silty sands	-	
3	37.00 – 66.00	29	Shale	-	
4	66.00 – 79.00	13	Shale	-	
5	79.00 –105.00	26	Bed rock low strength	0.66	Dry aquifer
6	105.00– 131.00	26	Bed rock low strength		
7	131.00– 223.00	92	Shale	-	
8	223.00– 270.00	47	Silt,	-	
9	270.00– 300.00	30	Silty sands	-	

Figure 33: Soil profile map with interpretation for the case of a dry aquifer in Bugesera.

In a second example (Figure 34), the aquifer contains water which can be exploitable, depending on the soil structure. The aquifer layer starts at 92m down to 200m. The bedrock is located to 200m and beyond.



Layer	Depth of layers	Layer size	Soil type	Aquifer thickness (m)	mean Void ratio (e)	Theoretical storage Capacity m³
1	0.00 – 31.00	31	Clay			
2	31.00 – 61.00	30	Silt, Sand clays			
3	61.00 – 92.00	31	Organic Silt, Silt clays			
4	92.00 – 123.00	31	Silty sands	108	0.66	**192,784.20**
5	123.00 –156.00	33	Silt			
6	156.00– 200.00	44	Shale			
7	200.00– 245.00	45	Bed rock low strength			
8	245.00– 300.00	55	bedrock medium strength			

Figure 34: Soil profile map with interpretation for the case of an aquifer with water

Detailed results can be found in Annexe 4.

1.2.8 Assessment of groundwater storage

Groundwater data are limited in Rwanda, making it difficult to estimate properly. Efforts are being invested in collecting the necessary data for properly estimating the available groundwater resources countrywide. Currently, the available information on groundwater are be found in several documents, detailed earlier. Additionally, boreholes data available (see section 1.2.4) and few recordings of groundwater level from the monitoring network of RWB (see section 1.2.5).

The intention of this assessment is to estimate the volume of groundwater resources to support the water allocation analysis being conducted in this study.

1.2.8.1 Methodology

The previous assessment conducted during the development of the first national water resources masterplan used isotopes to estimate the recharge of aquifers in Rwanda. This process was completed over a long time (approximately a year) and included mapping the lithology as well. Due to time and budget constraints, a different approach is adopted here to estimate groundwater resources. This assessment focused on estimating aquifer volume using their areas and depths, considering their spatial location in relation to the physiographic zonification of the country. To be able to conduct this assessment, some strategic assumptions were made. The assumptions were designed to facilitate a realistic estimation of the volume, from the available data.

Assumptions

With consideration of limited available data, the following assumptions were considered:

- Aquifers are considered with uniform characteristics in each physiographic zones.
- The extraction of water from the boreholes is constant.
- The return of water in the aquifers from the extraction is negligible.
- The available static water level data is the average water table.
- The total drilled depth of each borehole reaches the bottom layer of the active storage of the aquifer.
- The computed aquifer storage is the available groundwater resources for use and not necessarily the total available resources.

Approach

The approach applied in this assessment is GIS-based and consists in using:

- the lithology (see section 1.2.1, p57),
- the effective porosity (see section 1.2.2, p62),
- the physiography (see section 1.2.3, p62),
- and the boreholes database (see section 1.2.4, p64).

Firstly, the thickness was estimated using the available boreholes data, which were interpolated using the inverse distance weighting over the respective aquifer areas in each physiographic zone, leading to Figure 35. Secondly, the computed thickness was multiplied by the effective porosity and area of the aquifer, in the respective physiographic zone, to compute the available storage for use. Thirdly, all compute available storage for use were summed by aquifer type to produce a country estimate.

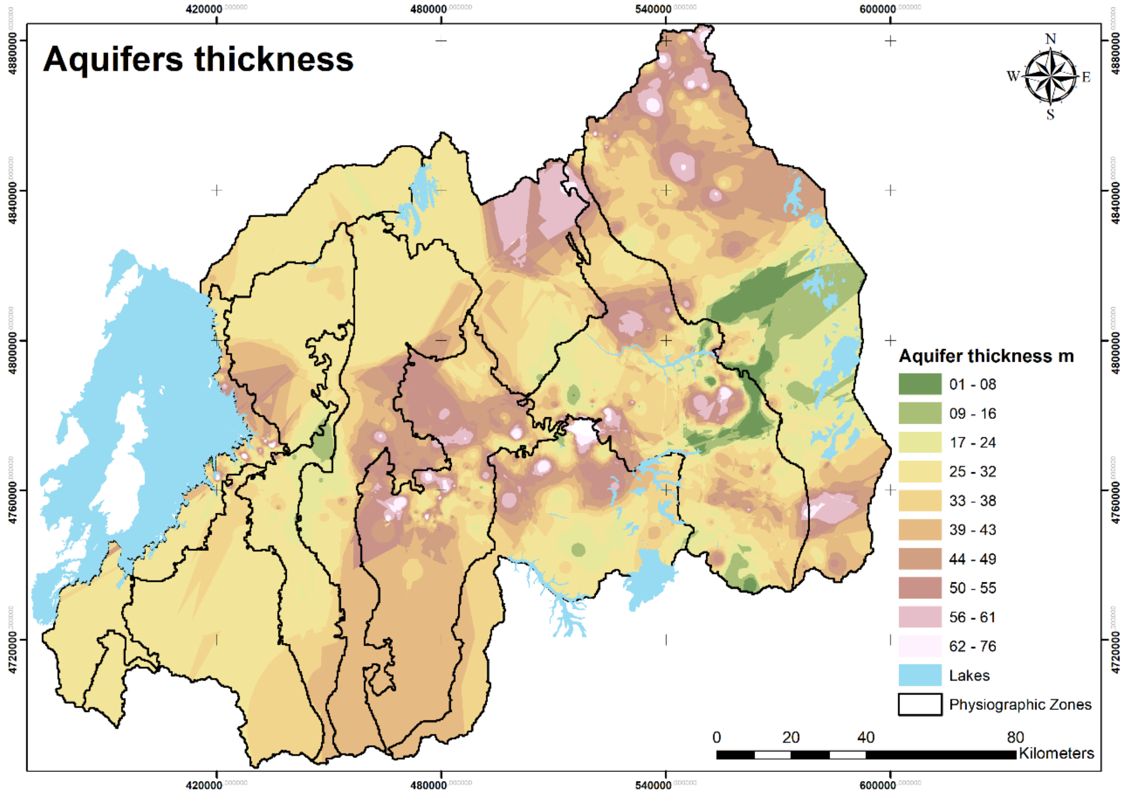


Figure 35: Estimated aquifer thickness.

1.2.8.2 Available groundwater resources for use

Following the methodology just presented and the typical values of effective porosity presented in Table 11 (p62), the available groundwater for use is summarised in the table below.

Table 18: Available groundwater resources for use per aquifer.

Aquifer type	Area (km^2)	Average thickness (m)	Effective Porosity	Used volume for exploitation (Mm^3)
Semi-permeable fractured aquifer (schist, mica and quartzite)	4,257.5	39	0.01	1755.85
Permeable fractured aquifer (quarzite on schist base)	2,820.1	31	0.01	909.01
Peat	269.1	42	0.14	1582.91
Organo-sedimentary alluvial aquifer (low permeability, clay base)	1,333.5	42	0.08	4344.13
Low permeable fractured aquifer (schist and micaschist)	3,548.7	36	0.01	1335.44
Fractured aquifer (granite and gneiss)	8,555.0	41	0.01	3710.82
Complex aquifer (volcanic rock)	1,743.0	40	0.10	6921.10
Alluvial aquifers	1,213.2	37	0.14	6277.77
Total volume				26,837.03

According to the ERT-2D resistivity field survey, all the aquifers surveyed had a thickness greater than 100m. This value is greater than the thicknesses of the boreholes drilled in different areas of the country. The difference is because drillers stop when they reach the yield they want or to the capacity of the drilling machines. Consequently, the groundwater in use presented above in Table 18 is below the total groundwater storage. The total aquifer storage was estimated by multiplying the available water in use with the ratio between the average thickness of the aquifer measured using ERT-2D resistivity and the average thickness of groundwater in use for a specific type of aquifer (Table 20).

Eventually, existing data allowed to estimate the volume of available groundwater for use (26,837.03 Mm3), which was finally extrapolated to the total groundwater storage of ca **80.7 BCM** by using the data from ERT-2D resistivity.

The groundwater storage per catchment is shown in Figure 36 and Table 19.

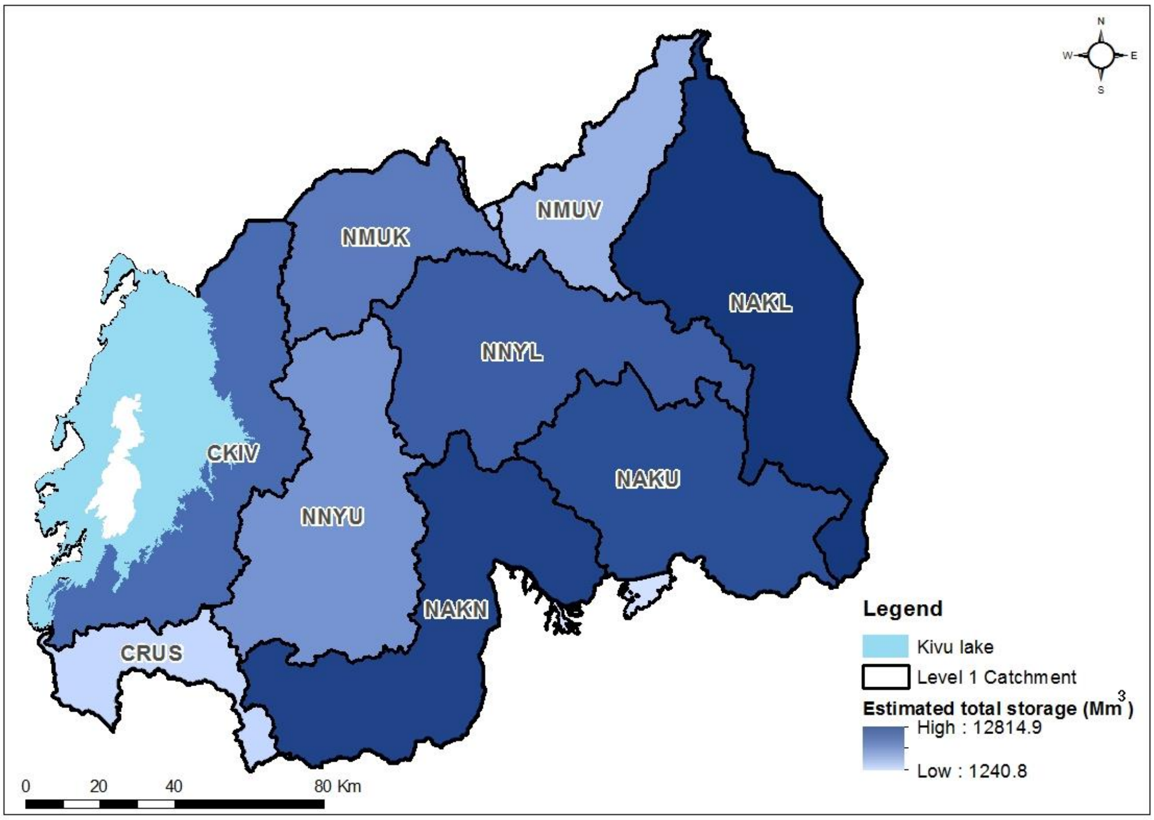
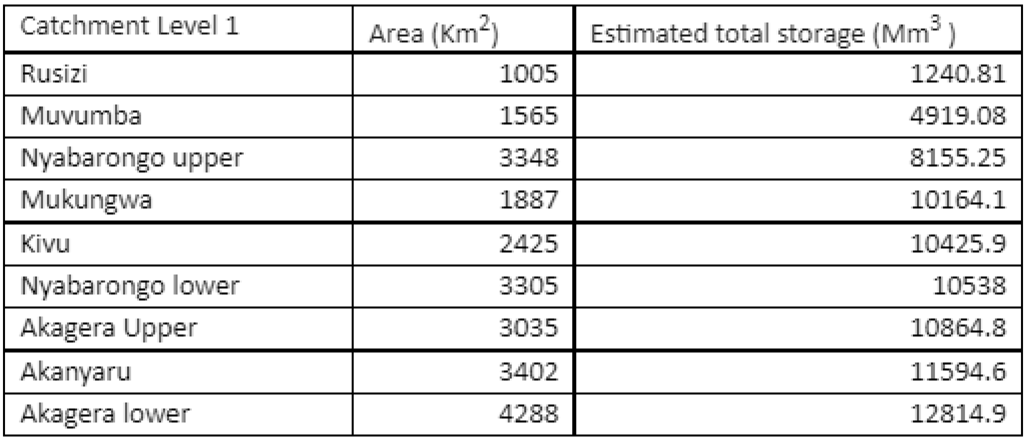


Figure 36: Ground Water Storage per catchment level one

Table 19: Ground Water Storage per catchment level one.



Catchment Level 1	Area (Km^2)	Estimated total storage (Mm^3)
Rusizi	1005	1240.81
Muvumba	1565	4919.08
Nyabarongo upper	3348	8155.25
Mukungwa	1887	10164.1
Kivu	2425	10425.9
Nyabarongo lower	3305	10538
Akagera Upper	3035	10864.8
Akanyaru	3402	11594.6
Akagera lower	4288	12814.9

Table 20: Estimated total groundwater storage

Sr.	Aquifer type	Area (km^2)	Average thickness (m)	Available storage for use (Mm^3)	Average thickness from borewell data	Effective Porosity	Estimated total storage (Mm^3)
1	Semi-permeable fractured aquifer (schist, mica and quartzite)	4,257.5	39	1,755.85	131	0.01	5,111.15
2	Permeable fractured aquifer (quarzite on schist base)	2,820.1	31	909.01	105	0.01	3,207.89
3	Peat	269.1	42	1,582.91	128	0.14	4,521.44
4	Organo-sedimentary alluvial aquifer (low permeability, clay base)	1,333.5	42	4,344.13	137	0.08	10,679.23
6	Low permeable fractured aquifer (schist and micaschist)	3,548.7	36	1,335.44	103	0.01	5,117.23
8	Fractured aquifer (granite and gneiss)	8,555.0	41	3,710.82	120	0.01	11,527.86
9	Complex aquifer (volcanic rock)	1,743.0	40	6,921.10	108	0.10	18,301.78
10	Alluvial aquifers	1,213.2	37	6,277.77	114	0.14	22,250.48
					Total storage		**80,717.05**

The final assessment of this study for total groundwater storage in Rwanda, 80.7 BCM, falls within the range in the literature. The following table summarises the comparison:

Table 21: Comparison of different assessments of groundwater storage available for Rwanda

Reference	Groundwater storage in km cubic meter (BCM)
This study	80.7
MacDonald et al., 2012[1]	6 - 198
NWRMP 2015	60.6

1.3 Level 2.5 catchment spatio-temporal hydrological assessment for the baseline situation

The results in this section show the output of the WEAP model for the baseline situation, defined as being the 2000 – 2019 timespan. This will serve as a reference scenario for analysing the impact of climate change on the hydrological water balance. The key hydrological variables considered for the water balance are:

- Precipitation
- Evapotranspiration
- Groundwater recharge
- Surface Runoff
- Interflow
- Runoff (Interflow + Surface Runoff)

Detailed model outcomes for each 2.5 catchment are provided in Annexe 6.

1.3.1 Precipitation

Maps of the mean annual precipitation are shown in Figure 37 for Level 1 and Level 2.5 catchments. As this considers the baseline and the precipitation given as input data, the results presented below are similar to those presented in the Hydrological data section (see section 1.1.3). The main differences between two outputs lie in the fact that rainfall data for the CRUS-catchment is represented by Princeton data rather than the Meteo-Rwanda historical dataset, and because the initial analysis considered 88 catchments rather than the 86 catchments presented here (see Annexe 5 for a detailed explanation). The precipitation is highest for CKIV and lowest for NAKL in the East.

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[1] Ibid.

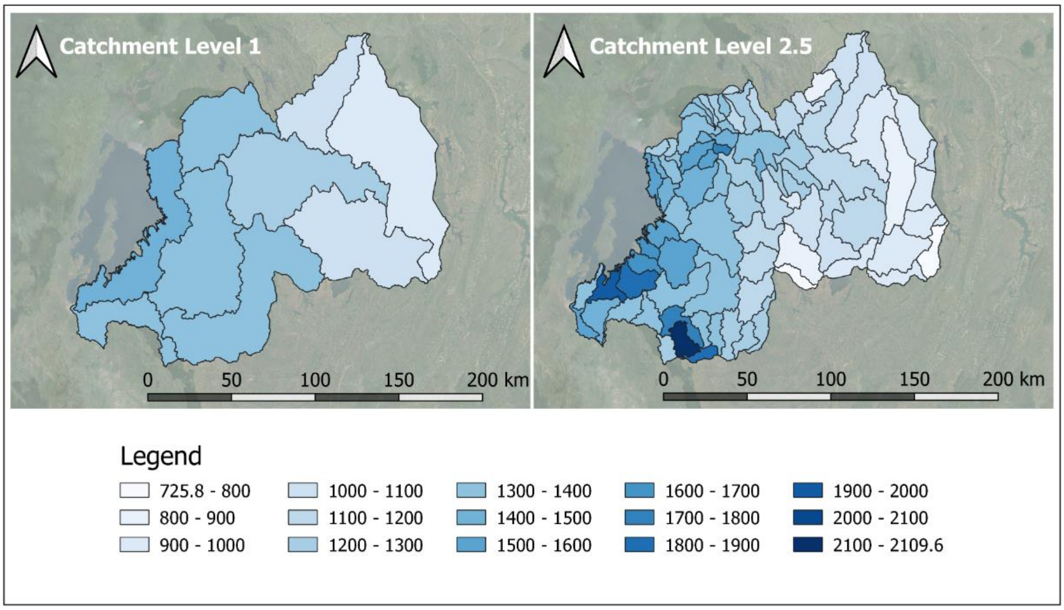

Figure 37. Catchment level precipitation for level 1 (left) and level 2.5 (right) for the baseline (2000 – 2019).

The annual precipitation for the baseline period for each of the nine level 1 catchment is shown in Figure 38. The CRUS catchments is represented from 2010 by a straight line as the data was averaged over 30 years (1980 -2010), as discussed under section 1.1.2. 2017 shows to be an odd year, although the data for this year did not show any missing values nor other consistency errors. As a consequence, the precipitation data for all but the CRUS (averaged) catchments show a local depression. Furthermore, most of the minima presented in Table 22 occurred in 2017 further stressing the impact of this 2017 depression on the baseline and thus climate projections. Furthermore, a depression around 2005, although less extreme, is also visible from the data.

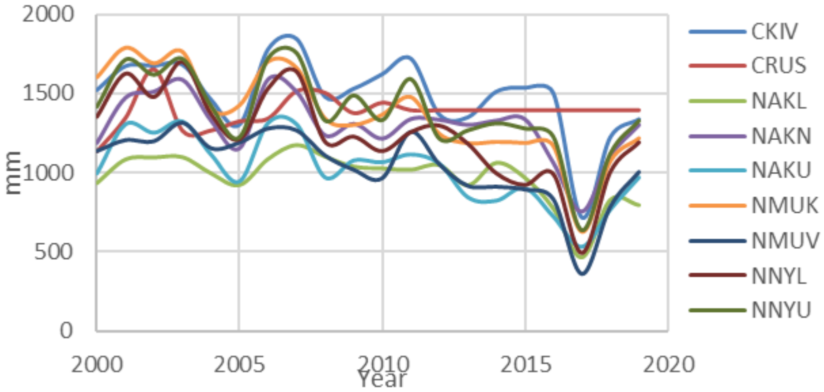

Figure 38. Historic annual precipitation (2000 – 2019) for each of the L1 catchments.

Table 22. Annual average, maximum and minimum precipitation for each level 1 catchment.

Baseline	*Max*	*Min*	*Average*
CKIV	2468	621	1493
CRUS	1780	1033	1387
NAKL	1447	207	951
NAKN	2756	294	1320
NAKU	1618	316	1028
NMUK	2161	251	1372
NMUV	1583	252	1041
NNYL	2048	402	1241
NNYU	1914	518	1388

Figure 39 shows the monthly variation of the Precipitation data for the baseline. All the catchments follow a similar seasonal pattern. The wetter regions (CKIV, CRUS) show slightly lower depressions during January and February. CKIV furthermore has on average a shorter dry season as the peak precipitation is reached around October rather than November for the other catchments.

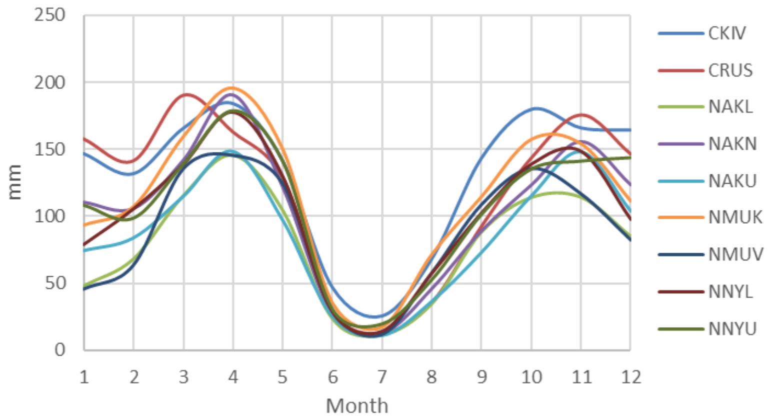

Figure 39. Monthly Average Precipitation for each level 1 catchment for the Baseline (2000 – 2019)

Table 23. Tabulated differences between the model output (2000 – 2019), the NWRMP (2015) and the Meteo-Rwanda (1981 - 2019) datasets at catchment level 1.

	Meteo-Rwanda (2000 - 2019) [mm/year]	*WEAP_Output (2000 - 2019) [mm/year]*	*NWRMP (2015) [mm/year]*	*Meteo-Rwanda/ NWRMP %change*	*WEAP Output/ NWRMP %change*
CKIV	1493	1486	1240	83%	83%
CRUS	2064	1389	1295	63%	93%
NNYU	1388	1400	1365	98%	98%
NMUK	1372	1405	1315	96%	94%
NNYL	1257	1250	1191	95%	95%
NAKN	1320	1312	1225	93%	93%
NAKU	999	1033	925	93%	90%
NAKL	970	912	835	86%	92%
NMUV	1041	1063	995	96%	94%

Table 23 shows the results for the Meteo-Rwanda dataset (not modified for CRUS), the WEAP output for precipitation (i.e. P is an input parameter but for this purpose studied as an output to capture the modifications discussed under 1.1.2), and the rainfall estimates presented in the NWRMP (2015) report. First of all, the main difference between the original Meteo-Rwanda data and the dataset used for WEAP is for CRUS, as previously discussed. Comparing the WEAP precipitation dataset with the estimates tabulated in the NWRMP (2015) shows a generally good relationship. Only for CKIV did the NWRMP present a significantly lower precipitation rate. Given the use of Meteo-Rwanda local data, it is considered that the results represented by Meteo-Rwanda and thus WEAP are most correct.

1.3.2 Actual evapotranspiration

The baseline output for actual evapotranspiration (ETa), presented in Figure 40, shows that on level 1, the eastern NAKL region has the lowest ETa, whereas CKIV has the highest. On level 2.5, the region representing Kigali central of the country shows the lowest evapotranspiration, which can be related to its high level of urban land use.

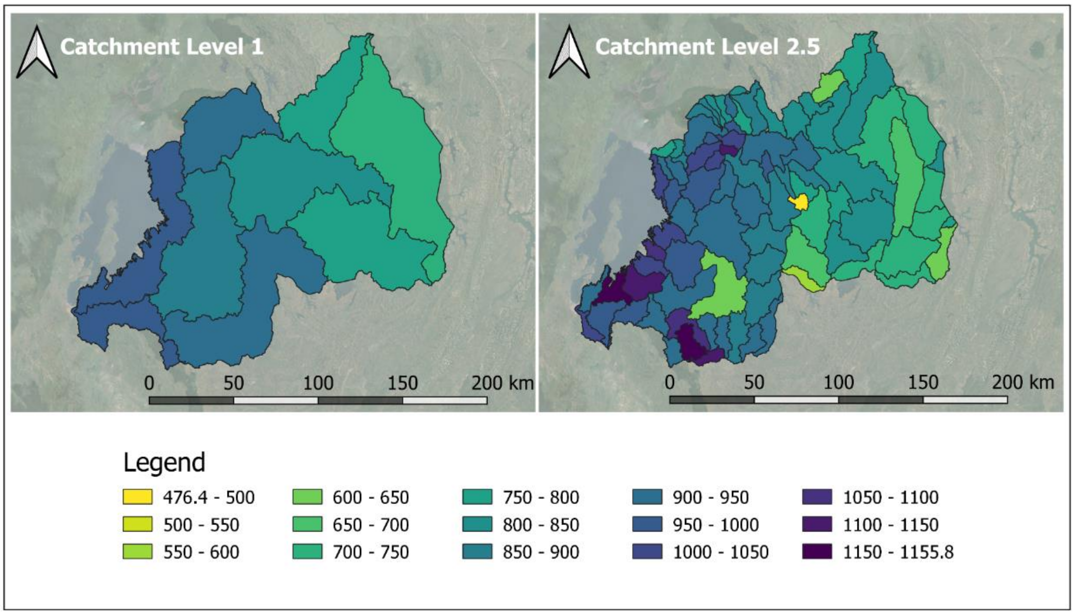

Figure 40. Catchment level evapotranspoiration for level 1 (left) and level 2.5 (right) for the baseline (2000 – 2019).

The annual ETa for the baseline period is shown in Figure 41. It can be seen that there is a decreasing trend for each level 1 catchment, with a dip around 2017 as a consequence of the depression observed for the precipitation data (Figure 38). The wetter regions (CKIV, NNYU, NMUK and CRUS) have the highest ETa estimates (Table 24). Also, here the 2005 depression is visible.

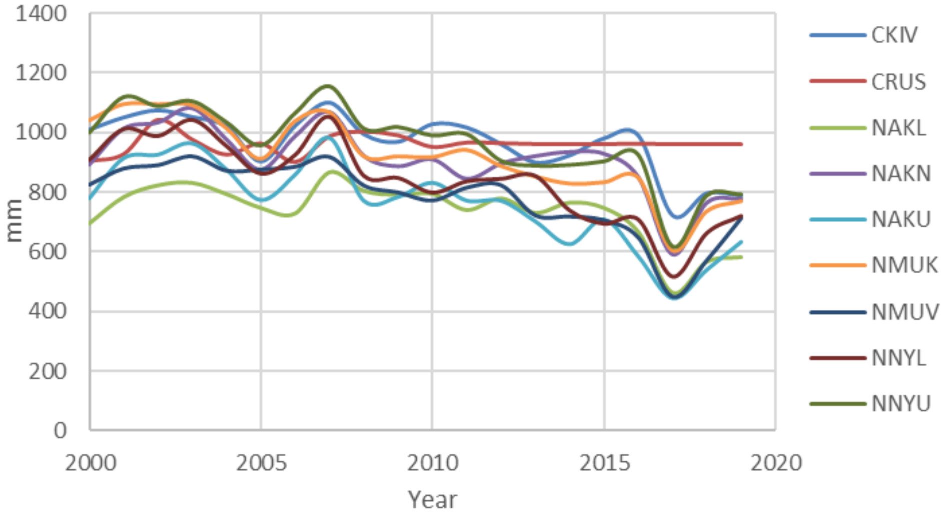

Figure 41. Historical data for Evapotranspiration (2000 – 2019) for each of the L1 catchments.

Table 24. Annual average, maximum and minimum ETa for each level 1 catchment.

Baseline	*Max (mm)*	*Min (mm)*	*Average (mm)*
CKIV	1308	647	967
CRUS	1114	849	962
NAKL	1136	274	747
NAKN	1307	303	876
NAKU	1259	452	913
NMUK	1183	342	850
NMUV	1185	296	770
NNYL	1209	510	918
NNYU	1100	641	922

Figure 42 shows for CKIV, CRUS, NNYU and NMUK (the wet regions) higher mean monthly evapotranspiration rates. In general, there are marginal seasonal trends in ETa, unlike the seasonal trend observed within the mean annual precipitation (Figure 39).

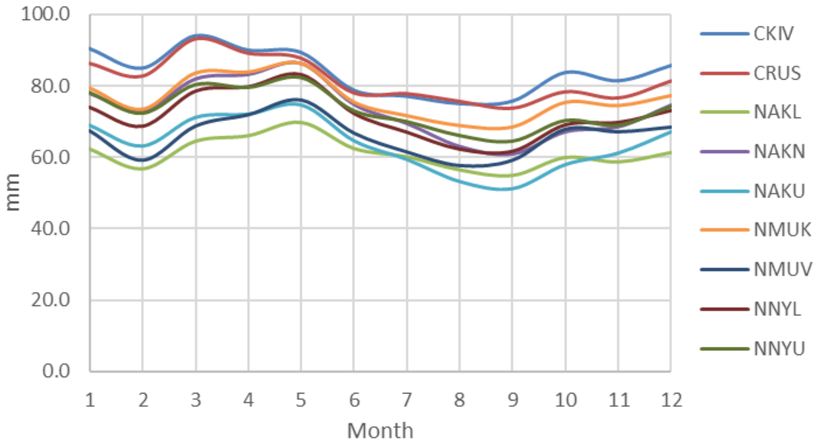

Figure 42. Monthly Average ETa for each level 1 catchment for the Baseline (2000 – 2019)

Comparing the obtained ETa WEAP results with WaPOR (see 1.1.3) and the NWRMP (2015), the estimates show that there is, in general, a good fit for both comparison datasets (on average).

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Table 25. Tabulated differences between the model output (2000 – 2019) and the NWRMP (2015) and the WAPOR (2009 – 2021) datasets at catchment level 1.

[mm/year]	*ETa (Wapor, 2021) [2009 - 2021]*	*ETa (WEAP model) [2000 -2019]*	*Wapor/ WEAP [%]*	*ETa (NWRMP, 2015)*	*NWRMP/ WEAP [%]*
CKIV	883	967	91%	870	90%
CRUS	816	960	85%	865	90%
NAKL	804	735	109%	624	85%
NAKN	835	909	92%	990	109%
NAKU	829	761	109%	760	100%
NMUK	765	919	83%	851	93%
NMUV	781	781	100%	872	112%
NNYL	787	841	94%	919	109%
NNYU	809	949	85%	980	103%

1.3.3 Groundwater recharge

Groundwater recharge can be determined with simple statistical approaches, or with dynamic physically-based hydrological modelling. For this study, the latter approach was preferred, using the dynamic simulations of the soil water balance performed by the WEAP model. These estimates were compared with a simpler generic approach proposed by MacDonald et al. (2021)[1].

MacDonald et al. (2021) developed a simple way to estimate recharge for African climate conditions by applying the following equation to annual precipitation estimates:

$$Log_e\ [LAT\ recharge] = \beta_0 + \beta_1 Log_e\ [LTA\ Rainfall] \qquad \text{[Equation 2]}$$

with $\beta_0 = -5$ and $\beta_1 = 1.388$

Using Equation 2 and the parameters for β_0 and β_1 as presented in the study, the long-term average (LTA in mm/year) for precipitation was determined by analysing the data provided by Meteo-Rwanda for the period 1981 – 2019. Subsequently, annual averages were inserted into equation 2 to obtain the recharge estimates for each of the level 2.5 catchments (Figure 43).

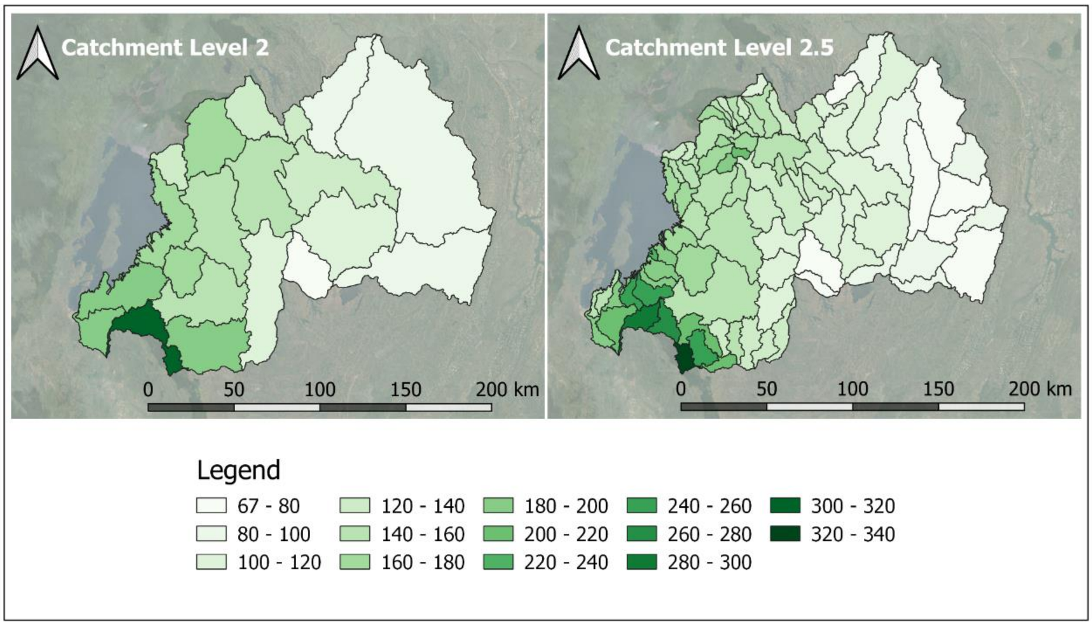

Figure 43. Annual averaged groundwater recharge for Rwanda (in mm/year) for both Catchment Level 2 (left) and 2.5 (right), based on Macdonald et al. (2021)[2].

Figure 44 presents the groundwater recharge rates as estimated by WEAP. What is seen is that recharge rates are high, with values between 300 – 350 mm/year in the southwestern corner of the country. Lower rates are found with values between 20 – 150 mm/year in the eastern parts of Rwanda.

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[1] Alan M MacDonald et al., 'Mapping Groundwater Recharge in Africa from Ground Observations and Implications for Water Security', *Environmental Research Letters* 16, no. 3 (16 February 2021): 034012, https://doi.org/10.1088/1748-9326/abd661.

[2] Ibid.

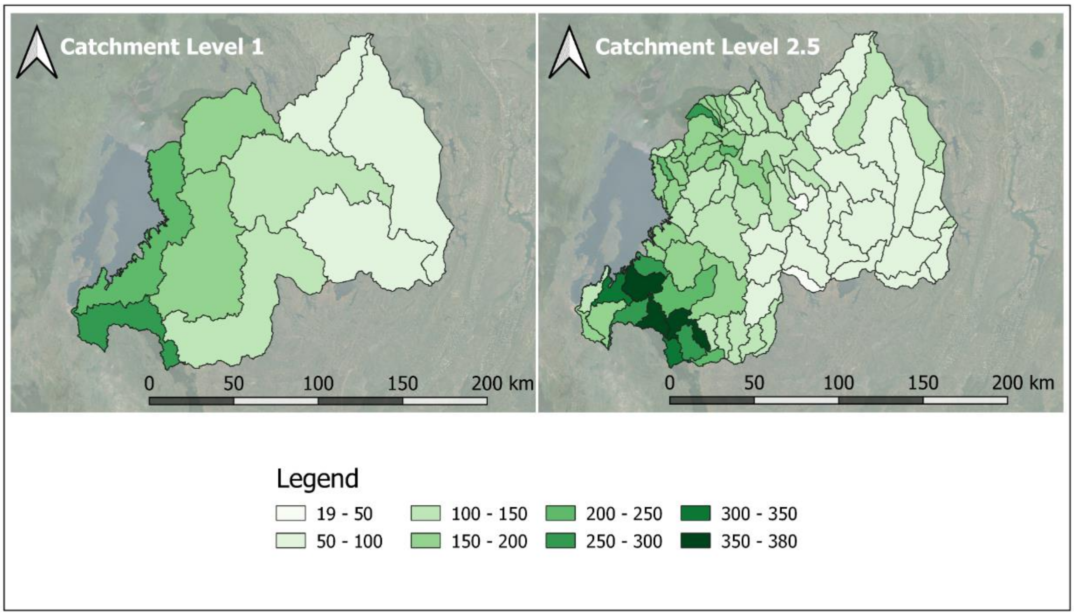

Figure 44. Annual averaged groundwater recharge (mm) for Rwanda obtained from the Baseline scenario WEAP model (2000 – 2019) for level 1 (left) and level 2.5 (right).

The Comparison of the results from MacDonald et al. (2021)[1] with the recharge rates from WEAP and the NWRMP-2015 shows some differences (Table 26). On Level 1, the WEAP model shows lower recharge estimates than those reported in the 2015 masterplan, except for NMUV. The MacDonald et al. (2021) study showed estimates closer to the WEAP output.

Table 26. Tabulated differences between the model output (2000 – 2019) and the NWRMP (2015) and the Macdonald et al. (2021) (1981 – 2019) datasets at catchment level 1.

	Recharge (Macdonald et al., 2021) [1981 - 2019]	*Recharge (WEAP) [2000 - 2019]*	*Macdonald/ WEAP [%]*	*Recharge (NWRMP, 2015)*	*NWRMP/ WEAP [%]*
CKIV	165	222	75%	250	113%
CRUS	259	252	103%	350	139%
NAKL	82	107	77%	125	117%
NAKN	141	151	93%	227	150%
NAKU	100	94	107%	115	123%
NMUK	153	200	77%	322	161%
NMUV	103	102	100%	71	69%
NNYL	132	142	93%	165	116%
NNYU	154	178	86%	292	164%

Focusing on the annual (Figure 45) and monthly (seasonal, Figure 46) trend in the historical data, the former shows that (neglecting CRUS) each of the datasets has a minimum in around year 2017, which is related to the 2017 depression observed in the precipitation dataset. The second depression of 2005 is also noticed. The data, in general, shows a fluctuating trend indicating that recharge is dependent on other processes and therefore not constant in space and time. Regarding the seasonal trend, recharge is highest around May and lowest around August for each of the nine catchments. This implies a small delay in recharge rates dropping/ increasing following precipitation as the peak precipitation falls around April and October, whereas the peak minimum occurs around July.

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[1] Ibid.

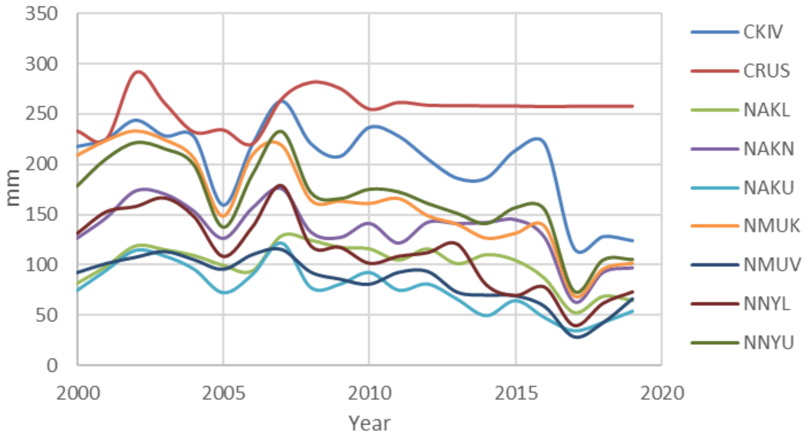

Figure 45. Historical data for Groundwater Recharge (2000 – 2019) for each of the L1 catchments.

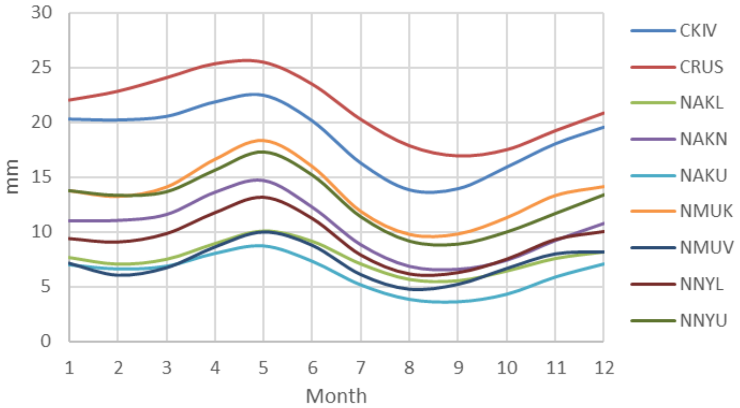

Figure 46. Monthly Average Groundwater Recharge for each level 1 catchment for the Baseline (2000 – 2019)

Table 27 indicates the annual minima, maximum and average for each of the nine catchments for the baseline period. Also here, a relationship with water availability is detected, since the catchments with the highest minima are the wetter regions.

Table 27. Annual average, maximum and minimum groundwater recharge for each level 1 catchment.

Baseline	*Max (mm)*	*Min (mm)*	*Average (mm)*
CKIV	441	66	203
CRUS	384	126	255
NAKL	209	10	97
NAKN	461	9	136
NAKU	150	14	75
NMUK	372	35	164
NMUV	150	14	85
NNYL	317	8	114
NNYU	333	39	166

1.3.4 Surface Runoff

WEAP calculates Surface Runoff directly. Figure 47 shows the spatial distribution of the obtained mean annual Surface Runoff estimates for the baseline period. NNYL, the catchment surrounding Kigali, shows the highest surface runoff, whereas NAKL and NMUV (in the Northeast) show the lowest surface runoff rates. Especially on level 2.5 is the impact of urbanised Kigali on surface runoff rates visible.

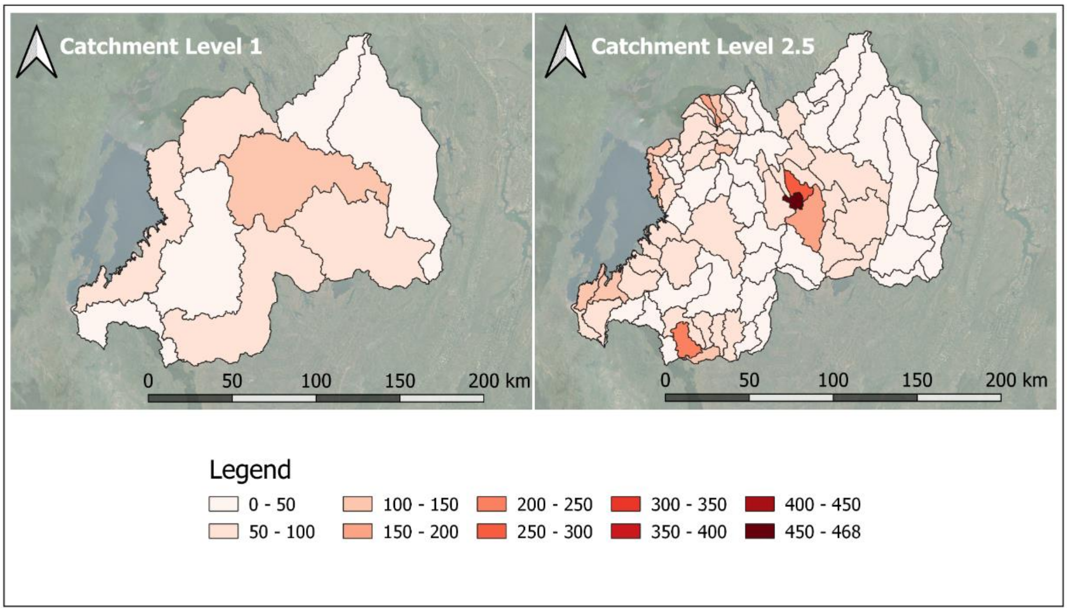

Figure 47. WEAP model output for mean annual surface runoff (mm/yr) for level 1 and level 2.5 (2000 – 2019).

From the historical time-series data, a slightly decreasing trend in surface runoff can be observed (Figure 48), with depression around 2005 and 2017 for each of the nine sub-catchments. NNYL, in the centre of Rwanda, shows significant peaks compared to the other catchments. On a monthly average (Figure 49), the higher peaks are obtained in NAKU, NNYL and CKIV, especially during October/ November. Again, a relationship with precipitation rates is noticeable; surface runoff rates tend to increase during peak precipitation.

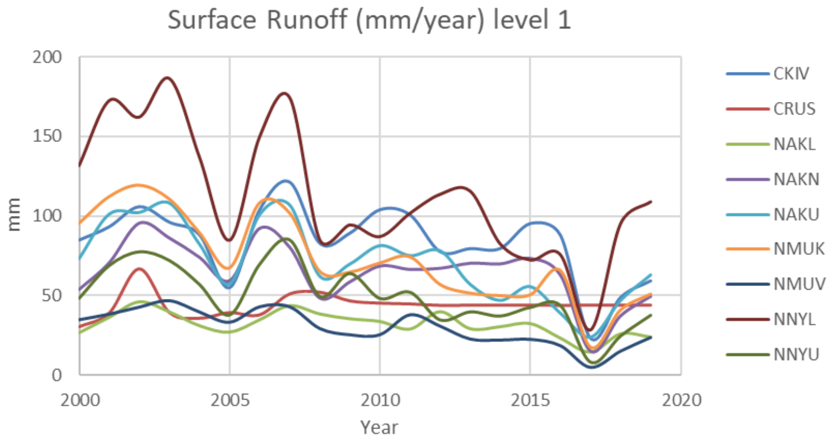

Figure 48. Historical Surface Runoff (2000 – 2019) for each of the L1 catchments.

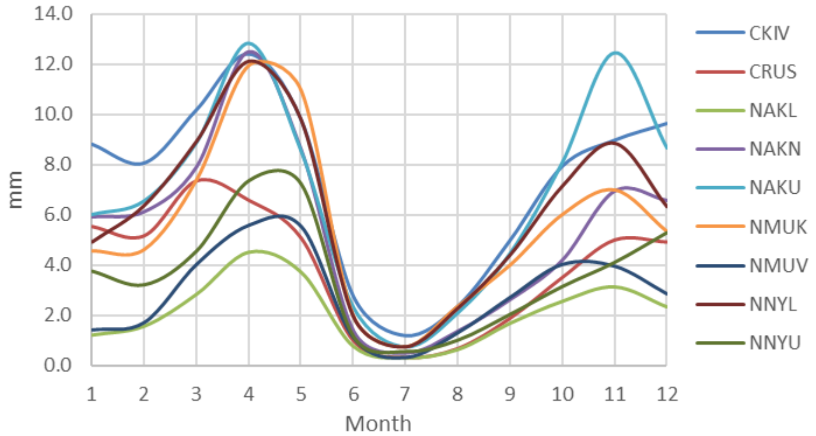

Figure 49. Monthly Average SW Runoff for each level 1 catchment for the Baseline (2000 – 2019)

Table 28. Annual maximum and minimum Surface Runoff for each level 1 catchment.

Baseline	*Max (mm)*	*Min(mm)*	*Average (mm)*
CKIV	250	8	84
CRUS	140	1	44
NAKL	81	0	25
NAKN	367	6	75
NAKU	286	7	80
NMUK	277	4	73
NMUV	112	2	36
NNYL	769	4	113
NNYU	105	6	46

Table 28 shows the retrieved annual average, minima and maxima surface runoff rates for each level 1 catchment (for level 2.5 resolution) from the WEAP model.

1.3.5 Interflow

WEAP calculates Interflow (= subsurface runoff) directly. Figure 50 shows for the baseline the spatial distribution of the obtained mean annual interflow estimates, representative for 2010. NNYL, the catchment surrounding Kigali, shows, in contrast to the surface runoff, a low value indicating that urbanisation has an opposite effect on interflow rates. The highest interflow occurs in the Western part of the country, in regions where the precipitation is high as well. NAKN_M in the south has the highest interflow rate of about 430 mm/year. This catchment is characterised by the highest mean annual precipitation (Figure 37), hence the impact of precipitation on interflow is noticeable.

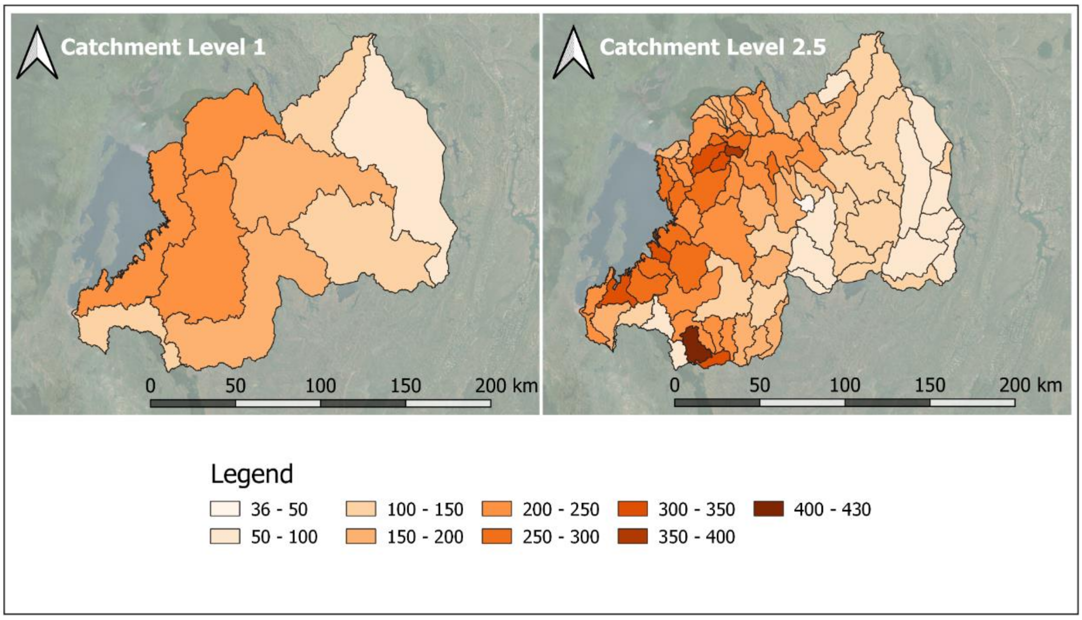

Figure 50. Interflow for the Baseline period for both level 1 and level 2.5 catchments (2000 – 2019)

As for the other hydrological variables, a clear depression around 2017 and a less severe dip around 2005 are detected in the historical datasets (Figure 51). Aside these depressions, the general trend of interflow is stable up to 2015, after which the impact of the 2017 depression cannot be separated.

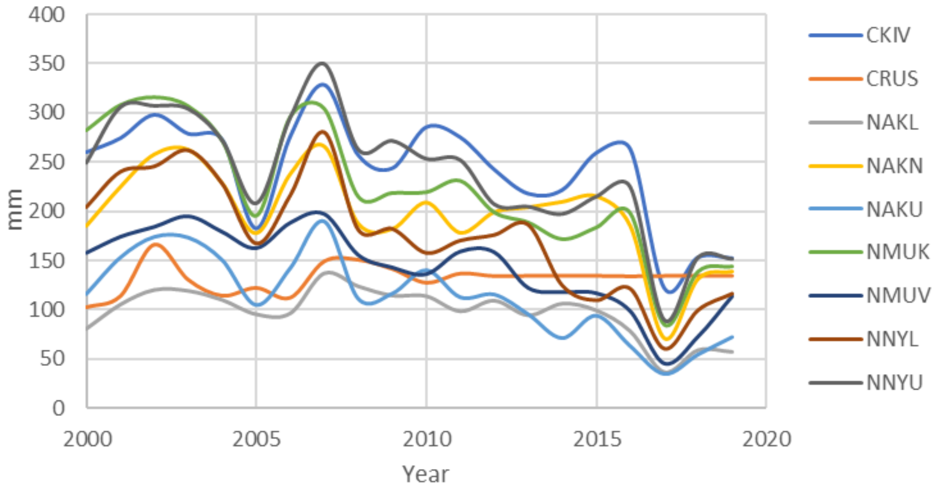

Figure 51. Historical Interflow (2000 – 2019) for each of the L1 catchments.

On a monthly average (Figure 52), the baseline scenario for Interflow shows an apex around April/ May and the nadir is reached around August/ September. This development corelates best with the mean monthly graph for groundwater recharge, and therefore it is argued that interflow has a delayed response to peak precipitation/ 'drought' events. Table 29 shows the annual averaged maxima and minima for interflow at catchment level 2.5 summarised per level 1.

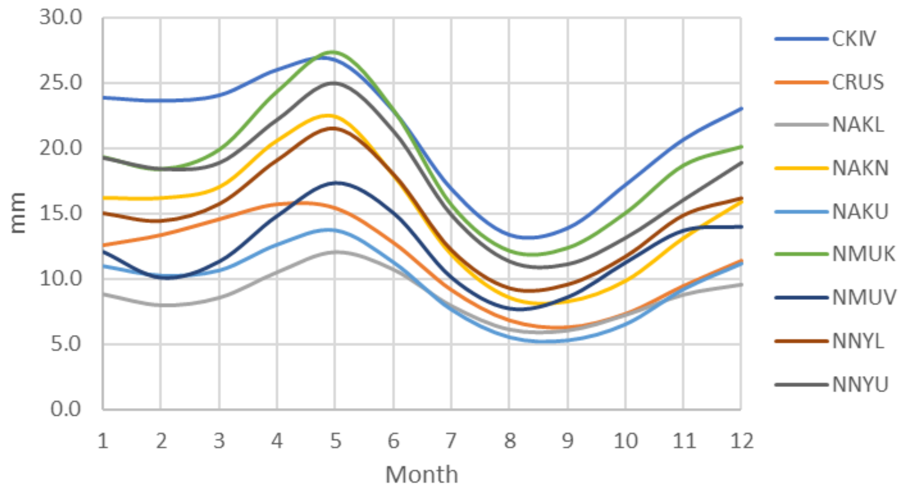

Figure 52. Monthly Average Interflow for each level 1 catchment for the Baseline (2000 – 2019)

Table 29. Annual maximum and minimum Interflow for each level 1 catchment.

Baseline	*Max (mm)*	*Min (mm)*	*Average (mm)*
CKIV	484	96	243
CRUS	305	45	132
NAKL	212	11	98
NAKN	539	13	198
NAKU	234	22	114
NMUK	469	26	224
NMUV	271	24	144
NNYL	422	14	176
NNYU	390	67	229

1.3.6 Runoff

Runoff is considered the sum of the WEAP surface runoff and the interflow in this assessment. Hence, in order to study runoff as a separate variable, the interflow and surface runoff components were individually summed. Figure 53 shows for this sum the spatial distribution. Comparing this figure with the previous separate components (Figure 47 / Figure 50) shows that the total runoff is mostly impacted by interflow rather than surface runoff, except for the region around Kigali where surface runoff is the dominant variable.

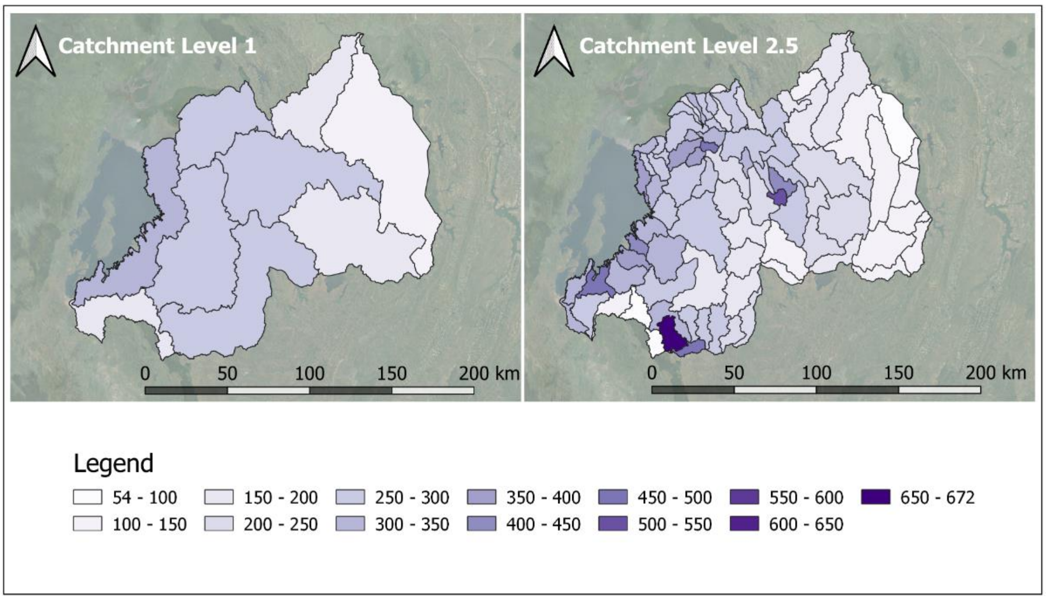

Figure 53. Runoff for the Baseline period for both level 1 and level 2.5 catchments (2000 – 2019)

1.3.7 Comparison with the NWRMP (2015)

Comparing these estimates with the values presented in the NWRMP (2015), the following can be observed (Table 31):

- The Precipitation and Evapotranspiration estimates are very comparable with the NWRMP-2015.
- Recharge estimates are typically lower than those estimated in NWRMP-2015.
- Runoff estimates are typically lower than those estimated in NWRMP-2015.
- Blue Water Availability estimates are typically lower than those estimated in NWRMP-2015. Blue Water Availability is the sum of Surface Runoff, Interflow and Groundwater recharge. It is also referred to as “Renewable Water Resources Availability”.

As a refresher, and to better understand Table 31, Table 30 shows the main definitions for each of the three Hydrological Indicators accounted for in the determination of the Blue Water Availibity.

Table 30. Overview of the main components that define Blue Water Availability as used in this study.

Hydrological Indicator	WEAP Components	Definition
Surface Runoff	Surface Runoff	Surface water inflow to river reaches represents either non-point runoff into the river, or the confluence of streams or rivers not otherwise modeled. In WEAP it is modelled as direct runoff of water (both precipitation and irrigation) from the surface of the land, before it enters the top bucket through the runoff link to the surface water destination.
Interflow	Interflow	Subsurface flow from the top bucket through the runoff link to the surface water destination.
Runoff	Surface Runoff + Interflow	Runoff is considered the sum of surface runoff and Interflow and is expected to be available within the modelling time step of 1 month.
Groundwater Recharge	Flow to Groundwater	The natural inflow to a groundwater source. This does not include return flows and inflows from a river. In this WEAP model, it is represented by the flow from the top bucket to the connected groundwater node through the infiltration link as the catchment node

		is connected to a groundwater node. Modelled in WEAP with the “Groundwater Wedge Connected to River”-methodology.
Blue Water Availability (same as Renewable Water Resources Availability)	Surface Runoff + Interflow + Groundwater Recharge	Blue Water refers to liquid waters in rivers and aquifers (Falkenmark & Rockström, 2006)[1]. Hence, Blue Water Availability is taken as the sum of Surface Runoff, Interflow and Groundwater Recharge. As constrained by the network topology, the model allocates water to meet any specific demand in the system, without regard to travel time. Thus, the model time step should be at least as long as the residence time of the study area. For this reason, a monthly time step was adopted for this HEA study.

Table 31. Comparison of NWRMP (2015) runoff and WEAP runoff (all in mm/year).

NWRMP	**NWRMP Precipitation**	**NWRMP ETa**	**NWRMP Recharge**	**NWRMP Runoff**	**WEAP/NWRMP Runoff[%}**	**NWRMP Blue Water Availability**	**WEAP/NWRMP Blue Water Availability (%)**
CKIV	1240	870	250	370		620	
CRUS	1295	865	350	430		780	
NAKL	835	624	125	211		336	
NAKN	1225	990	227	235		462	
NAKU	925	760	115	165		280	
NMUK	1315	851	322	464		786	
NMUV	995	872	71	123		194	
NNYL	1191	919	165	272		437	
NNYU	1365	980	292	385		677	
WEAP	**WEAP Precipitation**	**WEAP ETa**	**WEAP Recharge**	**WEAP Runoff**		**WEAP Blue Water Availability**	
CKIV	1493	967	222	327	88%	548	88%
CRUS	1387	962	252	176	41%	427	55%
NAKL	951	735	107	122	58%	229	68%
NAKN	1320	909	151	273	116%	424	92%
NAKU	1028	761	94	194	118%	288	103%
NMUK	1372	919	200	297	64%	497	63%
NMUV	1041	781	102	180	147%	283	146%
NNYL	1241	841	142	289	106%	432	99%
NNYU	1388	900	178	263	68%	441	65%

As NWRMP (2015) reports solely runoff estimates, WEAP surface runoff and interflow were summed to one variable. Comparing both runoff estimates, some close similarities indicate a reasonable fit with the NWRMP. For CRUS, NAKL, NMUK, NMUV and NNYU, major discrepancies with the 2015 masterplan remain.

1.3.8 Water Balance Baseline

The water balance for the Level 1 catchments are presented in Annexe 8. Outputs in various formats: figures, tables, including a water accounting diagram. Results are included for both level 2.5 as well as level 1.

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[1] Falkenmark, M., & Rockström, J. (2006). The new blue and green water paradigm: Breaking new ground for water resources planning and management. Journal of water resources planning and management, 132(3), 129-132.

1.4 Climate Change Assessment

1.4.1 Climate Change Projections

1.4.1.1 NEX-GDDP-CMIP6

The NEX-GDDP-CMIP6[1] dataset was used to analyse future trends in terms of temperature and precipitation for Rwanda. The NEX-GDDP-CMIP6 dataset is comprised of global downscaled climate scenarios derived from the General Circulation Model (GCM) runs conducted under the Coupled Model Intercomparison Project Phase 6 (CMIP6) and across four greenhouse gas emissions scenarios known as Shared Socioeconomic Pathways (SSPs). The dataset compiles climate projections from 35 CMIP6 GCMs and four SSP scenarios, for the period 2015-2100, as well as the historical experiment for each model, for the period 1950-2014. Each of these climate projections is downscaled to a spatial resolution of 0.25 degrees x 0.25 degrees.

Two SSP scenarios (SSP2-4.5 and SSP5-8.5) are analysed to provide a range of future climate projections. SSP2-4.5 represents a “stabilisation scenario”, in which greenhouse gas emissions peak around 2040 and are then reduced. Although often used as ‘business as usual’, the SSP5-8.5 is above the business-as-usual emission scenarios and designed as a worst-case scenario. We include this scenario as an upper limit to the possible future climate. These scenarios are selected as they represent an envelope of likely climate changes and hence cover a plausible range of possible future changes in temperature and precipitation relating to project implementation.

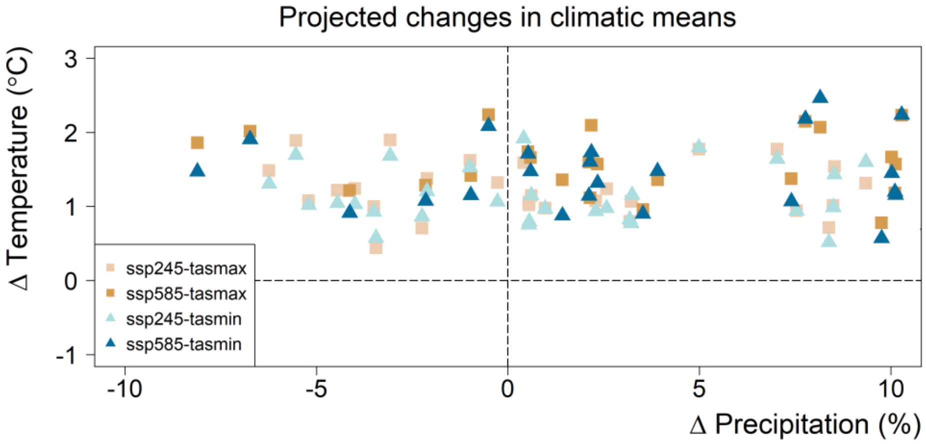

Figure 54. Projected temperature (max and min) and precipitation changes for Rwanda derived from NEX-GDDP-CMIP6. These indicate the difference (Δ) between historical (2010) and future (2050) time horizons across two SSP scenarios and individual GCMs.

A 20-year window was selected as appropriate for deriving average climate changes, effectively considering interannual variations in temperature and precipitation, and robust comparison. Alongside the two SSP scenarios, projections are evaluated at the following time horizons (see Figure 54):

- Reference period [2010]: 2000 – 2019.
- Future period [2050]: 2040 – 2059.

From Figure 54, temperature and precipitation trends for Rwanda can be summarised, as derived from the ensemble mean of the considered GCMs. Under both SSP scenarios (SSP2-4.5 and SSP5-8.5), precipitation is expected to vary considerably across individual GCMs, but the ensemble mean indicates that precipitation is to increase by 2.4% to 7.6%, respectively. Mean temperatures are expected to increase on average by about 1.1 °C to 1.4 °C, respectively.

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[1] https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6

Table 32. Projected temperature and precipitation trends for Rwanda (GCM ensemble mean)

SSP Scenario	*ΔP (%)*	*ΔTmax (°C)*	*ΔTmin (°C)*	*ΔTmean (°C)*
SSP2-4.5	2.4	1.3	0.9	1.1
SSP5-8.5	7.6	1.6	1.2	1.4

1.4.1.2 Climate projection for Rwanda under CMIP5

Meteo-Rwanda regional climate projections were used to provide an analysis of future trends for temperature and precipitation. The dataset, provided by Meteo-Rwanda, was obtained from the Coordinated Regional Climate Downscaling Experiment (CORDEX Africa 0.44), and based on CMIP5. The data is available from 2021 to 2070 and downscaled to 0.22 km pixel size. All data were bias-corrected, set to standard calendar. Table 33 provides an overview of the GCM and RCM model combinations used to derive the data. For each variable the Representative Concentration Pathways (RCP) 4.5 and 8.5 was used for the analysis.

Table 33. Details Meteo-Rwanda regional climate projections

Variable	*GCM*	*RCM*
Precipitation	MPI	REMO 2009
Tasmax	MOHC	CCLM 4-8-17
Tasmin	ICHEC	CCLM 4-8-17

Figure 55 and Table 34 show the expected minimum and maximum temperature (i.e., tasmax and tasmin) and precipitation changes derived for the nine considered catchments of Rwanda, between a historical and future time horizon. Under RCP 4.5 the expected temperature and precipitation trends are quite comparable across the nine catchments. Tasmin and Tasmax are projected to increase by about 1.1 °C to 1.2 °C, whereas precipitation is expected to remain relatively stable though a decrease by about -1.2% is expected (range between -4.2% decrease and 2.3% increase).

Under RCP 8.5, there is more variability expected in precipitation changes. The highest decreases in precipitation are expected for Lake Kivu (CKIV, -16.8%) and Upper Nyaborongo (NNYU, -10.7%) catchments. In contrast, the highest increases in precipitation are expected for Lower Akagera (NAKL, 5.1%) and Muvumba (NMUV, 3.7) catchments. On average, the Meteo-Rwanda regional climate projections foresee an average decrease in precipitation of about 5% and an increase of Tasmin and Tasmax by about 2.0 °C to 2.3 °C respectively.

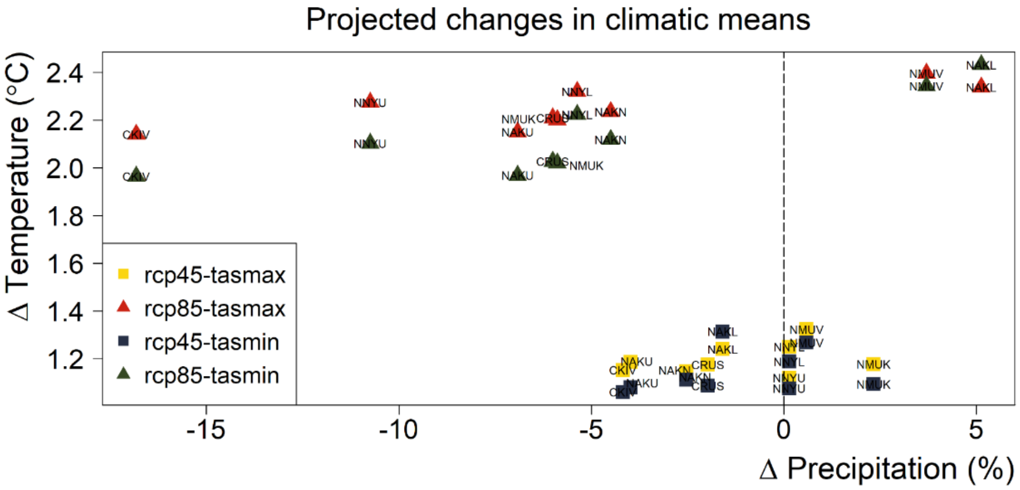

Figure 55. **Projected temperature (max and min) and precipitation changes for considered catchments of Rwanda derived from Meteo-Rwanda regional climate projections. These indicate the difference (Δ) between historical (2010) and future (2050) time horizons across two RCP scenarios and for nine catchments.**

Table 34. Projected temperature and precipitation trends for considered catchment in Rwanda

	CKIV	*CRUS*	*NAKL*	*NAKN*	*NAKU*	*NMUK*	*NMUV*	*NNYL*	*NNYU*
RCP 4.5 ΔP (%)	-4.2	-2.0	-1.6	-2.5	-4.0	2.3	0.6	0.1	0.1
RCP 4.5 ΔTmax (°C)	1.15	1.18	1.24	1.15	1.19	1.18	1.32	1.25	1.12
RCP 4.5 ΔTmin (°C)	0.97	1.00	1.39	1.08	0.97	1.01	1.21	1.13	1.03
RCP 8.5 ΔP (%)	-16.8	-6.0	5.1	-4.5	-6.9	-5.9	3.7	-5.4	-10.7
RCP 8.5 ΔTmax (°C)	2.14	2.21	2.34	2.24	2.15	2.20	2.40	2.32	2.27
RCP 8.5 ΔTmin (°C)	1.79	1.84	2.52	2.00	1.79	1.84	2.29	2.13	1.93

1.4.1.3 Illustrative case for Lower Nyabarongo (NNYL)

The Meteo-Rwanda regional climate projections were further analysed at catchment scale. The full analysis for all nine catchments can be found in Annexe 8; the most important findings for the Lower Nyabarongo (NNYL) are presented here.

Analysis of temperature data shows that temperatures are expected to increase between 2021 and 2070 (Figure 56 and Figure 57). Average annual temperatures are foreseen to increase from 21 ºC to 22-23 ºC, respectively under RCP 4.5 and RCP 8.5. The trends extracted from the yearly temperature time series have a medium statistical significance.

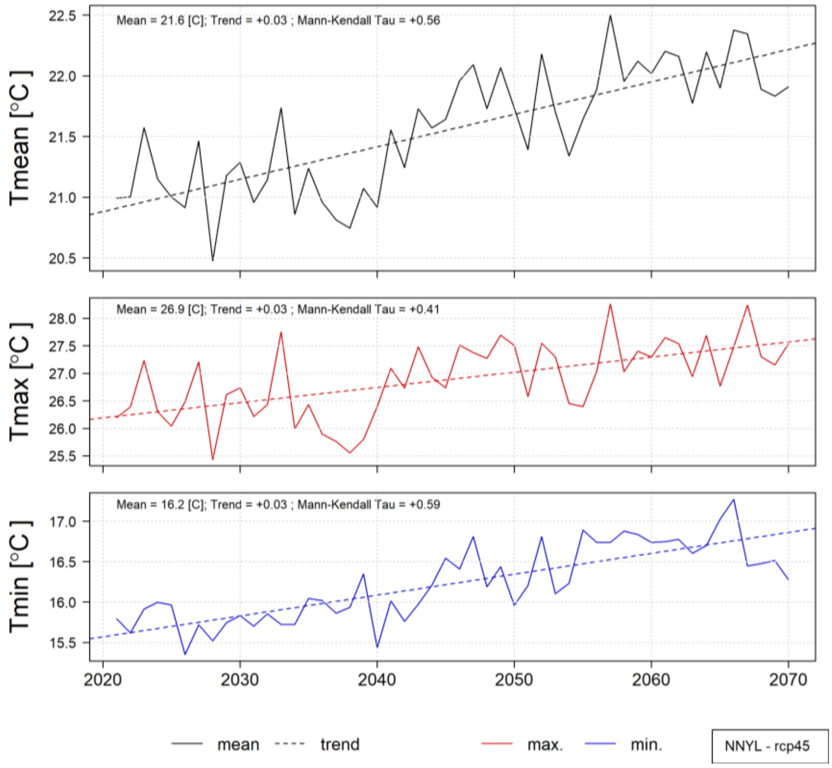

Figure 56. Avg, max and min daily temperatures per year under RCP 4.5 from Meteo-Rwanda dataset with trendline.

Mann Kendall Tau value indicates the strength of the monotonic trend of increase or decrease in a time series, with a value of 1 indicating a strong significant trend and -1 indicating no trend.

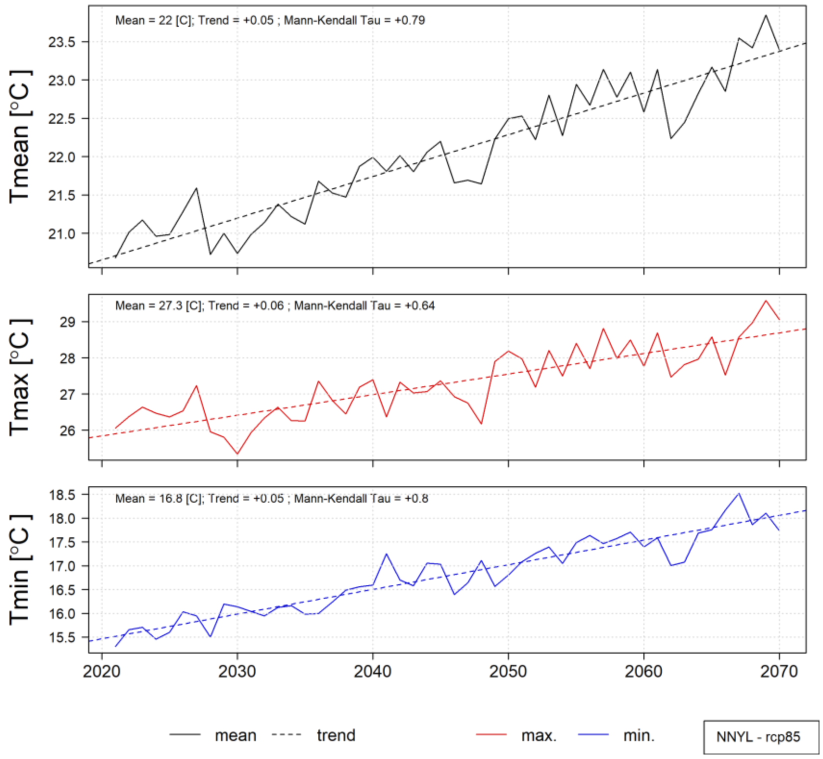

Figure 57 Avg, max and min daily temperatures per year under RCP 8.5 from Meteo-Rwanda dataset with trendline.

Mann Kendall Tau value indicates the strength of the monotonic trend of increase or decrease in a time series, with a value of 1 indicating a strong significant trend and -1 indicating no trend.

Fairly large intra-annual variations in temperature can be discerned (Figure 58), with average daily temperatures ranging from around 16 ºC to 27 ºC. A clear seasonality is also evident (Figure 59), with coolest period during the months Nov-Dec-Jan and hottest period during the months Jul-Aug-Sept.

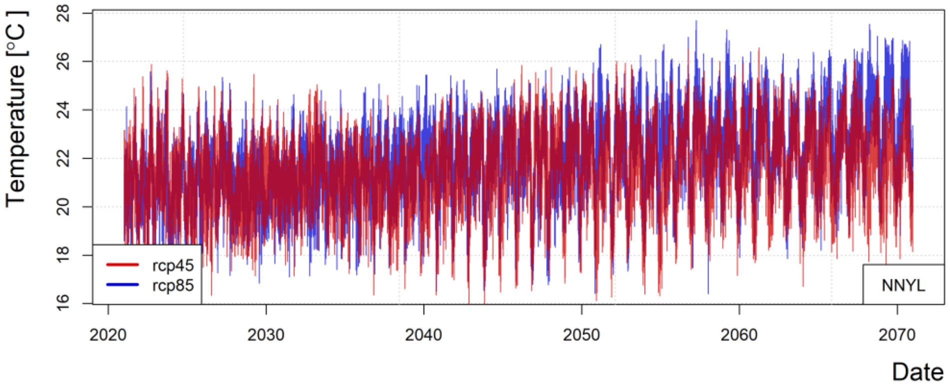

Figure 58. Daily average temperature from Meteo-Rwanda dataset under RCP 4.5 and RCP 8.5

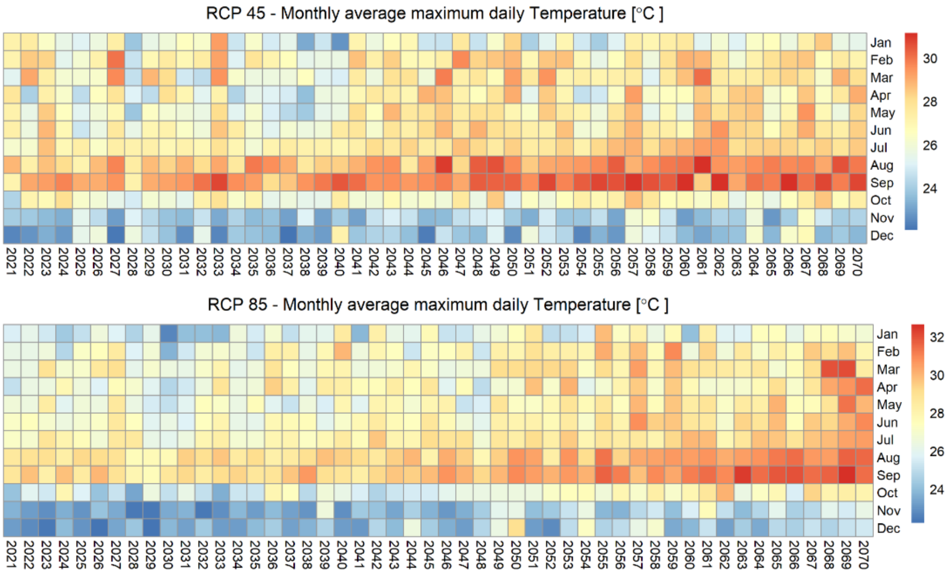

Figure 59. Seasonality in temperature from Meteo-Rwanda dataset under RCP 4.5 (top) and RCP 8.5 (bottom)

Meteo-Rwanda data on precipitation (Figure 60 to Figure 62) shows that average total annual precipitation is expected to remain relatively stable between 2021 and 2070, at around 1240-1270 mm on average under RCP 4.5 and RCP 8.5, respectively. A weak trend of decreasing total annual rainfall is apparent for the future period under RCP 8.5, but with lots of interannual variability and low statistical significance.

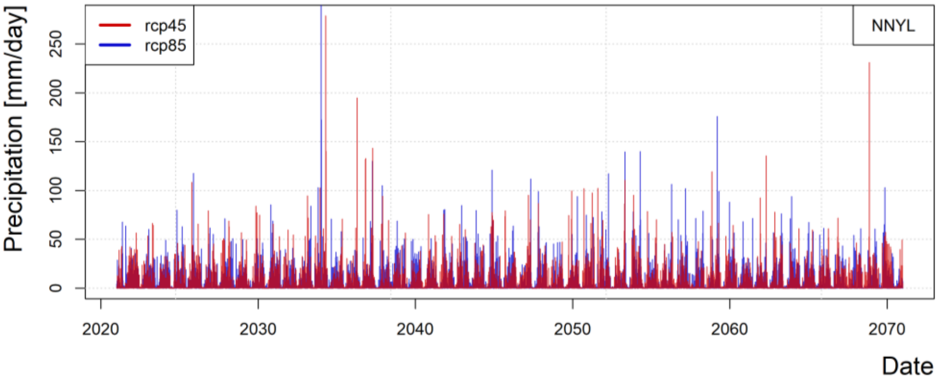

Figure 60. Daily precipitation from Meteo-Rwanda dataset under RCP 4.5 and RCP 8.5

The maximum daily precipitation for individual years, which is an indicator for extreme precipitation, does not indicate a clear trend (Figure 61 and Figure 62) under both RCP 4.5 and RCP 8.5 and demonstrates large interannual variability. As Figure 63 indicates, rainfall is almost completely absent during the months Jun-Jul-Aug; this trend is expected to remain stable in the future.

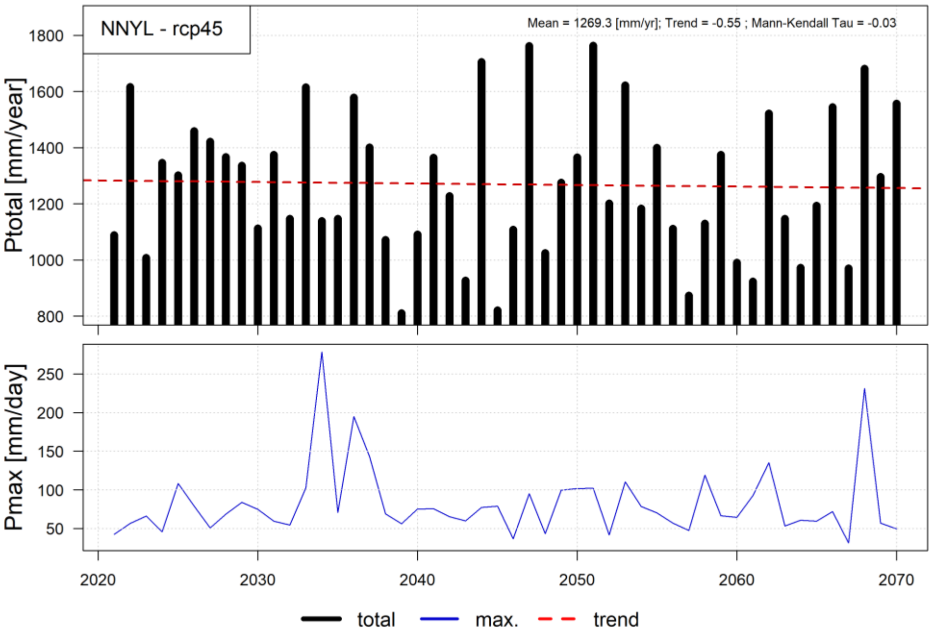

Figure 61. Total yearly and maximum one-day precipitation under RCP 4.5 from Meteo-Rwanda dataset with trendline.

Mann Kendall Tau value indicates the strength of the monotonic trend of increase or decrease in a time series, with a value of 1 indicating a strong significant trend and -1 indicating no trend.

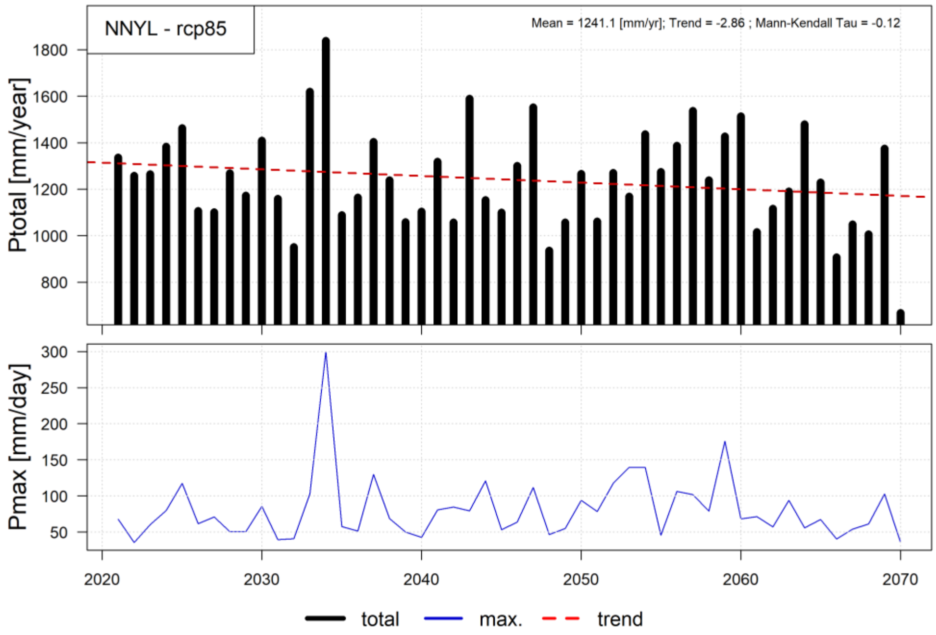

Figure 62. Total yearly and maximum one day precipitation under RCP 8.5 from Meteo-Rwanda dataset with trendline.

Mann Kendall Tau value indicates the strength of the monotonic trend of increase or decrease in a time series, with a value of 1 indicating a strong significant trend and -1 indicating no trend.

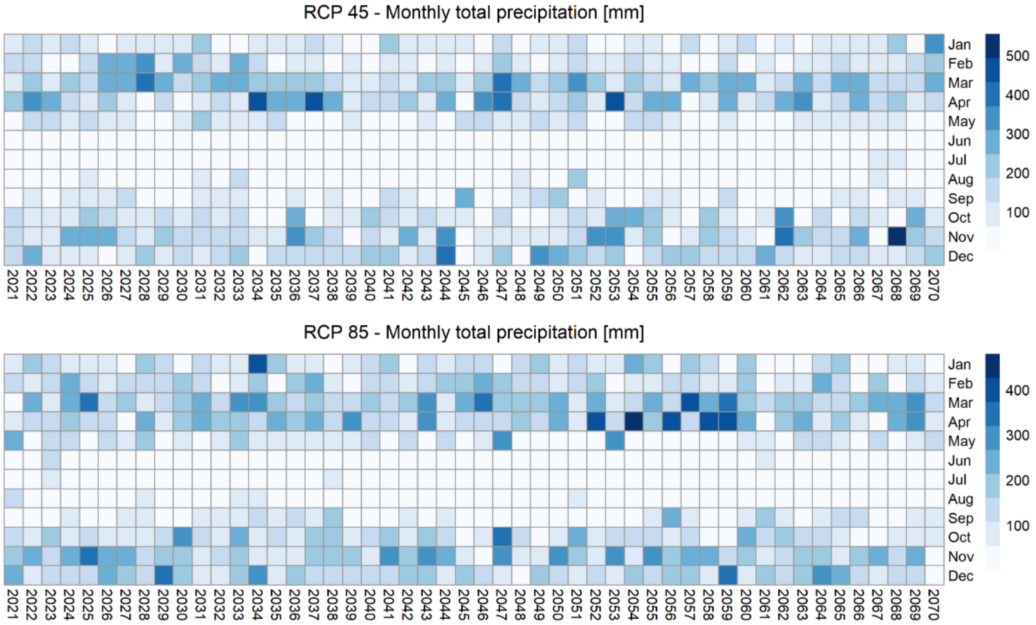

Figure 63. Seasonality of precipitation from Meteo-Rwanda dataset under RCP 4.5 (top) and RCP 8.5 (bottom)

1.4.2 Impacts on Water Balance

From the WEAP model, the results for groundwater recharge and surface runoff were analysed for the two projected climate scenarios, RCP 4.5 and 8.5. To quantify the impact, the baseline scenario was used as a reference to obtain relative and/ or absolute changes directly. The results thus present the change in monthly average from the baseline period (2000 – 2019), representative of year 2010, to the future period (2040 – 2059), representative of year 2050.

This section will briefly discuss the main impact on hydrology, a more detailed review of each of the subcatchments is presented in the following annexes:

1. Annexe 6: Level 2.5 Catchment Spatio-Temporal Hydrological Assessment: Baseline
2. Annexe 8: Level 2.5 Catchment Spatio-Temporal Hydrological Assessment: Baseline vs RCP 4.5 and RCP 8.5

For scenario RCP4.5 (Table 35), level 1 catchments indicate a slight decrease in precipitation and ETa resulting in a maximum decrease in groundwater recharge of -7.5% for CKIV and a decreased surface runoff of maximum -8.6% for the same catchment. In general, for ETa and Precipitation, the impact of climate change under the RCP 4.5 scenario is minimal, ranging between -3.0% (CKIV) to 1.6% (NMUK) for precipitation, and -1.6% (NAKU) to +1.8% (NMUK) for ETa. The effect on recharge and surface runoff lies within the range of -7.7% (NAKU) to -1.4% (NMUK) for the former, and between -8.6% (CKIV) and +1.4% (NMUK) for the latter. Hence, CKIV and NAKU seem to be most affected under RCP 4.5 and NMUK the least.

Table 35. Relative change (%) to baseline for both scenarios for each of the five hydrological variables

%-change Baseline	*Precipitation*		*ETa*		*GW Recharge*		*Surface Runoff*		*Interflow*	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
CKIV	-3.0	-12.2	-1.0	-7.2	-7.5	-20.8	-8.6	-27.2	-6.9	-20.2
CRUS	-1.5	-4.4	-0.2	-2.2	-5.3	-9.9	-5.7	-12.7	-5.0	-9.6
NAKL	-1.2	3.7	-0.4	3.3	-5.4	2.6	-3.5	5.3	-5.0	3.0
NAKN	-1.8	-3.3	-0.2	-1.2	-4.9	-7.3	-5.5	-8.8	-4.7	-7.1
NAKU	-2.8	-4.9	-1.6	-3.2	-7.7	-11.1	-5.5	-8.7	-7.6	-11.0
NMUK	1.6	-4.2	1.8	-2.1	-1.4	-10.2	1.4	-12.2	-0.5	-9.4
NMUV	0.4	2.6	0.8	2.5	-2.6	0.8	-1.6	3.2	-2.6	0.9
NNYL	0.1	-3.9	0.9	-1.8	-2.6	-8.8	-1.7	-9.8	-2.6	-8.7
NNYU	0.1	-7.7	1.0	-4.3	-2.6	-14.4	-1.9	-21.0	-2.1	-14.0

On level 1, the RCP 8.5 scenario has, as expected, a more severe drying impact on Rwanda as a whole. Most outspoken changes occur in CKIV, where 12% less rainfall (annual on average) is expected, and a decrease of 7.2% for ETa. These further impact groundwater recharge (Figure 66) and surface runoff (Figure 67), with a 21% and 27% reduction for CKIV respectively. This implies that the availability of renewable groundwater supply will significantly diminish under climate scenario RCP 8.5. A similar, yet somewhat less severe, observation is made for NNYU. This indicate that wet regions under the baseline (West of Rwanda) are most impacted by climate change. However, this implies that the country will face lower water availability and increased stress. In contrast, although not as significant, an opposite trend is spotted for the most eastern catchment of the country, NAKL, where the scenario RCP 8.5 indicates a positive effect with an increase in precipitation of about 3.7% and likewise for ETa, recharge and runoff, with respectively an increase of 3.3%, 2.6%, and 5.0%. This trend is specific to NAKL and NMUV, in the North of Rwanda, but for the latter the trend is less significant.

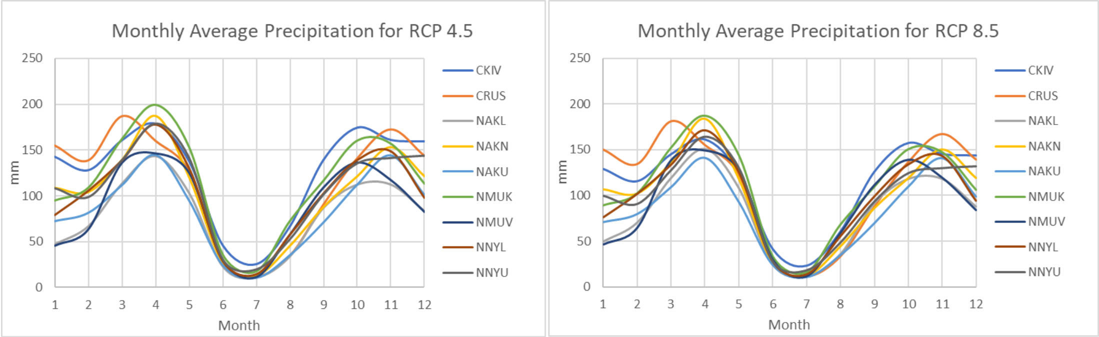

Figure 64. Monthly average precipitation for RCP 4.5 and RCP 8.5 for the period 2040 – 2059.

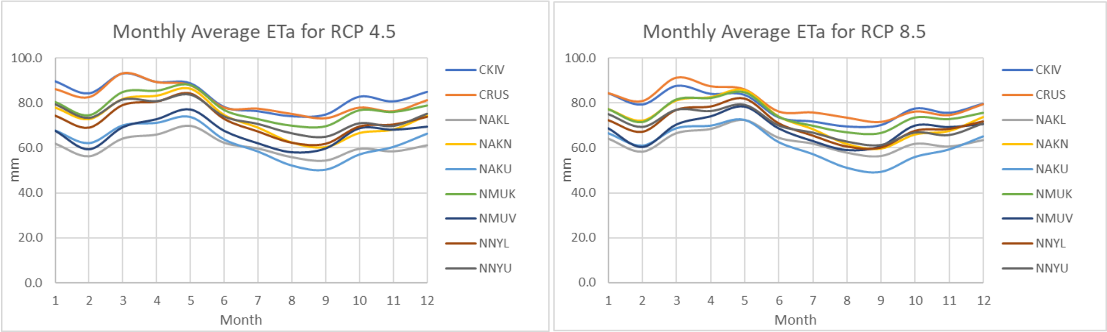

Figure 65. Monthly average ETa for RCP 4.5 and RCP 8.5 for the period 2040 – 2059.

The Figure 66 to Figure 68 show the expected relative changes for groundwater recharge, surface runoff and interflow under both climate scenarios. From the maps, it is noteworthy to highlight that CKIV shows to be the most affected for all scenarios for each of the hydrological variables, except for interflow under scenario RCP 4.5, where NAKU_E indicates to face the highest (negative) impact (-8.4%). Furthermore, as presented above, NAKL is the least affected under the various climate scenarios, especially under RCP 8.5 where the positive effects are the most visible.

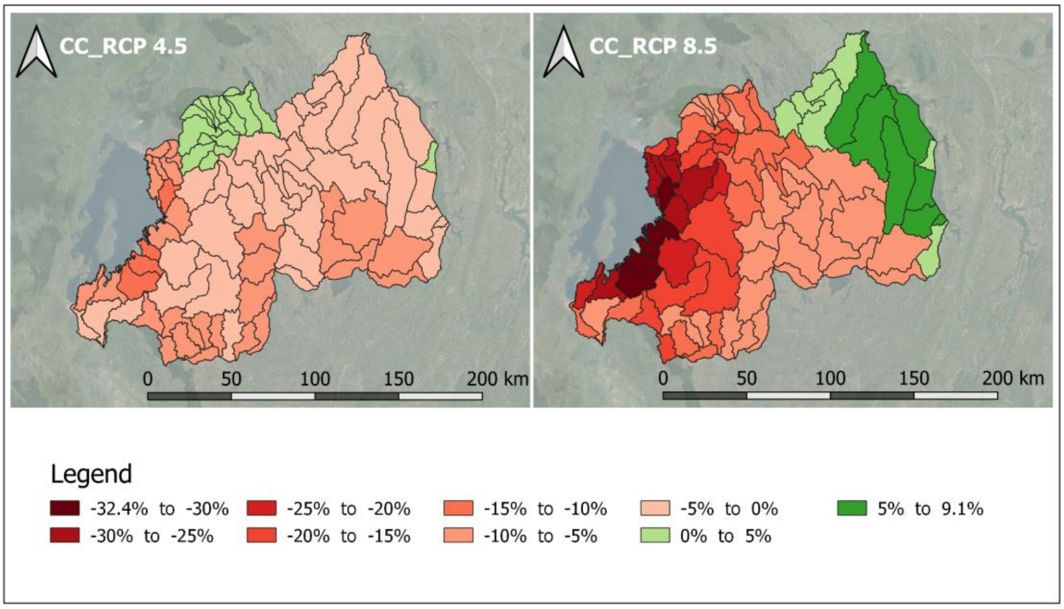

Figure 66. Groundwater Recharge: Relative difference for RCP 4.5 and 8.5 between 2010 (2000 – 2019) and 2050 (2040 – 2059) for each level 2.5 sub-catchment.

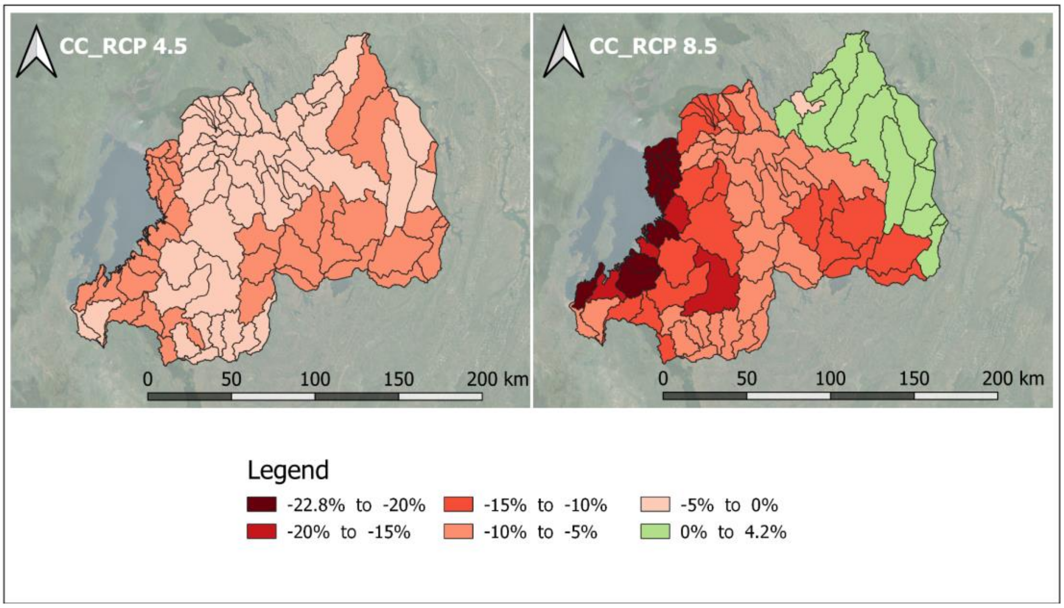

Figure 67. Surface Runoff: Relative difference for RCP 4.5 and 8.5 between 2010 (2000 – 2019) and 2050 (2040 – 2059) for each level 2.5 sub-catchment.

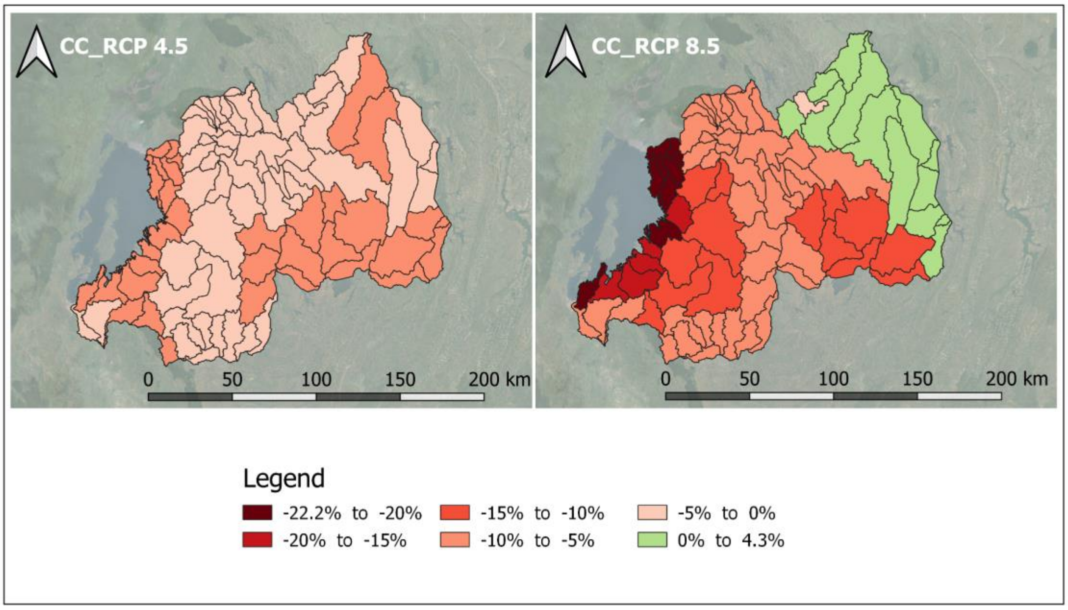

Figure 68. Interflow: Relative difference for RCP 4.5 and 8.5 between 2010 (2000 – 2019) and 2050 (2040 – 2059) for each level 2.5 sub-catchment.

As CKIV seems the most affected under both scenarios, the analysis below will summarise major trends for this level 1 catchment. The graphs and tables presented for CKIV are available for each of the level 1 and level 2.5 catchments and can be found in Annexe 8.

On level 2.5, CKIV_A shows that RCP 4.5 and RCP 8.5 both yield a reduced average monthly precipitation, with RCP 8.5 being more severe than RCP 4.5. The changes between the two scenarios are harder to detect for the other variables as the values are found within lower ranges. Figure 69 and Figure 70 show for each of the four variables the respective average monthly changes for the two climate scenarios. Comparing these monthly graphs with the graphs presented in the baseline scenario shows that no major seasonal changes occur for each hydrological variable, hence the primary effect of the two climate scenarios translates predominantly in an increased/ decreased rate (mm/year).

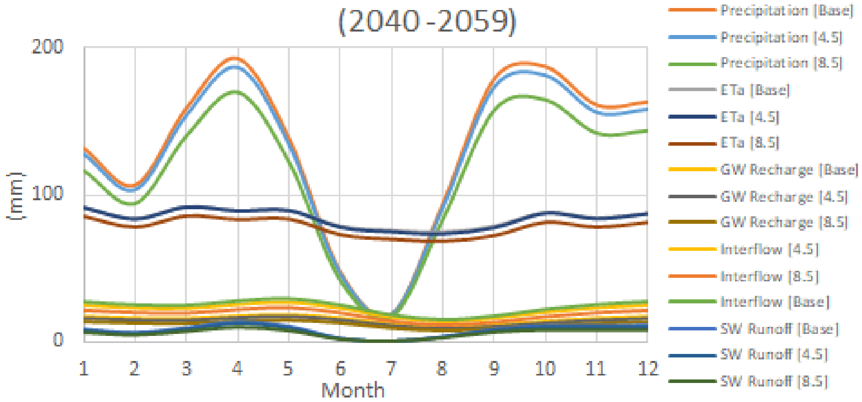

Figure 69. Sub-catchment CKIV_A (Lake Kivu): Monthly Mean for the five hydrological variables for the baseline and 2 climate scenarios (mm/year).

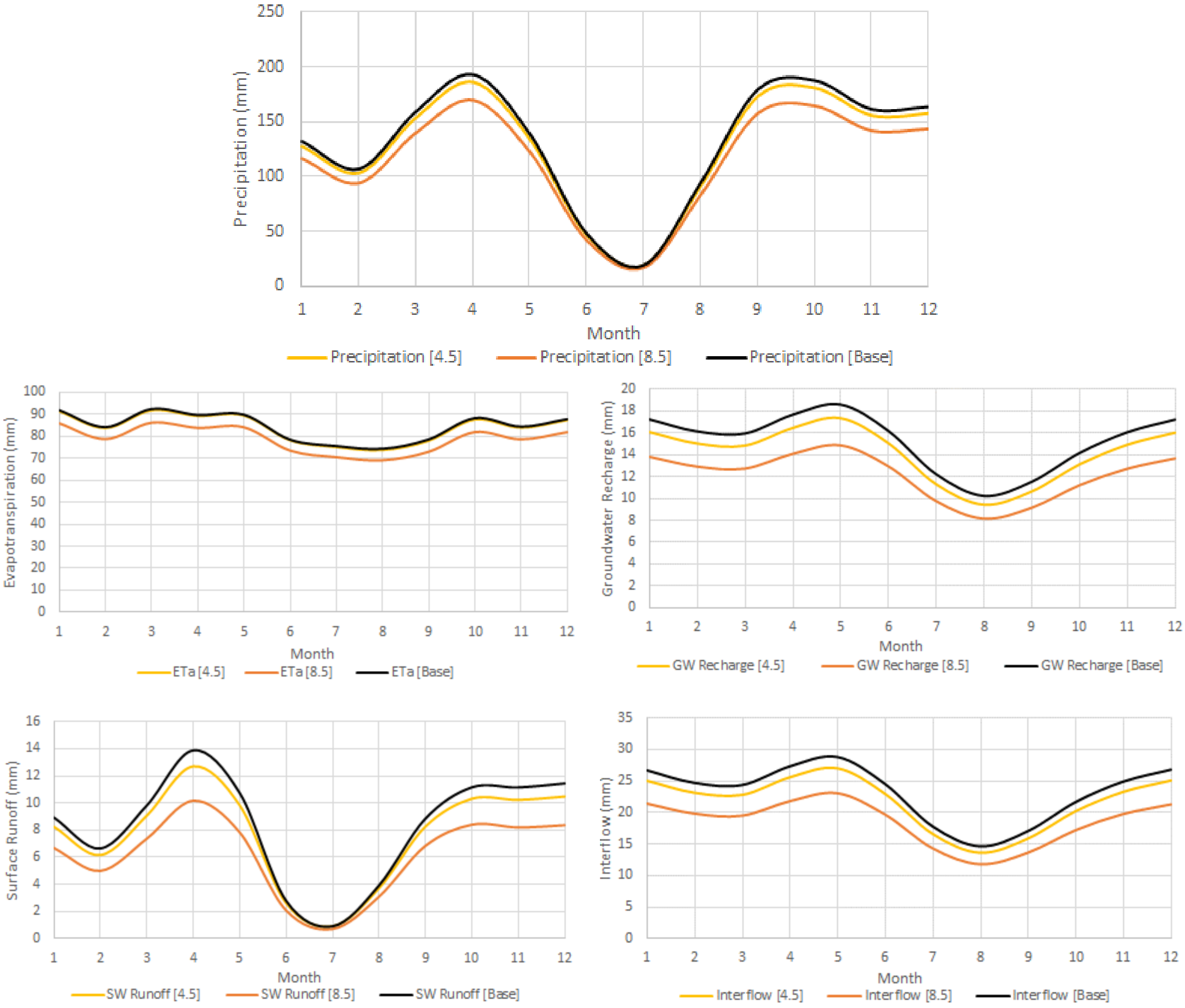

Figure 70. Sub-catchment CKIV_A (Lake Kivu): Monthly Mean Precipitation (top), Evapotranspiration (centre left), Groundwater Recharge (centre right), Surface Runoff (bottom left), and Interflow (bottom right) for 2 climate scenarios (mm/year).

Ultimately, these changing hydrological variables impact the water balance on the catchment level. Figure 71 shows for both RCP 4.5 and RCP 8.5 how the annual water balance on catchment level 1 is altered. Generally, as Table 36 indicates, groundwater recharge, interflow and surface runoff rates decreased for most level 1 catchment under scenario RCP 8.5 as compared to RCP 4.5, except for NAKL, which shows a marginal increase. As summarized in section 1.4.1, precipitation decreases for all catchments but catchment NAKL under RCP 8.5. Regarding ETa, NAKL and NMUV have slightly higher evapotranspiration rates under this climatic change (Table 36).

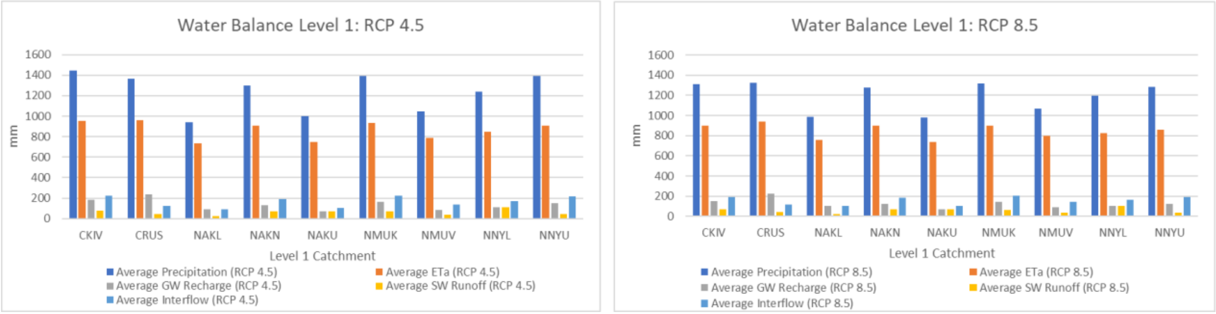

Figure 71. Water balances for each level 1 catchment under both climate scenarios.

Table 36. Average water balance under RCP 4.5 and 8.5 for each level 1 catchment.

RCP45 [mm]	*Average Precipitation*	*Average ETa*	*Average GW Recharge*	*Average SW Runoff*	*Average Interflow*
CKIV	1447	957	186	78	226
CRUS	1367	960	240	42	125
NAKL	940	732	94	23	93
NAKN	1296	907	129	71	188
NAKU	999	749	71	74	105
NMUK	1394	936	166	72	223
NMUV	1046	788	84	35	140
NNYL	1242	848	112	110	172
NNYU	1389	910	151	43	214
RCP85 [mm]	Average Precipitation	Average ETa	Average GW Recharge	Average SW Runoff	Average Interflow
CKIV	1311	897	148	67	194
CRUS	1326	940	222	40	119
NAKL	986	759	103	25	100
NAKN	1277	898	124	69	184
NAKU	977	737	68	71	101
NMUK	1314	900	144	66	203
NMUV	1069	801	88	36	145
NNYL	1193	825	102	103	161
NNYU	1281	862	121	38	188

2 Detailed Water Allocation Assessment

To identify and prioritize strategic investments in water resources infrastructure that are robust to climate change impacts, a water supply versus demand, or water allocation assessment is performed, incorporating the climate impact simulations on the hydrological flows (previous Chapter). This chapter presents the national-level water allocation assessment which has the goal to identify the areas where largest shortages occur and those areas where there is the highest potential to mitigate these shortages through infrastructure investments.

2.1 Update and projection of Water Demands by 2050

The following describes the projection of water demands up to 2050 per sector: domestic, irrigation, hydropower, industries and livestock.

2.1.1 Domestic Water Demand

The trends for domestic water demand are derived from two documents: Kigali's Water Supply Master Plan, dated 2021[1], and Rwanda National Integrated Water Supply and Sanitation Master Plan[2] from WASAC.

Regarding Kigali, the population is expected to grow from around 1.1 million in 2012 to the range of 3.2 million (low growth scenario) to 3.8 million (high growth scenario) in 2050. The water demand is assessed for the city itself and seven adjacent sectors (Shyrongi, Runda, Rugarika, Ntarama, Nyakaliro, Muyumbu and Gahengeri) as being the sum of:

- domestic water needs;
- non-domestic water needs (e.g., commercial, industries, public facilities);
- non-revenue water.

Figure 72 shows the trend and values at certain years are compiled in Table 37.

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[1] WASAC, 'Water Supply Master Plan for City of Kigali in the Republic of Rwanda' (Kigali, Rwanda: Water and Sanitation Corporation, 2021).

[2] WASAC, 'Development of Rwanda National Integrated Water Supply and Sanitation Master Plan' (Kigali, Rwanda: Water and Sanitation Corporation, 2021).

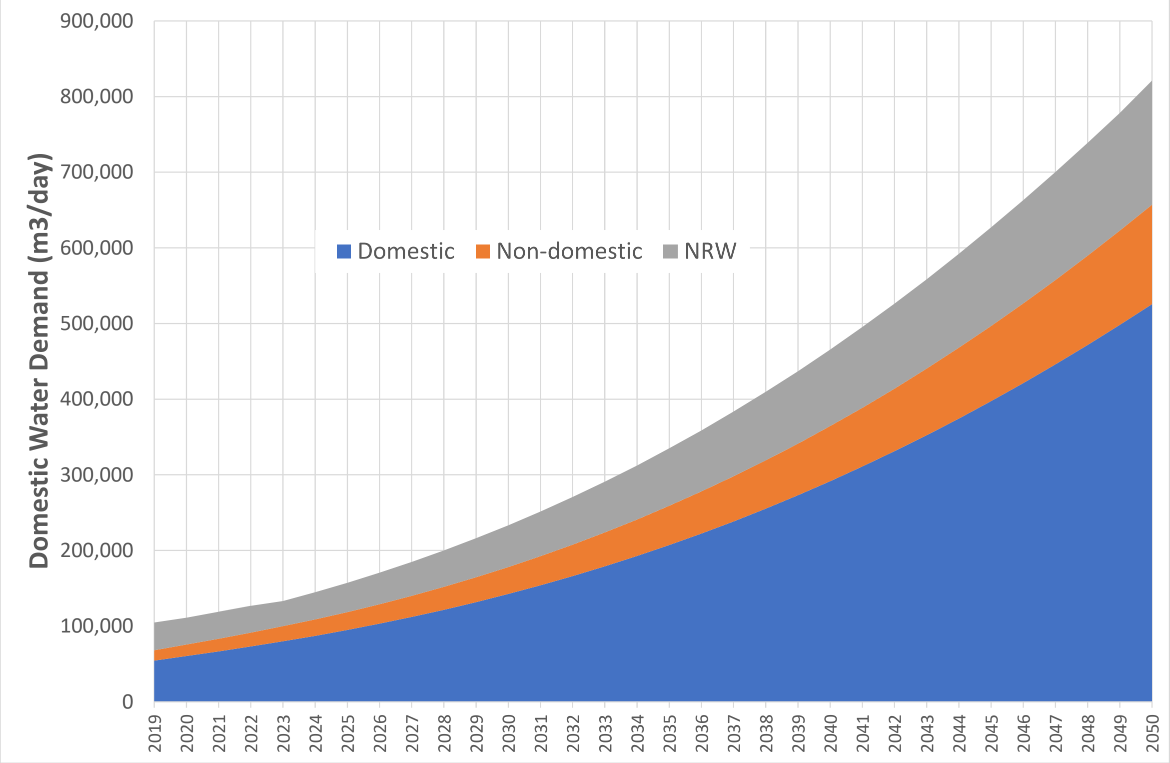

Figure 72: Projected Domestic Water Demand for Kigali city and adjacent sectors (Source: Kigali's Water Supply Master Plan[1])

Table 37: Projected Domestic Water Demand for Kigali city and adjacent sectors (Source: Kigali's Water Supply Master Plan[21])

	2020	2025	2030	2035	2040	2045	2050
Domestic (m3/day)	60,455	94,831	142,480	207,164	291,472	397,445	525,559
Non-domestic (m3/day)	15,114	23,708	35,620	51,791	72,868	99,361	131,390
NRW (m3/day)	35,562	38,707	55,180	76,012	101,156	130,231	164,237
Total (m3/day)	111,131	157,246	233,280	334,967	465,496	627,037	821,186
Total (Mm3/year)	40.6	57.4	85.1	122.3	169.9	228.9	299.7

These values were computed assuming the unit per capita consumption summarised in Table 38 and the percentage of non-revenue water in Table 39. These parameters are categorised as per urban and rural zones found in Kigali and adjacent sectors.

Table 38: Projected unit per capita consumption for Kigali city and adjacent sectors, in L/cap/day (Source: Kigali's Water Supply Master Plan[3])

	2019	2025	2030	2035	2040	2045	2050
Urban	80	88	94	101	107	114	120
Rural	50	56	61	65	70	75	80

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[1] WASAC, 'Water Supply Master Plan for City of Kigali in the Republic of Rwanda'.
[2] Ibid.
[3] Ibid.

Table 39: Projected non-revenue water for Kigali city and adjacent sectors (Source: Kigali's Water Supply Master Plan[1])

	2019	2025	2030	2035	2040	2045	2050
Urban	35%	25%	24%	23%	22%	21%	20%
Rural	50	56	61	65	70	75	80

The water sources in the present situation and plans for 2050 are placed in Table 40.

Table 40: Sources of domestic water supply for Kigali and adjacent sectors (Source: Kigali's Water Supply Master Plan[2])

	2019	2050
River	51%	59%
Groundwater	40%	33%
Lake	7%	6%
Spring	2%	2%

As for the other parts of the country, domestic water demand is categorised per rural and urban zones and is summarised in Figure 73 and Table 41. It can be noted that water demand is predicted to decrease towards 2030, due to a reduction in the rural population. The demand picks up again afterwards due to increased urban population. Eventually, the share of urban demand continuously increases while it is the contrary for rural demand. Non-revenue water in the present situation (2019) is about 45% and Rwanda National Integrated Water Supply and Sanitation Master Plan[3] expects it to reduce by about 20% in 2050.

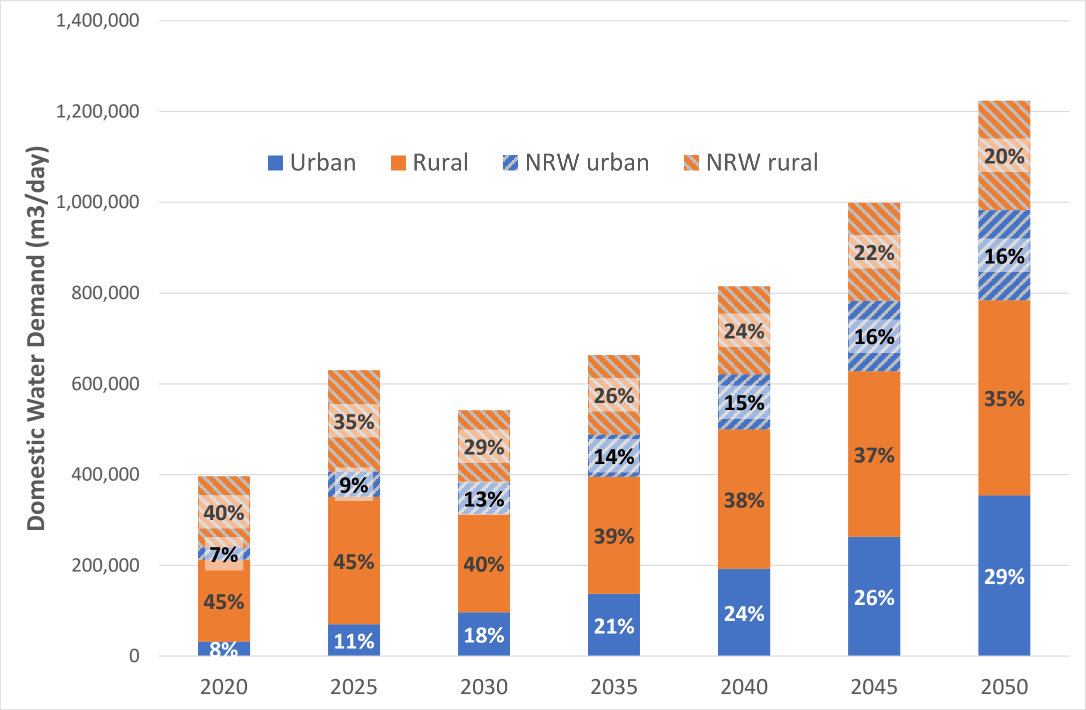

Figure 73: Projected Domestic Water Demand for Rwanda, except Kigali city. The percentages indicate the share to the total water demand (Source: Rwanda National Integrated Water Supply and Sanitation Master Plan[4])

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[1] Ibid.

[2] Ibid.

[3] WASAC, 'Development of Rwanda National Integrated Water Supply and Sanitation Master Plan'.

[4] Ibid.

Table 41: Projected Domestic Water Demand for Rwanda, except Kigali city. (Source: Rwanda National Integrated Water Supply and Sanitation Master Plan[1])

	2020	2025	2030	2035	2040	2045	2050
Urban (m3/day)	32,000	70,448	96,435	137,258	192,100	262,698	354,302
Rural (m3/day)	180,078	280,544	216,354	257,863	307,359	365,162	429,747
NRW urban (m3/day)	27,463	55,587	70,351	92,903	121,199	155,217	198,794
NRW rural (m3/day)	156,952	223,363	158,912	175,386	194,485	215,979	241,050
Total (m3/day)	396,493	629,942	542,052	663,410	815,143	999,056	1,223,893

2.1.2 Irrigation Water Demand

Information on irrigation has been extracted from Rwanda Irrigation Master Plan[2] from RAB. The predominant irrigated crops are maize, common bush beans, paddy, vegetables and perennial fruits like banana. The master plan advises the cropping pattern presented in Table 42. Food crops include maize, climbing beans and soya. Vegetable crops include tomato, onion, cabbage, carrots, garlic, watermelon, green beans and chilies. Fruit crops include avocado, mango, citrus, passion fruit and bananas.

Table 42: Proposed cropping patterns by zones (Source: Rwanda Irrigation Master Plan[3])

Stratum	Crop pattern	Season A	Season B	Season C
Marshland	**M1** Paddy	Paddy 100%	Paddy 100%	nil
	M2 Food + horticulture	Maize 50%; soya 30%, vegetables 20%	Maize 50%; beans 30%; vegetables 20%	Vegetables 50%
	M3 Sugarcane	Sugarcane 100%	Sugarcane 100%	Sugarcane 100%
Hillside	**H1** Food + horticulture	Maize 50%; soya 30%, vegetables 20%	Maize 50%; beans 30%; vegetables 20%	Vegetables 50%
	H2 Fruit trees + food + horticulture	Fruit 55%; maize 20%; soya 10%, veg 5%	Fruit 55%; maize 20%; beans 10%, veg 5%	Fruit 55%; vegetables 15%
	H3 Irish potatoes + food + horticulture	Potato 25%; maize 25%; beans 25%; veg 25%	Potato 25%; maize 25%; beans 25%; veg 25%	Vegetables 50%

The irrigation efficiency of the different irrigation systems is placed in Table 43. The master plan assesses a potential of about 500,000 ha of irrigated in Rwanda (Table 44), distributed along six irrigation sources. These areas include existing irrigation schemes.

Table 43: Irrigation efficiencies of the different irrigation systems (Source: Rwanda Irrigation Master Plan[4]).

Irrigation system	Overall efficiency (%)
Marshland surface with lined primary canals and earthen (clay) secondary/tertiary canals	54
Hillside surface with lined canals/pipes	57
Hillside overhead with lined canals/pipes	71
Hillside drip with pipes	86

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[1] Ibid.

[2] RAB, 'Rwanda Irrigation Master Plan' (Kigali, Rwanda: Rwanda Agriculture and Animal Resources Development Board, 2020).

[3] Ibid.

[4] Ibid.

Table 44: Irrigation potential in Rwanda (in ha, Source: Rwanda Irrigation Master Plan[1])

Domains	CRUS	CKIV	NMUK	NNYU	NNYL	NAKN	NAKU	NAKL	NMUV	All
Runoff for small reservoirs domain	2,148	5,179	4,165	7,155	7,056	7,270	6,521	9,162	3,344	52,000
Dam Potential	167	1,447	172	7,058	15,610	12,859	894	1,430	12,464	52,100
River Potential	-	-	-	12,373	3,677	36,127	25,288	46,241	8,466	135,880
Lake Potential	-	22,680	-	-	28,376	8,972	27,030	12,140	-	102,364
Marshland Potential	3,700	4,702	6,398	9,060	8,942	26,571	32,087	22,385	7,735	123,164
Groundwater	3,000	5,000	5,000	7,000	4,000	5,500	2,500	3,000	1,000	36,000
SUM	**9,015**	**39,008**	**15,735**	**42,646**	**67,662**	**97,299**	**94,320**	**94,358**	**33,009**	**493,050**

The areas in Table 44 contain command areas located between 80 and 120m above potential rivers and lakes, which were eventually excluded from the master plan as the energy requirement would make implementation difficult. Excluding, in addition, existing irrigated areas and the category "Runoff for small reservoir domain"[2], the master plan has identified the target for new irrigated areas under three zones of priority for investment (Table 45). This corresponds to a total of about 361,500 ha to develop in Rwanda.

Table 45: Potential for new irrigated areas, per priority zones. SSIT stands for Small Scale Irrigation Technology, to be developed from Dams / Marshlands (Source: Rwanda Irrigation Master Plan[3])

	Potential new irrigable area, ha		
Priority	**1**	**2**	**3**
Domain / catchment	**NAKU** **NAKL** **NMUV**	**NNYL** **NAKN** **CRUS**	**CKIV** **NMUK** **NNYU**
River / Lake (<80m lift)	93,423	61,566	24,156
Dam / Marshland	62,295	38,586	16,774
Groundwater	6,500	12,500	17,000
SSIT	13,630	12,036	3,636
TOTAL	**175,848**	**124,688**	**60,945**

The water demand associated with these new areas amounts to almost 2,400 Mm^3/year (Table 46), compared to approximately 340 Mm^3/year in the current situation. The greatest potential is along the Akagera and Akanyaru rivers, which have high investment priorities. The greatest sources are from surface waters (90% nationwide), predominantly from rivers, while groundwater has a small potential and is only important in some catchments (Mukungwa, Rusizi and Nyabarongo Upper) of lower priority for investment. Dams eventually have a small potential, except in Muvumba catchment; existing lakes have greater potential, especially in Kivu catchment and Nyabarongo Lower catchment.

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[1] Ibid.

[2] This category corresponds to water demand for small kitchen gardens, which are not part of official planning.

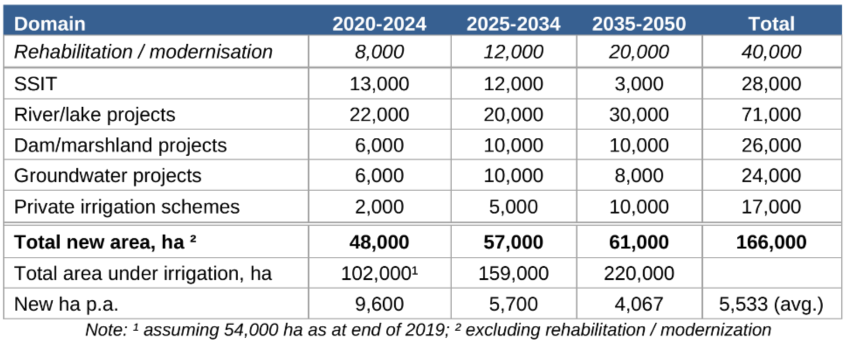
[3] RAB, 'Rwanda Irrigation Master Plan'.

Table 46: Irrigation water demand per level 1 catchment and sources for potential new irrigation areas. "Priority" refers to the priority for investment (Source: Rwanda Irrigation Master Plan[1])

Priority	Catchment	New demand (Mm3/year)							Existing demand (Mm3/year)
		Dam	Dam under design	Lake (<80 m lift)	Marshland	River (<80 m lift)	Ground water	Total	
1	Akagera Lower (NAKL)	6.4	96.9	63.4	123.4	240.8	27.0	557.9	74.0
	Akagera Upper (NAKU)	5.4	57.3	154.7	170.4	99.3	18.0	505.1	55.2
	Muvumba (NMUV)	54.9	29.6	0.0	20.2	53.4	6.0	164.1	44.6
2	Akanyaru (NAKN)	16.6	91.2	40.3	120.7	185.1	38.5	492.3	49.6
	Nyabarongo Lower (NNYL)	7.8	68.7	128.2	49.7	15.9	27.0	297.3	36.5
	Rusizi (CRUS)	0.8	0.0	0.0	2.1	0.0	18.0	20.9	24.2
3	Kivu (CKIV)	6.1	0.0	74.6	10.4	0.0	30.0	121.1	13.2
	Mukungwa (NMUK)	0.9	0.0	0.0	23.4	0.0	31.0	55.3	17.2
	Nyabarongo Upper (NNYU)	13.1	17.3	0.0	46.2	46.2	49.0	171.8	24.4
	Total	**112.0**	**361.0**	**461.1**	**566.4**	**640.7**	**244.5**	**2,385.8**	**338.8**
	Percentage	**5%**	**15%**	**19%**	**24%**	**27%**	**10%**		

However, of this total potential, only a portion is planned to be developed by 2050. The masterplan aims to develop 166,000 ha by 2050, about 45% of the total to develop (Table 47). The plan suggests a schedule for developing these new areas, as per the priority catchments of Table 45, which leads to Table 48.

Table 47: Schedule for developing new irrigated areas until 2050, in ha. SSIT stands for Small Scale Irrigation Technology, to be developed from Dams / Marshlands (Source: Rwanda Irrigation Master Plan[2])



Domain	2020-2024	2025-2034	2035-2050	Total
Rehabilitation / modernisation	*8,000*	*12,000*	*20,000*	*40,000*
SSIT	13,000	12,000	3,000	28,000
River/lake projects	22,000	20,000	30,000	71,000
Dam/marshland projects	6,000	10,000	10,000	26,000
Groundwater projects	6,000	10,000	8,000	24,000
Private irrigation schemes	2,000	5,000	10,000	17,000
Total new area, ha ²	**48,000**	**57,000**	**61,000**	**166,000**
Total area under irrigation, ha	102,000¹	159,000	220,000	
New ha p.a.	9,600	5,700	4,067	5,533 (avg.)

Note: ¹ assuming 54,000 ha as at end of 2019; ² excluding rehabilitation / modernization

Table 48: Cumulated percentage of new water demand of Table 46 being developed as per the priority catchment presented in Table 45 (Source: derived from the Rwanda Irrigation Master Plan[3])

	River+Lake			Dam + Marshland (with SSIT)			Groundwater		
Catchment	2020-2024	2025-2034	2035-2050	2020-2024	2025-2034	2035-2050	2020-2024	2025-2034	2035-2050
Priority 1 (NAKU, NAKL and NMUV)	24%	45%	77%	25%	38%	51%	92%	92%	92%

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[1] Ibid.
[2] Ibid.
[3] Ibid.

Priority 2 (NNYL, NAKN, CRUS)	0%	0%	0%	0%	24%	24%	0%	92%	92%
Priority 3 (CKIV, NMUK and NNYU)	0%	0%	0%	0%	0%	15%	0%	0%	47%

Table 49: Cumulated new water demand being developed as per the priority catchment presented in Table 45 (Source: derived from the Rwanda Irrigation Master Plan[1])

Priority	Catchment	Cumulated New demand (Mm3/year) up to 2020-2024							Existing demand (Mm3/year)
		Dam	Dam under design	Lake (<80 m lift)	Marshland	River (<80 m lift)	Groundwater	Total	
1	Akagera Lower (NAKL)	1.6	24.3	14.9	30.9	56.7	24.9	153.3	74.03
	Akagera Upper (NAKU)	1.3	14.3	36.4	42.7	23.4	16.6	134.8	55.16
	Muvumba (NMUV)	13.7	7.4	0.0	5.1	12.6	5.5	44.3	44.6
2	Akanyaru (NAKN)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	49.58
	Nyabarongo Lower (NNYL)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	36.48
	Rusizi (CRUS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.22
3	Kivu (CKIV)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.16
	Mukungwa (NMUK)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.22
	Nyabarongo Upper (NNYU)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.39
	Total	**16.7**	**46.0**	**51.4**	**78.6**	**92.7**	**47.1**	**332.4**	**338.8**
	Percentage	**5%**	**14%**	**15%**	**24%**	**28%**	**14%**		

Priority	Catchment	Cumulated New demand (Mm3/year) up to 2025-2034							Existing demand (Mm3/year)
		Dam	Dam under design	Lake (<80 m lift)	Marshland	River (<80 m lift)	Groundwater	Total	
1	Akagera Lower (NAKL)	2.4	37.0	28.5	47.1	108.3	24.9	248.3	74.03
	Akagera Upper (NAKU)	2.0	21.9	69.5	65.1	44.7	16.6	219.9	55.16
	Muvumba (NMUV)	21.0	11.3	0.0	7.7	24.0	5.5	69.6	44.6
2	Akanyaru (NAKN)	0.0	21.6	0.0	28.6	0.0	35.5	85.8	49.58
	Nyabarongo Lower (NNYL)	0.0	16.3	0.0	11.8	0.0	24.9	53.0	36.48
	Rusizi (CRUS)	0.0	0.0	0.0	0.5	0.0	16.6	17.1	24.22
3	Kivu (CKIV)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.16
	Mukungwa (NMUK)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.22
	Nyabarongo Upper (NNYU)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.39
	Total	**25.5**	**108.1**	**98.1**	**160.9**	**177.0**	**124.2**	**693.7**	**338.8**

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[1] Ibid.

Percentage	**8%**	**33%**	**29%**	**48%**	**53%**	**37%**

Priority	**Catchment**	**Cumulated New demand (Mm3/year) up to 2035-2050**							**Existing demand (Mm3/year)**
		Dam	**Dam under design**	**Lake (<80 m lift)**	**Marshland**	**River (<80 m lift)**	**Groundwater**	**Total**	
1	Akagera Lower (NAKL)	3.3	49.8	48.9	63.4	185.7	24.9	375.9	74.03
	Akagera Upper (NAKU)	2.8	29.5	119.2	87.6	76.6	16.6	332.2	55.16
	Muvumba (NMUV)	28.2	15.2	0.0	10.4	41.2	5.5	100.5	44.6
2	Akanyaru (NAKN)	3.9	21.6	0.0	28.6	0.0	35.5	89.7	49.58
	Nyabarongo Lower (NNYL)	1.9	16.3	0.0	11.8	0.0	24.9	54.8	36.48
	Rusizi (CRUS)	0.2	0.0	0.0	0.5	0.0	16.6	17.3	24.22
3	Kivu (CKIV)	0.9	0.0	0.0	1.5	0.0	14.1	16.5	13.16
	Mukungwa (NMUK)	0.1	0.0	0.0	3.4	0.0	14.6	18.2	17.22
	Nyabarongo Upper (NNYU)	1.9	2.6	0.0	6.8	0.0	23.1	34.3	24.39
	Total	**43.2**	**134.9**	**168.1**	**214.0**	**303.4**	**175.9**	**1,039.5**	**338.8**
	Percentage	**13%**	**41%**	**51%**	**64%**	**91%**	**53%**		

2.1.3 Hydropower demand

The source of information for hydropower demand is the 2021 Least Cost Power Development Plan[1] from REG. The installed capacity from 2019 to 2040 is placed in Figure 74. The capacity installed in 2019 is 121 MW, although the average available capacity is 55 MW.

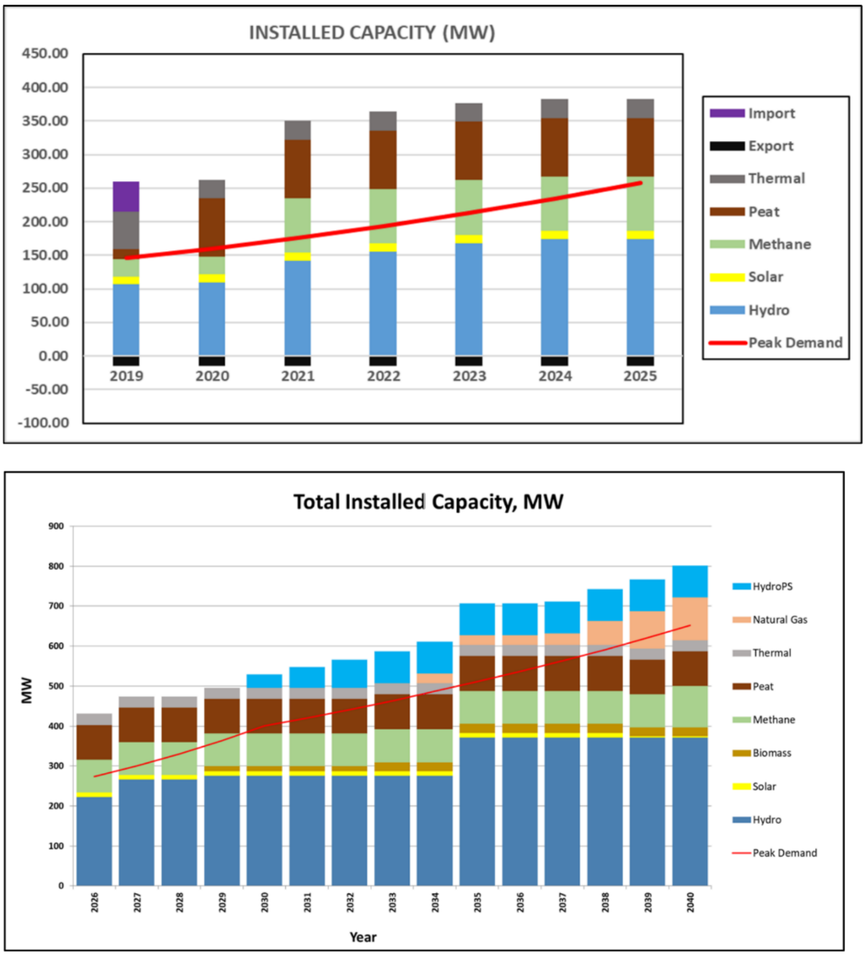

Figure 74: Installed capacity in Rwanda from 2019 to 2040 (Source: 2021 Least Cost Power Development Plan[2])

The new hydropower projects are summarised in Table 50 and the annual target for hydropower production is placed in Figure 75.

Table 50: Planned hydropower plants. Underlined plants are regional projects (Source: 2021 Least Cost Power Development Plan[3])

Plant	Nominal Capacity (MW)	Expected date of commission
Rusumo	26.7	2021
Giciye III	9.8	2021
Ntaruka A	2.1	2021
Ngororero	2.7	2022

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[1] REG, 'Rwanda: Least Cost Power Development Plan 2020 – 2040' (Kigali, Rwanda: Rwanda Energy Group, 2021).
[2] Ibid.
[3] Ibid.

Plant	Nominal Capacity (MW)	Expected date of commission
Nyundo	4.5	2022
Rwondo	2.3	2022
Rukarara VI	9.8	2024
Base 1	2.9	2024
Base 2	2.9	2024
Rusizi III	48.3	2026
Nyabarongo II	43.5	2027
Rusizi IV	95.9	TBD
Bihongore	4.2	TBD
Kore	1.3	TBD
Rucanzogera	1.9	TBD
Rukore	2.0	TBD

Year	Production (GWh/year)
2019	497
2020	490
2025	1,132
2030	1,830
2035	2,350
2040	2,583

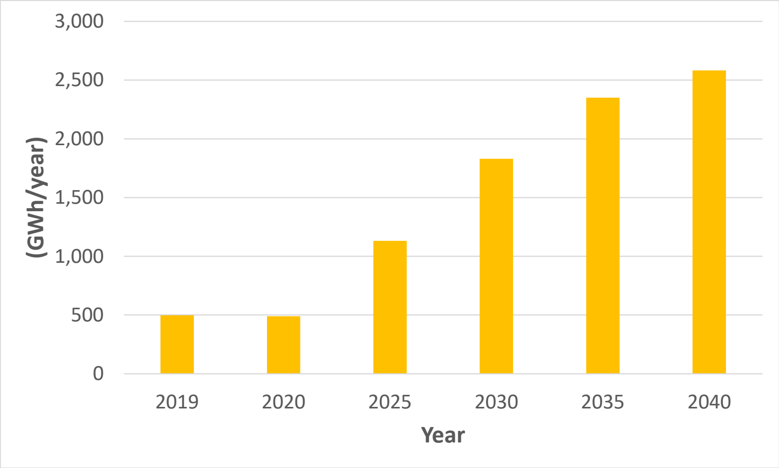

Figure 75: Target for electricity production from hydropower (Source: 2021 Least Cost Power Development Plan[1]).

2.1.4 Industries and mines

The current water demand for industries and mines has been extracted from the Water users and uses database from RWB, as summarised in Table 51 per catchment. The magnitude of the demand is much smaller than for domestic and irrigation water demands.

Table 51: Current water demand for industries and mines (Source: Water users and uses database from RWB)

	Water Demand (Mm3/year)	
Catchment	**Industries**	**Mines**
Akagera Lower (NAKL)	0.01	0.66
Akagera Upper (NAKU)	0.38	0.29
Akanyaru (NAKN)	0.05	0.39
Kivu (CKIV)	0.12	0.22
Mukungwa (NMUK)	1.26	0.53

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[1] Ibid.

Muvumba (NMUV)	0.34	0.00
Nyabarongo Lower (NNYL)	0.82	1.65
Nyabarongo Upper (NNYU)	0.19	1.02
Rusizi (CRUS)	0.04	0.06
Total	**3.21**	**4.82**

2.1.5 Coffee washing stations

The data, for the current situation, is also extracted from the Water users and uses database from RWB, and is summarised in Table 52 per catchment. This type of water demand is even smaller than for industries and mines.

Table 52: Current water demand for coffee washing stations (Source: Water users and uses database from RWB)

Catchment	**Water Demand (Mm3/year)**
Akagera Lower (NAKL)	0.05
Akagera Upper (NAKU)	0.07
Akanyaru (NAKN)	0.19
Kivu (CKIV)	0.28
Mukungwa (NMUK)	0.01
Muvumba (NMUV)	0.01
Nyabarongo Lower (NNYL)	0.16
Nyabarongo Upper (NNYU)	0.03
Rusizi (CRUS)	0.08
Total	**0.88**

2.2 Level 2.5 water allocation plan development

The WEAP model developed as part of the Hydro-Economic analysis was updated to develop the water allocation plan. The updates consisted of:

- Allocation rules according to the Water Law (Official Gazette no.Special of 21/09/2018).
- Secured/ planned dams were added (Nyabarongo II, Akanyaru, Warufu and Muvumba) as individual nodes in the WEAP model.
- The SEI Hydro-Economic Analysis (2022)[1] model demand data was verified and found consistent with the demands obtained from the latest strategic documents (see previous section 2.1).

The allocation priority implemented in WEAP is as per the Water Law:

Table 53. Allocation rules according to the Water Law (Official Gazette no.Special of 21/09/2018)

Allocation Rule	*Sector*
1	Domestic
2	Environmental Flows
3	Agricultural and Industrial Demands

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[1] Swedish Environment Institute. 2022. A Water Resilient Economy: Hydro-Economic and Climate Change Analysis for Rwanda.

Based on discussions with the RWB, the Water Resilient scenario was chosen since it can be considered the most likely and desirable scenario in terms of water resources development for the country. This is the base-scenario onto which the storage development will be added and prioritised.

Before prioritising water storage infrastructure, a good picture needs to be obtained for (1) the water that can be allocated according to the allocation rules and availability, in space and time, and (2) the surplus and deficits in time and space, considering the measures and demand growth included in the Water Resilient scenario. This section 2.2 deals with (1) and the following section 2.3 with (2).

A Water Allocation Plan is defined here as the result of balancing water availability and demands by following the allocation rules (Table 53), extracting a collection of indicators and water balances, including sectoral water balance information, from the model outputs; this way characterising the water balance situation of the catchment as a whole. The sectoral balance sets out how much water each sector receives based on the water allocation rules but also considering downstream demands. WEAP is the integrated modelling framework that dynamically considers all these processes and can be used to extract those water balances.

The Water Allocation Plan extracted from the WEAP model based on the dynamical simulation of the climate under an RCP 4.5 scenario in the Water Resilient scenario for the period 2040-2059 is presented in Annexe 9 of this report, for all 86 Level 2.5 catchments. The most likely climate scenario (RCP 4.5, as compared to RCP 8.5) is used in this analysis for both the water allocation plans and the potential dam prioritisation process, as requested by the ToR. Meteo Rwanda provided during the first phase of the project historical Precipitation and Temperature data which was used as the basis for the Water Resilient scenario and climate projected data for RCP 4.5 and RCP 8.5 respectively analysed with the Water Resilient 4.5 and Water Resilient 8.5 scenarios. Table 54 shows the marginal differences between the two established climate scenarios in this analysis, i.e., RCP 4.5 and RCP 8.5, and how they relate to a no climate change (noCC) scenario (Water Resilient). As requested by RWB, preference need to be given to the former throughout the subsequent analysis steps as it is deemed to be the more likely climate scenario; RCP 8.5 was never meant to be a business-as-usual scenario (Hausfather & Peters, 2020)[1].

Table 54. General descriptive statistics for the total coverage (%) and absolute shortage [MCM] estimates for each scenario without storage, summed for the 6 demand sectors.

	Sum of sectors, Water Resilient		*Sum of sectors, Water Resilient245*		*Sum of sectors, Water Resilient585*	
	Coverage [%]	**Absolute Shortage [MCM]**	**Coverage [%]**	**Absolute Shortage [MCM]**	**Coverage [%]**	**Absolute Shortage [MCM]**
min	0.16	0.0	0.15	0.0	0.15	0.0
max	1.00	122.0	1.00	135.3	1.00	139.7
mean	0.91	7.6	0.91	8.5	0.91	8.6
SD	0.15	21.4	0.15	23.4	0.15	24.0

As mentioned, the outputs presented in the Water Allocation Plans (Annexe 9) go beyond solely a water allocation table, but instead provide a more in-depth insight into the entire water balance at Level 2.5. More specifically, this Annexe provides:

- **Key indicators**: 8 indicators summarising the Level 2.5 catchment in terms of Area, Population, Precipitation, Local storage, Demand, Supply, and Shortage (Table 55).

Table 55. Example of the Key Indicators for NAKU_A catchment

Total area (km2)	231	Total demand (MCM/y)	40.7

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[1] Hausfather, Z., & Peters, G. P. (2020). Emissions–the 'business as usual'story is misleading.

Population	92,221	Total supply (MCM/y)	41.2
Precipitation (mm/y)	1,045	Total shortage (MCM/y)	-0.4
Precipitation (MCM/y)	241	Total shortage (%)	-1%
Local storage (MCM)	0		

- **Hydrological Water Balance**: Precipitation, Irrigation, Evapotranspiration, Runoff, Groundwater recharge and Delta Storage. The hydrological water balance represents all natural and artificial storage in the basin (Table 56).

Table 56. Hydrological Water Balance for NAKU_A (MCM/y)

Precipitation	241
Irrigation	37
Evapotranspiration	-172
Runoff	-84
Groundwater recharge	-13
Delta storage	0

- **Annual Water Balance** consists of the hydrological water balance components but shows its annual variability, indicating also the significant role storage (natural and artificial) plays in regulating the variability of water availability. An example figure here for Sub-catchment NAKU_A (Upper Akagera) (Figure 76).

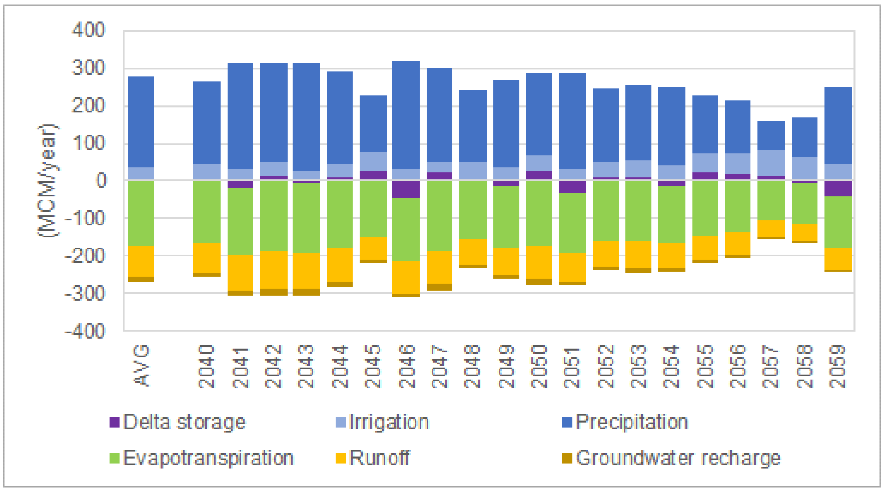

Figure 76. Annual Water Balance for NAKU_A catchment.

- **Monthly Hydrological Characteristics** – a graph presenting the seasonal variability of the key hydrological variables in the catchment, as discussed in previous section 1.3 (p81) of this report and presented in Annexe 8 (Figure 77).

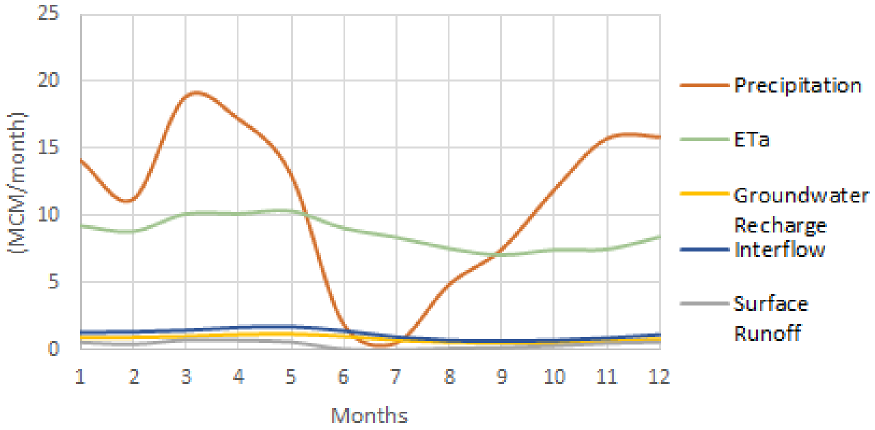

Figure 77. Monthly Hydrological Characteristics for NAKU_A

- **Monthly Blue Water Availability and Water Demand** – a graph presenting the seasonal variability of Blue Water availability (runoff, interflow and groundwater recharge), against demand, to present surplus and potential deficits (which can be regulated by natural and artificial storage) (Figure 78).

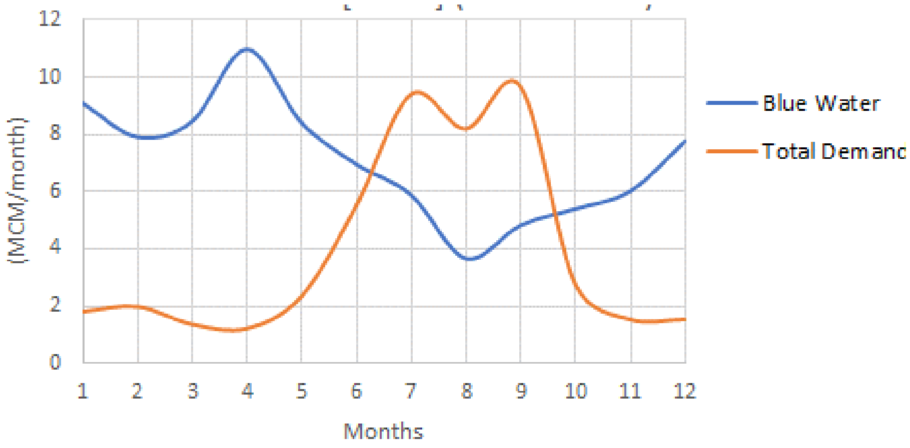

Figure 78. Monthly Blue Water Availability and Water Demand for Sub-catchment NAKU_A (Upper Akagera).

- **Sectoral Water Allocation Table** – a table showing how much water is supplied under the allocation rules depending on the water availability in the catchment for each sector (Table 57). The unmet demand is noted as a negative value; a value of -0.1 MCM means that there is a shortage of 0.1 MCM.

Table 57. Sectoral Water Allocation Table for NAKU_A (Upper Akagera).

Monthly Water Balance for 2040 - 2059 [MCM]										
[MCM]	**Blue Water**	Fishpond	Irrigation	Large Scale Irrigation	Domestic	Industry	Livestock	**Sum of Supply**	**Sum of Demand**	**Unmet Demand**
Jan	**9.1**	0.0	0.0	1.4	0.3	0.0	0.0	**1.8**	**1.8**	**0.0**
Feb	**7.9**	0.0	0.0	1.7	0.3	0.0	0.0	**2.0**	**2.0**	**0.0**
Mar	**8.4**	0.0	0.0	1.0	0.3	0.0	0.0	**1.3**	**1.3**	**0.0**
Apr	**11.0**	0.0	0.0	0.9	0.3	0.0	0.0	**1.2**	**1.2**	**0.0**
May	**8.4**	0.0	0.1	1.9	0.3	0.0	0.0	**2.3**	**2.3**	**0.0**
Jun	**6.9**	0.0	0.4	4.6	0.3	0.0	0.0	**5.4**	**5.5**	**-0.1**
Jul	**5.9**	0.1	1.6	7.1	0.3	0.0	0.0	**9.1**	**9.4**	**-0.3**

Aug	**3.6**	0.0	1.4	6.1	0.3	0.0	0.0	**7.8**	**8.2**	**-0.3**
Sep	**4.8**	0.0	0.5	8.6	0.3	0.0	0.0	**9.5**	**9.7**	**-0.2**
Oct	**5.4**	0.0	0.0	2.6	0.3	0.0	0.0	**3.0**	**2.7**	**0.0**
Nov	**6.0**	0.0	0.0	1.3	0.3	0.0	0.0	**1.6**	**1.5**	**0.0**
Dec	**7.7**	0.0	0.0	1.2	0.3	0.0	0.0	**1.5**	**1.5**	**0.0**

All this information can be found for each Level 2.5 catchment in Annexe 9.

2.3 Level 2.5 water surplus and deficits

2.3.1 Level 1 water balances

The water surplus and deficits were analysed with the WEAP model in space and time, considering the developments and measures included in the Water Resilient scenario and the most likely climate change (RCP 4.5). The Water Allocation Plans (Annexe 9) present the surplus and deficits at the Level 2.5. High-level information on surplus and deficits are presented below at the Level 1.

More specifically, the information presented at Level 1 giving insight into the water balance (surplus and deficits included), encompasses the following:

- **A Follow the Water diagram** – presents the water accounts in a clear-cut figure for each L1 catchment (Figure 79). The term Evapotranspiration includes irrigation and agricultural demands.

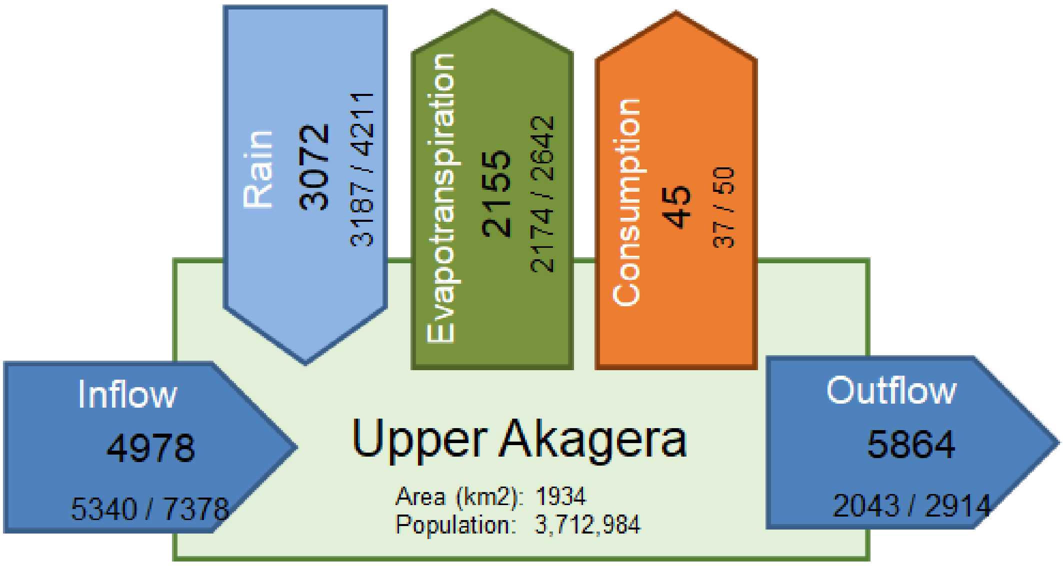

Figure 79. Follow the Water Diagram for NAKU (Upper Akagera). Smaller numbers are the minimum / maximum values in a year over a period of 20 years.

- **Mean annual water balance of the catchment** – the numbers behind the Follow the Water diagram in a table (Table 58).

Table 58. Mean annual water balance for NAKU (Upper Akagera).

	(MCM/y)	(mm/y)
IN		
Inflow	4978	1628
Precipitation	3072	1004

Total IN	**8049**	**2632**
OUT	0	0
Outflow	5864	1918
ET Actual	2155	705
Consumption	45	15
Delta Storage	-15	-5
Total OUT	**8049**	**2632**
DIFF	*0*	*0*

- **Key characteristics of catchment –** similar to L2.5, this table presents the Area, Population, Precipitation, Local storage, Demand, Supply, and Shortage (Table 59).

Table 59. Key Characteristics for NAKU (Upper Akagera).

Total area (km2)	3,058	Total demand (MCM/y)	702.2
Population	3,712,984	Total supply (MCM/y)	496.2
Precipitation (mm/y)	1,004	Total shortage (MCM/y)	206.1
Precipitation (MCM/y)	3,072	Total shortage (%)	76%
Local storage (MCM)	3		

- **Summary of sectoral demand, supply, shortages** – for the main sectors, the demand, supply and shortage (Table 60).

Table 60. Summary of Sectoral demand, supply and shortages for NAKU (Upper Akagera).

	Demand [MCM/year]	Supply [MCM/year]	Shortage [MCM/year]	Shortage [%]
Irrigation	560.6	355.2	205.4	37%
Domestic	135.5	135.5	0.0	0%
Industry	1.6	1.0	0.6	40%
Livestock	3.6	3.6	0.0	0%
Fishpond	0.9	0.9	0.0	0%
Total	0.0	0.0	0.0	76%

- **Annual variability of sectoral demand and supply** –Figure 80 presents the inter-annual variability of supplies and demands to the main sectors for the catchment for the future 20 years.

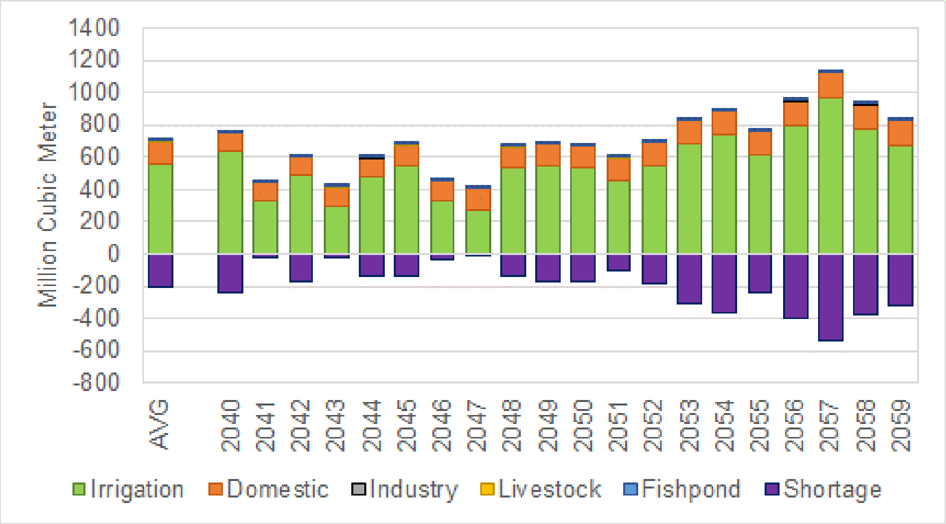

Figure 80. Annual variability of sectoral demands and supply at level 1 for NAKU (Upper Akagera).

- **Monthly variation in Blue Water (internal renewable water resources) availability and demand** – a figure showing how water availability (water generated within the catchment) compares with water demand in the catchment (Figure 81).

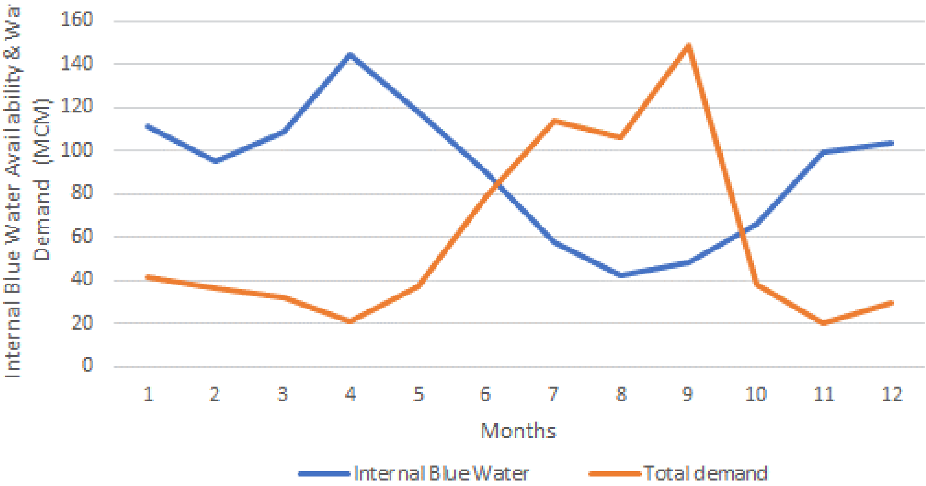

Figure 81. Monthly variation in internal (produced within the catchment) blue water availability (renewable water resources availability) and demand for NAKU (Upper Akagera), for 2050.

All this information is presented for all Level 1 catchments in Annexe 9, with more granular information for the Level 2.5 catchments.

2.3.2 Spatial distribution

The spatial distribution of surplus and deficits in Rwanda is represented using several maps in this section. First of all, Table 61 and Table 62 present a summary for all Level 1 catchments of the Blue Water Availability, Demands, allocated Supplies, and the difference between Blue Water Availability and Demand, which gives an indication of whether there is surplus or deficit in the L1 catchment, for respectively the baseline (2000 – 2019) and the future (2040 – 2059). Figure 82 presents the spatial distribution of this indicator for both periods.

Water surplus is defined as the annual average blue water availability minus the annual average total demand. The shortage is defined as the annual average of the total water supply, based on the allocation rules and storage dynamics simulated by the WEAP model, minus the annual average of the total water demand for the defined period.

Table 61: Values summarized per Level 1 catchment for 2000 – 2019.

	Total area [km2]	*P [mm]*	*Demand [MCM/y]*	*Supply [MCM/y]*	*Blue Water Availability [MCM/year]*	*Demand/ BWA [%]*	*Total shortage [MCM/y]*	*Surplus or deficit [MCM/y]*
CKIV	2,425	1,566	34	34	1,368	2.5	0	1,334
CRUS	1,021	1,391	14	14	440	3.2	0	426
NAKL	4,288	950	40	39	956	4.2	0	917
NAKN	3,405	1,250	80	79	1,262	6.3	0	1,182
NAKU	3,058	1,034	70	69	851	8.2	1	781

NMUK	1,887	1,366	32	31	859	3.7	0	828
NMUV	1,569	1,055	31	30	422	7.3	1	391
NNYL	3,307	1,220	74	72	1,209	6.1	1	1,135
NNYU	3,350	1,289	59	59	1,371	4.3	0	1,312

Table 62: Values summarized for Water Resilient scenario per Level 1 catchment for 2040 – 2059 under the RCP 4.5 climate.

Catchment	*Total area [km2]*	*P [mm]*	*Demand [MCM/y]*	*Supply [MCM/y]*	*Blue Water Availability [MCM/year]*	*Demand/ BWA [%]*	*Total shortage [MCM/y]*	*Surplus or deficit [MCM/y]*
CKIV	2,425	1,518	168	161	1,338	12.6	8	1,169
CRUS	1,021	1,370	42	40	422	10	2	380
NAKL	4,288	939	582	546	1,255	46.4	36	673
NAKN	3,405	1,232	836	454	1,437	58.1	382	602
NAKU	3,058	1,004	702	496	1,085	64.7	206	382
NMUK	1,887	1,388	101	99	872	11.5	1	771
NMUV	1,569	1,060	243	192	463	52.4	50	220
NNYL	3,307	1,221	585	435	1,284	45.5	149	700
NNYU	3,350	1,325	323	311	1,443	22.4	12	1,120

Table 61 and the maps on the top of Figure 82 give the average values for the historical reference period 2010 (2000-2019). The figure shows a clear distinction between Eastern and Western catchments. The Western catchments have higher absolute water surpluses, whereas the Eastern catchments show the most water shortage. In 2000-2019, the shortage is in the range of 0.1 – 1.1 MCM/y, whereas this has grown in 2040-2059 to almost 300 MCM/y for the NAKN catchment specifically, which is the highest.

The water surplus grows for the reference 2050 period (2040-2059) as well compared to 2000-2019. Whereas the latter shows a maximum of around 700 MCM/y in CKIV, the former dictates a surplus maximum of 1350 MCM/y for the same level 1 catchment. NMUV has the lowest amount of water surplus for 2010 which is also observed for the 2050 reference period.

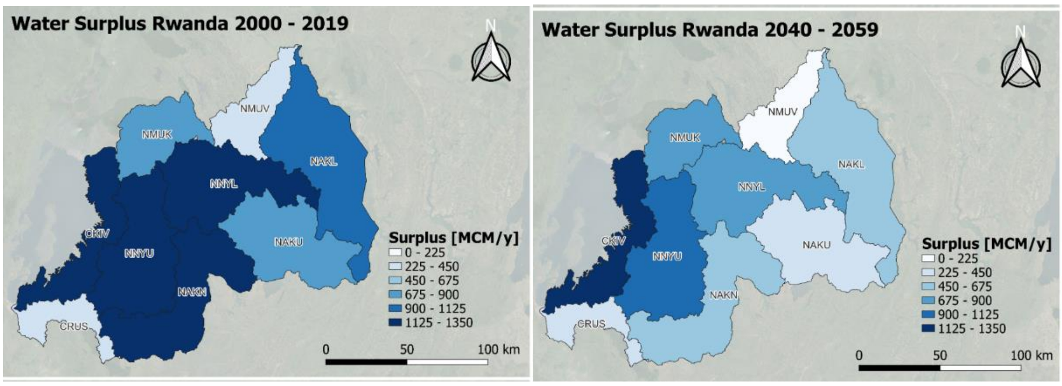

Figure 82: Surplus versus shortage per level 1 catchment for both the current (2000 – 2019) and the future climate RCP 4.5 for 2040 – 2059 period.

Furthermore, the shortages are also mapped for level 2.5 catchments. At level 2.5, the current distribution of water resources and infrastructure leads to shortages across Rwanda, as shown in Figure 83, similar to the trends observed at level 1 (Figure 82). Shortages are mostly present in the Eastern part of the country, but the central and southern parts also suffer shortages in the order of 100 MCM/yr.

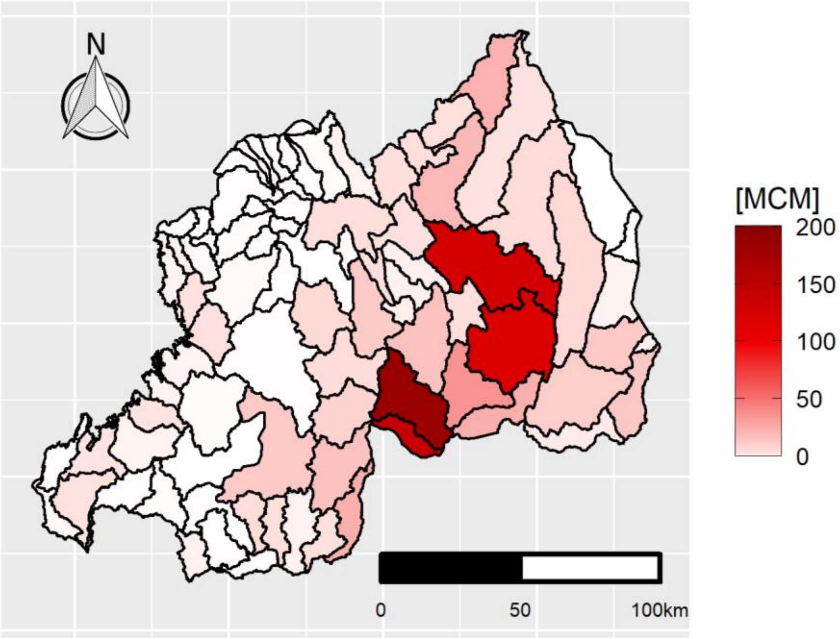

Figure 83: Absolute Shortages per level 2.5 catchment for the period 2040 - 2059 under an RCP 4.5 climate.

2.4 Options for strategic water resources infrastructure

2.4.1 Conceptualisation in the model

From the previous section it can be concluded that there is a certain potential to reduce shortages when water is brought from a period with surplus to a deficit period. To make this feasible, the storage of water should be enhanced in the basin. Natural storage reservoirs in the landscape are soils, groundwater and lakes (sometimes also called “green infrastructure”). Use of these natural storage features can be optimized through Nature-based Solutions. Investments in artificial infrastructure to enhance water storage potential consist of water storage reservoirs. Potential locations to increase surface water storage (prepared for Task 3, see section 3.1, p146), were reviewed to detect its completeness for conceptualising all the potential dams.

As this study focuses on the impact of additional storage in a future scenario, that is by 2050, it was pivotal that both existing as well as planned – also referred to as secured – dams were left out of this potential list. Annexe 10 shows a map with the location of each of these dam categories in Rwanda. In total, 132 dams were identified as potential, 4 were identified as planned or secured dams, i.e. Nyabarongo II (883 MCM), Akanyaru (333 MCM), Muvumba (55MCM), and Warufu (25 MCM); and a total of 48 dams were found to be already constructed for which dam estimates were obtained from the Water Storage Status report of June 2021 (RWB, 2021b)[1]. Regarding the secured/ planned dams, a live storage of 80% was assumed except for Muvumba dam for which a live storage volume of 40 MCM was assumed which is in line with the revised design of this reservoir.

A three-step process was followed to quantify the most realistic potential storage capacity (MCM) for each potential dam. Step 1 establishes an upper limit for the potential dams based on hydrological

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[1] ANNUAL WATER STORAGE STATUS REPORT FOR 2020 -2021, Rwanda Water Resources Board. June 2021.

criteria. Step 2 establishes an upper limit from physical criteria. Finally, step 3 combines both criteria to obtain the minimum attainable volume. This upper limit is the active storage accounted for in WEAP, which simulates the water balance dynamically for each reservoir and from which dynamic outputs were obtained for each dam site (aggregate on catchment level 2.5) in terms of filling and water levels. The three steps explained in detail are:

1. The first step is to define a realistic upper bound for potential active reservoir storage for each site based on hydrological criteria. This is based on the assumption that a reservoir is oversized when it does not receive enough water to fill within a reasonable amount of time. For this purpose:
    a. First, the Mean Annual Inflow (MAI) for each of the 132 potential dams was estimated by multiplying the runoff (sum of surface runoff and interflow from WEAP) averaged for 2040 - 2059 under an RCP 4.5 scenario with the contributing catchment area, obtained from a thorough GIS analysis.
    b. Subsequently, the upper bound for the potential storage volume was obtained for each dam site by assuming that a reservoir needs to be filled in not more than three years, assuming zero outflows. These three years are in this analysis termed as the Over Year Active Storage Factor (OYASF). This assumption only holds for storage dimensioning, within the WEAP model itself, storage reservoirs are dynamically modelled with continuous inflow and outflow. Note that this OYASF is on the high conservative side – the hydrological study at pre-feasibility stage will likely find a lower value to be more realistic. Note also that the WEAP model does consider the variability of inflow for this analysis based on the simulated flows at level 2.5. This hydrology-based upper limit volume at site-level was obtained by multiplying MAI with the Over-Year Active Storage Factor (OYASF) for which three years were assumed in the WEAP model. The influence of the OYASF is subject of the sensitivity analysis in section 2.6 (p143).

2. The second step is to calculate the upper limit from physical (geometric) principles. This physical upper limit is based on its maximum height (m) and flooded area (ha), calculated from GIS and the DEM, as will be done in Task 3 (see section 3.1, p146). As the WEAP model only accounts for active storage, the physical active storage is presented and is determined as follows:

    $$\begin{gathered} Physical\ Active\ Storage\ Capacity\ [m3] = \\ Max\ Height\ (m) * Max\ Flooded\ Area\ (m2) *\ Reservoir\ Shape\ Factor\ (0.5) * \\ Active\ Storage\ Factor\ (0.8)) \end{gathered}$$

    Using GIS, a digital terrain model was analysed for each potential location, from which a maximum flooded area (m2) and maximum height (m) were determined. A conservative estimate was obtained for the upper limit using the above formula. The *Reservoir Shape Factor* (0.5) accounts for the longitudinal slope profile. This factor is likely on the high side, which was preferred as a more detailed storage estimate can be obtained during flagship preparation, based on the dynamic WEAP model outputs. Of course, this will be further refined during pre-feasibility studies. The Active Storage Factor is the volume of stored water which can be actually used and is set to 80% of storage capacity, assuming 20% dead storage.

3. An overview of the obtained physical and hydrological upper limits can be found in Annexe 10. To define the final upper limit, the minimum of both values was taken.

The 132 potential storage locations, and their associated volumes, were then aggregated at level 2.5 to implement them into WEAP and analyse their impact at that level of detail. Table 63 indicates for each of the 86 level 2.5 catchments the total estimated active storage potential obtained from one or more potential storage locations. The allocation rule chosen in WEAP is summarised in Table 64. Storage was given the same priority as agriculture and industrial demands (3). Figure 84 visualises and unveils the spatial variation in water storage potential per level 2.5 catchment.

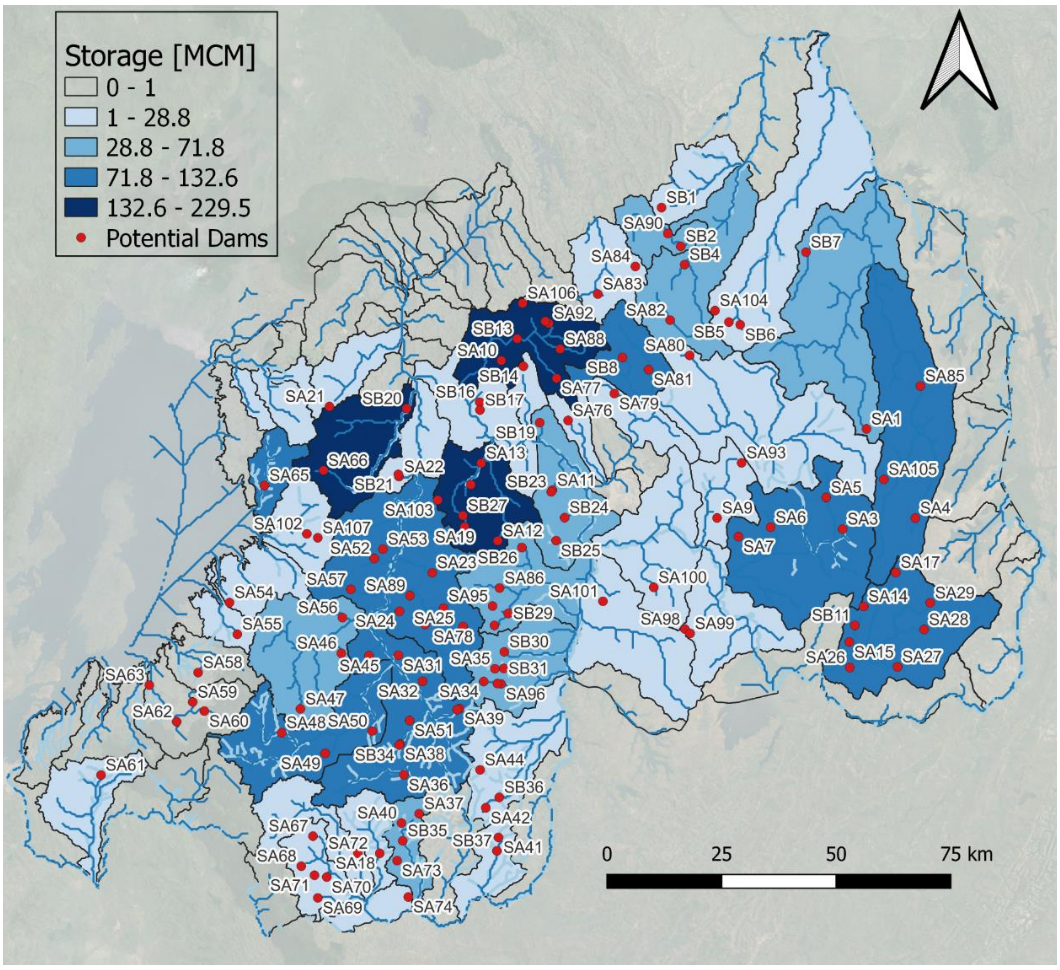

Figure 84. Aggregated level 2.5 active storage volumes and the 132 dam locations (see Annexe 10).

Table 63. Aggregated Potential Active Storage at level 2.5 (see Annexe 10).

Aggregated Storage [MCM] per level 2.5 for the Wresilient_Storage_FullPot scenario					
CKIV_A	0.0	**NAKN_B**	1.8	**NMUK_K**	0.0
CKIV_B	99.3	**NAKN_C**	45.3	**NMUK_L**	0.0
CKIV_C	19.8	**NAKN_D**	0.0	**NMUK_M**	0.0
CKIV_D	15.3	**NAKN_E**	21.3	**NMUK_N**	0.0
CKIV_E	18.3	**NAKN_F**	0.0	**NMUK_O**	0.0
CKIV_F	0.0	**NAKN_G**	28.8	**NMUK_P**	0.0
CKIV_G	8.6	**NAKN_H**	0.0	**NMUV_A**	0.0
CKIV_H	19.6	**NAKN_I**	58.2	**NMUV_B**	4.5
CKIV_I	19.6	**NAKN_J**	8.5	**NMUV_C**	71.8
CKIV_J	0.0	**NAKN_K**	5.4	**NMUV_D**	39.5
CKIV_K	0.0	**NAKN_L**	24.7	**NMUV_E**	17.2
CKIV_L	0.0	**NAKN_M**	15.9	**NNYL_A**	0.0
CKIV_M	0.0	**NAKU_A**	0.0	**NNYL_B**	18.0
CKIV_N	0.0	**NAKU_B**	112.5	**NNYL_C**	0.0
CRUS_A	0.0	**NAKU_C**	0.0	**NNYL_D**	22.8
CRUS_B	21.0	**NAKU_D**	3.8	**NNYL_E**	102.0
CRUS_C	0.0	**NAKU_E**	102.6	**NNYL_F**	18.9
CRUS_D	0.0	**NAKU_F**	16.5	**NNYL_G**	36.9
CRUS_E	0.0	**NAKU_G**	21.3	**NNYL_H**	11.1
NAKL_A	0.0	**NMUK_A**	0.0	**NNYL_I**	5.1
NAKL_B	26.4	**NMUK_B**	0.0	**NNYL_J**	180.3
NAKL_C	132.6	**NMUK_C**	18.0	**NNYL_K**	229.5
NAKL_D	37.2	**NMUK_D**	0.0	**NNYU_A**	161.1
NAKL_E	0.0	**NMUK_E**	0.0	**NNYU_B**	19.8
NAKL_F	0.0	**NMUK_F**	0.0	**NNYU_C**	103.1
NAKL_G	0.0	**NMUK_G**	0.0	**NNYU_D**	46.6
NAKL_H	0.0	**NMUK_H**	0.0	**NNYU_E**	103.5
NAKL_I	0.0	**NMUK_I**	0.0	**NNYU_F**	81.6
NAKN_A	63.2	**NMUK_J**	0.0		

Table 64: WEAP Priorities adopted in the model

Allocation Rule	*Sector*
1	Domestic
2	Environmental Flows
3	Agricultural and Industrial Demands as well as Storage Resevoirs.

It is worth noting that, as mentioned in the introduction of this section, the potential active storage simulated in this study could also partially be provided by green infrastructure rather than solely grey. In fact, hybrid approaches (combining green and grey) are recenlty often preferred. Therefore, during the formulation of flagship projects, specific attention was given to looking into viable options to implement or enhance green infrastructure (especially wetlands) as part of the potential storage realisation. For example, water harvesting measures could be advantageous in rural areas. Note that for some 2.5 catchments, such as NNYU_A and NNYU_D, an account of water harvesting measures was already implemented in the model established by SEI for the Hydro-Economical Analysis (SEI, 2022)[1].

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[1] Swedish Environment Institute. 2022. A Water Resilient Economy: Hydro-Economic and Climate Change Analysis for Rwanda.

The complementation of grey infrastructure with Nature-based Solutions was also considered (see section 3.1.2.9, p170). Some of the NbS measures also provide storage benefits due to increased infiltration and groundwater recharge and thus improved use of the storage capacity of soil and aquifers.

The subsequent sections discuss how the introduction of this optional additional active storage affects the water surplus and the deficits identified in section 2.3 (p122). It is essential to note that in the WEAP model, priorities were assigned in accordance with the Water Law, using a straight-forward three-tiered system. Priority 1 was reserved for all domestic demands whereas priority 2 was assigned to all environmental flow demands. All other demands, agricultural sectors and industry, but also storing water in the reservoir were given priority 3. . By setting equal demands for storage filling and industrial/ agricultural demands, a more realistic dam-operation approach was assumed by limiting uncontrolled water releases.

2.4.2 Impacts on catchment water balances

The results of sections 2.2 and 2.3 serve as the baseline for comparing the impact of added potential active storage throughout Rwanda. The associated scenario, with no new reservoirs, is referred to in this study as *WResilient_NoStorage*.

Adding the total of 132 potential storage reservoirs to the model, by means of aggregation per L2.5, allowed to analyse the local as well as cross-catchment feedbacks. This scenario with all the 132 potential new reservoirs is called *WResilient_Storage_FullPot*. Figure 85 to Figure 87 show the spatial distribution of the change from *WResilient_NoStorage* to *WResilient_Storage_FullPot*. The *WResilient_NoStorage* and *WResilient_Storage_FullPot* scenarios were run for both projected climate pathways (RCP 4.5 and 8.5), for which only results of the former are presented given the major similarities between both scenarios, and the higher relevance of the former for hydraulic infrastructure planning (Hausfather & Peters, 2020)[1]. In addition, for this initial step in the prioritisation process, the WEAP model only focuses on active storage as the full storage capacity is to be defined during the feasibility phase once the flagship projects have been identified. In this section, results on level 2.5 are discussed for total shortage [MCM] (Figure 87), delta coverage [%] (Figure 85) and absolute delta coverage [MCM] (Figure 86). The latter two are obtained by subtracting the coverage (% or absolute) of *WResilient_NoStorage* with the *WResilient_Storage_FullPot* estimate.

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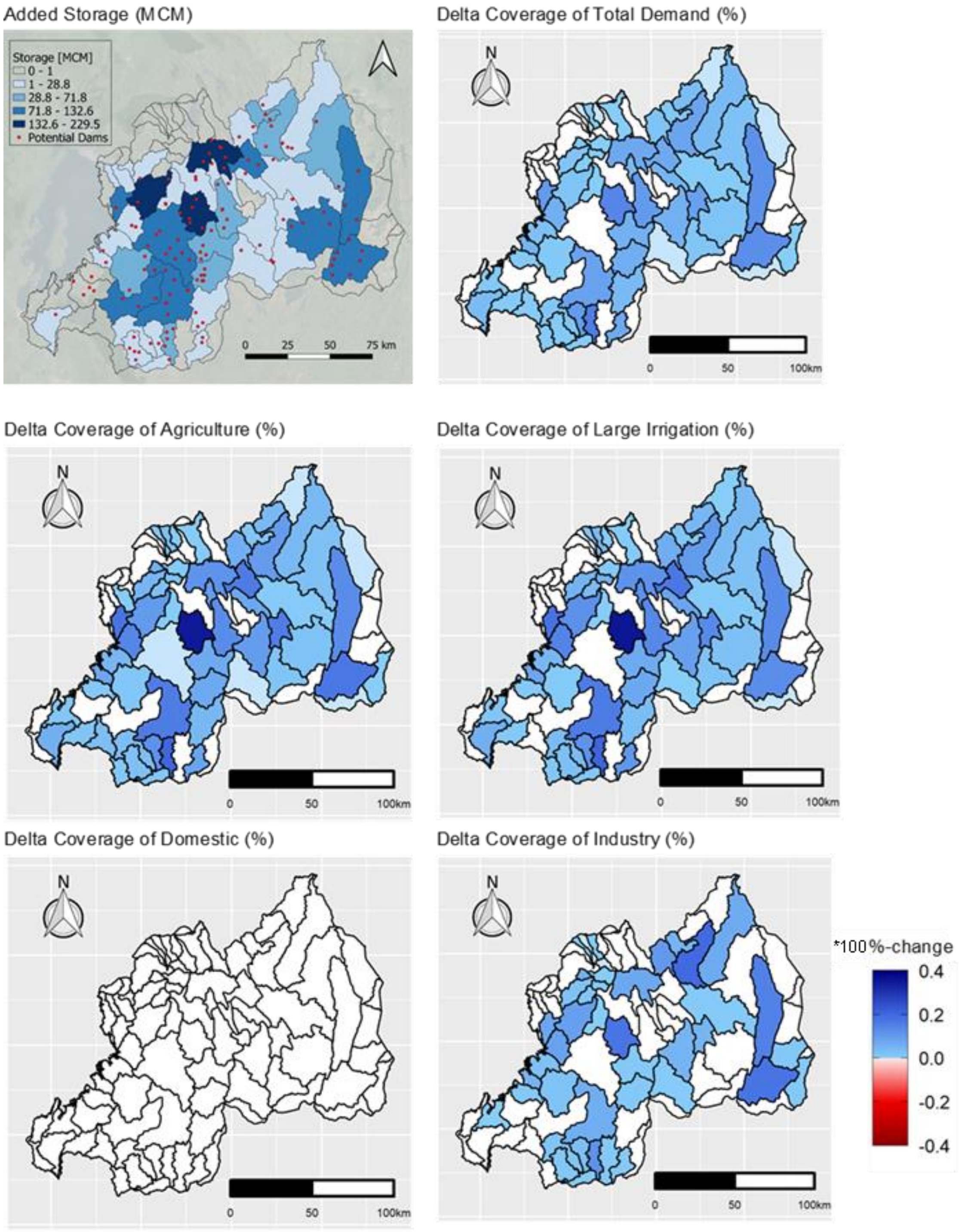
[1] Hausfather, Z., & Peters, G. P. (2020). Emissions–the ‘business as usual’story is misleading.


Added Storage (MCM)

Delta Coverage of Total Demand (%)

Delta Coverage of Agriculture (%)

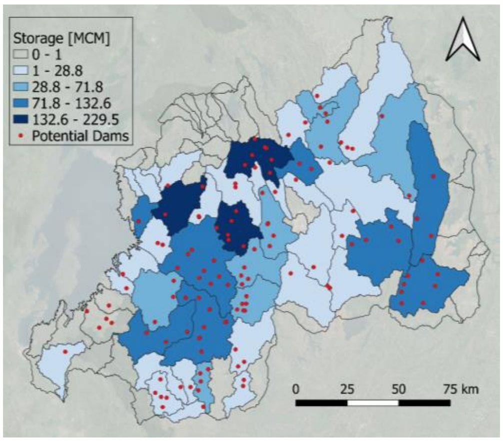
Delta Coverage of Large Irrigation (%)

Delta Coverage of Domestic (%)

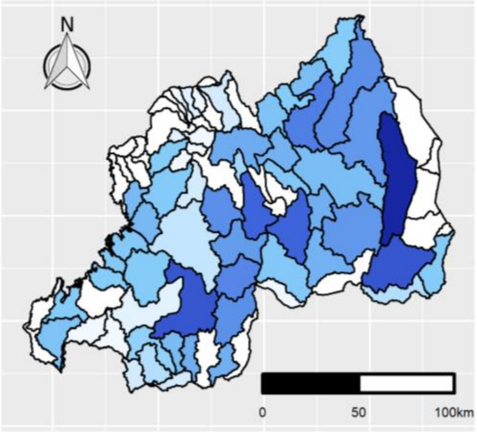
Delta Coverage of Industry (%)

Figure 85. Delta Coverage [%] for sectoral demands for *WResilient_Storage_FullPot* scenario for RCP 4.5, averaged over the period 2040 – 2059 to represent 2050. In the top left, an overview of the added storage and the location of the potential dams are shown.

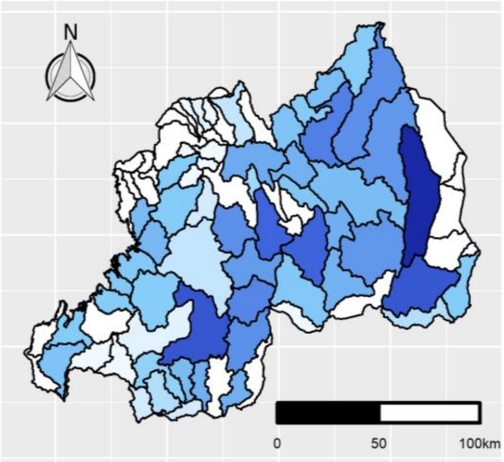
Added Storage (MCM)



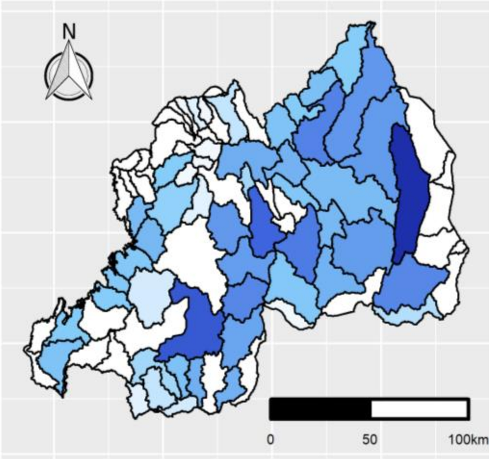
Delta Coverage of Total Demand (ABS)



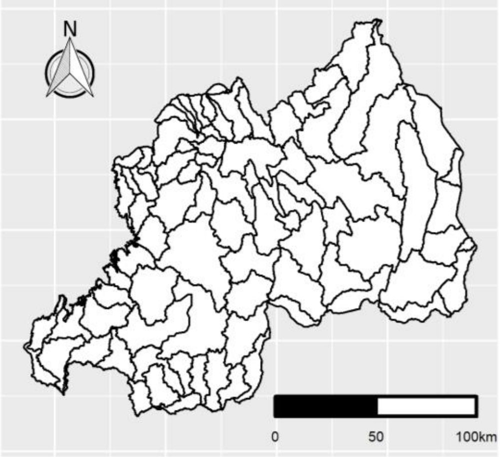
Delta Coverage of Agriculture (ABS)



Delta Coverage of Large Irrigation (ABS)



Delta Coverage of Domestic (ABS)



Delta Coverage of Industry (ABS)

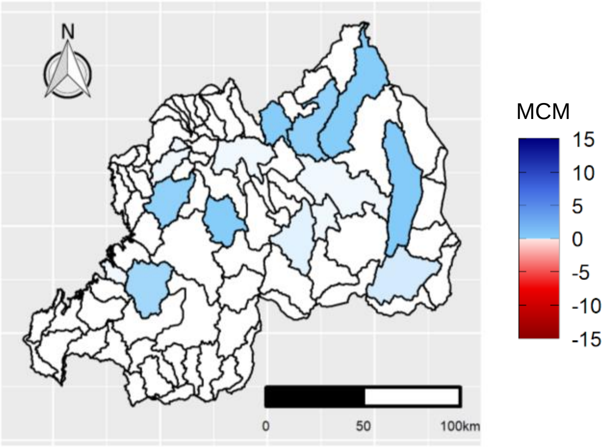
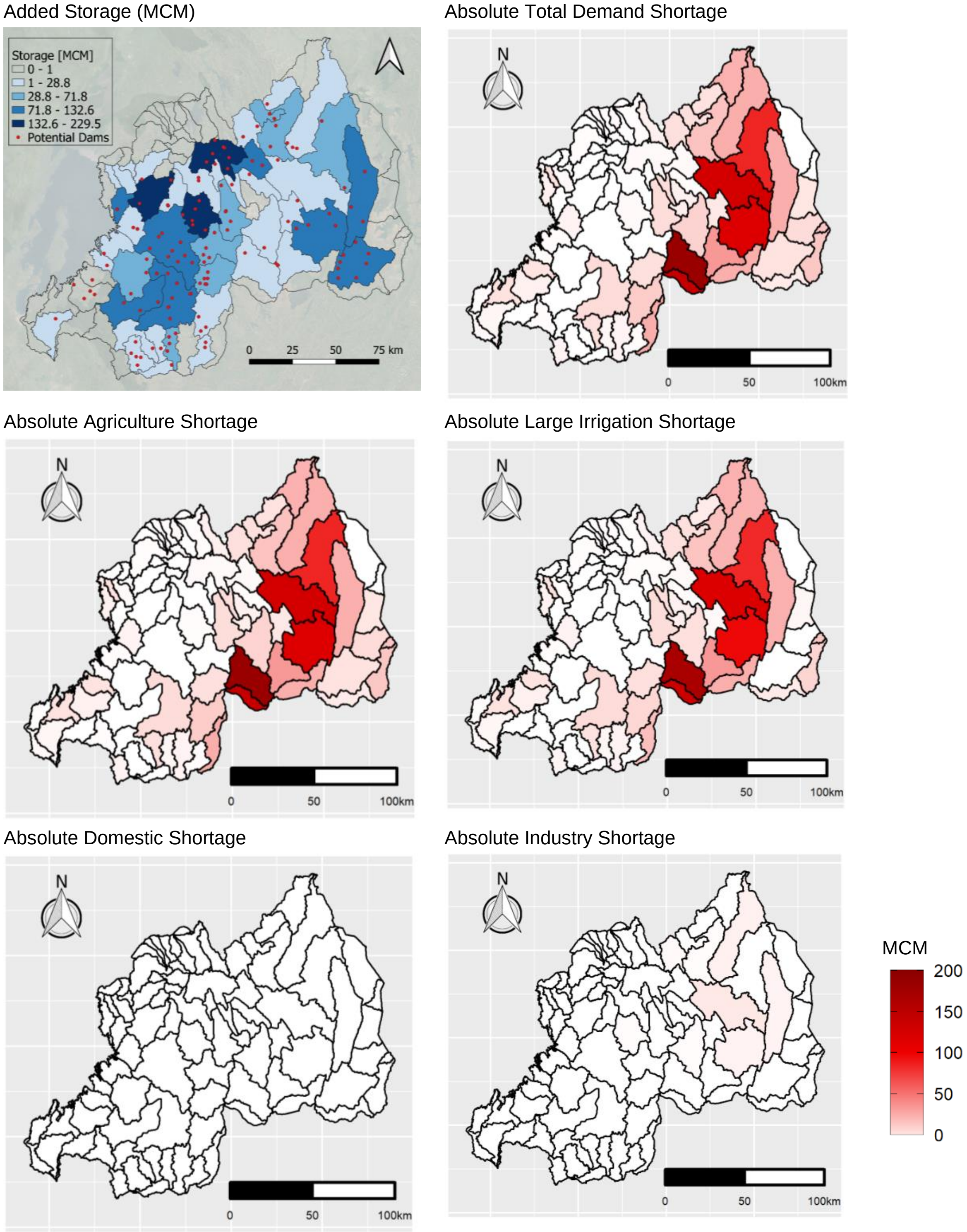


Figure 86. Delta Coverage [absolute, MCM] for sectoral demands for *WResilient_Storage_FullPot* scenario for RCP 4.5, averaged over the period 2040 – 2059 to represent 2050. In the top left, an overview of the added storage and the location of the potential dams are shown.



Added Storage (MCM)

Absolute Total Demand Shortage

Absolute Agriculture Shortage

Absolute Large Irrigation Shortage

Absolute Domestic Shortage

Absolute Industry Shortage

Figure 87. Absolute shortage [MCM] for sectoral demands for the *WResilient_Storage_FullPot* scenario for RCP 4.5, averaged over 2040 – 2059 to represent 2050. In the top left, an overview of the added storage and the location of the potential dams are shown.

The maps presented in Figure 85 to Figure 87 give an overview of the effect of adding 100% of potential dams on water availability and deficit. As shown in Figure 85, the coverage increases for most of the 86 sub-catchments. It shows significant increases in the following level 1 catchments: NAKL, NNYL, NNYU and NMUV. The Water Balance analysis of *WResilient_NoStorage* (section 2.3, p122) indicated that shortage is highest in these catchments (Figure 83). It is clear from Figure 86 that the catchments with highest potential active storage capacity also show the highest delta coverage increases. Also, it is noticeable that agriculture, specifically large irrigation, accounts for the highest increase as domestic demands are mostly met in the *WResilient_NoStorage* scenario and industry demands are significantly lower than the agricultural demands for most catchments. Some catchments without potential storage locations also show a positive increase in coverage [%] which is attributed to changing upstream/ downstream interactions at catchment level 2.5.

Similarly, Figure 86 shows the magnitude [MCM] of change from the *WResilient_NoStorage* to *WResilient_Storage_FullPot* scenarios. The trend is similar to Figure 85. NAKL_C shows the highest absolute increase in coverage, of about 15 MCM, mostly due to covering large irrigation demand.

In terms of absolute shortages, after implementing all the potential active storage, NAKN_B and NAKN_D show the highest remaining annual shortages, of about 140 MCM. It is worth noting that the local climate data provided by Rwanda Meteorological Agency is different to the original Princeton dataset used in the Hydro-Economic Analysis (SEI, 2022)[1], especially for these two subcatchments. As a consequence, significantly less precipitation is noticed and might explain party the differences with the shortage estimates presented in the Hydro-Economic Analysis. Further, significant shortages are also observed for NAKL_D, NNYL_F and NAKU_E, in the order of 100 MCM. Shortages are most significant for the agricultural water demands in absolute terms, as their corresponding demands are much higher in magnitude to industrial demands. Domestic demands, in contrast, are fully met as it is assigned the highest priority in the WEAP model (Table 64, p129).

It should be noted that, even though introducing dams has a positive effect on coverage (%), some L2.5 catchments still face shortages in general; yet these have significantly decreased because of the added storage.

2.4.3 Water Transfer Lower Akagera

The results shown in the previous section make evident that generaly there is enough water available to meet demands, but due to the seasonality and inter-annual variability of the available water, considerable shortages occur. With increased storage capacity this will reduce, if well managed – as such this study identifies the key opportunities to improve the regulation of the available water through investments in infrastructure and Nature-based Solutions.

In some cases though, shortages are less a consequence of storage capacity, but rather a consequence of low water availability. A supply-side measure to reduce such shortage is to transfer water from another catchment. A recent study considered various water transfer options in various parts of Rwanda. One of the potentially preferred options (6c) has been examined in the WEAP model to study its effect on the level 2.5 water balances. Given the scope of this report on studying and prioritizing additional storage reservoirs, this water transfer analysis is not part of the prioritisation but was analysed separately for which results are presented in this section.

The option 6c was implemented in the WEAP model by means of a diversion from Akagera River (downstream of the NAKL_I confluence) to the NAKL_C subcatchments where it adds to the headflow. A maximum monthly diversion capacity of 3.6 cms was applied which is the maximum capacity of the transfer pipe according the study (Figure 88).

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[1] Swedish Environment Institute. 2022. A Water Resilient Economy: Hydro-Economic and Climate Change Analysis for Rwanda.

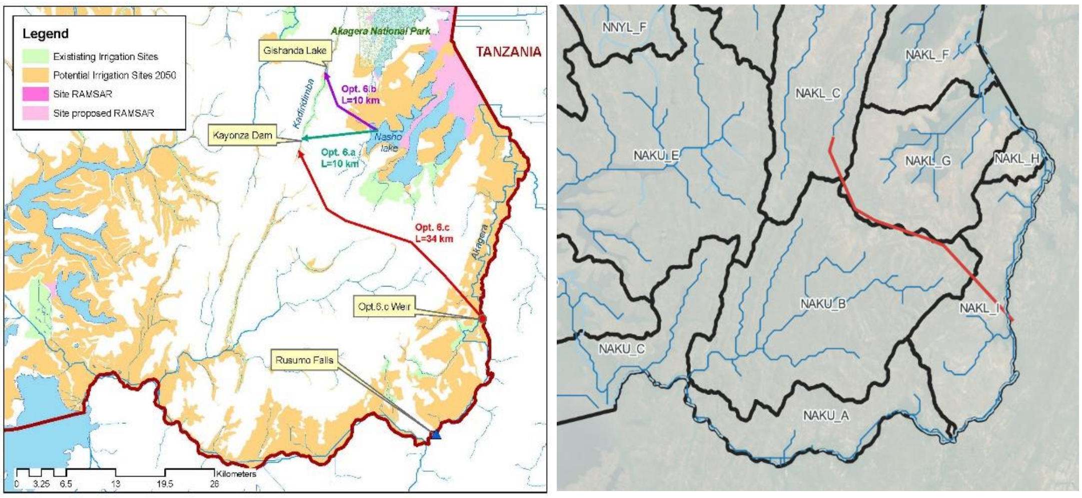

Figure 88. Transfer option 6c accounted for in the WEAP model from Akagera R|iver (below NAKL_I) to NAKL_C.

The results of having a water transfer from Akagera downstream of NAKL_I to subcatchment NAKL_C (option 6c) subcatchment (WResilient_NoStorage_Transfer) were studied against the WResilient_NoStorage scenario. Initial findings show that the transfer resulted in a significant increased coverage for NAKL_C of 94% as opposed to the coverage of 64% obtained with the WResilient_NoStorage scenario.

In addition, from Figure 89 to Figure 91, it is evident that the water transfer positively impacts the supply delivered for Large Irrigation, which is the main demand site within NAKL_C. Especially during the drier months, June to September, the water transfer has enabled more water to be supplied to the large irrigation demand site. This is further confirmed by Figure 91, which shows that in 2057, which is a dry year, the impact of the water transfer on the supply delivered is most significant.

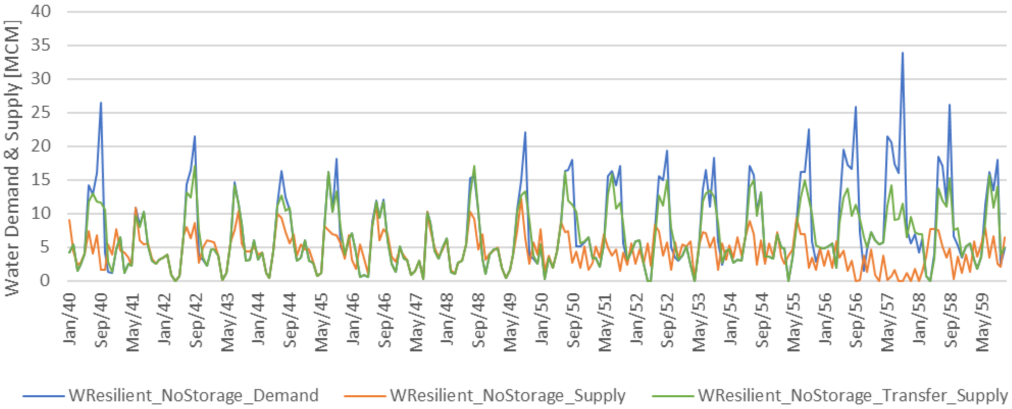

Figure 89. Water Demand & Supply for large irrigation within NAKL_C for WResilient_NoStorage with and without Transfer option 6c considered for 2040 and 2059 under RCP 4.5.

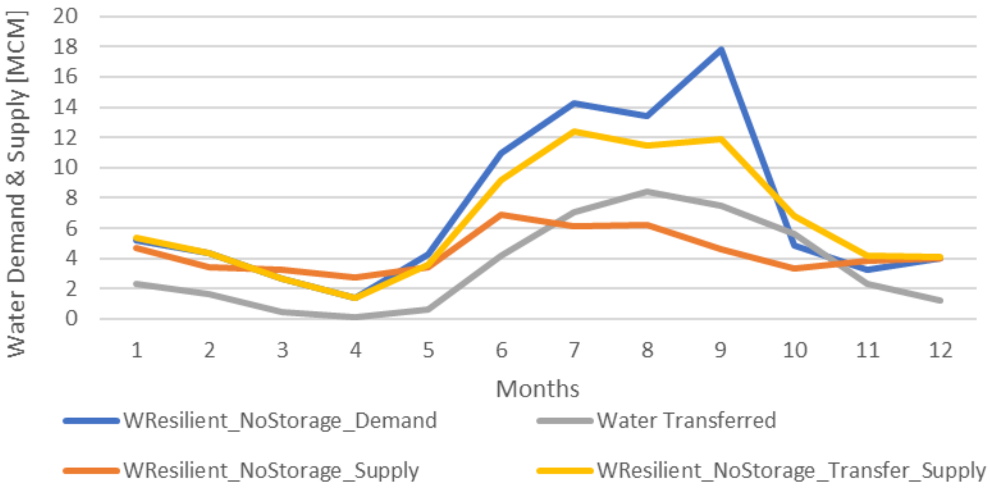

Figure 90. Water demand & Supply for Large Irrigation for NAKL_C for the WResilient_NoStorage scenario with and without a water transfer (option 6c). In addition, the averaged monthly diversion [MCM] is shown.

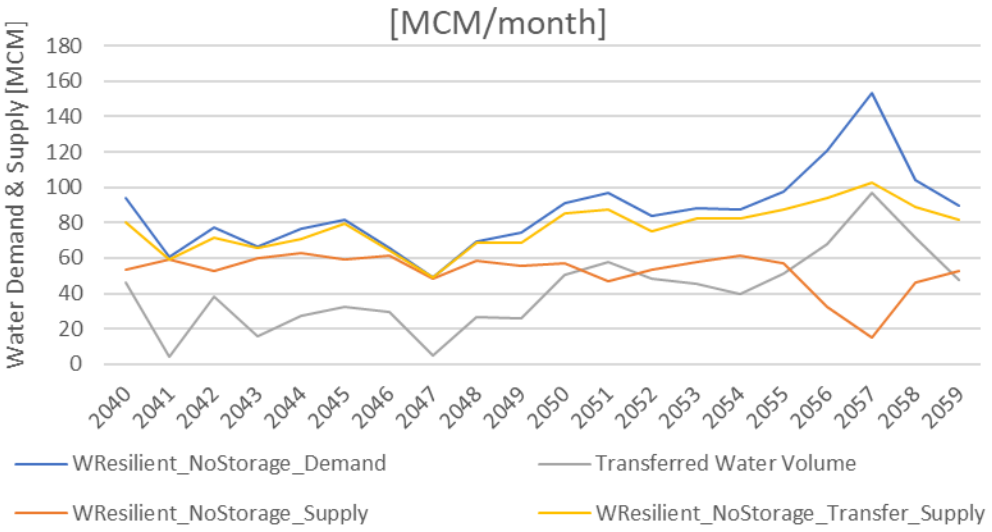

Figure 91. Annual totals for Water demand & Supply for Large Irrigation in NAKL_C for the WResilient_NoStorage scenario with and without a water transfer (option 6c). The annual totals for total diverted water are shown in grey.

Hence, as expected, for NAKL_C, as the receiving catchment, the transfer is highly beneficial. However,obviously, the water diverted to NAKL_C will no longer be available downstream of the diversion and therefore might evoke increased water stress downstream. There may be an impact on water users and uses that rely on water in the river's main stem. For NAKL, an important water user relying on water from the Akagera river are the wetlands. These systems are fed partially by water coming in directly from the river. Reduced flows due to the diversion may thus reduce the health of the wetlands. To what extent this impact will be significant needs to be studied separately. But as an indication, the recent catchment study on Lower Akagera (FutureWater, 2021)[1] indicated that demands for wetlands, which are an essential part of the Lower Akagera (NAKL) catchment, are about 419 MCM/year, most of these are situated below the diversion in catchments NAKL_A, NAKL_E, NAKL_F, and NAKL_G. The diverted flows (41 MCM) are about 10% of this amount.

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[1] FutureWater. 2021. Bio-Physical Assessment and Hydrological Analysis for Akagera Lower catchment – Final Report.

2.5 Prioritisation of strategic water resources infrastructures

2.5.1 Method to prioritise

Two main prioritisation scenarios have been established:

1. The first scenario *WResilient_Storage_FullPot* aims to generate an overall picture of how adding all potential active storage (making a total storage of 2,239 MCM) under an RCP 4.5 climate scenario, influences the water resources situation (see Table 65). From this analysis, a first prioritisation of the potential dam locations was applied, using the following criteria:
    a. a relative increase in coverage of more than 5% is realised at catchment level 2.5, to assume an error margin of about 2% and focuse on these catchments with the most significant increase in coverage; and
    b. a minimum absolute increased coverage of 2 MCM was obtained from added active storage, to eliminate potential dams for which the absolute change in coverage is insignificant.

2. These criteria resulted in a selection of 69 storage locations situated in 16 sub-catchments (2.5L). This scenario is referred to as *WResilient_Storage_Prio*. The 69 dams were ranked according to the *delta max supply delivered (MCM)*, which was defined as the supply delivered in the *WResilient_Storage_FullPot storage* scenario minus the supply delivered in the *WResilient_NoStorage* scenario; it serves as a proxy for the maximum annual supply provided by the added active storage during the 2040 – 2059 period.

3. Lastly, *WResilient_Storage_Val05*, *_Val1* and *_Val5* are scenarios studied in the sensitivity analysis presented in section 2.6. An overview of the WEAP simulations, some of which are analysed in this report, is presented in Table 65. Departure from the assumptions of the original model, established under SEI during the Hydro-Economic Analysis, for the three main scenarios discussed in this study (*WResilient_NoStorage*, *WResilient_Storage_FullPot* and *WResilient_Storage_Prio*) is presented in Table 66.

Table 65. Overview of scenarios modelled in WEAP

WEAP Scenario	Scenario Name Report	Description
Water Resilient		Based on: Water Resilient Vision 2050 Scenario as defined in the Hydro-Economic Analysis (SEI, 2021). No potential storage is accounted for except for secured/ planned dams which are: Nyabarongo II (846 MCM), Akanyaru (333 MCM), Muvumba (55 MCM) and Warufu (25 MCM).
Water Resilient45	WResilient_NoStorage	Based on Water Resilient with a projected climate data-set based on projections received by Meteo-Rwanda (2022) reprecentative for RCP4.5.
Water Resilient85		Based on Water Resilient with a projected climate data-set based on projections received

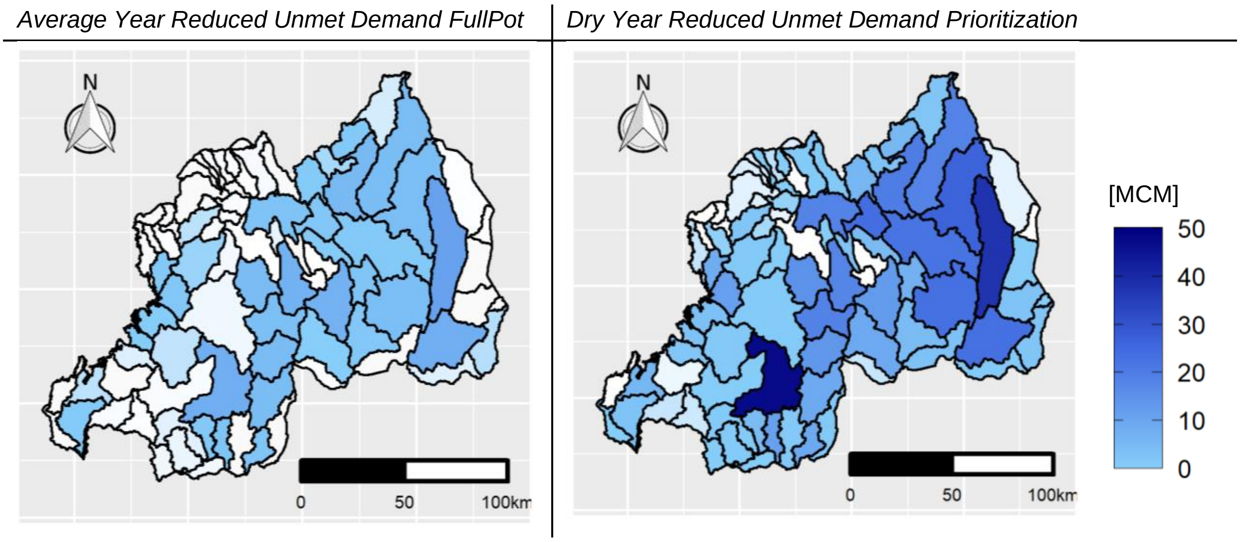
		by Meteo-Rwanda (2022) representative for RCP8.5.
WResilient_Storage_45_FullPot	WResilient_Storage_FullPot	Based on Water Resilient45, with an implementiation of all the potential storage locations (132), thereby assuming an OYASF of 3.0.
WResilient_Storage_45_Prio	WResilient_Storage_Prio	Based on WResilient_Storage_45_FullPot but with a representation on level 2.5 for the 69 prioritized dams. This is done to detect if the change from 132 to 69 dams has any major unexpected impacts.
WResilient_Storage_45_Val05	WResilient_Storage_Val05	Based on WResilient_Storage_45_FullPot with an implementiation of all the potential storage locations (132), thereby assuming an OYASF of 0.5. “Val” indicates this scenario is only used for the Sensitivity Analysis.
WResilient_Storage_45_Val1	WResilient_Storage_Val1	Based on WResilient_Storage_45_FullPot with an implementiation of all the potential storage locations (132), thereby assuming an OYASF of 1.0. “Val” indicates this scenario is only used for the Sensitivity Analysis.
WResilient_Storage_45_Val5	WResilient_Storage_Val5	Based on WResilient_Storage_45_FullPot with an implementiation of all the potential storage locations (132), thereby assuming an OYASF of 5.0. “Val” indicates this scenario is only used for the Sensitivity Analysis.
Water Resilient45_Transfer	WResilient_NoStorage_Transfer	Based on WResilient_NoStorage scenario with a water transfer (diversion) from Akagera to NAKL_C tributary with a max diversion rate of 3.6 cms from 2035 onwards.

Table 66. Main changes relevant to the scenario as applied in the WEAP model

Scenario Element	WResilient_NoStorage	WResilient_Storage_FullPot	WResilient_Storage_Prio
Storage	Existing Storage and Planned/ Secured Dam Locations: Nyabarongo II (846 MCM), Akanyaru (333 MCM), Muvumba (55 MCM) and Warufu (25 MCM).	A total of 132 dams were identified as potential at the onset of the prioritization analysis. Each of these dams were aggregated on catchment level 2.5.	Based on the delta coverage (>5%) and the delta absolute shortage (<-2 MCM), a selection of 69 potential dams in 16 level 2.5 subcatchments were identiefied.
Environmental Flow	30% of historical unimpaired flow, set as a fixed volume. Which is according international standards.	30% of historical unimpaired flow, set as a fixed volume. Which is according international standards.	30% of historical unimpaired flow, set as a fixed volume. Which is according international standards.
Demand Prioirities	Domestic has demand priority 1, Environmental flows 2, and all other sectoral demands as well as storage dams were assigned a priority of 3.	Domestic has demand priority 1, Environmental flows 2, and all other sectoral demands as well as storage dams were assigned a priority of 3.	Domestic has demand priority 1, Environmental flows 2, and all other sectoral demands as well as storage dams were assigned a priority of 3.

2.5.2 Results

Using the prioritisation method presented above, a list of 69 dams was obtained (Table 67). In addition to the prioritisation criteria, the maximum annual delta supply delivered for the period 2040 – 2059 was analysed to study the general max supply delivered, and thus the highest required active water storage requirement for a given year for each L2.5 sub-catchment. With these estimates, the list of prioritised dams was subsequently ranked by ordering the sub-catchments for this parameter from highest to lowest. Figure 92 shows the obtained delta max supply delivered estimates for each of the 86 level 2.5 sub-catchments, based on the *WResilient_Storage_FullPot* scenario.


Average Year Reduced Unmet Demand FullPot

Dry Year Reduced Unmet Demand Prioritization

Figure 92. Reduced Unmet Demand (FullPot) for a dry year calculated by subtracting the sum of sectoral supply for *WResilient_NoStorage* from the *WResilient_Storage_FullPot* scenario, estimated over the 2040 – 2059 period for RCP 4.5.

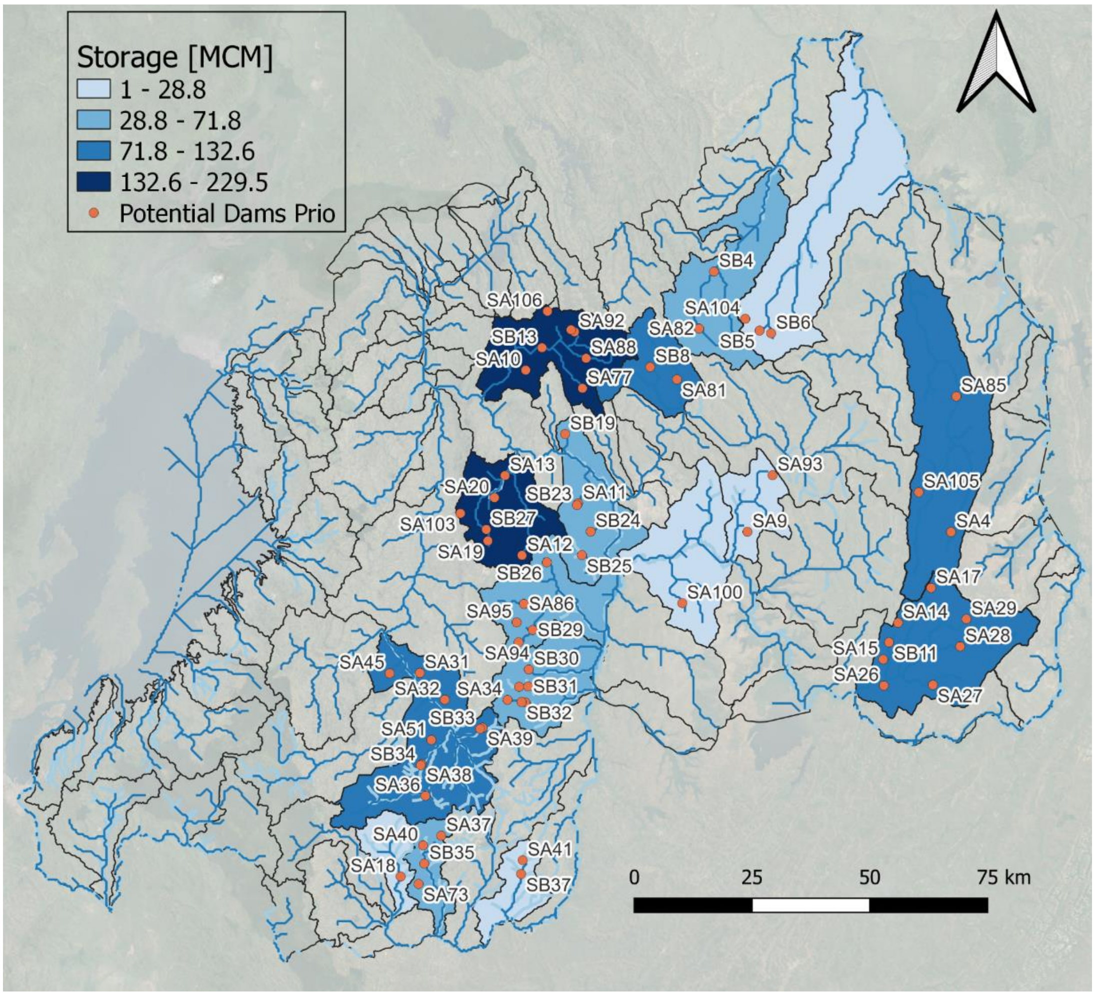


Figure 93. Map with an overview of the prioritized storage locations as identified by the *WResilient_Storage_Prio* scenario (RCP 4.5, 2040 - 2059).

Table 67. List of 69 prioritised storage locations situated within 16 sub-catchments.

Rank	*Potential Dams Locations*	*ID Code*	*Flooded Area [ha]*	*Max Height [m]*	*Max physical active storage (80%) [MCM]*	*Mean Annual Inflow (MAI) (WEAP) [MCM]*	*Over Year Active Storage (OYAS) [3]*	*Model Active Storage [MCM]*	*Delta Max Supply Delivered MCM*
1	NAKL_C	SA105	136	395	214.5	0.7	2.1	2.1	41.6
1	NAKL_C	SA4	1331	80	425.9	4.7	14.1	14.1	41.6
1	NAKL_C	SA85	7317	50	1,463.4	38.8	116.4	116.4	41.6
2	NMUV_C	SA82	223	35	31.3	11.8	35.4	31.3	38.7
2	NMUV_C	SB4	1751	205	1,435.5	13.5	40.5	40.5	38.7
3	NNYU_F	SB34	30	60	7.3	0.1	0.3	0.3	28.6
3	NNYU_F	SA31	74	70	20.6	2.9	8.7	8.7	28.6
3	NNYU_F	SB33	129	50	25.9	0.8	2.4	2.4	28.6
3	NNYU_F	SA39	221	40	35.4	3.1	9.3	9.3	28.6
3	NNYU_F	SA38	220	55	48.4	3.1	9.3	9.3	28.6
3	NNYU_F	SA45	224	60	53.8	6.2	18.6	18.6	28.6
3	NNYU_F	SA51	300	80	95.9	3.2	9.6	9.6	28.6
3	NNYU_F	SA36	413	80	132.1	3.8	11.4	11.4	28.6
3	NNYU_F	SA32	538	70	150.7	4.0	12.0	12.0	28.6
4	NAKL_B	SA104	33	40	5.2	0.5	1.5	1.5	25.3
4	NAKL_B	SB6	592	55	130.2	4.6	13.8	13.8	25.3
4	NAKL_B	SB5	811	100	324.2	3.7	11.1	11.1	25.3
5	NNYL_K	SA92	30	90	10.8	0.2	0.6	0.6	25.1
5	NNYL_K	SB15	91	65	23.6	3.0	9.0	9.0	25.1
5	NNYL_K	SB12	110	70	30.9	3.4	10.2	10.2	25.1
5	NNYL_K	SA77	247	40	39.5	5.9	17.7	17.7	25.1
5	NNYL_K	SA10	161	75	48.3	1.3	3.9	3.9	25.1
5	NNYL_K	SA106	95	155	59.0	0.7	2.1	2.1	25.1
5	NNYL_K	SB13	2083	90	749.9	45.2	135.6	135.6	25.1
5	NNYL_K	SA88	2317	120	1,112.3	16.8	50.4	50.4	25.1
6	NAKU_B	SA27	89	55	19.7	2.4	7.2	7.2	22.2
6	NAKU_B	SB11	186	60	44.5	1.7	5.1	5.1	22.2
6	NAKU_B	SA15	233	80	74.6	2.2	6.6	6.6	22.2
6	NAKU_B	SA14	389	90	139.9	1.8	5.4	5.4	22.2
6	NAKU_B	SA17	510	80	163.1	2.0	6.0	6.0	22.2
6	NAKU_B	SA26	1082	95	411.1	3.5	10.5	10.5	22.2
6	NAKU_B	SA29	781	150	468.7	3.2	9.6	9.6	22.2
6	NAKU_B	SA28	2368	90	852.5	20.7	62.1	62.1	22.2
7	NNYL_J	SA103	13	65	3.4	0.2	0.6	0.6	15.8
7	NNYL_J	SA20	91	75	27.4	6.9	20.7	20.7	15.8
7	NNYL_J	SB28	183	40	29.2	2.3	6.9	6.9	15.8
7	NNYL_J	SA12	223	45	40.1	3.4	10.2	10.2	15.8
7	NNYL_J	SA19	500	60	120.0	4.9	14.7	14.7	15.8
7	NNYL_J	SB22	719	65	186.9	7.0	21.0	21.0	15.8
7	NNYL_J	SB27	916	85	311.6	6.9	20.7	20.7	15.8
7	NNYL_J	SA13	1097	130	570.4	28.5	85.5	85.5	15.8
8	NAKN_A	SB26	75	40	11.9	5.3	15.9	11.9	15.6
8	NAKN_A	SA86	114	55	25.1	9.1	27.3	25.1	15.6
8	NAKN_A	SA94	197	45	35.4	1.5	4.5	4.5	15.6

8	*NAKN_A*	*SA95*	*219*	*60*	*52.6*	*2.6*	*7.8*	*7.8*	*15.6*
8	NAKN_A	SB29	518	45	93.2	4.6	13.8	13.8	15.6
9	NNYL_E	SB8	141	60	33.8	5.6	16.8	16.8	15.6
9	NNYL_E	SA81	941	150	564.4	28.4	85.2	85.2	15.6
10	NNYL_G	SA11	115	50	22.9	1.0	3.0	3.0	15.4
10	NNYL_G	SB19	232	85	78.9	3.2	9.6	9.6	15.4
10	NNYL_G	SB25	369	75	110.6	4.5	13.5	13.5	15.4
10	NNYL_G	SB23	274	120	131.7	0.9	2.7	2.7	15.4
10	NNYL_G	SB24	531	110	233.6	2.7	8.1	8.1	15.4
11	NAKN_C	SA96	95	55	20.8	0.3	0.9	0.9	13.5
11	NAKN_C	SB32	136	40	21.7	4.0	12.0	12.0	13.5
11	NAKN_C	SA35	159	50	31.8	3.3	9.9	9.9	13.5
11	NAKN_C	SB30	283	55	62.2	4.6	13.8	13.8	13.5
11	NAKN_C	SA34	183	85	62.3	1.4	4.2	4.2	13.5
11	NAKN_C	SB31	285	75	85.5	1.5	4.5	4.5	13.5
12	NAKU_G	SA100	857	50	171.4	7.1	21.3	21.3	11.4
13	NAKN_I	SA73	138	50	27.6	2.5	7.5	7.5	9.1
13	NAKN_I	SB35	272	50	54.3	10.7	32.1	32.1	9.1
13	NAKN_I	SA40	206	70	57.7	3.2	9.6	9.6	9.1
13	NAKN_I	SA37	247	70	69.1	3.0	9.0	9.0	9.1
14	NAKN_G	SB37	259	40	41.4	6.3	18.9	18.9	7.7
14	NAKN_G	SA41	396	70	111.0	3.3	9.9	9.9	7.7
15	NAKU_F	SA9	145	55	31.8	2.5	7.5	7.5	7.0
15	NAKU_F	SA93	430	95	163.4	3.0	9.0	9.0	7.0
16	NAKN_K	SA18	129	35	18.1	1.8	5.4	5.4	4.9

Subsequently, the 69 prioritised storage reservoirs obtained from the 132 potential dams, were modelled as a separate run to detect how the prioritisation compares to the *WResilient_Storage_FullPot* scenario. Table 68 shows an overview of the change in Unmet Demand (MCM), at national level, for the *WResilient_Storage_FullPot* to *WResilient_Storage_Prio* scenarios. It shows that after the prioritization, the total reduction in unmet demand is still significant indicating that the level 2.5 subcatchments with the highest reduction in unmet demand retain their impact after prioritization. Table 68 shows that during a dry year , the difference between both scenarios is about 15% whereas for an average year the difference drops to about a 30% decrease.In addition, the scatterplot presented in Figure 94, shows that only two sub-catchments have a coverage [%] that is significantly affected from this prioritisation, namely, CKIV_H and NNYL_B, for which the change is actually a significant positive increase. On the contrary, the negative change in coverage [%] obtained after prioritisation is for sub-catchments NNYL_I, NMUV_D and CKIV_B (all less than 7% change). Hence, the change in coverage of total demand (%) is limited at level 2.5 when implementing the 69 prioritised dams instead of all the 132 potential dams and it is concluded that the prioritised dams still tackle the major water deficits observed in Rwanda.

Table 68. Differences in Reduced Unmet Demand for a Dry and Average year under RCP 4.5 for both the WResilient_Storafe_45_FullPot and WResilient_Storage_45_Prio scenario.

National Level Reduced Unmet Demand [MCM]	*Dry Year*	*Average Year*
WResilient_Storage_FullPot	473	95
WResilient_Storage_Prio	400	63

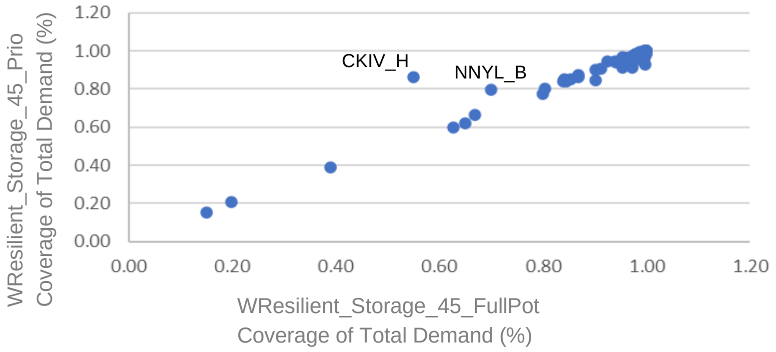


Figure 94. Comparison scatter plot for coverage [%] of demands for both WResilient_Storage_FullPot and WResilient_Storage_Prio.

The last parameter analysed to compare the effect of the prioritisation is the change in maximum supply delivered, as a proxy for estimating the maximum supply delivered at L2.5 under a the RCP 4.5 climate scenario. This parameter is to explore the maximum benefit of new infrastructures, i.e., in times when most needed, such as during dry years. Figure 95 shows the obtained delta max supply delivered [MCM] for *WResilient_Storage_Prio* as opposed to the *WResilient_NoStorage* scenario.

Average Year Reduced Unmet Demand Prioritization	*Dry Year Reduced Unmet Demand Prioritization*

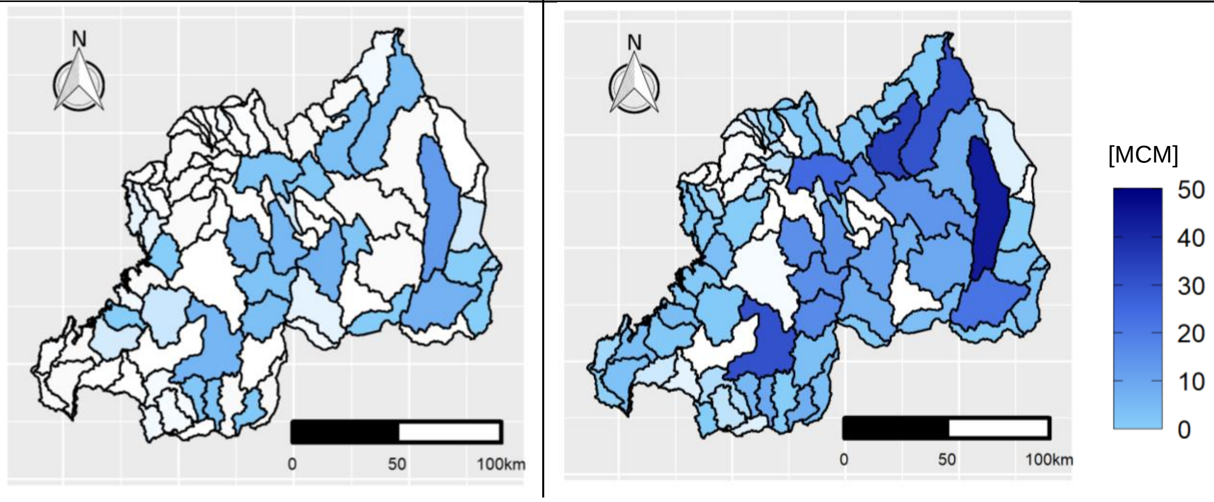


Figure 95. Reduced Unmet Demand (prio) for a dry year calculated by subtracting the sum of sectoral supply for WResilient_NoStorage from the WResilient_Storage_Prio scenario, estimated over the 2040 – 2059 period for RCP 4.5.

2.6 Sensitivity analysis

To conduct a sensitivity analysis on the WEAP potential dam prioritisation analysis, the over-year active storage factor (OYASF) was varied with increments of 2, i.e., 1.0, 5.0 were applied to the *WResilient_Storage_FullPot* run given that previous chapters assumed an OYASF of 3.0 (Annexe 10). Each run was studied solely for the RCP 4.5 scenario, as Table 54 (p119) shows that there is only minor variation between RCP 4.5 and RCP 8.5, and given the latter is assumed not relevant as a business-as-usual scenario (Hausfather & Peters, 2020)[1]). In addition, a run with an OYASF of 0.5 was added

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[1] Hausfather, Z., & Peters, G. P. (2020). Emissions–the 'business as usual'story is misleading.

(*WResilient_Stroage_4.5_Val05*) to detect the impact of further reducing the added active storage in the model.

Figure 96 shows on national level for Rwanda how potential active storage [MCM] relates to the incremental increase in max delta supply delivered [MCM]. As seen from the graph, under varying OYASF, the added storage increases linearly while the delta max supply delivered increases less rapidly. The latter is 0 if no additional storage is added, and 351 MCM if the OYASF is equal to five (and the added storage is equal to 3731 MCM). Hence it shows the added supply per increment of added storage and indicates that adding significantly more storage does not result in significantly more added supply delivered on national level.

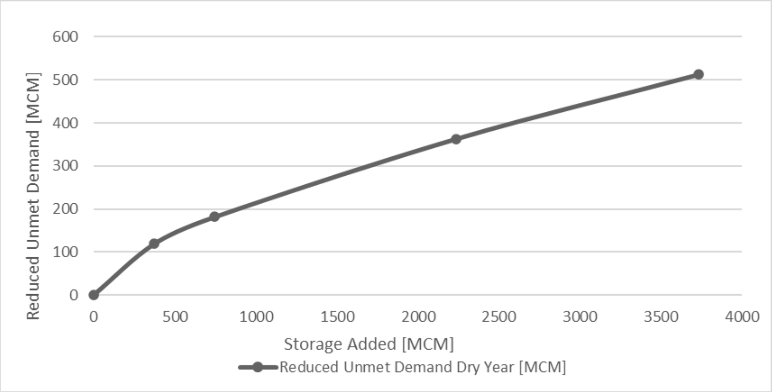

Figure 96. National impact of varying OYASF factors obtained from WResilient_Storage_FullPot run.

However, within level 1 (Figure 97), different responses to increased potential storage are noticeable. On level 1, the impact of extra storage on max supply delivered (delta, MCM) is most pronounced for NNYL, NAKN, NMUV and NAKL, which are all catchments prioritised in the analysis. NMUK and CRUS, in contrast, show the least change from adding additional storage, which is explained by the low number of potential dams in these level 1 catchments (Figure 84, p128). Focusing on the incremental change between different levels of added storage (MCM), one can see that between an OYASF of 0 and 0.5 the effect of additional storage results in a steeper increase of delta max supply delivered [MCM] when compared to the subsequent interval between 0.5 and 5. This trend is for all level 1 catchments, but CKIV which shows a negative impact for an over-year active storage factor between 3.0 and 5.0.

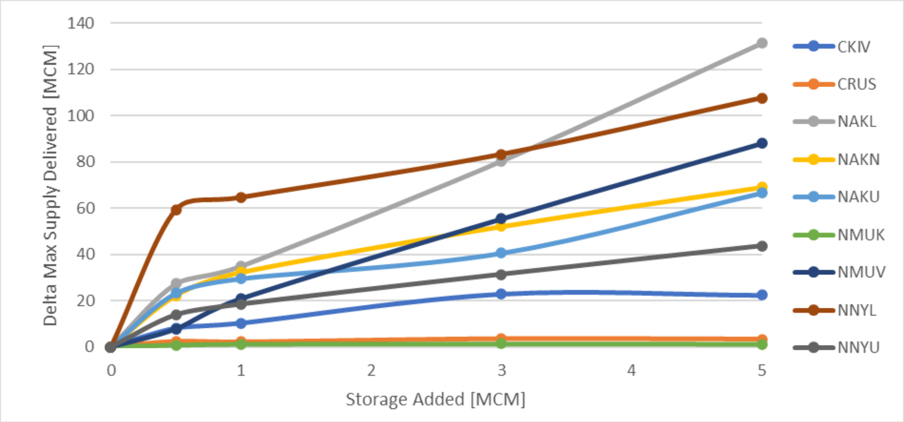

Figure 97. Sensitivity Analysis for varying OYASF factors of 0, 0.5, 1.0, 3.0 and 5.0 for each level 1 catchment under an RCP 4.5 climate averaged for 2040 – 2059.

Hence from this Sensitivity Analysis it can be concluded that, in essence, adding storage capacity will only show changes in the model if sufficient water is available to fill the dam and if there is a certain degree of scarcity. For regions where the water scarcity is minimal, or where streamflow is not enough to fill a dam, the model will not show sensitivity to changes in the OYASF, and thus to changes in storage capacity which is the main focus of this study.

Also it can be seen, that the model output (i.e. delta supply) is very sensitive for values of this parameter below more or less a value 1, whereas the response of the analysis is roughly linear with the additional storage; while for values of around three the system does not respond that strongly as it reaches its saturation point: additional storage has still an effect, but given the hydrological variability and the dynamic water balance of the reservoirs, an increment in storage does not yield a similar increase in beneficial reduced shortage. In other words, the value taken for this analysis as upper bound (3) is appropriate.

2.7 Assessment of legal and capacity needs to implement the water allocation plan

The current legal framework for water resources management in Rwanda provides enough guidance on how to allocate water resources and implement a water permitting system. Law No 49/2018 of the 13th August 2018, which determines the use and management of water resources in Rwanda, provides for the need to allocate water resources to various needs under its article 19 and highlights the priority to be followed during the allocation process: first priority should be domestic water supply, followed by environmental protection and lastly economic activities.

Article 21 of the same law provides for the types of activities subject to a water use permit. These are those susceptible to modifying the flow, or water level, to degrade their quality or threaten water-related ecosystems. The law provides for a Ministerial Order that shall establish the list of specific activities that should be subject to a water use permit and determine conditions and procedures for acquiring a water use permit. A draft Ministerial Order has been elaborated and is awaiting approval. Once this Ministerial is published, the current legal framework could be considered sufficient and could be updated in the future if needs arise. The focus should now be on enforcing the provisions under the current law as people wait for the Ministerial Order to be approved.

Regarding the capacity needs for water resources allocation, RWB has adopted the WEAP software. This tool has been used over the last five years, starting with the development of the first batch of catchment plans in 2016. The advantage of the selected software is that it is free of charge for users in developing countries working with either public institutions or non-profit organizations. However, the capacity to use the software is still low, not only within the mandated institution for water resources allocation but also within the wider community of water experts.

Therefore, it is recommended to put in place a continuous learning program on the use of WEAP. This should target not only relevant staff within RWB but also a larger group of young water professionals so that the country can have a large pool of water experts mastering the software. This could be a kind of a “WEAP Community of Practice in Rwanda”.

RWB can coordinate this community of practice through the division in charge of water resources allocation and, when needed, can seek support from specialized entities or experts.

3 Strategic Water Resources Conservation and Development

3.1 Technical appraisal of prioritised strategic water resources development infrastructures

The current assessment of potential artificial storage development in Rwanda focused on analysing potential sites, previously identified and validated in the 2015 National Water Resources Master Plan. The technical appraisal was closely coordinated with the prioritisation conducted using WEAP modelling (Task 2).

3.1.1 Assessment approach

The technical appraisal was conducted in three different steps:

1. Identify and characterise all the potential new dam projects, leading to 132 projects.
2. Run a first prioritisation using the WEAP model, narrowing to 69 sites.
3. Run a second prioritisation to refine the list of prioritised infrastructures, leading to 39 prioritised sites.

This section presents steps 1 and 3, while step 2 was presented earlier in sections 2.4 (p126) and 2.4.3 (p134).

3.1.1.1 Identification of all potential new dam projects

The assessment is a spatially-based assessment of identified sites, with potential artificial storage development, and their geomorphological characterisation. The parameters analysed for this assessment ranged from site location, targeted stream classification, site elevation and shape, potential site upstream catchment and inundation areas and its associated soil, geology, lithology, land use land cover and soil erosion risk.

This assessment is very vital for the next phases of analysis. The rationale for conducting above analysis is provided in Table 69. Hydraulic characteristics were estimated for each dam. These include the dam height, catchment area, flooded area, physical storage capacity as well as the estimated cost for each dam. It should be noted that potential dams located at the run-of-river hydroelectricity were not considered as priority dams.

Table 69: Rationale of analysed site parameters

Parameter	Rationale
Catchment size	The catchment size indicates how much water can be potentially drained to the selected site for storage. Larger catchments have a high potential for runoff generation.
Slope	Slope information provides the following information: • The slope indicates how feasible will the dam axis be at the proposed site. The steeper and narrow the proposed site is, the better for the dam axis and construction requirement. • In the upstream catchment area, slope indicates the sensitivity of the area to soil erosion and landslide that can potentially affect the reservoir capacity and anticipated benefits from the proposed site.

Parameter	Rationale
Geology	Geological information indicates the status of the soil parent materials in the area. For the proposed dam site, this information is crucial for assessing the foundation requirement at the proposed site. For the inundation area of the dam, geology can help supplement the understanding of the water holding capacity of the reservoir.
Soil type	Soil information is also very useful as it describes the mechanical properties of the soil at the proposed site and the inundation area. This information is most of the time used in complementarity with geological information, to understand the nature of infiltration and permeability of the area, which regulates the amount of water lost in the reservoir.
Land cover/ land use	Information on land cover and land use provide indications on: • The potential impacts of developing the proposed site, especially looking at the inundation area and the land to be affected. • The upstream catchment landscape condition, which can either be degraded or not. Degraded landscape mostly indicates high soil erosion and landslide potential with potential impact on the reservoir.
Site accessibility	Information on the accessibility of the proposed sites is related to the availability of roads in the vicinity of the site. This information is useful in terms of construction cost requirements and economic connectivity of the beneficiaries.

A database was prepared by crossing GIS information, providing the values of several parameters, the location, inundated areas, lithology, erosion risk and potential restoration measures.

The previous assessment conducted during the development of the first national water resources masterplan[1] identified 143 potential sites (Figure 98). Out of these sites, several of them have been developed while others are in development.

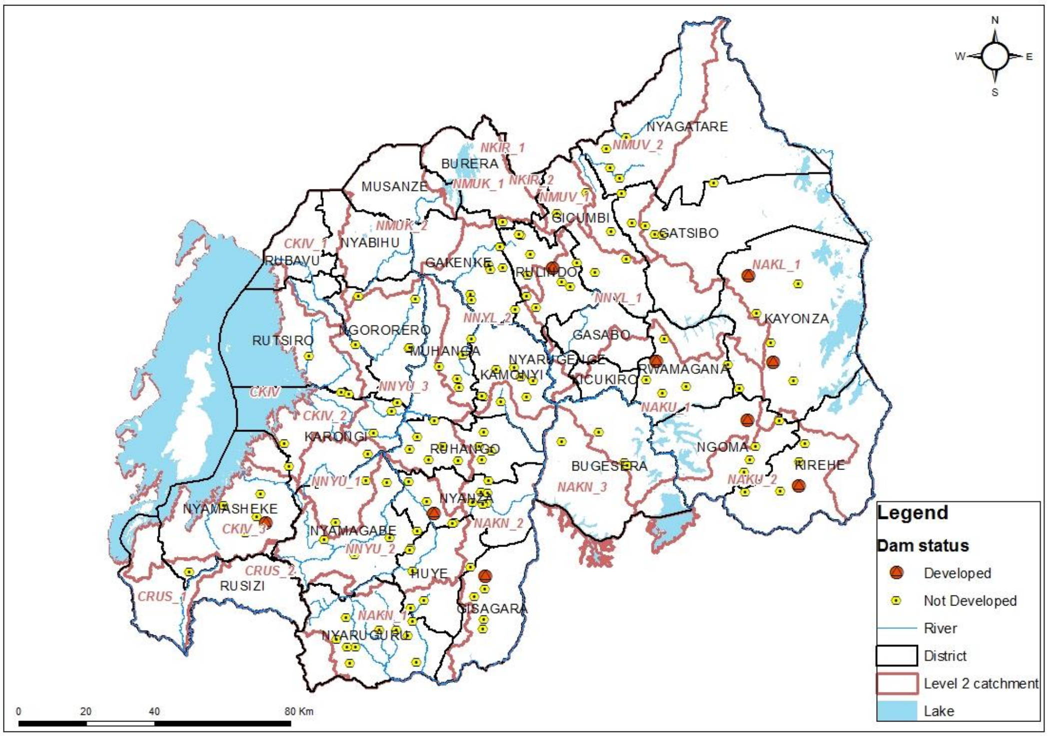

Figure 98: Identified dam sites in the 2015 water resources masterplan[2].

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[1] RNRA, 'Rwanda National Water Resources Master Plan' (Kigali, Rwanda: Rwanda Natural Resources Authority, 2015).
[2] Ibid.

Eventually, a total of 132 dams have been identified as potential. The distribution of these sites is such that some areas in the country have more sites than others (Figure 99). Out of the nine Level 1 catchments, Mukungwa and Rusizi catchments have the least number of potential sites; while Akanyaru, Nyabarongo Upper and Nyabarongo lower had the highest number of identified potential sites (more than 30 sites). Also, the distribution of potential sites per district is such that out of 30 districts, only 25 have potential sites identified. From the 25 districts, Kamonyi, Nyaruguru, Nyanza, Ruhango and Rulindo have the highest number of potential sites. Burera and Karongi have the least number of sites.

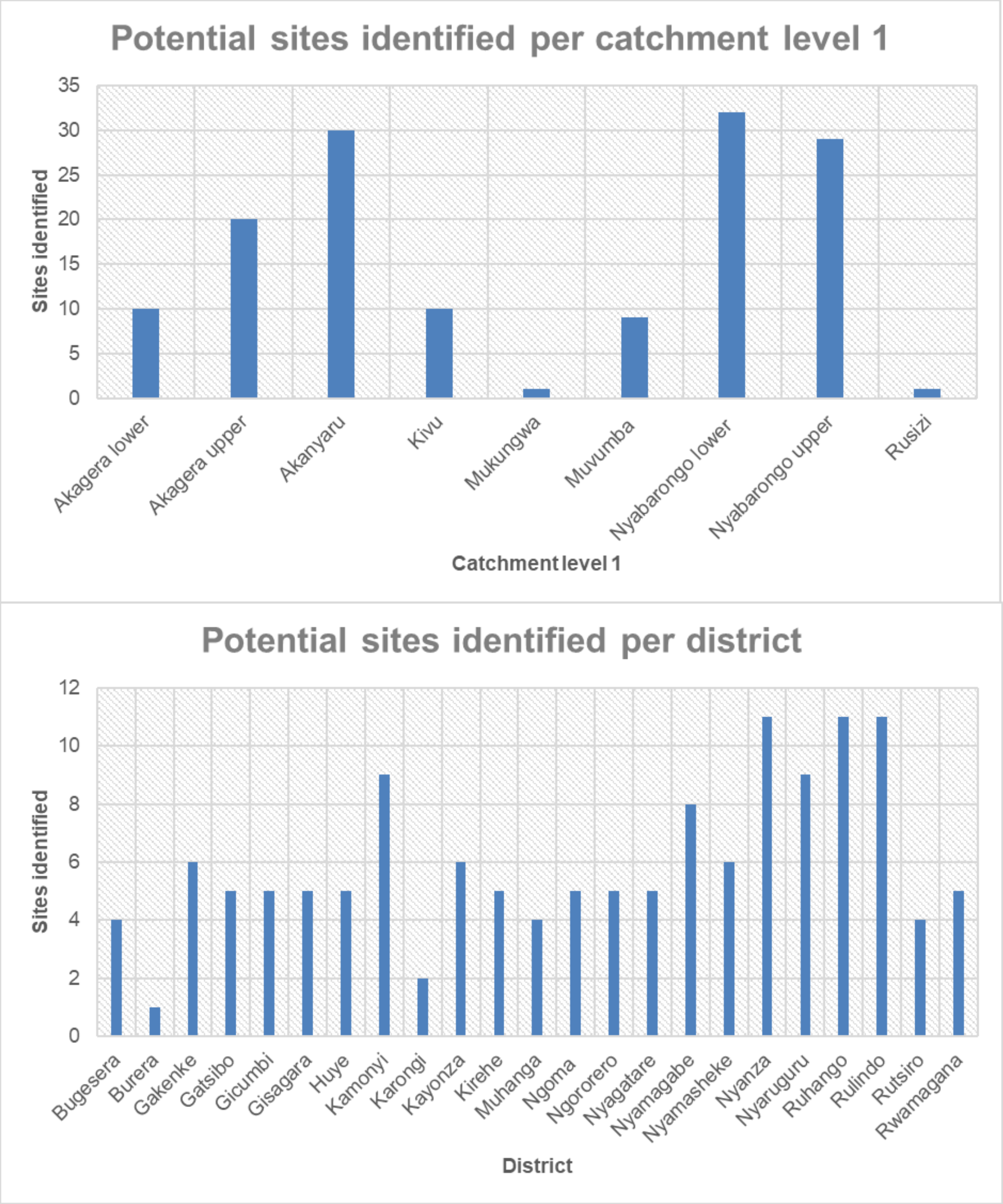

Figure 99: Distribution of identified potential sites.

3.1.1.2 *Second prioritisation*

This second round of prioritisation was another element of the technical appraisal. It is a spatial assessment of the sites identified in Task 2, where potential artificial storage development was assessed based on their strategic use, geomorphological and geospatial characterisation. The parameters analysed for this assessment ranged from site location, targeted stream classification, site elevation and shape, potential site upstream catchment and inundation areas and its associated soil, geology, lithology, land use land cover and soil erosion risk. Please see Annexe 11 for a summary of the field visits.

The elevations of the proposed sites and their shapes were estimated from field observations. All the proposed sites are V-shaped and their widths were analysed for different heights starting from 5m up to 70m. Using topographic information provided by the national 10 m Digital Elevation Model (DEM) for each identified site, the upstream catchment was delineated using the hydro-processing approach described by Maathuis and Wang (2006)[1]. The inundation area was estimated using spatial analyst tools provided in ArcGIS software.

The geomorphology of delineated upstream catchment areas of each site and inundation area was assessed using the existing database of soil type[2], geology[3], lithology[4], land use land cover[5] and soil erosion risk[6]. From the list of 132 potential new dams, 69 remained after the first round of prioritisation in Task 2 (see section 2.4.3, p134). As depicted in Figure 100, Nyabarongo lower has the greatest number of dam sites, followed by Akanyaru, Akagera upper, Nyabarongo upper, Akagera lower and Muvumba catchment. Kivu, Mukungwa and Rusizi have no potential prioritised sites.

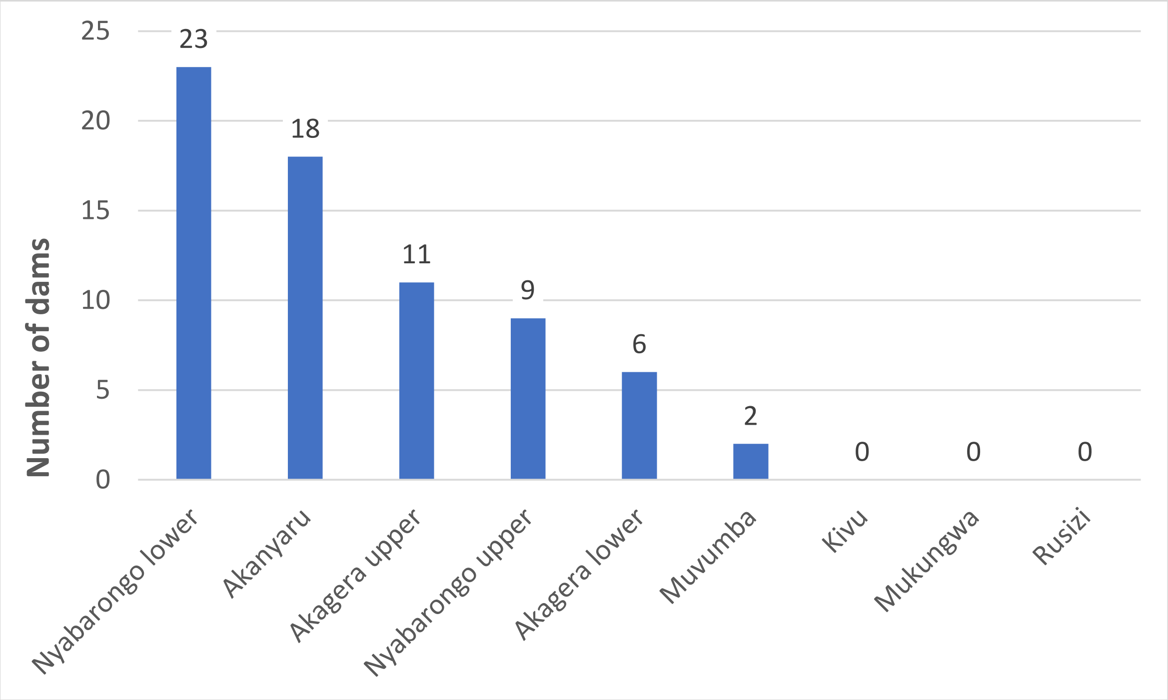

Figure 100: Distribution across the catchments of the 69 potential prioritised sites (after modelling).

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[1] Maathuis, B. H. P., & Wang, L. (2006). Digital Elevation Model Based Hydro-processing. *Geocarto International, 21*(1), 21-26. doi:10.1080/10106040608542370

[2] E Birasa et al., ‘Carte Pédologique Du Rwanda’ (Kigali, Rwanda: MINAGRI, 1990).

[3] K Theunissen, M Hanon, and M Fernandez, ‘Carte Géologique de Rwanda’ (Musee Royal de l’Afrique Centrale, 1991).

[4] RNRA, ‘Rwanda National Water Resources Master Plan’.

[5] RLMUA, ‘Land Use Land Cover Map of Rwanda’ (Kigali, Rwanda: Rwanda Land Use and Management Authority, 2018).

[6] MoE, ‘Erosion Control Mapping Report’ (Kigali, Rwanda: Ministry of Environment, 2020).

The next exercise was to effect the second level of prioritisation by employing the following parameters compiled in Table 70 below.

Table 70: Rationale for further prioritisation

Parameter	Rationale
Potential use per (Water supply, irrigation and hydropower plant)	● Step 1: The shapefile of the 70 prioritised dams were overlaid on level 2.5 catchments and their coordinates were recorded for site assessment. ● Step 2: Aided by GIS tool, potential & existing irrigation command areas from the Irrigation Master Plan of 2020, potential water sources for domestic water supply from the National Water Supply Master Plan (draft of 2022), and potential & existing hydropower plants from REG were overlaid to assess the need and suitability of every potential dam site.
Catchment size	The catchment's size indicates how much water can be potentially drained to the selected site for storage. Larger catchments have high potential for runoff generation.
Slope	Slope information provided the following information: ● At the site, slope indicates how feasible will the dam axis be at the proposed site. The steeper and narrow the proposed site is, the better for the dam axis and construction requirement. ● In the upstream catchment area, slope indicates the sensitivity of the area to soil erosion and landslide that can potentially affect the reservoir capacity and anticipated benefits.
Geology	● Geological information provided indication on the status of the soil parent materials in the area. This information is crucial for assessing the foundation requirement at the proposed site. Regarding the inundation area, geology can help supplement the understanding of the water holding capacity of the reservoir. ● The main geological considerations for a prioritised dam site are: (a) the underlying rocks must have enough strength to withstand the dam's weight and the resultant thrust. (b) rocks should be impervious to prevent water leakage beneath the dam's sole. ● Priority has been given to sites with geological formation dominated by rocks (granites, quartzite and schist) and avoiding as much as possible alluvial materials and shales. The secondary geological and lithological data used have been collected at RWB.
Soil type and Soil Erosion Risk	● Soil information describes the mechanical properties of the soil at the proposed site and the inundation area. This information is mostly used in complementarity with geological information, to assess infiltration and permeability, and therefore the amount of water lost in the reservoir. ● Identified potential dam sites are free from harmful salts as per the geology information of the area. ● The potential dam areas have been located in areas with moderate levels of soil erodibility as generated by CROM DSS by RWB (Figure 16, p50). This is to minimise the level of eroded materials that could be carried in the reservoir and affect its life span.

Parameter	Rationale
Land cover/ land use	Information on land cover and land use provide indications on: ● The potential impacts of developing the proposed site, especially looking at the inundation area and the land affected. ● The upstream catchment landscape condition, which can either degraded or not. Degraded landscape mostly indicates high soil erosion and landslide potential with potential impact on the reservoir. ● Priority dams have been located in areas dominated by bare soil, sparse forest and agricultural (perennial), as represented in Figure 15, p48. ● Potential reservoir should not submerge habited areas, fertile lands or developed agricultural lands.
Site accessibility	Information on the accessibility of the proposed sites is related to the proximity to roads. This information is useful regarding construction cost requirements, on the one hand, and economic connectivity of the beneficiaries, on the other hand. While assessing these potential dams, site visits for unknown dams was conducted.
Evaporation (deep or shallow reservoir)	Reservoirs with a narrow but deep inundated area are preferred, as opposed to wide but shallow reservoirs, to minimise the evaporation from the reservoir. The area-volume relationship method has been utilised to this end (see Annexe 10).
Lithology	● The lithological characteristics of selected dam sites and catchment areas are dominated by: ○ Semi-permeable fractured aquifer (schist, mica and quartzite), ○ Low permeable fractured aquifer (schist and micaschist), ○ Fractured aquifer (granite and gneiss), ○ Permeable fractured aquifer (quartzite on schist base), ○ Complex aquifer (volcanic rock), ○ Alluvial aquifers, ○ Organo-sedimentary alluvial aquifer (low permeability, clay base), and ○ Peat ● Potential dam sites located in areas with the following lithology were given priority: fractured aquifer, low permeable fractured aquifer, semi-permeable fractured aquifer and alluvial aquifers. Conversely, little interest has been given to complex aquifer, organo-sedimentary alluvial aquifer and lastly, peat.
Downstream/upstream	In case of potential dams located on the same river, the dam with the greatest storage and serving the biggest potential uses downstream was selected.

Besides the criteria presented above, a final selection was conducted and resulted in additional dams, to cover the deficit in the water-scarce catchments; this is the case for the dam SA27 in Upper Akagera. Another critical area considered is the floods, resulting in sediment transport and deposition in most major rivers of Rwanda. During the stakeholder consultations for chapter 4 (see sub-section 4.1.1, p201), the RWB suggested planning at least four regulatory dams on rivers with high sediment loads. Therefore, four additional regulatory dams were identified through a further consultation process. One was proposed on Rubagabaga River, upstream of the existing Rubagabaga HP, another on Giciye river, upstream of Giciye HP cascades, a third upstream Nyabarongo 1 HP and the last on Satinstyi river (SB20). In addition to protect the downstream users of water resources against sedimentation, the regulatory dams will contain the migration of rare and endangered species into HP plants. These regulatory dams are meant for trapping sediments and not for storage, which is why the heights proposed for these reservoirs are rather limited and, therefore, the storage capacity. Another factor limiting their height is to avoid flooding existing infrastructures (district roads, schools and other infrastructures). For the Mukungwa catchments, a height of less than 10m was considered, and for the Nyabarongo catchment a height of less than 15m.

The dams on Rubagabaga and Giciye rivers have storage smaller than 1 MCM. Finally, the sites of the regulatory dams do not portray potential use as per existing water use master plans.

Finally, a total of 39 dams were selected at the end of the second prioritization. In relation to the Strategic water storage plan presented in Chapter 4 (see section 4.1, p201), the dams were prioritised in a sequencing manner where five, ten and twenty-four are planned to be completed by 2030, 2035 and 2050, respectively.

3.1.1.3 *Cost assessment*

The cost estimation was based on the experience of constructing the six existing dams and those with completed feasibility studies (Muyanza, Nyanza, Sebeya, Rwamagana 34, Kayonza 4, Muvumba, Kagitumba "Concrete Gravity Dam, and Upper Rubavu).

Cost metrics reflect variables such as dam site, terrain characteristics and catchment areas and materials to be used for the construction; it has been realised that the dam cost is proportionally dependent on these variables. The equation shown in Figure 101Figure 101 was used to approximate the cost. The estimated cost covers the storage and related infrastructures and other services, including study and supervision. It is emphasised that these costs might not be exact and give an indication for resource mobilisation.

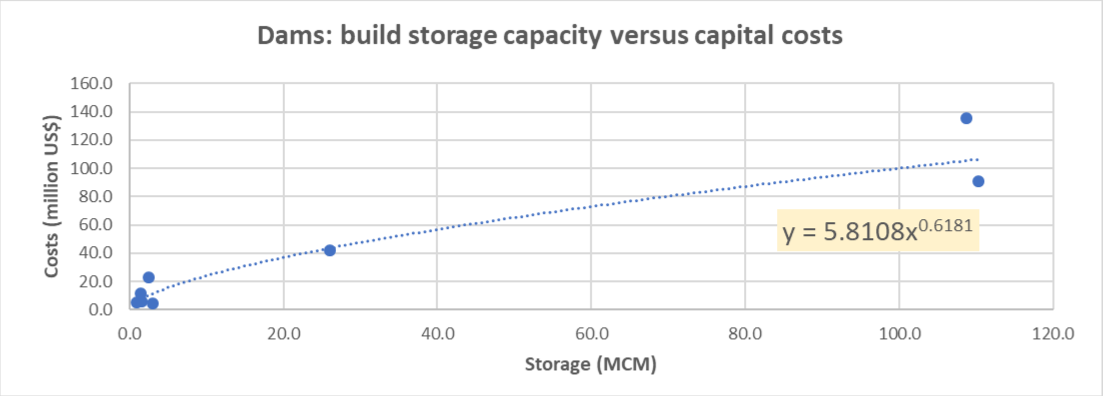

Figure 101: Equation used to assess the cost.

3.1.2 Description of the prioritised sites

A total of 39 dams were selected at the end of the second prioritisation, which includes four regulatory dams (upstream in Nyabarongo, SB20, on Rubagabaga river and on Giciye river). These dams are ranked as per their potential, considering the parameters described in Table 70. Please refer to Annexe 11 for the details on these dams.

3.1.2.1 *Location of the 39 prioritised dams*

The distribution of the identified sites is irregular across the level 1 catchments (see figures below). Of the nine level 1 catchments Rusizi have no dams; while Akanyaru, Nyabarongo Upper and Nyabarongo lower have the highest number of sites (more than 30 sites). Kamonyi, Nyaruguru, Nyanza, Ruhango and Rulindo districts have the highest number of identified sites; Burera and Karongi had the least number of sites.

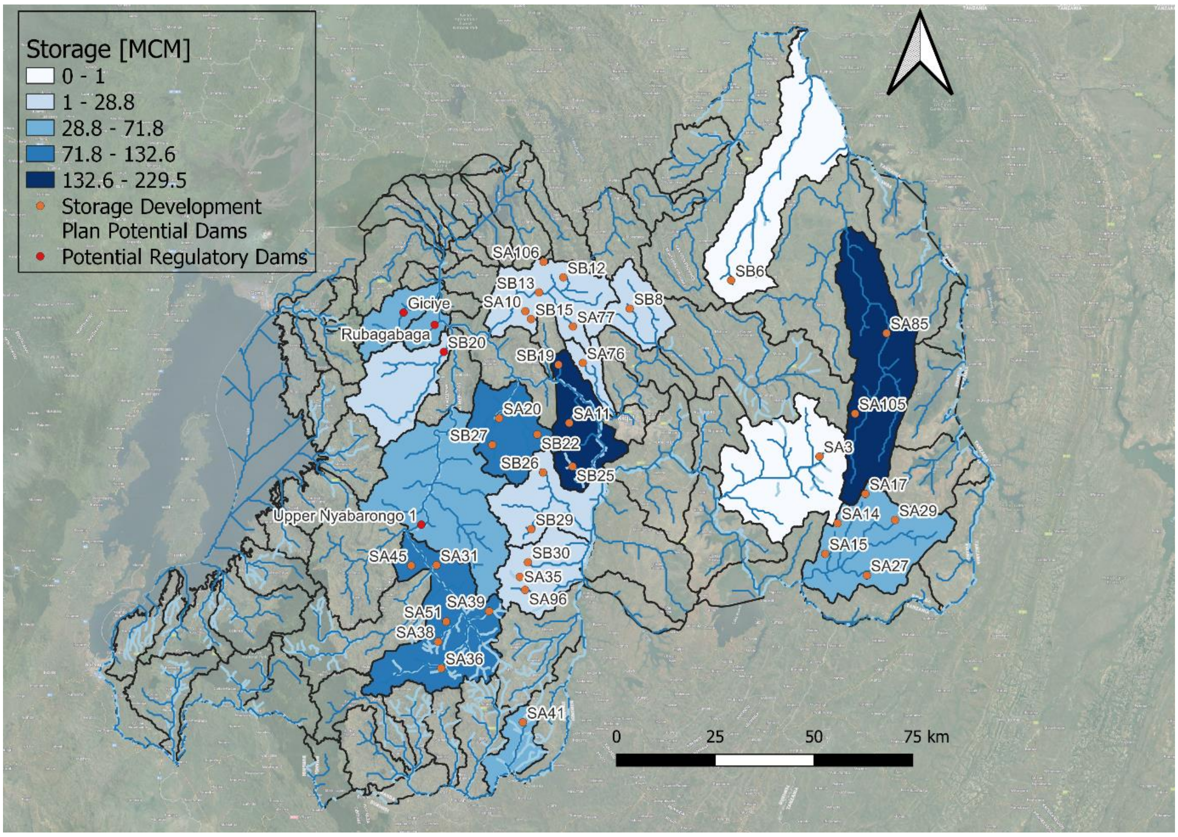

Figure 102: : Location of the 39 prioritised dam sites in Rwanda.

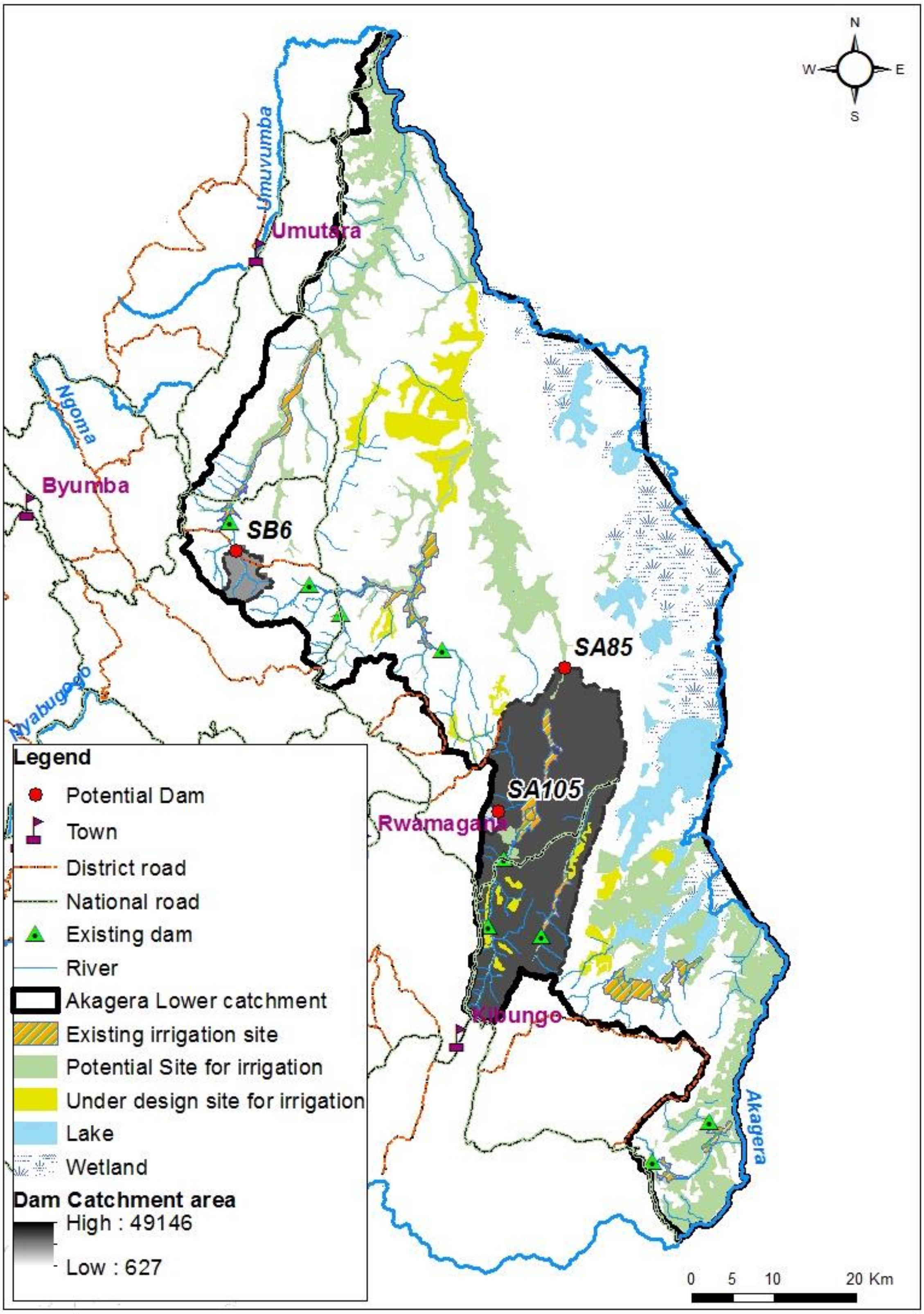

Figure 103: Prioritised dams in Akagera Lower catchment.

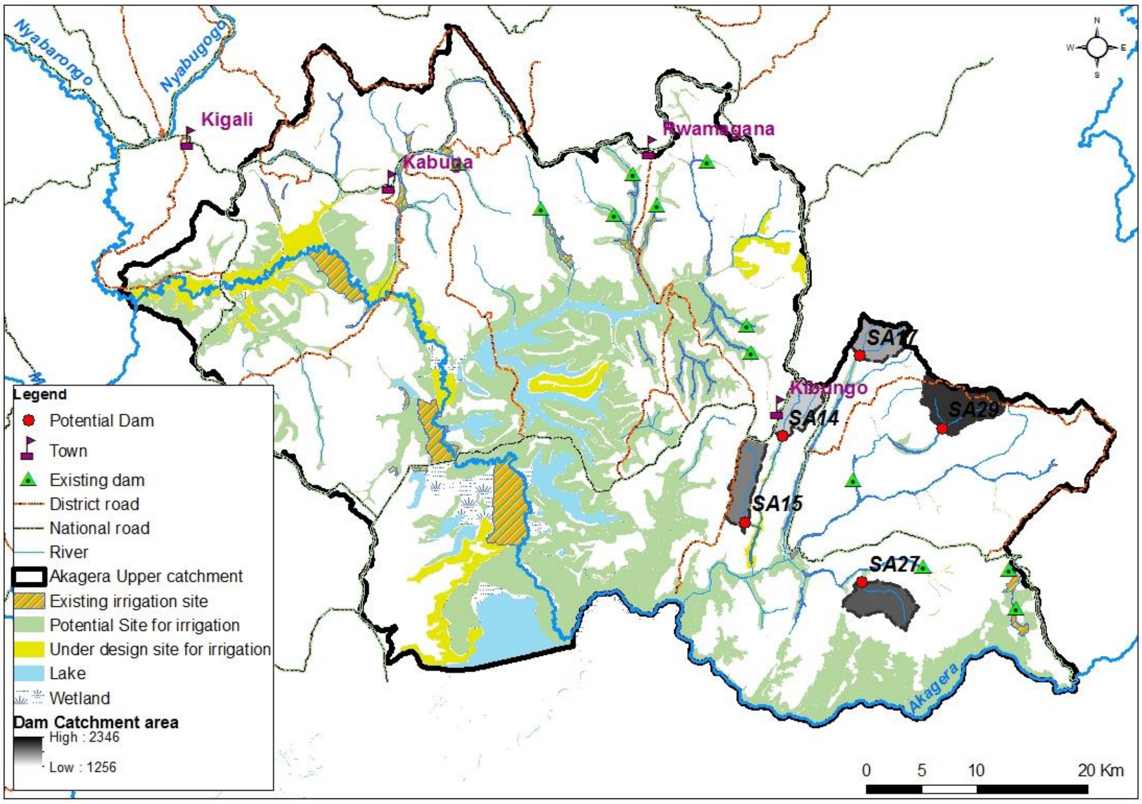

Figure 104: Prioritised dams in Akagera Upper catchment.

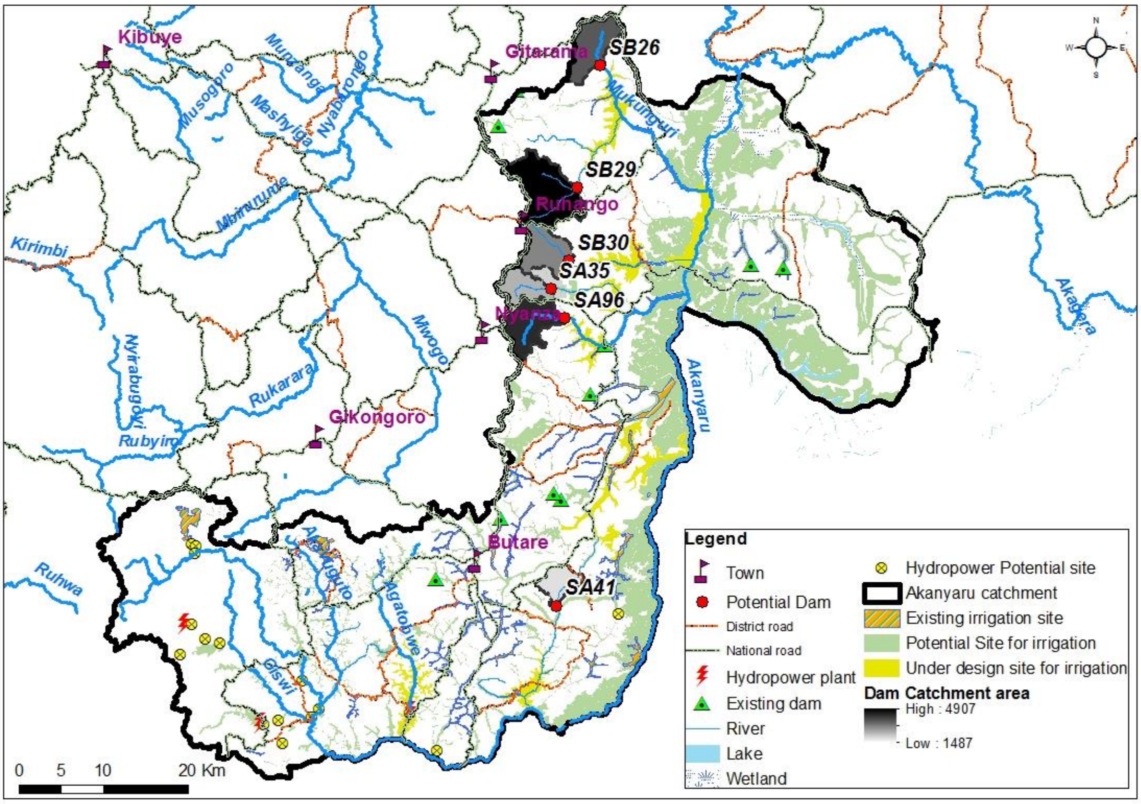

Figure 105: Prioritised dams in Akanyeru catchment.

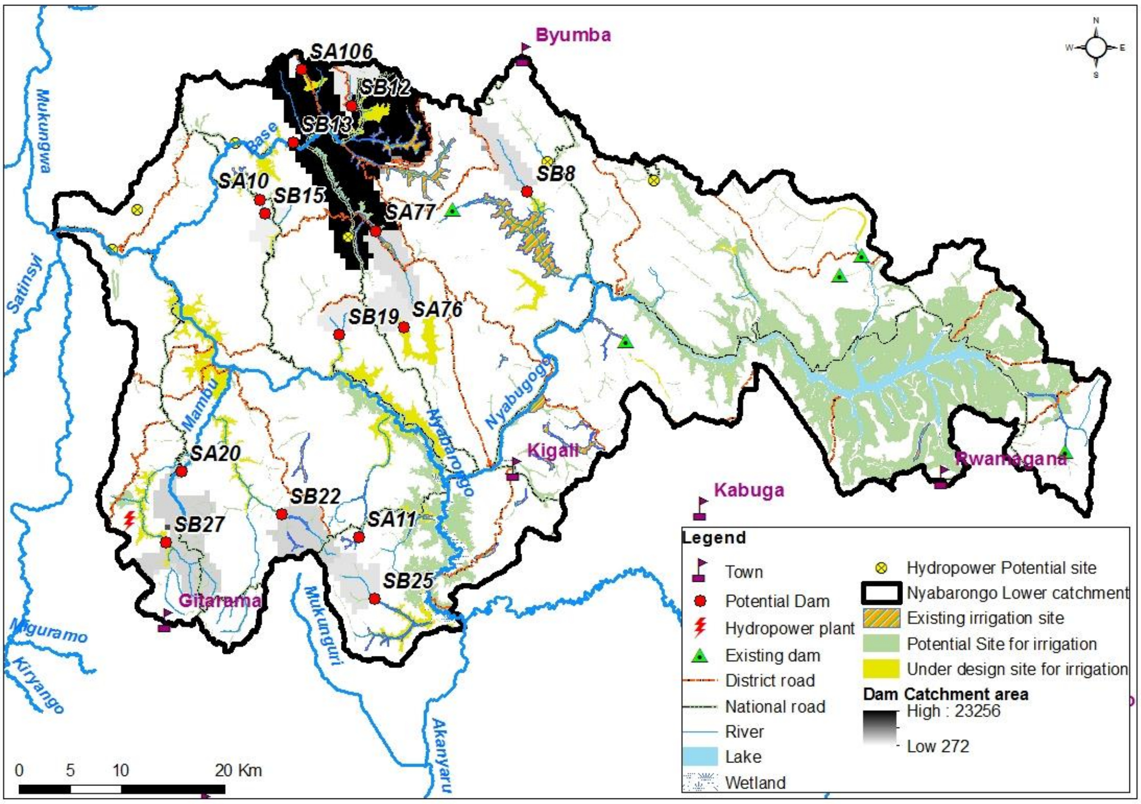

Figure 106: Prioritised dams in Nyabarongo Lower catchment.

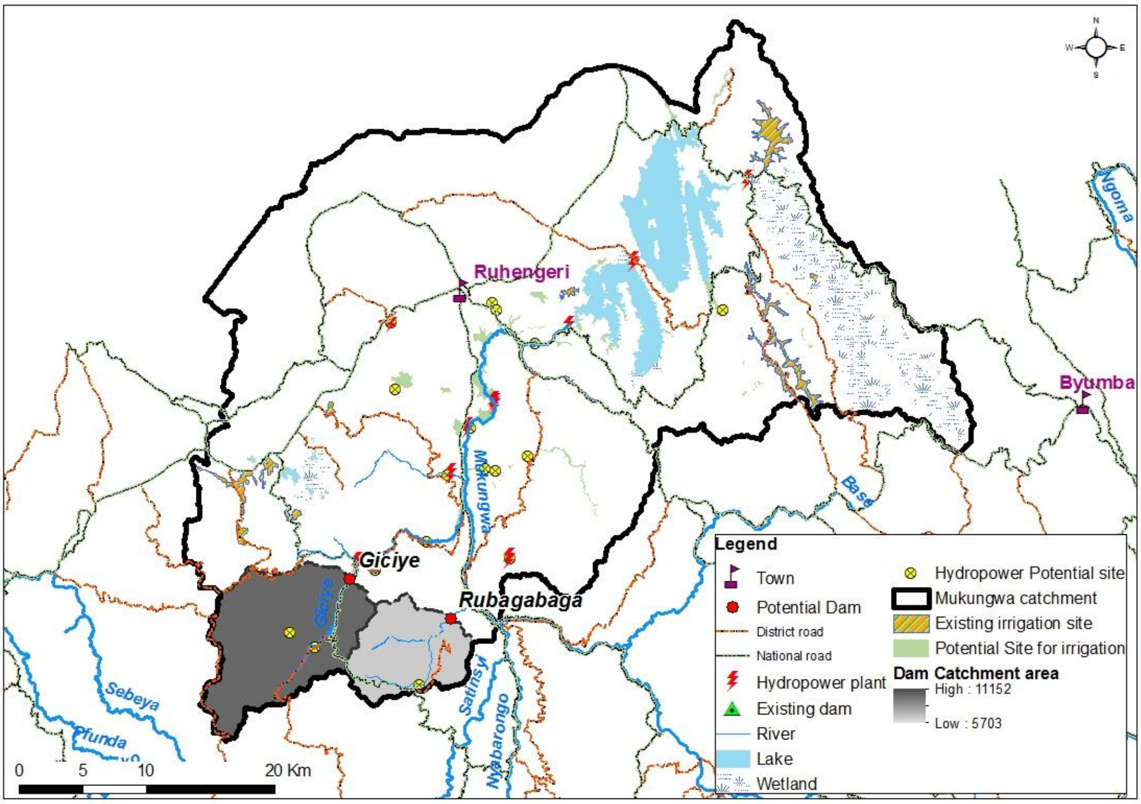

Figure 107: Prioritised dams in Mukungwa catchment.

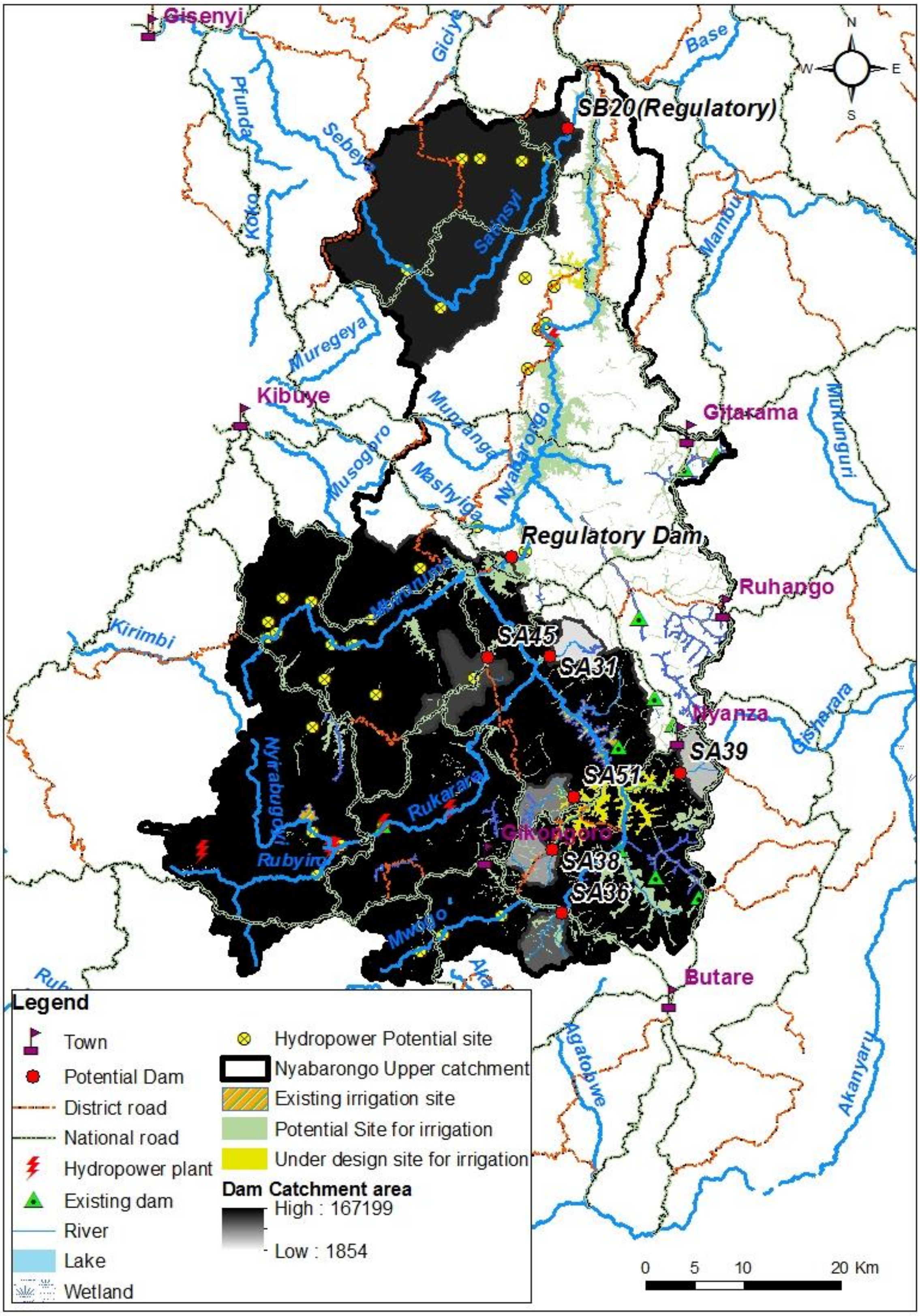

Figure 108: Prioritised dams in Nyabarongo Upper catchment.

District-wise, Nyanza has the greatest number of sites, followed by Rulindo, Kamonyi and Ruhango (Figure 109). Consultation with WASAC revealed that the folwing districts are WASAC's priority for developing dams:

- Central Southern part of Rwanda, known as Amayaga;
- Muhanga District;
- Ruhango District;
- Nyanza District;
- Gisagara District;
- Kamonyi District;
- Kayonza District;
- Kirehe District;
- Ngoma District;
- Rutsiro District.

Except for Amayaga and Rutsiro, all these districts are covered with prioritised dams.

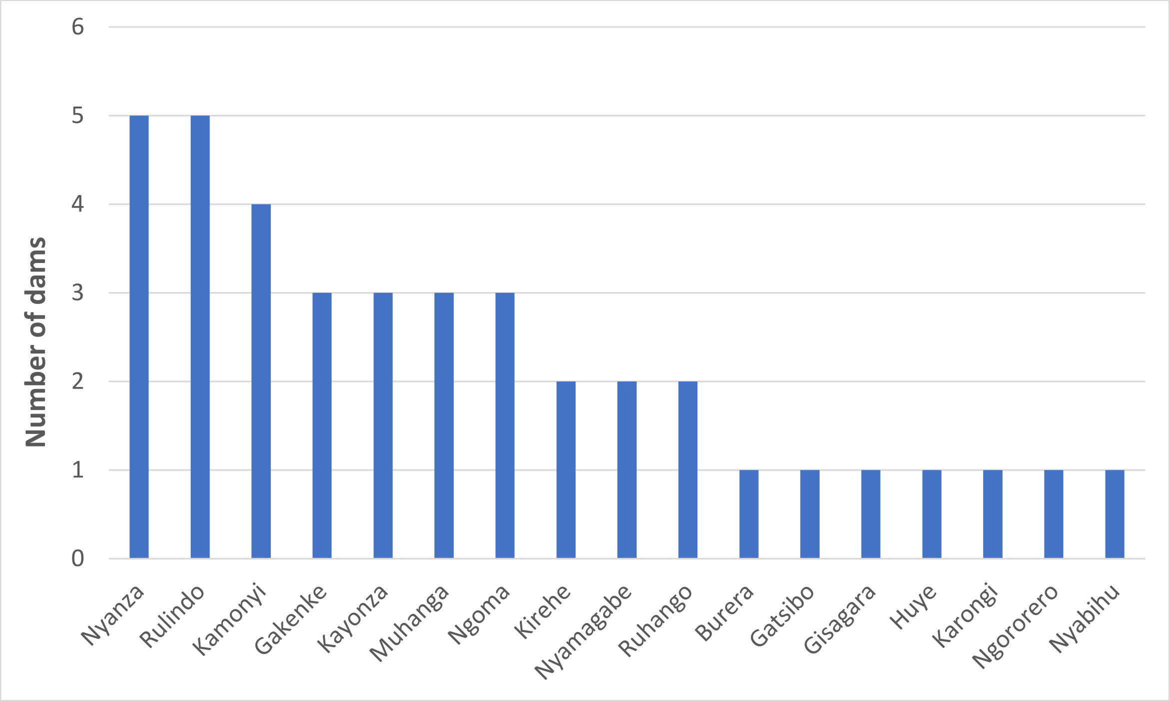

Figure 109: Distribution across the districts of the 39 prioritised sites.

3.1.2.2 *Storage capacity*

The storage capacity of the prioritised dams refers to the total physical storage, i.e., the maximum volume of water that can be stored in the reservoir[1]. It ranges from 168 to less than 1 MCM (Figure 110), the minimum values being for regulatory dams. The cumulated active storage for the 39 prioritised dams is about 812 MCM. The dams SB13 (168 MCM) and SA85 (148 MCM), located respectively in Nyabarongo lower and Akagera lower, have the largest storage.

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[1] In the modelling work of Chapter 2, the active storage was considered instead, understood as the usable volume of water stored in reservoir, not accounting for dead storage. The active storage was taken equal to 80% of the storage capacity.

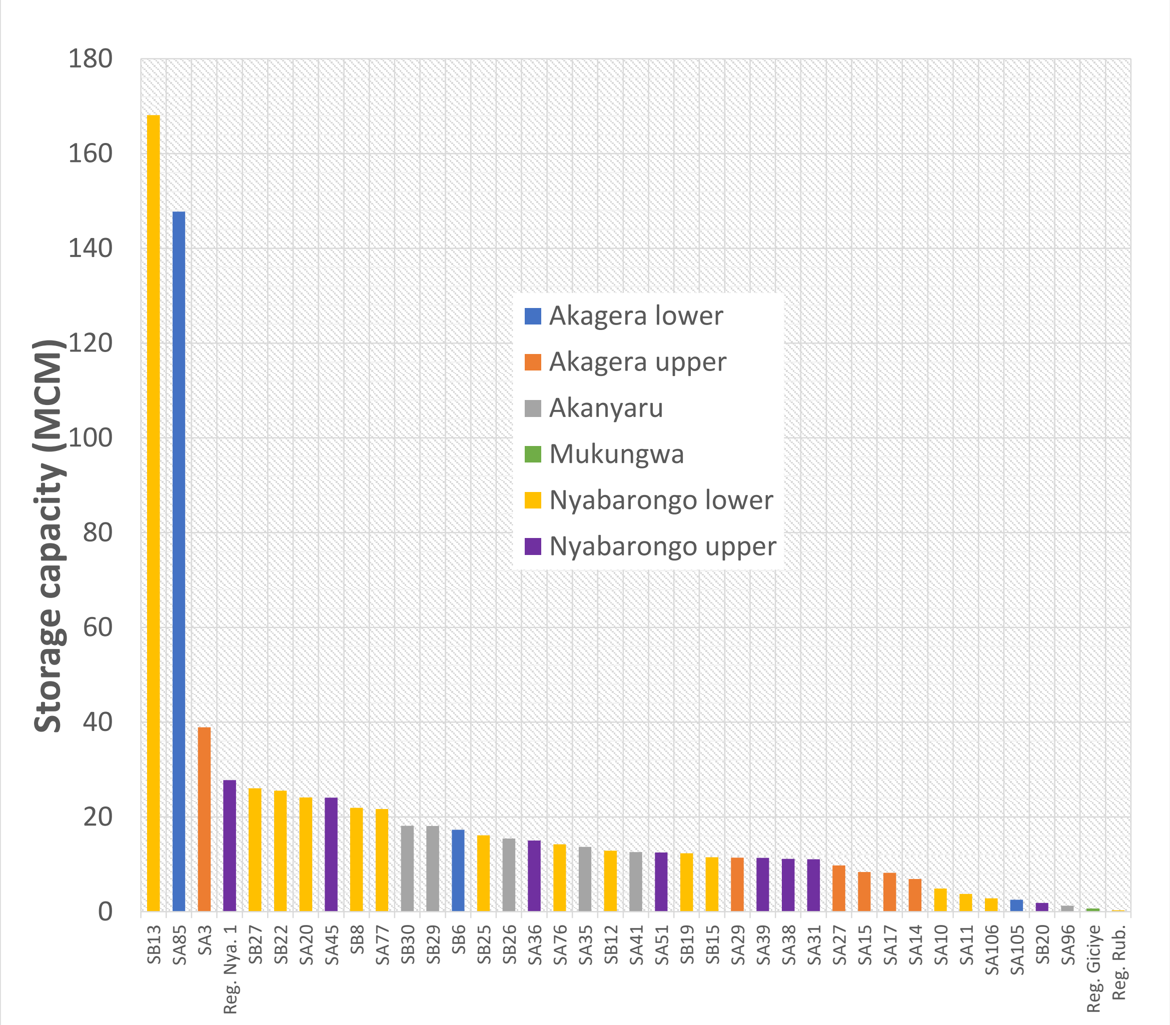

Figure 110: Storage capacity of the prioritised dams, categorised per L1 catchment

The 39 dams are distributed across 18 districts (Figure 109). The largest dams SB13 and SA85 are respectively located in Gakenke and Kayonza districts. Summing all the storage per district, the latter two districts cumulate the storage districts, followed by Rulindo and Kamonyi (Table 71).

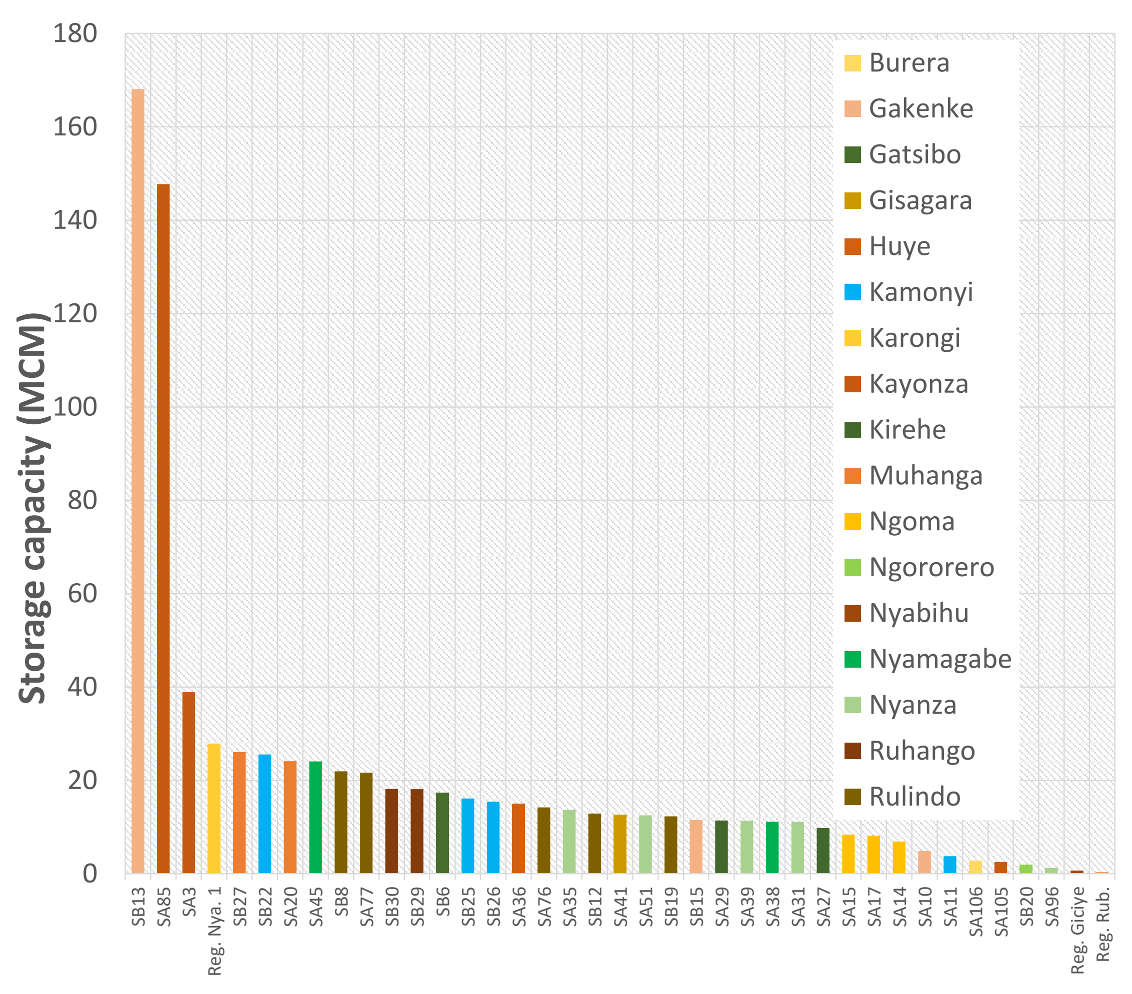

Figure 111: Storage capacity of the prioritised dams, categorised per district.

Table 71: Storage capacity of the prioritised dams, cumulated per district

District	Cumulated storage capacity [MCM]
Kayonza	189.2
Gakenke	184.5
Rulindo	83.0
Kamonyi	60.8
Muhanga	50.5
Nyanza	49.9
Ruhango	36.3
Nyamagabe	35.2
Karongi	27.8
Ngoma	23.5
Kirehe	21.2
Gatsibo	17.3
Huye	15.0
Gisagara	12.6
Burera	2.8
Ngororero	1.9
Total	**812.1**

3.1.2.3 Dam height

The dam heights are plotted in Figure 112. The range is from 76 m (sor SB13) to 5 m (Regulatory dam on Giciye river). The regulatory dams have the smaller heights.

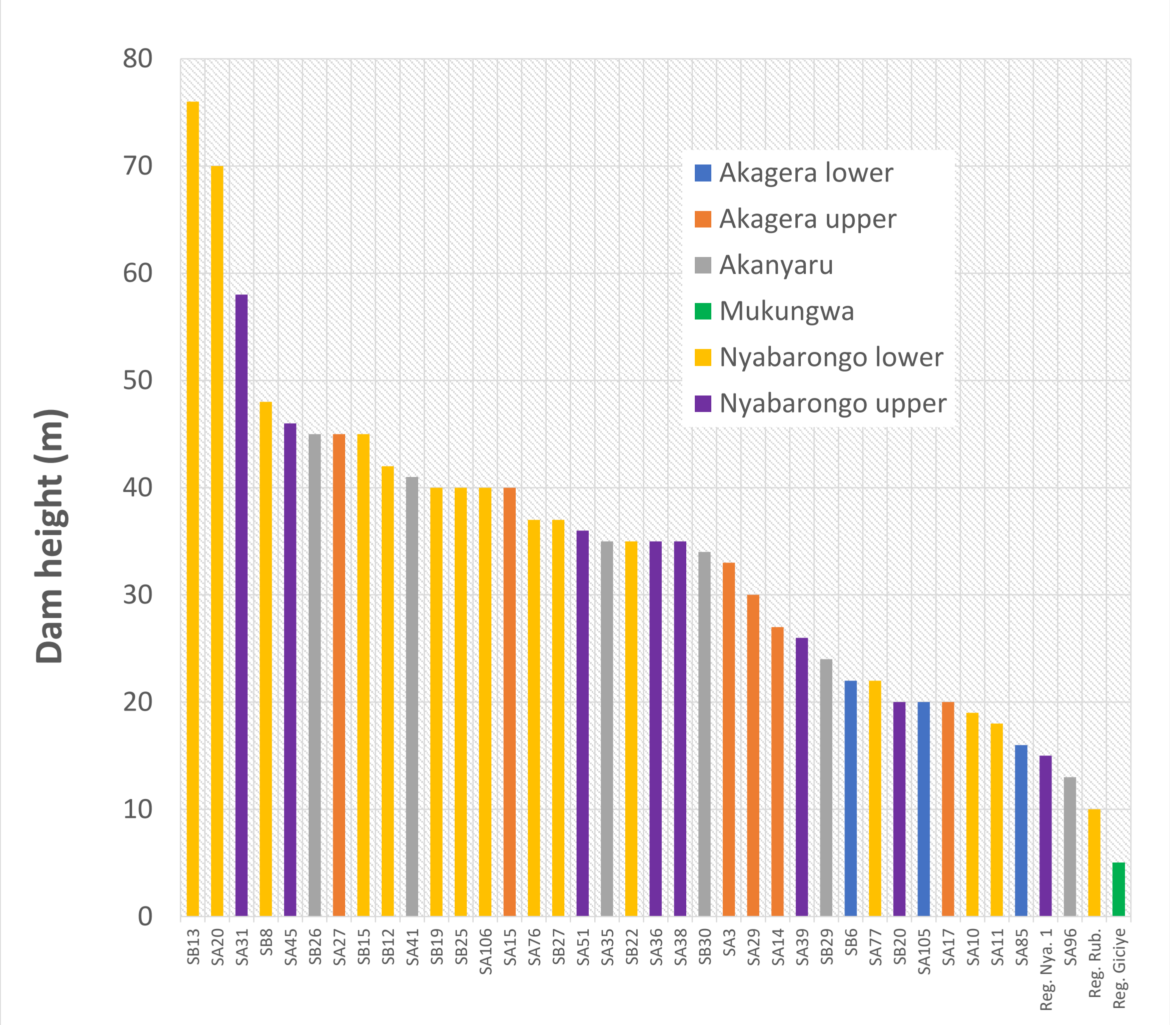

Figure 112: Dam height of the prioritised dams, categorised per L1 catchment

3.1.2.4 Catchment areas

Most of the identified sites have catchment areas smaller than 15,000 ha (Figure 113) and are located on streams with a permanent flow. However, the regulatory dams, especially the one in Nyabarongo upper located on the main river, SA85 and SB13 have large catchment areas, over 20,000ha, and are located on large rivers.

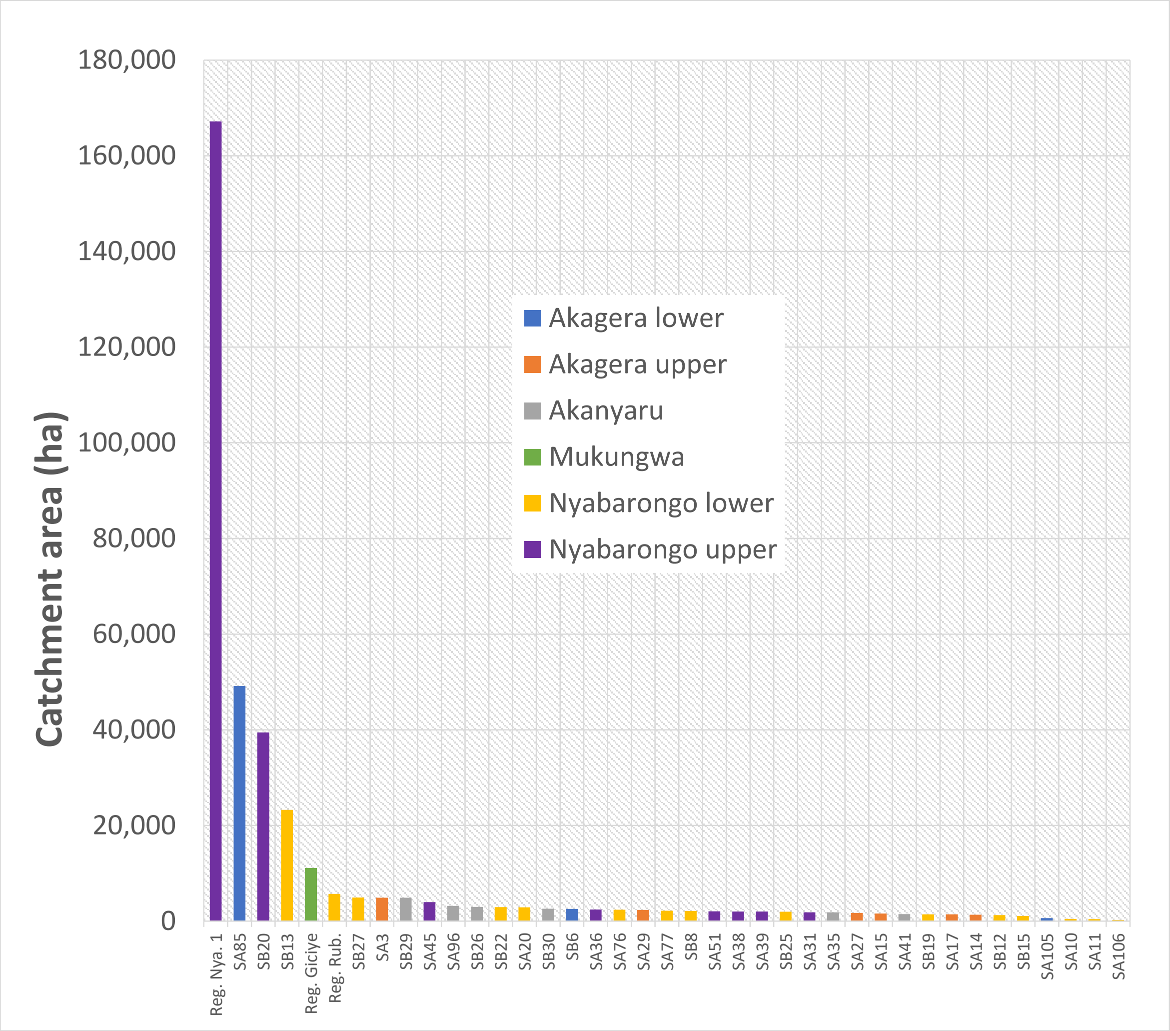

Figure 113: Catchment areas of the prioritised dams, categorised per L1 catchment

3.1.2.5 Inundated areas

The inundated area, being the area of the reservoir being flooded, is shown in Figure 114. The dams SA85 and SB13 have the largest areas being flooded, which goes hand in hand with their largest storage capacity. Most of the dams are inundating less than 200 ha. Albeit their large catchment areas, the regulatory dams do not have large inundated areas due to their small storage capacity.

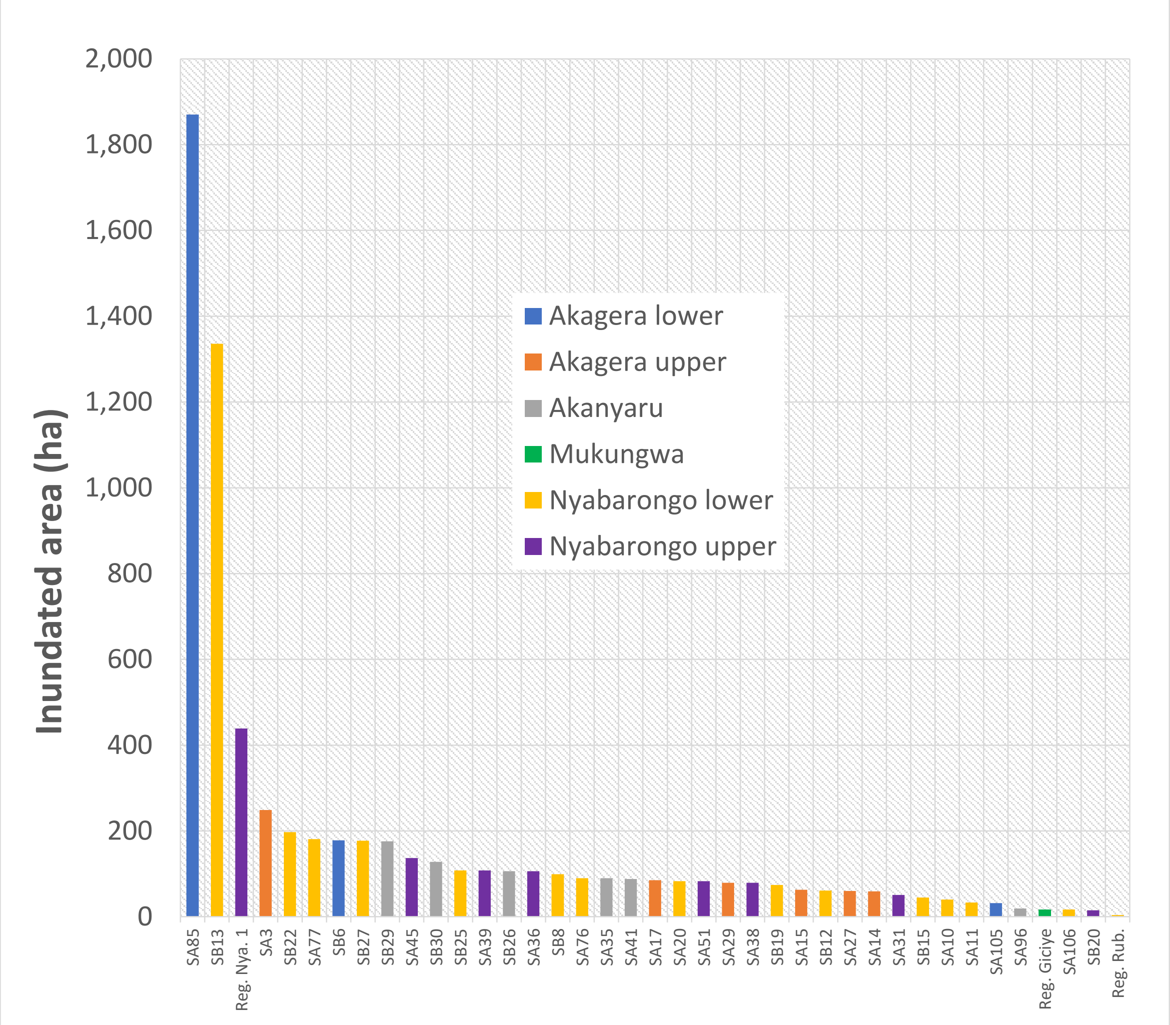

Figure 114: Inundated area of the prioritised dams, categorised per L1 catchment

3.1.2.6 Geology

The geologies of the catchment areas are mainly of shale and granite, followed by alluvial materials, quartzite, schist and volcanic (Figure 115). Quartzite, volcanic and basalt are mostly observed in small catchments. Dam sites have been prioritised based on the geomechanical properties of rocks; seismotectonic and seismic risk analysis of the sites as well as the importance of geologic structures in the identification and assessment of karst hydrogeology. The geological requisites of all selected potential dam sites were: (1) a tight basin of ample size; (2) a narrow outlet requiring a relatively narrow and deep reservoir, with foundations able to sustain the dam; (3) an opportunity for building a safe and ample spillway to dispose of surplus water; (4) available materials of which to construct the dam; (5) assurance that the basin will not fill with mud and sand carried in the water in too short a time. Moreover, the selection focused on prioritising sites with geological materials rich in silt and clay-sized particles to increase the potential to hold a greater quantity of water, and favor minimum quantity of seepage.

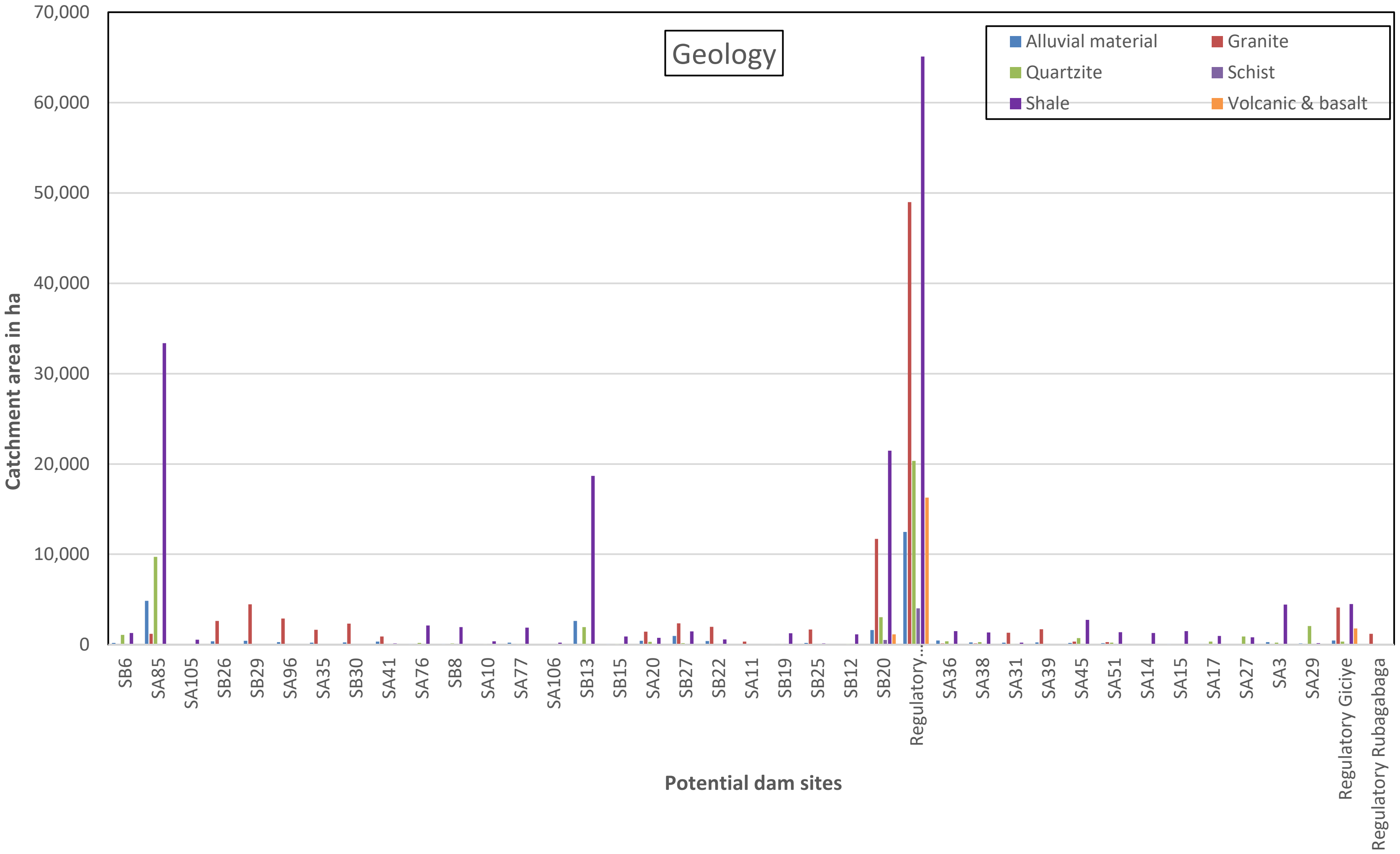

Figure 115: Distribution of sites catchments' geology.

Shales are generally fine-grained, clastic sedimentary rocks, formed from mud that is a mix of clay flakes and tiny fragments (silt-sized particles) of other minerals, especially quartz and calcite. Due to clay minerals, shales have minimum infiltration, which is a good characteristic for storage development. On the other hand, granite is a coarse- or medium-grained intrusive igneous rock, rich in quartz, feldspar and mica. Due to this coarse texture, infiltration capacity is higher in granite; therefore, appropriate storage management measures will be required to minimise losses.

3.1.2.7 Lithology

The main aquifers observed in the sites are alluvial aquifers, fractured aquifers, and permeable fractured aquifers (Figure 116).

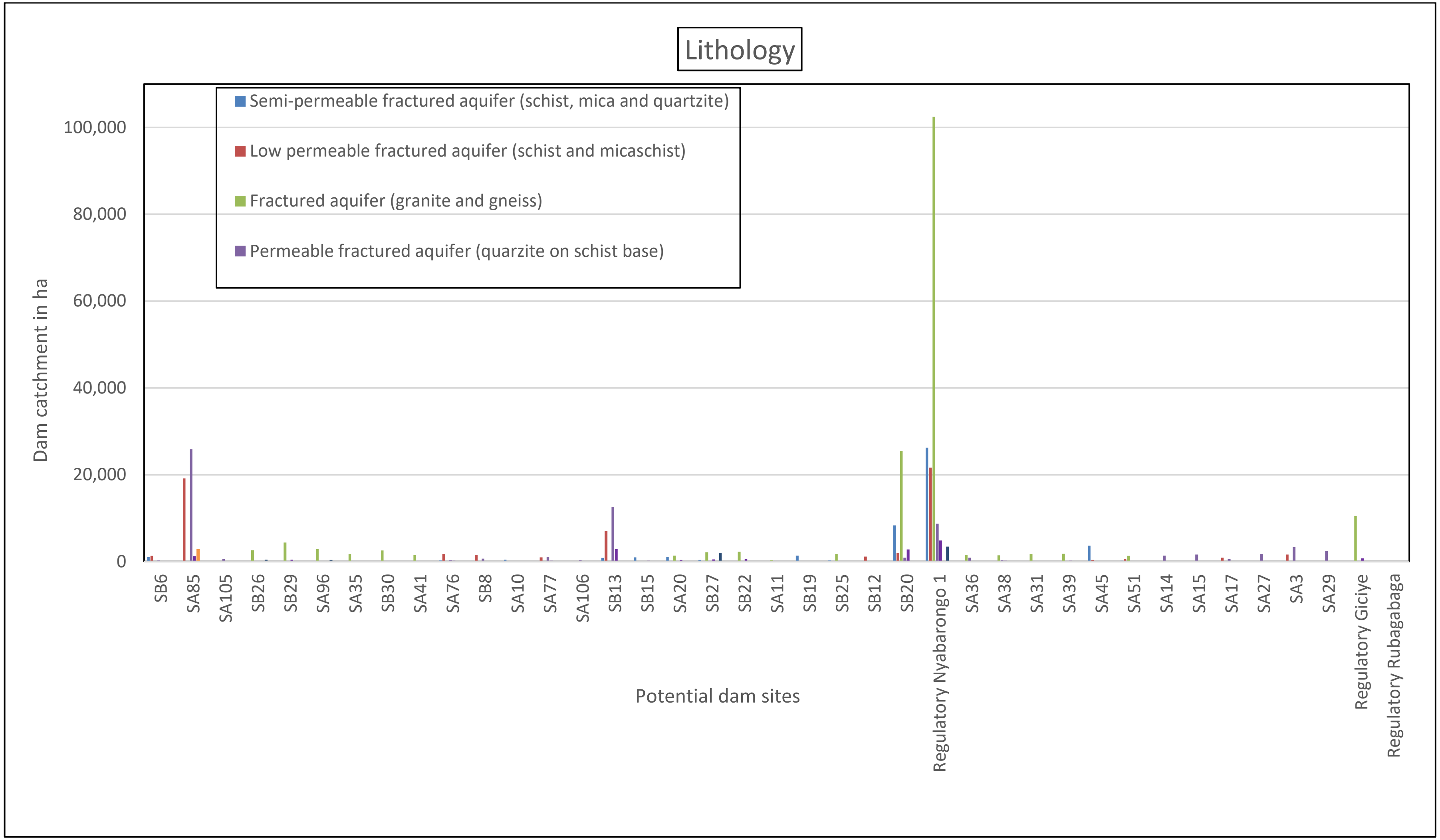

Figure 116: Site catchments' lithology

3.1.2.8 Catchments soil erosion risk

Since artificial storage development requires heavy investment, assessing the threat that could affect the integrity of the reservoir is always advisable. In this analysis, three categories of soil erosion risk were adopted. Most of the delineated catchments are under moderate and high erosion risk (Figure 117). Few sites are located under very high and extremely high risk of soil erosion. These observations justify the need to associated storage development program with landscape restoration measures, as will be tackled in section 3.1.2.9 (p170) below.

Topography is mostly one of the important factors regulating soil erosion risk. Logically, a similar pattern to soil erosion risk was observed (Figure 118). The catchment slope varies mostly between 16 and 60%, which allows the dam site to collect more water as the time of concentration reduces with steeper slopes.

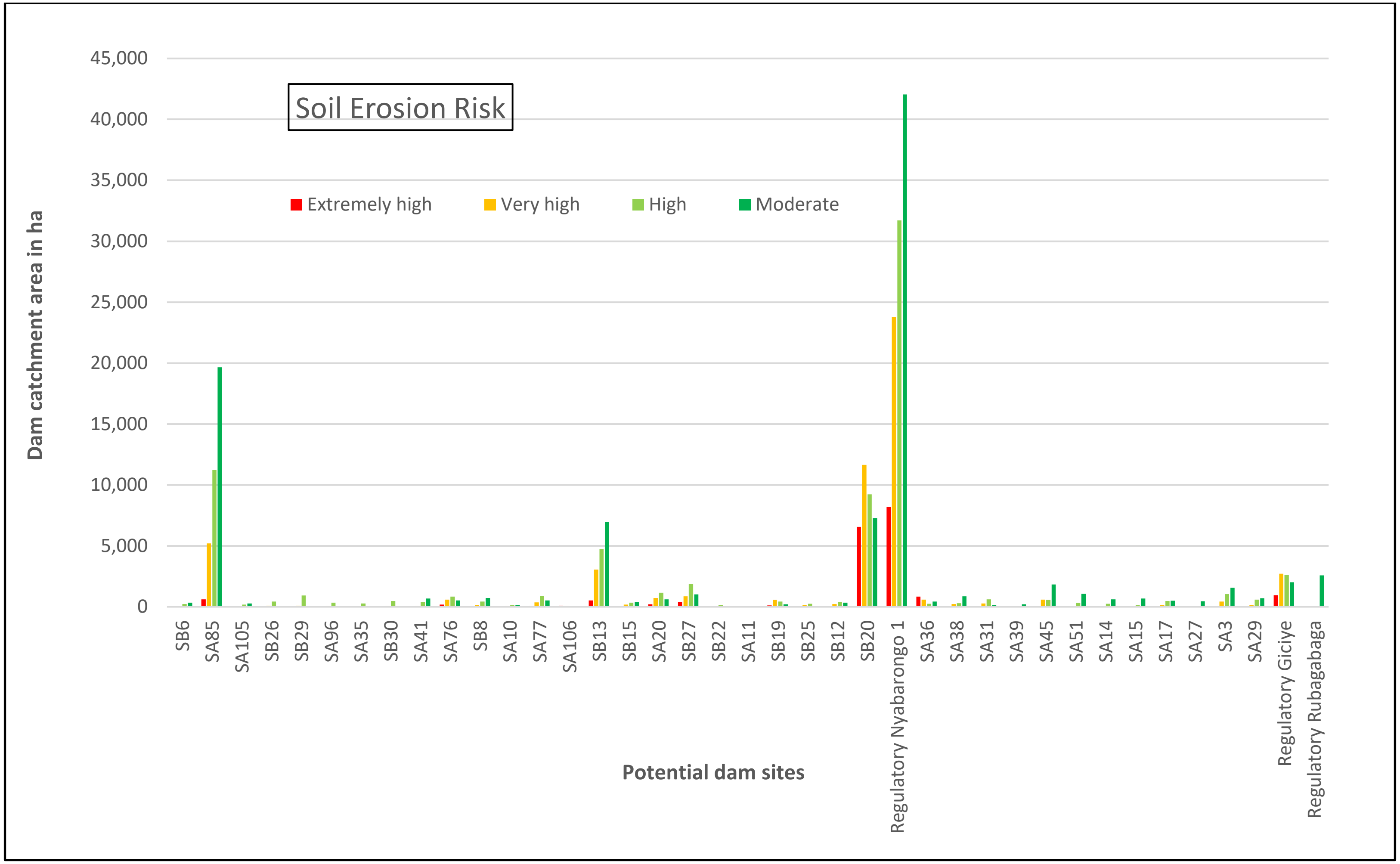

Figure 117: Soil erosion risk distribution in the delineated site catchments

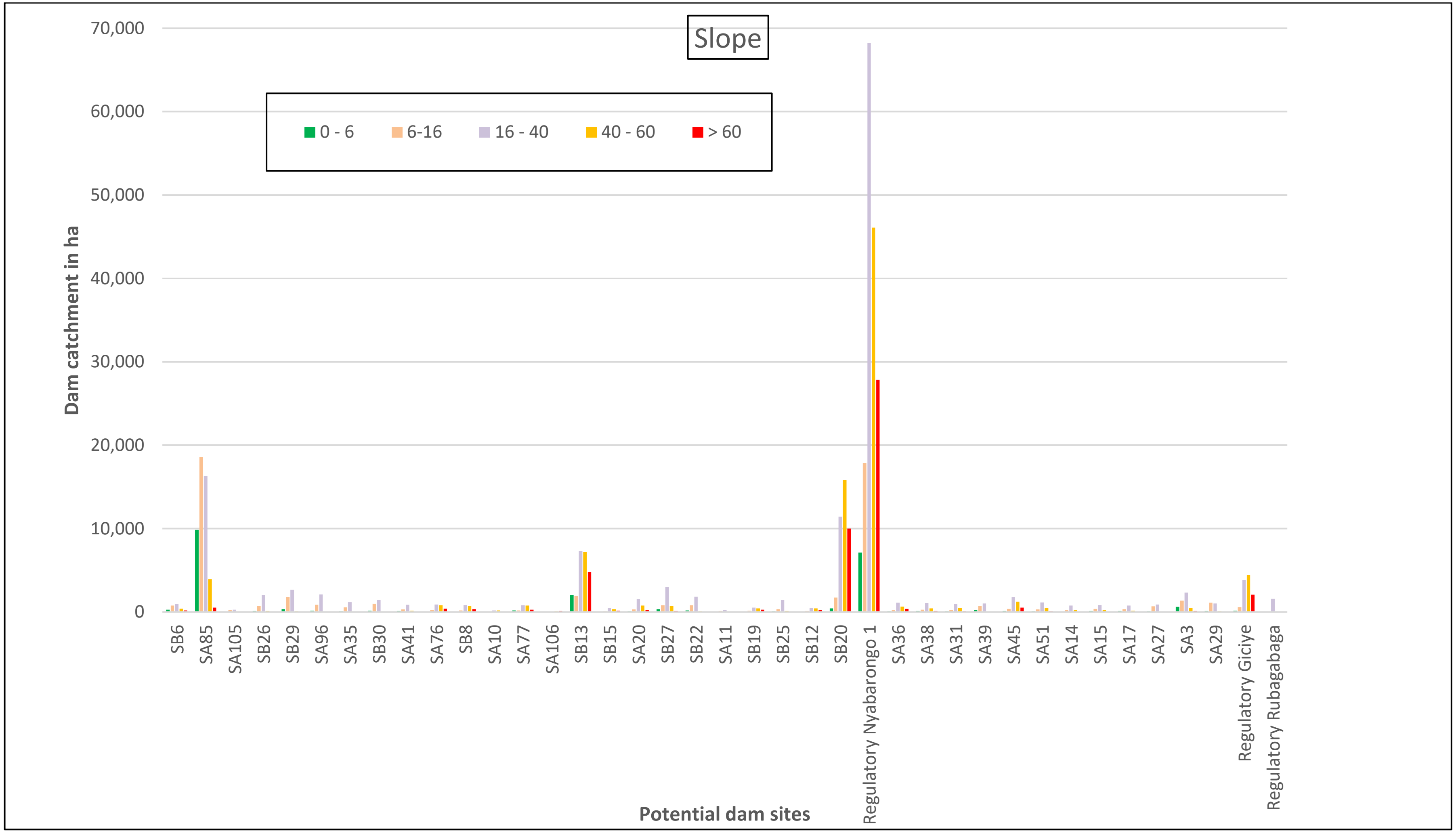

Figure 118: Slope distribution in site catchments

3.1.2.9 Cost

The cost of the 39 dams is shown in Figure 119. The cost ranges from a bit less than 3 to 138 MUS$. Two dams (SB13, in Nyabarongo lower, and SA85, in Akagera lower) are distinctively more expensive than other dams, due to their significant greater storage.

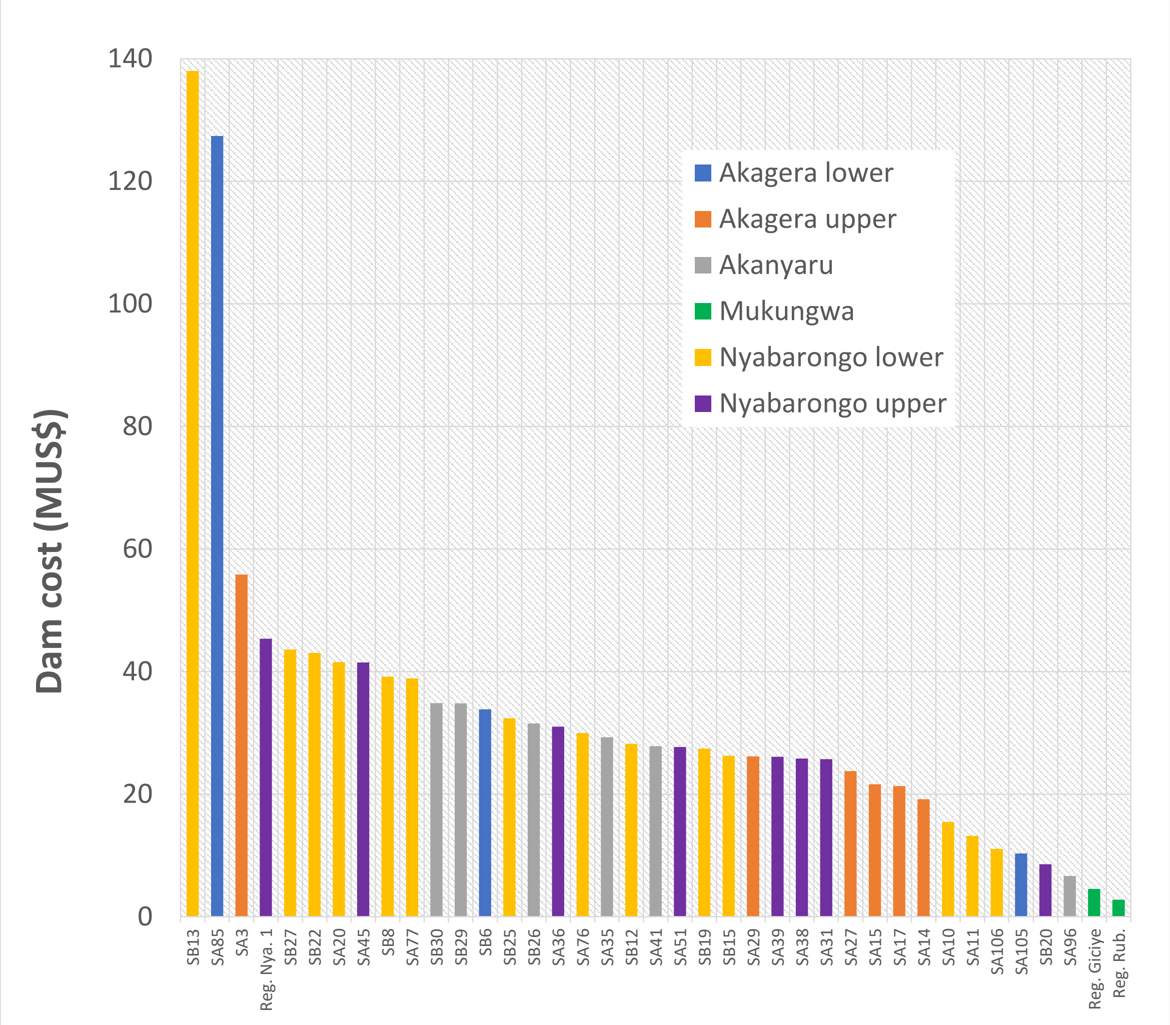

Figure 119: Cost of the prioritised dams, categorised per L1 catchment

3.2 Assess the contribution of Natural based Solutions

To ensure the sustainability of the prioritised water storage infrastructures recommended for development in the near future, nature-based interventions have been proposed within each dam site catchment area to mitigate the dam siltation once constructed. The proposal for interventions is derived from the updated Catchment Restoration Opportunity Mapping Decision Support System (CROM DSS). The tool consists of a geo-database (spatial data infrastructure), a series of automated processes identifying risks, locating existing protection, assessing priority areas, and classifying land according to slope and soil depth to identify suitable restoration options.

The proposed measures include mainly afforestation, agroforestry, hedgerows, bench terraces, contour bank terraces, reforestation, grassed waterways, riverside bamboo and savannah restoration as illustrated in the maps below (Figure 120 to Figure 124).

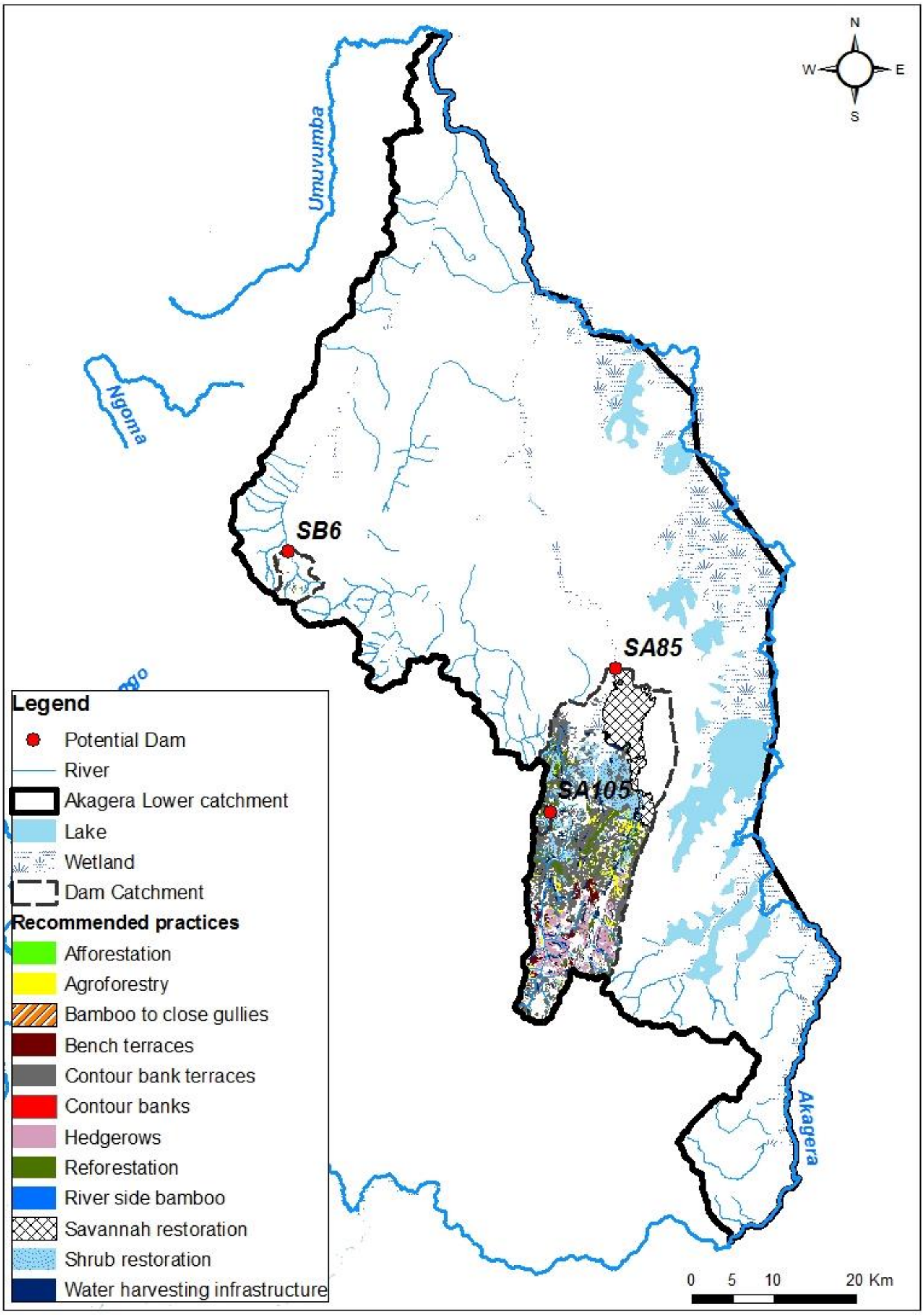

Figure 120: Map of the proposed NbS interventions in Akagera Lower catchment.

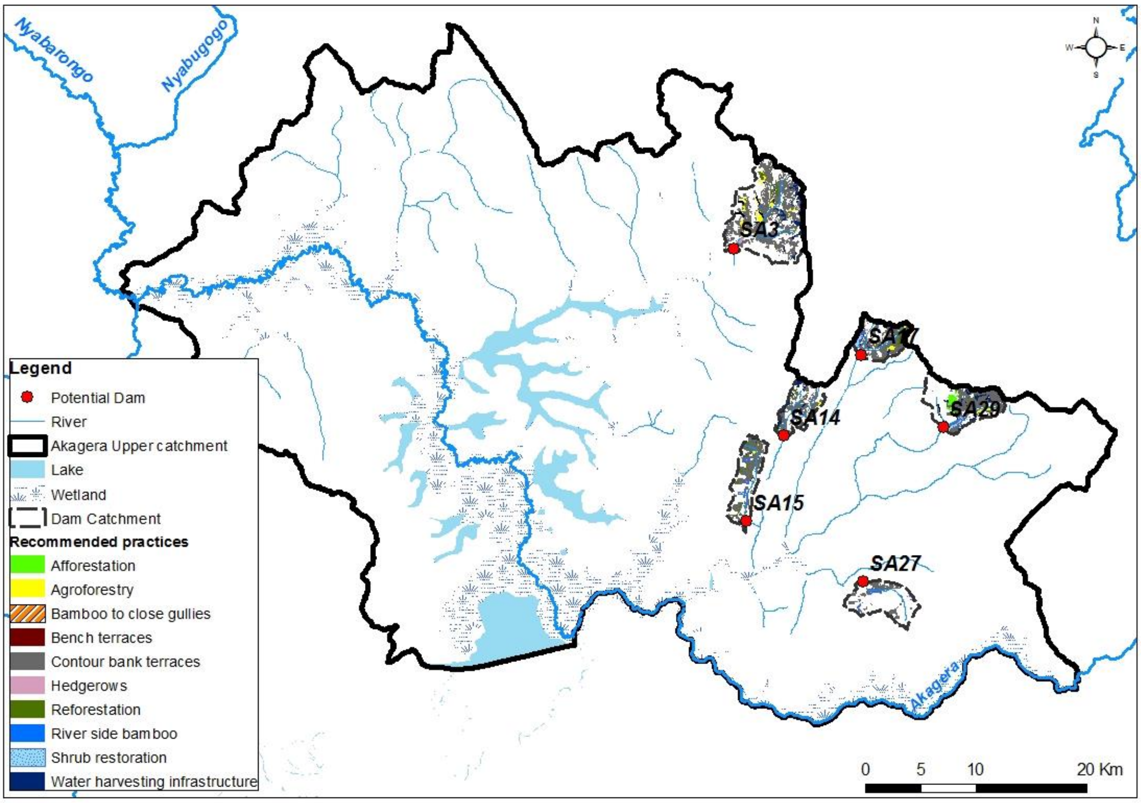

Figure 121: Map of the proposed NbS interventions in Akagera Upper catchment.

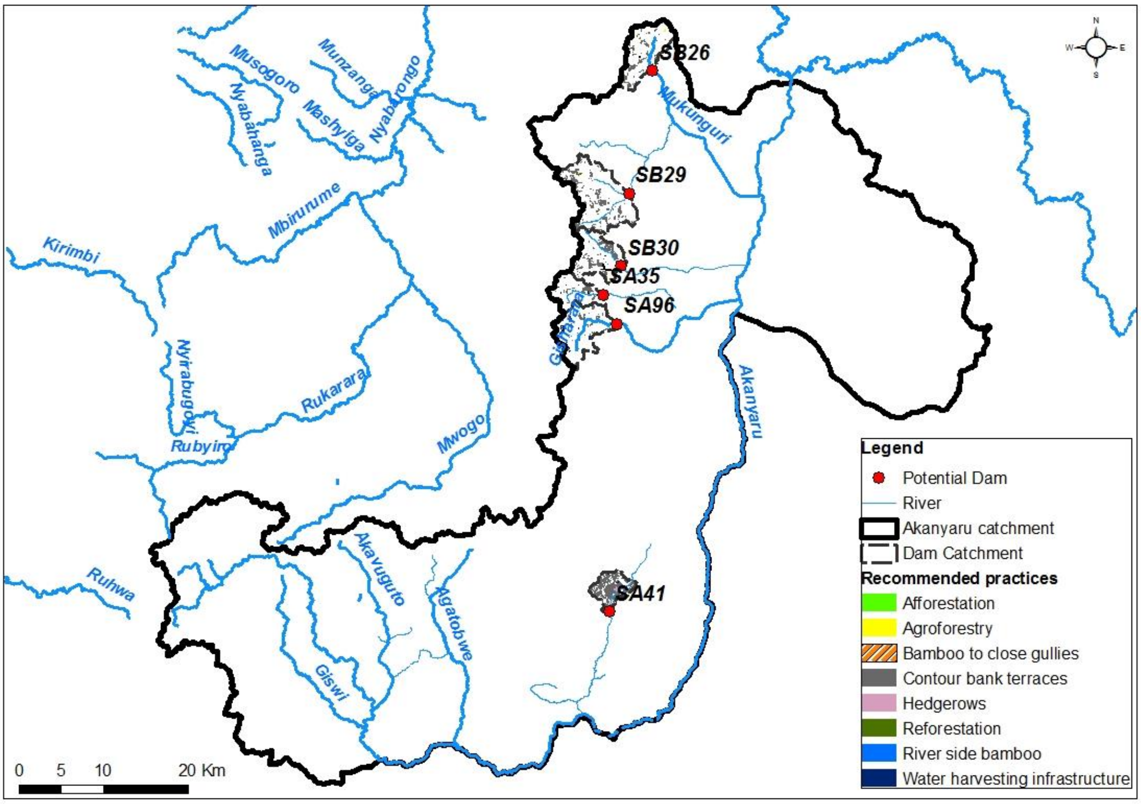

Figure 122: Map of the proposed NbS interventions in Akanyeru catchment.

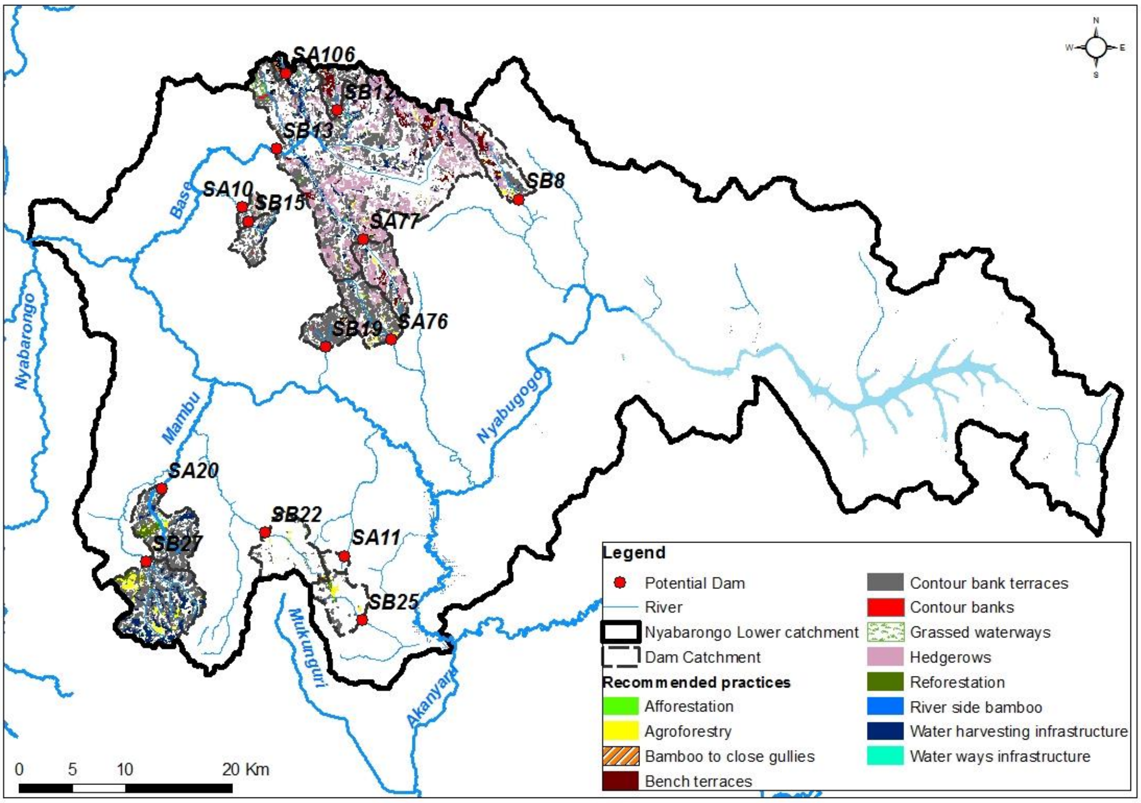

Figure 123: Map of the proposed NbS interventions in Nyabarongo Lower catchment.

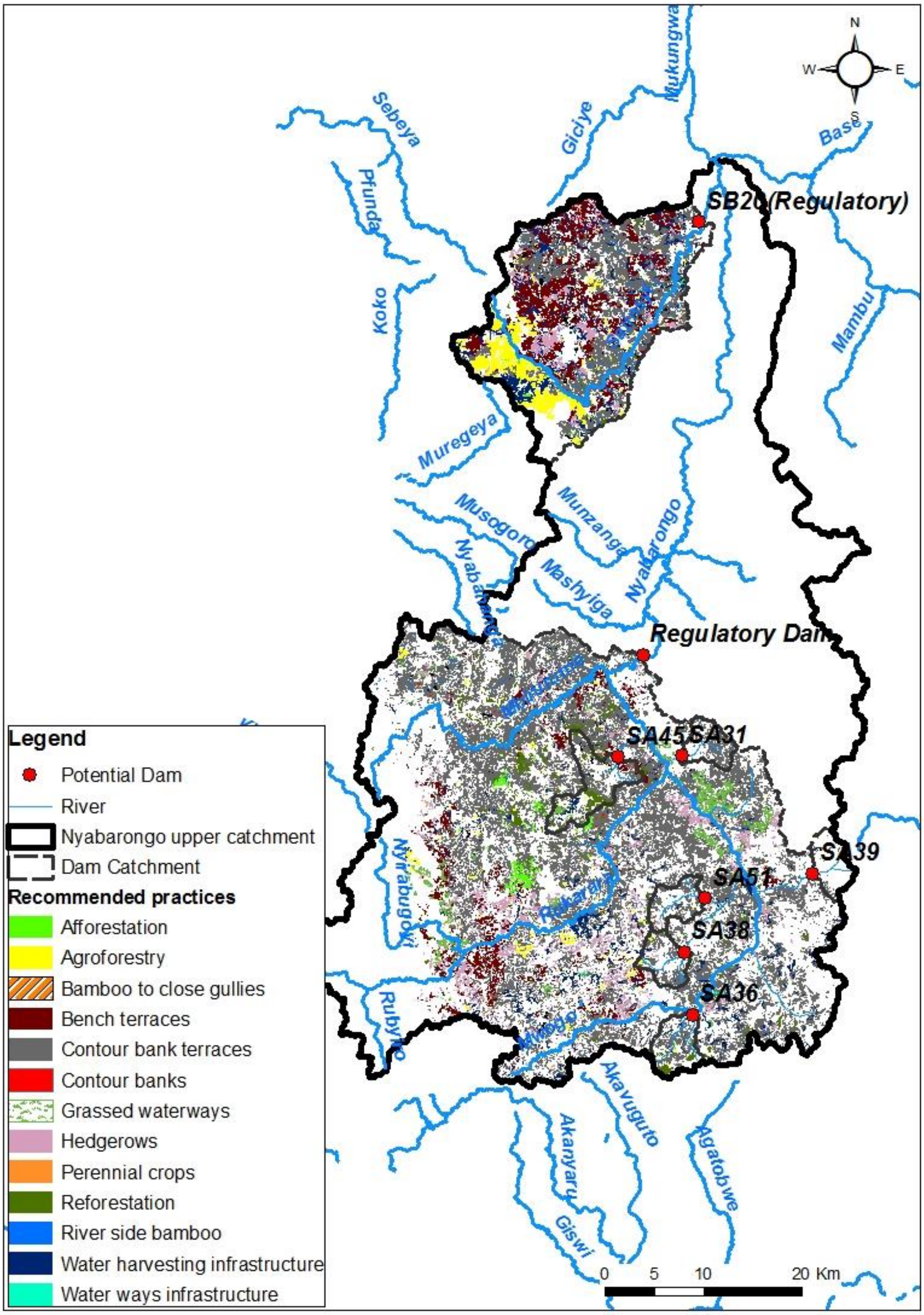

Figure 124: Map of the proposed NbS interventions in Nyabarongo Upper catchment.

The area to be covered by each nature-based intervention for each potential dam site catchment area is provided in Annexe 13. The proposed interventions are predominantly contour bank terraces, hedgerows, reforestation, agroforestry and bench terraces covering respectively 31,864 ha, 5,100 ha, 3,028 ha, 1,964 ha and 1,326 ha.

Implementing the recommended nature-based interventions will largely contribute to the sustainability of the prioritised dams through the prevention of their sedimentation and therefore ensuring their full water storage potential. A recent study on the state of soil erosion in Rwanda has revealed that an estimated average value of 27 million tons of topsoil is lost annually (RWB, 2022). This is about 25 t/ha/annum. Considering that the total catchments' areas for the 39 prioritised dam sites under this study are 115,356 ha, it can be assumed that around 2.8 million tons of topsoil per annum are being lost within those catchments. This implies that this volume of eroded soil will end up being deposited within the 39 dams, if constructed without implementing the recommended nature-based interventions, and this will reduce the total storage capacity of the 39 dams by 2,800 m^3 annually.

3.3 Update the Water Resources Development National Guidelines

This section presents the water resources development recommendations at the national and level 1 catchment levels. The guidelines at national level build on the Hydro-Economic Analysis and the current study. Besides information from the modelled water resources assessment for each catchment, key messages from the stakeholder consultations (e.g., RWB, WASAC, REG/EDCL, MoE, NELSAP) were also distilled in this write-up. The guidelines presented here are those for the long-term, towards 2050 and cover generic national recommendations (supply-side, demand-side and legal/regulatory aspects).

National considerations are then specified for level 1 catchments, accounting for the list of prioritised dams identified in this study.

3.3.1 National considerations

3.3.1.1 Supply-side guidelines

Surface storage

Current surface water storage in Rwanda is less than 30 MCM . This small total capacity is furthermore being reduced by the effects of erosion and sedimentation. The foremost guideline is to investigate the conditions of existing dams and upgrade those being severely impacted by sedimentation, to restore or even increase further their storage capacity. The upgrade should include the financing of an integrated plan to manage sediments, as will be detailed below for new dams.

Based on projects sanctioned or currently being implemented, the storage level is assumed to increase to almost 100 MCM under that baseline with the addition of three large dams. Under the Vision 2050 and Water Resilient 2050 scenarios, the aim is to increase storage by an additional 300 MCM by 2050. The current study has prioritised the location catchment-wise of these additional dams by 2050. The prioritisation was done based on an assessment of future water availability and demand, completed by a technical appraisal to account for local conditions.

It has become evident from the assessment that changes in storage for irrigated agriculture, via small and large reservoirs, have noticeable impacts, especially for dry years, at both the level of individual catchments and at macro-economic scales. The geographic differences have been shown in the hotspot maps of the Hydro-economic analysis (HEA), where the driest parts of Rwanda show unmet demands even with added surface water storage. This was corroborated during the current study. From the macroeconomic perspective, the cost-benefit analysis performed in the HEA study shows that investment in storage has positive benefits for discount rates ranging from 2 to 7 percent over the 30-year time horizon. The current study will perform in Chapter 4 a more localised and detailed cost-benefit analysis for three flagship projects.

For artificial storage (dams), it is essential to preserve the storage capacity as much as possible, to ensure the long-term performance of the investments in water storage infrastructure. For this purpose, these investments need to be accompanied by an integrated plan to manage sediments. This plan should cover (i) catchment interventions to reduce erosion and resulting sedimentation in reservoirs and other water bodies (as was examined in previous section 3.1.2.9, p170), (ii) a regular maintenance plan to remove sediments deposited in the reservoir and (iii) exploration of business opportunities to reuse dredged sediments. Different techniques to remove and store sediments (e.g., mechanical or suction dredging) should be explored; important here is to avoid techniques which flush the sediments towards downstream infrastructures. Next, different opportunities to sell collected sediments should be investigated to fund the entire integrated sediment management plan. Examples exist for that matter, such as reuse for building roads (Maherzi and Ben Abdelghani, 2014[1], Kasmi et al., 2017[2]), construction material (Xu et al, 2014.[3]), or even for agriculture, be it to improve soil fertility (Braga et al., 2019[4]) or soil amendment (Walter et al., 2012[5]). Often sediment management is not included in the initial investment cost. Therefore, this integrated plan to manage sediments should be budgeted as part of the CAPEX of any new investments and considered in the regular O&M costs.

Investing in new dams, or in upgrading existing ones, should promote multi-purpose uses (e.g., domestic water supply, irrigaiton, aquaculture, hydropower, recreational) of stored water as the multi-functionality of the dam operations can contribute to several development goals simultaneously, such as energy, water and food security, economic development, and climate resilience. In this line, it is as important to develop recreational and eco-tourism activities along the dam and reservoir (e.g., boating, site seeing, hotels) to build a notion of heritage and generate additional revenue streams for the investment.

Rwanda also has several forms of natural surface storage, in lakes and wetlands. Preserving or restoring this green infrastructure is clearly a more cost-effective strategy, where possible, and should therefore be prioritised above any new artificial (grey) storage infrastructure. A good example is Lake Mugusera: this lake has a recognised important regulatory function in the system currently, but also will face increasing pressure on its related water resources and ecological values. Planned irrigation developments will need to adjust, and consider these values, for example by establishing buffer zones which go beyond the current practice (50 meters) and control these, besides other measures.

To make optimal use of this natural storage infrastructure, though, it is important to acknowledge that any type of storage infrastructure (artificial or natural) has a certain amount of unusable or dead storage. For some of the Rwandan lakes (e.g. Burera and Ruhondo), this dead storage is very high: a significant amount of water cannot be managed and cannot be considered active storage[6]. Therefore, assessing

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[1] Walid Maherzi and Farouk Ben Abdelghani, 'Dredged Marine Sediments Geotechnical Characterisation for Their Reuse in Road Construction', *Engineering Journal* 18, no. 4 (16 October 2014): 27–37, https://doi.org/10.4186/ej.2014.18.4.27.
[2] Abdelhafid Kasmi et al., 'Environmental Impact and Mechanical Behavior Study of Experimental Road Made with River Sediments: Recycling of River Sediments in Road Construction', *Journal of Material Cycles and Waste Management* 19, no. 4 (October 2017): 1405–14, https://doi.org/10.1007/s10163-016-0529-5.
[3] Yang Xu et al., 'The Use of Urban River Sediments as a Primary Raw Material in the Production of Highly Insulating Brick', *Ceramics International* 40, no. 6 (July 2014): 8833–40, https://doi.org/10.1016/j.ceramint.2014.01.105.
[4] Brennda Bezerra Braga et al., 'From Waste to Resource: Cost-Benefit Analysis of Reservoir Sediment Reuse for Soil Fertilization in a Semiarid Catchment', *Science of The Total Environment* 670 (20 June 2019): 158–69, https://doi.org/10.1016/j.scitotenv.2019.03.083.
[5] Katja Walter, Günter Gunkel, and Nadia Gamboa, 'An Assessment of Sediment Reuse for Sediment Management of Gallito Ciego Reservoir, Peru', *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use* 17, no. 4 (December 2012): 301–14, https://doi.org/10.1111/lre.12008.
[6] FutureWater 2021, Bio-Physical Assessment and Hydrological Analysis for Mukungwa and Akagera Lower catchments in Rwanda

the active storage capacity of the country’s natural storage infrastructure (lakes and wetlands) is recommended. Natural lakes also have a role in buffering water, mitigating floods and making water available during dry seasons. Lakes also help to control sediments in streams and therefore protect downstream infrastructures.

Recommendations:

- Existing dams should be investigated to assess impact of sedimentations and those most impacted should be upgraded to restore or even increase further their storage capacity. The upgrade should include financing an integrated plan to manage sediments, as for new dams.
- Rwanda needs to increase its storage capacity. This study has suggested a list of prioritised dams, to develop new storage reservoirs (grey infrastructure).
- Any new infrastructures, or upgraded existing dams, should be associated with an integrated plan to manage sediments, to extend the lifetime of new projects. This plan should also be applied to existing infrastructures and should cover: (i) soil and water conservation measures (NbS) in the upstream catchment, (ii) regular maintenance to remove sediments from the reservoir and (iii) economic valorisation of collected sediments in civil engineering and agriculture.
- The integrated sediments management plan should be accounted for in the CAPEX and O&M costs.
- Multi-purpose dams are preferred as the multi-functionality of the dam operations can contribute to several development goals simultaneously, such as energy, water and food security, economic development, and climate resilience.
- As a form of multi-purpose use, developing recreational and eco-tourism activities along the dam and reservoir (e.g., boating, site seeing, hotels) can build a notion of heritage and generate additional revenue streams for the investment.
- There is also the potential to make better use of natural (green) infrastructure. An assessment of the active storage capacity of lakes and wetlands is needed.

Underground storage (groundwater)

Groundwater has the potential to address some of the water supply-demand gaps. Aquifers store the water they receive from recharge, release it through springs and discharge it to rivers (baseflow). This natural process can be stimulated by sustainable land management measures that increase natural recharge, in addition to slowing the water runoff and regulating river flows.

The full potential groundwater in Rwanda is not yet fully understood. This study has provided an updated estimate of groundwater storage capacity, using regional studies coupled with latest data from wells and specific field surveys. So far, estimates of groundwater storage/potential range from 6 BCM per year (REMA, 2015[1]) to more than 10 times that amount over 60 BCM in the 2015 NWRMP. This study concludes that total groundwater storage capacity is approximately of 81 BCM (see section 1.2.8.2, p76).

Similar to a surface water reservoir, the amount of water which can be exploited sustainably from aquifers, depends on the renewable water flowing into the system (groundwater recharge), and the discharge from the system groundwater discharge to the river or wetlands), considering the environmental values and water uses attached to this discharge. This study has estimated the groundwater recharge on average at around 3,500 MCM/year. Which part of this can be sustainably pumped from the aquifers, where and where not, depends on the characteristics and dynamics of the aquifers, which require detailed studies.

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[1] REMA, ‘State of the Environment and Outlook Report’ (Kigali: Rwanda: Rwanda Environment Management Authority, 2015).

Using groundwater as a form of natural storage has certain advantages compared to surface water reservoirs, especially reduced evaporation losses and, depending on the aquifer characteristics, more localised access. However, it is crucial to realise that the aquifers play a crucial role in regulating surface water flows (through baseflow) and that groundwater withdrawals may have unintended consequences on downstream water users, which may face more irregular surface water flows. So for Rwanda to take advantage of this and pursue the effort to assess groundwater potential, there is a need to invest in a detailed assessment of the groundwater flows in the relevant aquifers.

In some areas, it is feasible to boost the function of the groundwater body further to retain and buffer water, by implementing artificial recharge, also called Managed Aquifer Recharge. However, the potential of this technology, and its associated costs, need to be studied locally, as it is highly dependent on the climate and the hydraulic groundwater properties and flows.

Consultation with WASAC revealed that groundwater is considered as an important opportunity for water supply distribution due to two main factors. First, surface water is costly to treat. Second, in some areas, surface water is unavailable or not enough to satisfy the water supply demand, as is the case in the eastern part of Rwanda.

Groundwater can be an affordable option, particularly with the possibility of solar pumping, if initial capital costs can be subsidised for the poor. Solar-powered water systems have become significantly and increasingly attractive for countries like Rwanda, as a reliable and clean solution for agricultural and domestic water supplies, especially in areas with high-incident solar radiation. However, it has also been observed in other parts of the world that solar pumping can lead to overexploitation of groundwater, creating conflicts among users and environmental impacts. Solar pumping must therefore be accompanied by control and monitoring systems.

The private sector might play a role in understanding potential groundwater yields and economic value. Furthermore, the private sector could also bring technical capacity and financial resources to support groundwater extraction and the maintenance of pumps and associated infrastructures. Where groundwater offers a more accessible and reliable supply to private firms, albeit at a flow rate usually lower than from surface water resources, it might be an attractive option for industries or mining. However, the expansion of groundwater use through the private sector would also need to be accompanied by strong licensing and monitoring systems to ensure withdrawals remain sustainable.

Groundwater levels and abstractions can be monitored reliably using ground-based equipment: either mobile using surveys or with fixed equipment installed in wells. Indirect techniques using remote sensing can yield relevant results, as is the case for example for the recent study from UNICEF (2022)[1] , which identified zones of high potential for groundwater in Southeastern Rwanda.

Recommendations:

- Groundwater is relatively unknown and little used in Rwanda. This study attempted to bring additional knowledge but relied predominantly on sparse information and assumptions. Therefore, dedicated studies and surveys are required to understand groundwater (e.g., storage, availability, quality).
- Once groundwater is better known, the benefits and challenges of Managed Aquifer Recharge (MAR) in Rwanda should be investigated.
- Groundwater can potentially improve the coverage of water demands, especially for drinking water, and possibly irrigation. A prerequisite before promoting greater exploitation of groundwater is to establish a cap on groundwater abstractions, consistent with the renewal rate

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[1] UNICEF, 'Mapping of Groundwater Potential in Southeastern Rwanda' (UNICEF, 2022).

of the groundwater (i.e. the rate of abstraction should be less or at maximum equal to groundwater recharge). Due consideration should also be given to the impacts of increased abstraction on groundwater discharge to the river (baseflow), dependent users (surface water withdrawals for domestic, industry and irrigation), and the environment.

- A strict licensing (water and drilling permits) and monitoring system should be implemented for groundwater abstractions, given the decentralised nature of groundwater exploitation, taking lessons from experiences elsewhere (e.g., groundwater user associations).
- Solar groundwater pumping has great potential for decentralised / communities exploitation of groundwater. However, existing implementations elsewhere have shown that solar pumping has to be strictly licenced and monitored.
- Due to the extended nature of the groundwater resource, local communities and the private sector can contribute to understanding and monitoring groundwater resources.
- In line with the previous recommendation, open information systems on groundwater should be shared with key stakeholders, similarly to the current water portal from RWB.
- The use of satellite-based technologies to monitor groundwater is emerging. Its application to Rwanda should be investigated, as was recently the case with the study UNICEF (2022)[1].

Source water protection and Payment for Ecosystem Services

Ecosystems provide a wide range of essential services to ensure freshwater supply. However, despite the obvious importance of ecosystems to human well-being and biodiversity, they are constantly being degraded. The increasing demand for natural resources like timber, fuel, fiber, freshwater and food, has resulted in considerable losses in the diversity of life on earth. The growing production of natural products has, indeed, contributed to economic development and important gains for human well-being. But on the other hand, it has caused substantial degradation of ecosystems and their services, raised poverty of large groups of people, and increased risks for future generations whose livelihoods depend equally on ecosystem services (IUCN, 2009[2]).

Water security in particular, or ensuring that water supply is reliable and of good quality, is increasingly important to the health and resilience of the people and the overall economy of Rwanda. Effective planning and implementation of water source protection efforts require a clear understanding of risks to drinking water supply. Consultation with WASAC confirmed, for instance, that siltation and sedimentation of the existing water supply storage dams are affecting the performances. This is mainly a result of human activities (e.g., agriculture, mining) upstream and catchment being not protected to avoid soil erosion. REG/EDCL also reported that they are impacted negatively by water pollution from mining companies. Planning should therefore include the motivations and incentives that influence primarily the communities, private sector actors, and civil society stakeholders to prioritise, plan and implement water source protection.

The relationship between rural communities' livelihoods and ecosystem services is extremely interwoven (Tallis et al. 2011[3]). The predicament of rural poverty can arise from unsustainable use or depletion of natural resources, but also from environmentally degrading practices of rural population that contribute to their poverty. The adoption of Payment for Ecosystem Services (PES) could contribute to addressing the combined challenges of rural poverty and environmental degradation (Klein, 2020[4]). PES constitutes

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[1] UNICEF, 'Mapping of Groundwater Potential in Southeastern Rwanda' (UNICEF, 2022).

[2] Thomas Greiber et al., eds., *Payments for Ecosystem Services: Legal and Institutional Frameworks*, IUCN Environmental Policy and Law Paper, no. 78 (Gland, Switzerland: IUCN, in collaboration with the IUCN Environmental Law Centre, Bonn, Germany, 2009).

[3] Peter Kareiva et al., eds., *Natural Capital: Theory and Practice of Mapping Ecosystem Services* (Oxford University Press, 2011), https://doi.org/10.1093/acprof:oso/9780199588992.001.0001.

[4] Mariel Klein, 'An Evaluation of Payment for Ecosystem Service Models Implemented in Areas of Rural Poverty in China, Rwanda, Zimbabwe, and Mexico', *Life: The Excitement of Biology* 8 (31 August 2020): 77–104, https://doi.org/10.9784/LEB8(2)Klein.01.

one of the pillars of Rwanda's vision 2050, which sets the country's vision for its economic transformation and development agenda. Recently, Rwanda and Costa Rica signed a Memorandum of Understanding on environment cooperation that will specifically focus on exchanging experiences on PES. There are other examples of successful funding schemes for protecting sources of urban drinking water. Two specific examples are the Nature Conservancy's Water Fund Model in Nairobi and Peru's green infrastructure investments through utility tariffs. In many cases, the effectiveness of funding modalities for water source protection can depend on stakeholder buy-in and willingness to pay as well as fund management (e.g. how resources are raised and allocated). In the institutional context of East Africa, Namirembe et al. (2018[1]) note that uncertain financing and the need to align with existing watershed management frameworks constrain the range of effective designs, with broadly targeted PES schemes generally performing better than ones directed at individual farmers.

In 2018, through the Water for Growth Program, a proposal for a PES scheme was elaborated to address the national imperatives of food, water, biodiversity and energy security within the context of sustainable livelihoods and the optimisation and expansion of existing and available natural, human and financial resources.

PES can contribute to stopping the loss of topsoil. This can help farmers gain a sustainable income while sustaining the surrounding environment. Mining is another sector where PES should be explored further. Small-scale mining in Rwanda has local impacts on water quality, especially on river sedimentation, with potential for heavy metals (lead, cadmium, zinc, copper) to accumulate in soils and enter the food chain, especially in floodplains used for agriculture and irrigation. Going beyond individual sectors, a synergetic approach to funding for PES should involve all sectors and development partners: local entities such as water utilities and hydropower facilities dependent on reliable water flows; international actors such as countries or utilities seeking to offset carbon emissions (e.g. Clean Development Mechanism under the Kyoto Protocol), tourist operators dependent on biodiversity, government agencies, and nongovernmental organisations.

Government of Rwanda's efforts to solve the water scarcity problem have mostly focused on expanding and rehabilitating the physical infrastructure and law enforcement. Even if the will and efforts towards environmental management remain unwavering, more environmental actions shall always be welcomed. The failure of water and electricity utilities to cover their investment and operational costs, and the difficulty of households to afford these services have led the government to subsidise the production and consumption of water and electricity constantly. The problem of increasing supply-side costs and the failure of past policies to inspire appropriate sustainable environment management opens the opportunity to use economic incentives for ecosystem services to ensure regular flows of water resources. PES can be a valuable tool to incentivise positive change, such as at Bijyojyo, Mbobo and Gatumba (in the Upper-Nyabarongo catchment).

The chosen institution to manage PES in Rwanda may be a government body, a local community group, an individual, or an intermediary body such as a local NGO. The entity must have adequate administrative and technical capacity to manage and sell the ecosystem services. It is crucial to determine who will be the staff member or responsible person(s) to liaise on the production of the service, identification of the market and buyer, the sale itself, and the disbursement of any revenues received (IUCN, 2009[2]). PES should be funded by different sectors benefiting from ecosystem services, proportionate to their respective financial capabilities. FONERWA would logically be the appropriate

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[1] S. Namirembe, J.K Mwangi, and J.M. Gathenya, 'Institutional Considerations in Payments for Watershed Ecosystem Services in East Africa', in *Co-Investment in Ecosystem Services: Global Lessons from Payment and Incentive Schemes*, ed. S. Namirembe et al. (Nairobi, Kenya: World Agroforestry Centre (ICRAF), n.d.).

[2] Greiber et al., *Payments for Ecosystem Services*.

government body to receive funds from different streams and sectors to finance the different players in PES schemes.

It is worth noting that PES requires strong regulatory, monitoring and accountability mechanisms, along with technical skills to be effective. There are successful cases in Africa (see section 3.4.2.1, p196) for discussion on some examples), but PES programs alone cannot reduce the poverty of rural farmers in Rwanda.

Recommendations:

- It should be explored how the PES scheme could operate within the context of at least four immediately pathways:
  - PES schemes address national security concerns of food, water, biodiversity and energy;
  - They do so by identifying one key place to intervene in the system, namely soil health;
  - Soil, together with other factors such as water, can be classified as replenishable natural capital and it forms the basis for all terrestrially-based ecosystem services;
  - Ecosystem services that will benefit from enhanced soil health and a reduction in soil movement include soil productivity, increased carbon sequestration, improved soil water retention, reduction of damages due to natural disasters, improvement in human health, a reduction in water treatment cost, etc.
- PES programs should be integrated with other rural development initiatives to increase incomes with particular emphasis on restoring, or preserving, ecosystems and raising awareness of the importance of ecosystem services.
- There is need to explore other complementary initiatives to PES specifically in the mining sector and this can build on the piloted Enterprise Partnership Initiative (EPI), under the Water for Growth Program, which provided subsidies to private sector initiatives to promote integrated water resources management. Most of the funded projects were small-scale mining projects. Documenting the lessons learned from this initiative is crucial to inform any follow-up PES scheme.
- Going beyond a particular individual sector, a synergetic approach to funding for PES should involve all sectors and development partners.
- FONERWA would logically be the appropriate government body in Rwanda to receive funds from different streams and sectors to finance PES schemes.
- PES could help shape a private sector response that also has a bearing on land use practices to manage erosion and flooding and provides some water storage solutions. The Government also needs to reflect through a water lens on the different strategies of sticks and carrots that lead to more efficient water use and investment portfolio management. Multi-Stakeholder Partnership could be an ideal forum to explore these different approaches and reach some consensus on the way forward.
- PES nevertheless require strong regulatory, monitoring and accountability mechanisms, along with technical skills to be effective. There are successful cases in Africa, but PES programs alone cannot reduce the poverty of rural farmers in Rwanda

Flood control

Climate change is likely to affect future flooding patterns. More extreme events are likely and the degree of damage from these events relates to land cover. In compromised landscapes, intense rainfall can lead to erosion that further degrades the landscape leading to potential flash floods over time and more erosion.

Investment in flood-mitigating infrastructure in Rwanda is crucial as the climate continues to change. As presented in a recent publication by the World Bank Group on the climate risk profile for Rwanda, rainfall trends have shown an increased occurrence of extremes since the 1960s across various regions of the country. Over this period, Rwanda's eastern region has experienced frequent dry episodes. In the northern and western provinces, rainy seasons are becoming shorter and more intense, resulting in increased erosion risk in these mountainous areas of the country (WB, 2021). The same report indicates a likely increase in annual rainfall, with the increase likely to occur during the main rainy season, December to April, with drier tendencies from July to September. The intensity of heavy rainfall is expected to increase from +3% to +17% and the frequency is expected to increase from +9% to +60% by the end of the century. Therefore, Rwanda needs to invest in increasing the technical capacity and skills to predict possible flood impacts that may arise from the projected climate variability and to design adequate mitigation measures. Although conventional flood-mitigating infrastructures may be beneficial, consideration should also be given to the role of natural landscapes, such as forestland, in mitigating or lowering the risk of extreme flooding in Rwanda.

Recommendations:

- Increase the technical capacity to understand and predict flood patterns under a changing climate.
- Implement early-warning systems to react in time to unfolding events. This implies a whole chain of processes which need to be effective, with real-time monitoring, dissemination and communication, and the capacity of local authorities and communities to respond adequately.
- Explore the flood mitigating measures through a mix of grey infrastructures (e.g., new multi-purpose dams) and nature-based solutions.

Smart association of hydropower and solar energy for electricity production

Hydropower is essential in Rwanda as it generates almost half of the total production. Solar, however, currently has a small role in the energy mix, while it can be smartly associated with hydropower production to reduce the burden on the latter (Sterl et al., 2020[1]). Solar energy can, for instance, produce electricity during the mid-day peak in demand. Synergies between solar and hydro electricity generation should therefore be explored in Rwanda. One promising approach is to use floating PV panels in the reservoirs of hydropower plants (Sanchez et al., 2021[2], Farfan and Breyer, 2018[3]): the reservoir surface provides areas for PV deployment, reducing the burden on lands, the cooling provided by the water increases the PV panels' efficiency, and floating PV reduce evaporation from the reservoir. Another opportunity to use floating PV is in Pump-Storage Power Plants, to power the water pumping back to the upper reservoir.

Recommendations:

- Increase the use of solar energy and its synergies with hydropower, to reduce the burden on the latter.
- Explore in particular the use of floating PV panels in the reservoirs of hydropower plants.
- Solar energy could be well suited to Pump-Storage Power Plants.

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[1] Sebastian Sterl et al., 'Smart Renewable Electricity Portfolios in West Africa', *Nature Sustainability* 3, no. 9 (1 September 2020): 710–19, https://doi.org/10.1038/s41893-020-0539-0.

[2] Rocio Gonzalez Sanchez et al., 'Assessment of Floating Solar Photovoltaics Potential in Existing Hydropower Reservoirs in Africa', *Renewable Energy* 169 (1 May 2021): 687–99, https://doi.org/10.1016/j.renene.2021.01.041.

[3] Javier Farfan and Christian Breyer, 'Combining Floating Solar Photovoltaic Power Plants and Hydropower Reservoirs: A Virtual Battery of Great Global Potential', *Energy Procedia* 155 (November 2018): 403–11, https://doi.org/10.1016/j.egypro.2018.11.038.

3.3.1.2 *Demand-side guidelines*

PPP for Water supply

Growing urban populations are putting increased pressure on drinking water supplies, requiring expansion of existing infrastructure and better management of existing systems. Addressing water management and demand issues, were discussed in detail in section 2.3 (p122).

The last two decades have seen a rise in Public Private Partnerships (PPP), implemented in more than 134 developing countries, contributing about 15–20 percent of total infrastructure investment. As a result, many developed and developing governments are now seeking to tap the private sector's expertise and capital to minimise their infrastructure, human capital, and technological deficits (Osei-Kyei & Chan, 2015[1]). The rationale for governments to engage in PPP is three-fold: (i) to attract private capital investment (often to either supplement public resources or release them for other public needs); (ii) to increase efficiency and use available resources more effectively; and (iii) to reform sectors through a reallocation of roles, incentives, and accountability (ADB, 2022[2]).

In terms of investment in new infrastructures, Rwanda has already started looking beyond traditional government and donor finance sources. For example, in Kigali, a Build, Operate and Transfer (BOT) arrangement was designed, in which the private investor financed the design, construction, and operation of the water production and treatment facilities. The Metito consortium successfully won the contract in November 2017 and agreed to invest US$ 75 million in the development of the scheme and its operation for 25 years. This case is the first-ever Bulk Surface Water Supply PPP Project in Sub-Saharan Africa (South Africa excluded). The plant was officially launched in February 2021 and has a total capacity of supplying 40 million litres a day of potable water. Examples and details on requirements for PPP are discussed in section 3.4.1 (p194).

Recommendations:

- Additional learning is needed from the innovative PPP scheme between Metito consortium and the Government of Rwanda. This should serve to replicate such capital-intensive infrastructure projects in other cities and other water-related infrastructure and service delivery in Rwanda.

Supplementary irrigation for rainfed agriculture

Given that rainfed agriculture is a relatively small part of the overall economy, it is unlikely to show significant shifts in macroeconomic variables or watershed hydrology. However, it can substantially impact livelihood security in dry areas, reducing migration patterns at a relatively low cost. In addition, the modelling in this assignment has shown that not all irrigation expansion planned for in the Irrigation Master Plan is feasible, even with additional storage. In particular, hillside irrigation may not be feasible in all locations, considering the energy costs it may bring to pump water to higher areas. Consequently, supporting rainfed agriculture with improved water and agronomic practices may be a more cost-effective alternative, even though the productivity will typically be lower than in areas under full irrigation.

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[1] Robert Osei-Kyei and Albert P.C. Chan, 'Review of Studies on the Critical Success Factors for Public–Private Partnership (PPP) Projects from 1990 to 2013', *International Journal of Project Management* 33, no. 6 (1 August 2015): 1335–46, https://doi.org/10.1016/j.ijproman.2015.02.008.

[2] 'A Governance Approach to Urban Water Public–Private Partnerships: Case Studies and Lessons from Asia and the Pacific' (Asian Development Bank, 1 March 2022), https://doi.org/10.22617/SPR220100.

Instead, water productivity of rainfed agriculture can be further promoted. In this respect, supplemental irrigation and rainwater harvesting are key to promoting improved and sustainable land management practices. Furthermore, irrigation development can support rainfed farmers in climate adaptation by overcoming dry spells and boosting crop yields.

Studies in dry regions within Rwanda have shown that supplemental irrigation can lead to higher maise yields (Kannan et al., 2011[1]; Uwizeyimana et al., 2018[2]). Supplemental irrigation can provide rainfed agriculture with the ability to bridge dry spells during critical stages of the life cycle of crops. Given that much of rainfed agriculture can be at the level of subsistence, this technique can provide some degree of insurance against short dry periods and shifts in rainfall patterns due to climate change.

However, Rwanda's irrigation development typically results from government-led initiatives and donor support. Few irrigation projects have been initiated by private commercial farmers and smallholder farmers. Farmer Led Irrigation Development is not new in the country; in 2015, the GoR launched the Small-Scale Irrigation Technology (SSIT) subsidy program, intending to support smallholder farmers in overcoming the financial, knowledge and technology constraints associated with small-scale irrigation development. The main component of the SSIT program is the provision of a partial subsidy for farmers to acquire small-scale irrigation kits. The subsidy part of the SSIT program has been developed to promote widespread use of demand-driven, affordable, and locally assembled irrigation technologies; it is a technology-driven intervention where farmers are supported to acquire small-scale irrigation equipment, such as portable diesel/petrol pumps and hose pipes, solar-driven irrigation units, treadle pumps and dam sheets. The goal is to develop 25,000 ha of newly small-scale irrigated land by 2024 with an annual budget of around 1.15 billion RwF [3], and increase the total irrigated area to about 550,000 ha by 2050[4]. Between 2015 and 2021, the program supported the development of 17,000 ha of small-scale irrigation[5].

To facilitate access to SSIT kits, the GoR concluded contracts with private irrigation service providers (SSIT equipment suppliers/companies) operating across the country. Drip irrigation is one of the SSIT technologies promoted in the country through the SSIT subsidy program. It is a low-cost technology whose interdiction can help mitigate the impact of rainfall variability that small-scale farmers experience; it conserves water as it applies water directly to the roots, minimising runoff and evaporation. At the plot level, this can lead to significant water savings for the farmer, compared to surface irrigation. At the system level (community, irrigation system, or sub-basin level), the actual savings may be much more limited. This is due to the importance of considering return flows. Traditional surface irrigation can be considered poorly efficient at the plot level, but still very efficient at a large scale, as the infiltrated irrigation water recharges the groundwater and can be exploited by other users. Another issue with drip irrigation is that, instead of maximising water use efficiency, farmers tend to maximise the water they access by enlarging their irrigated area or intensifying their cropping cycles, especially if they have to invest in the drip irrigation technology. Consequently, the amount of water extracted from the system is eventually not reduced.

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[1] Narayanan Kannan et al., ‘Effect of Irrigation Regimes Under Different Doses of Organic Manure on Maize Crop in Isae Farm at Rubirizi, Rwanda’, *International Journal of Ecology and Development* 20 (1 January 2011): 44–59.

[2] Dieudonne Uwizeyimana et al., ‘Effect of Water Conservation Measures on Soil Moisture and Maize Yield under Drought Prone Agro-Ecological Zones in Rwanda’, *International Soil and Water Conservation Research* 6, no. 3 (September 2018): 214–21, https://doi.org/10.1016/j.iswcr.2018.03.002.

[3] MINAGRI. 2018. Rwanda’s Strategic Plan for Agriculture Transformation phase 4 (PSTA 4).

[4] MINAGRI. 2020. Update of the Rwanda Irrigation Master Plan. Ministry of Agriculture and Animal Resources. Republic of Rwanda.

[5] World Bank (2021). Assessment of Small-Scale Irrigation Technology Program. Draft Report by Resilience BV

Because of these pitfalls around irrigation technologies, FAO and FutureWater[1] have recently launched a report which coins the concept of *Real Water Savings*. FAO recommends that any irrigation investment project accounts for the water flow in the entire system, instead of purely at the plot level.

Recommendations:

- Apply supplemental irrigation to provide rainfed agriculture with the ability to bridge dry spells during critical stages of the crops' life cycle. This can be done via rainwater harvesting through small storage structures (typically 100-1,000 m3).
- Continue to support and encourage smallholder farmers to adopt Small-Scale Irrigation Technology (SSIT). This shall support farmers in climate adaptation by overcoming dry spells and boosting crop yields. The technical support in SSIT should be accompanied by regulatory, monitoring and enforcing mechanisms to ensure that SSIT does not increase water consumption but water efficiency.
- There is a need for Rwanda to enhance the productive use of water with a systemic perspective: instead of solely focusing on increasing water efficiency at the farmer level, consider the dependencies between water users and the role of return flows. It requires, for instance, to:
    - Increase the capacity of stakeholders in the irrigation and agricultural sector on the concept of *Real Water Savings*[2];
    - Accompany any irrigation investment plan with water accounts;
    - Implement caps on water withdrawals and control mechanisms so that targeted water savings of irrigation projects materialise and benefit water users and uses downstream.

Increased water productivity in large irrigation schemes and industrial systems

There is scope to achieve higher production rates in irrigated and industrial systems in Rwanda using water-efficient technologies. In the irrigation sector, technologies exist to improve irrigation efficiency and water productivity. These improved techniques can range from low-cost interventions ensuring that irrigation better matches the water requirements (e.g., irrigation advisory, capacity building, information systems) to more investment-intensive technologies, like drip irrigation. A low-cost example of a climate-smart water-saving practice for rice – currently largely irrigated in furrows - is Alternate Wetting-Drying (AWD) irrigation. It has been seen that water reduction rates range from 25-70 percent with the same production levels (Ishfaq et al., 2020[3]).

More costly irrigation techniques have the potential for areas where high-value crops are feasible, which depends on access to markets and physical conditions, as these technologies are more energy-demanding. These irrigation techniques and technologies must be accompanied by proper regulations, control and monitoring to prevent indirect and negative effects on the water resources situation occur. Also, the *Real Water Savings* concept developed by FAO and FutureWater, and the importance of a systemic view on water savings and flows, are considered critical when designing investment programmes around water savings. In many cases, targeted savings of investments have not been realised, by far, due to (1) the lack of consideration of flows, and return flows at the system level, and dependent users and uses, and (2) the incentive to the beneficiary of the investment to use the water saved for increasing production (rebound effect).

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[1] FAO and FutureWater, 2021, Guidance on realizing real water savings with crop water productivity interventions https://www.fao.org/documents/card/en/c/cb3844en/

[2] FAO and FutureWater, 2021, Guidance on realizing real water savings with crop water productivity interventions https://www.fao.org/documents/card/en/c/cb3844en/

With proper incentives around water pricing and enforcement, increasing water productivity can be a very cost-effective measure. Also, conservation agriculture can be very cost-effective in reducing total water losses and enhancing soil health and crop productivity.

Wastewater reuse in domestic (non potable uses), irrigation and industrial systems

Consultation with WASAC revealed that the corporation plans to construct more centralised wastewater treatment plants in Rwanda. However, WASAC representatives believe reusing wastewater for drinking is not viable as the treatment process to reach a potable level will require a lot of investment, operation and maintenance costs. But reusing treated wastewater for non-potable uses, such as cleaning and gardening, could be an additional potential expansion of the water supply. Reused water can be cost-effective and reliable but requires adequate monitoring to meet safety standards.

While wastewater treatment plants are often the responsibility of the local government or water utilities, there is an increasing interest within the private sector in recycling water, through recycling and reuse (Klemeš, 2012[1]). For example, Bralirwa Plc has constructed a new wastewater treatment plant for its brewery, which is expected to have a production capacity of over 210 m^3 per day. The new treatment plant costs €5.4 million to build and uses a two-stage process. Wastewater from the brewery is first treated under anaerobic conditions using bacteria to break down the organic matter into biogas. The biogas can be collected and used as a renewable energy source. The remaining effluent is then treated using aerobic bacteria before being returned to surface water. The Wastewater Treatment Plant treats the water to such a standard that it can now be discharged back into Lake Kivu in compliance with Rwandese environmental legislation. Today, there is a large range of technologies for recycling and reuse, many of which are well-established, with prospects for a future shift to viewing wastewater as a resource (Ranade & Bhandari, 2014[2]).

This approach both addresses any pollution issue and, in some cases, even ensures reduced reliance on intermittent public water supply.

Recommendations:

- Reusing treated wastewater should be explored for particular uses, such as non-potable domestic uses, irrigation and industrial processes.

Non-revenue water reduction

Water loss in municipal systems can be caused by physical losses, such as leaky pipes, and water diverted from the system for productive use. Revenue can be lost even when water is delivered to its intended users, through poor billing and collection systems, or poorly maintained meters. The Rwanda Utilities Regulatory Authority Statistics reports in March 2020 that non-revenue water (NRW) losses are on the order of 45 percent (as communicated by WASAC in 2022), so that for every cubic meter of water billed, 1.8 cubic meters are abstracted. Revenue losses are substantial, estimated to be around 26 million USD[3]. NRW losses of this magnitude also impact water security and energy consumption for pumping, transport, and treatment.

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[1] Jiří Jaromír Klemeš, 'Industrial Water Recycle/Reuse', *Current Opinion in Chemical Engineering* 1, no. 3 (August 2012): 238–45, https://doi.org/10.1016/j.coche.2012.03.010.

[2] Vivek V. Ranade and Vinay M. Bhandari, 'Industrial Wastewater Treatment, Recycling, and Reuse—Past, Present and Future', in *Industrial Wastewater Treatment, Recycling and Reuse* (Elsevier, 2014), 521–35, https://doi.org/10.1016/B978-0-08-099968-5.00014-3.

3 Calculations based on current water production by WASAC, the current water tariff and NRW reported by WASAC in 2022. The loss calculated is the revenue loss and does not include the production cost.

In economic terms, under Vision 2050, the domestic portion of the overall water demand is dwarfed by irrigation agriculture. However, NRW reduction is likely to be a worthwhile investment for domestic water utilities. A pricing model developed by Wyatt (2010[1]) showed that the optimal level of NRW prevention increases with the tariff rate. Accounting for the fact that Rwanda increased tariff rates substantially in 2019 for some customers but also keeping in mind that financial objectives must be balanced against social objectives (Marson and Savin, 2015[2]), it is worth exploring whether significant NRW reduction may be more cost-effective under the new rates.

Economic valuation

There is a wide range of possible economic incentives to induce changes in water demands, including subsidies, penalties, and tariffs. These can be used to incentivise more efficient water-using technologies across all sectors. Adopting the users' pay principle provides a basis for pricing and allocating scarce water among different users and sectors, which could help improve water use efficiency and reduce conflicts in sharing scarce water. At the same time, adequate water pricing for household use is vital to balance the basic right to water with the cost of providing services. Rwanda has lowered its water tariffs in recent years, which may help with one set of development objectives, but raise questions about cost recovery of water treatment and delivery costs for the commercial water suppliers, like WASAC and rural private operators..

In terms of having a bigger impact on water use, the pricing structure for irrigation is arguably more important. Several issues are involved in pricing irrigation water to achieve water use efficiency. These include pricing irrigation water without transfer of water rights, which could promote technical efficiency; transfer of water rights that could promote allocative efficiency; and incorporation of environmental costs, which could promote ecological efficiency. In addition, water productivity is not constant over the growing season; consequently, the economic value of water also highly varies. Therefore, the accepted basis for pricing irrigation water is to consider 'water' as one 'input' among others in the agriculture production system and charge for water based on the quantity used. Another approach is to charge for irrigation water based on output per area, i.e., irrigators pay a certain water fee for each unit of output they produce.

The Government also recognises the need for revenue to be generated for wider water management and protection activities, including pollution and downstream impacts. Taxes and fees for water and wider natural resource use create positive incentives to use the resource efficiently and improve its management. Conversely, taxes or fees placed on discharges to the environment can create a disincentive to continuing degradation or resource depletion. There are proposals in place for a new Water Use Fee Scheme in Rwanda that would be based on the value of water generated by various economic activities, including Drinking water supply, Wastewater treatment plant, Irrigation, Aquaculture, Mining, Hydropower generation, and Industries (coffee, tea, beverages). Such a fee structure would be implemented in conjunction with a more comprehensive water use permit system. Currently, only a small portion of the existing water abstraction sites and wells are officially registered in the permitting system.

Recommendations:

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[1] Alan Wyatt, ‘Non-Revenue Water: Financial Model for Optimal Management in Developing Countries’ (Research Triangle Park, NC: RTI Press, 2 June 2010), https://doi.org/10.3768/rtipress.2010.mr.0018.1006.

[2] Marta Marson and Ivan Savin, ‘Ensuring Sustainable Access to Drinking Water in Sub Saharan Africa: Conflict Between Financial and Social Objectives’, *World Development* 76 (December 2015): 26–39, https://doi.org/10.1016/j.worlddev.2015.06.002.

- A clear policy framework for water financing is needed to ensure the sustainability and long-term financial viability of integrated water resources management. The polluter pays principle provided for in the law No 49/2018 determining the use and management of water resources in Rwanda needs to be enforced. This principle is fundamental to many environmental policies worldwide, including Europe and the USA. Similarly, the users' pay principle should be adopted in Rwanda to provide a basis for water pricing and allocating scarce water resources among different users.

Reduce water pollution

A comprehensive water quality monitoring report for Rwanda (RWFA, 2019[1]) identified the following pollutants that are almost always at unacceptable levels: Dissolved oxygen (DO), Fecal coliform (F.C), Escherichia coli (E. coli), Total Suspended Solids (TSS) and Turbidity. The likely sources of this pollution are the sedimentation/siltation of water bodies caused by soil erosion, and poor sanitation systems and practices.

Improved water quality is essential to boost economic growth and alleviate poverty. Sustainable agriculture and mining practices can be an effective way to address soil erosion and this can be supported by a PES scheme, while appropriate sanitation can address the problem of microbial contaminants. In Rwanda, wastewater treatment still has opportunities for improvement. In a study by Theoneste et al. (2020[2]), the research team evaluated the performance of the Kacyiru Sewage Treatment Plant and its effluent impacts on the receiving wetland. The wastewater treatment at this plant was found to not comply with Rwanda's national standards requirements for domestic wastewater discharge. The recency of this study points to the relevance of the conversation around wastewater treatment improvement in Rwanda. The Water and Sanitation Corporation (WASAC) has initiated a process to rehabilitate and improve the management of wastewater treatment plants at various estates within the city of Kigali, including the Kacyiru estate, to improve their performance.

Umulisa et al. (2020)[3] evaluated the occurrence, residue levels, spatial distribution, and sources of Persistence of Organic Pollutants (POPs) in the Nyabarongo lower catchment in Rwanda. The results indicated that degradation products were major POPs and were detected in 44 samples (40 percent). The degradation ratios confirmed both the historical and recent application of Dieldrin, even though Rwanda banned the use of Dieldrin and other POPs, including pesticides, industrial products, and unintentional sub-products in 2002. The highest residues were detected close to Lake Muhazi and areas surrounding Kigali city, which points to the prevalence of these substances in Rwanda's urban areas. A more recent study on Rwanda's water quality by Umwali et al. (2021)[4] assessed the spatial-seasonal variation of water quality in relation to land use types in Lake Muhazi, Rwanda. Using the National Sanitation Foundation Water Quality Index, the results revealed a poor water quality status at the Mugorore and Butimba sites in the rainy season, then at Mugorore and Bwimiyange sites in the dry season. The study concluded that the level of water quality deterioration and the extent of the impact varies based on the area's characteristics with a wide range of possible changes in Land Use. These changes include removing forests, increasing cropland, substituting grasslands, and urban expansion

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[1] RWFA, 'IWRM Programme Rwanda Water Quality Monitoring in Rwanda Final Report' (Kigali, Rwanda: Rwanda Water and Forestry Authority, 2019).

[2] Sindikubwabo Theoneste, Nsanzumukiza Martin Vincent, and Nshimiyimana François Xavier, 'The Effluent Quality Discharged and Its Impacts on the Receiving Environment Case of Kacyiru Sewerage Treatment Plant, Kigali, Rwanda', 29 February 2020, https://doi.org/10.5281/ZENODO.3692398.

[3] Viviane Umulisa et al., 'First Evaluation of DDT (Dichlorodiphenyltrichloroethane) Residues and Other Persistence Organic Pollutants in Soils of Rwanda: Nyabarongo Urban versus Rural Wetlands', *Ecotoxicology and Environmental Safety* 197 (July 2020): 110574, https://doi.org/10.1016/j.ecoenv.2020.110574.

[4] Edovia Dufatanye Umwali et al., 'Spatio-Seasonal Variation of Water Quality Influenced by Land Use and Land Cover in Lake Muhazi', *Scientific Reports* 11, no. 1 (December 2021): 17376, https://doi.org/10.1038/s41598-021-96633-9.

on a large scale. Land-use change plays a critical role in the outcomes of water quality and must be considered as Rwanda continues its development strategy.

Countrywide water quality monitoring has not been consistent over the past years and this presents a big challenge in guiding decision-making. This was done in 2012 and 2019, covering all the level two catchments with more than 30 sampling sites and key physical, chemical and biological parameters. The two campaigns present similar findings whereby the parameters not meeting the surface water quality standards are mainly physical and biological, indicating that the main factors impacting water quality are soil erosion and inadequate sanitation.

Recommendations:

- Develop and implement a consistent water quality monitoring program to:
    - track any positive impacts arising from the efforts being made in soil erosion control and extract lessons learnt for future projects;
    - track any positive impacts in the area of waste water treatment and reuse;
    - leverage on the remote sensing satellite data to monitor soil cover and erosion risks;
    - identify erosion hotspots which need urgent interventions.

3.3.1.3 Legal, regulatory, and institutional strengthening

All the above interventions require effective legal, regulatory, and institutional mechanisms. Without the supporting governance structures, infrastructure will degenerate over time, and any allocation decisions will be undermined, leading to a less secure water future for Rwanda.

Investment in governance is as critical as any other aspect of water planning. The effective delivery of Vision 2050 will require strengthening the sector's water governance framework to help manage trade-offs across water users. Improvements in governance structures and regulation can increase accountability and improve the enabling environment for broader engagement, specifically in the private sector.

Rwanda's regulatory environment needs to be strengthened to maximise the engagement of the expanding number of stakeholders in the sector and wider economic development. The Rwanda Utilities Regulatory Authority (RURA) mandate is to regulate the provision of water and sanitation services to promote fair competition and oversee the efficient use of resources and quality of water services whilst Rwanda Water Resources Board is mandated to regulate the use of water resources.

Barriers need to be removed at several levels, including inadequate enforcement mechanisms to guide water use and management. The lack of established regulatory norms and standards, and their inconsistent enforcement, has increased the risk for private sector actors to engage in the sector and beyond. Furthermore, mechanisms must be implemented to facilitate broader policy discussions, so stakeholders feel engaged in decision-making. Platforms, e.g., Multi-Stakeholder Partnership, can also share knowledge and experiences to create a collaborative environment, promote innovation and maximise comparative advantages.

Rwanda would benefit from investments in data systems to track the use of water and measure the performance of institutions engaged in its distribution and use. Measuring institutions' performance will need to vary based on their responsibilities and roles in the sector, and as a result, a range of tools and indicators will need to be used. While the wider adoption and mainstreaming of the WEAP tool within the government systems and processes will add significant value to decision-making, the sector also needs systems to track how water resources are being allocated and that it is being priced effectively. To support this effectively, the sector needs to make a technological leap forward in the coming years to embrace innovation in information and communication technology.

Improvements in data could also support improvements in basin planning, which would in turn enable the more effective mobilisation, targeting and monitoring of resources in the sector. The Vision 2050 provides the Government with a platform to make strategic investment decisions and optimise scarce financial resources. Advancements in water-related data collection and management can further improve such systems. Increased clarity on investment needs and priorities can support dialogue with the private sector and enable Rwanda to tap the private sector's potential in skills, innovation and resources.

3.3.2 Catchment-level considerations

This section builds on the guidelines and recommendations proposed for the national level. This guidance does not apply uniformly in Rwanda and distinctions can be made for level-1 catchments. The following Table 72 summarises the specificities per level-1 catchment, with a scoring system. Different strategic water resources management options were proposed in the national guidelines, but only those that can be specified spatially are shown in the table.

Table 72: Catchment-specific strategic water resources management options extracted from the national guidelines. The scoring system characterises the relevancy of a particular measure as follows: not relevant or applicable (○○○), little relevant (●○○), moderately relevant (●●○), very relevant (●●●)

Strategic water resources management options			CKIV	CRUS	NAKL	NAKN	NAKU	NMUK	NMUV	NNYL	NNYU
Supply-side	1. Surface storage	1.1. Upgrade existing dams	○○○	○○○	●●●	●●○	●●○	●●○	●●○	●●○	●●○
		1.2. New dams to be developed by 2050	○○○	○○○	●○○	●●○	●●○	●○○	○○○	●●●	●●○
		1.3. Use natural lakes	●○○	●○○	○○○	●○○	○○○	●●○	○○○	○○○	○○○
	2. Groundwater	2.1. Conduct surveys	○○○	○○○	●●●	●●●	●●●	●●●	●●●	●●○	○○○
		2.2. Develop use for domestic water supply	○○○	○○○	●●○	●○○	●○○	○○○	●●○	●○○	○○○
		2.3. Develop use for small irrigation	○○○	○○○	●○○	○○○	○○○	○○○	●○○	○○○	○○○
	3. PES	3.1. In mining sector	●●●	●○○	●○○	●●○	●●○	●●●	●●○	●●●	●●●
		3.2. In industries	●○○	●○○	●○○	●●●	●●●	●○○	●○○	●●●	●●●
	4. Flood protection	4.1. Grey infrastructures	●○○	●○○	●●●	●○○	●●●	●○○	●○○	●●●	●●●
		4.2. NbS	●●●	●●●	●●●	●●●	●●●	●●●	●●○	●●●	●●●
		4.3. Early warning systems	●●●	●●●	●●●	●●●	●●●	●●●	●●○	●●●	●●●
Demand side	5. Domestic water supply	5.1. PPP	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
		5.2. Rainwater harvesting	○○○	●○○	●●●	●●●	●●●	○○○	●●●	●●○	○○○
	6. Reuse of treated domestic wastewater	6.1. For irrigation	○○○	○○○	●●○	●○○	●●○	○○○	●●○	●○○	○○○
		6.2. For industries	●○○	●○○	●●○	●●○	●●○	●○○	●●○	●●○	●○○
		6.3 For gardening	○○○	○○○	●●○	○○○	●●○	○○○	●●○	●○○	○○○
	7. Irrigation	7.1 Rainwater harvesting for supplementary irrigation	○○○	●○○	●●●	●●●	●●●	○○○	●●●	●●○	○○○

Strategic water resources management options			CKIV	CRUS	NAKL	NAKN	NAKU	NMUK	NMUV	NNYL	NNYU
	8. Monitor water quality	8.1. Monitor impact from soil erosion controls.	●●●	●●●	●○○	●●○	●○○	●●●	●●●	●●●	●●●
		8.2. Monitor improvement in domestic wastewater treatment.	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●

3.4 Requirements to set up a Private Public Partnership and Payment for Ecosystems services frameworks

3.4.1 Private Public Partnership (PPP)

3.4.1.1 Recent experiences of PPP in Rwanda

Rwandan national investment policy aims to expand PPPs to sectors that demonstrate a potential for sustainable development gains. PPPs are viewed as a suitable step to attracting both foreign and domestic investors to make investments in the provision of public goods and services. Investments planned to be carried out as PPPs are aligned with national priorities and are required to pass four gateway procedures during their investment cycle, including: the approval of full feasibility; the approval of implementation; implementation and monitoring; and the ex-post evaluation.

In 2004, Rwanda opted for PPPs to satisfy rural water supply demand. Official figures report that around 73% of rural water supply is provided through PPPs support. This was made possible by the Government of Rwanda policy decision to decentralise water services delivery and encourage the private operation of rural water supply throughout the country. The management model adopted gives a solid role to district government and can hence be considered as a real partnership for PPPs goods and services delivery. In 2016, the Law Nº 14/2016 of 02/05/2016 was enacted to govern all matters relating to PPPs.

PPP models in the water sector in Rwanda can vary across districts and range from a simple maintenance contract with a small company for one single source water supply to complex lease agreements for extensive piped networks with international companies. Private operators are responsible for operating, maintaining, and collecting revenues, while districts are given 10% of revenues to cover major infrastructure repairs or extensions. The Rwandan PPPs model is characterised by the following interesting features (UNICEF, 2015[1]):

- A strong national policy supporting PPPs for rural water services allows the private sector to develop and establish a clear model for PPP service delivery.
- The Federation of Private Operators provides the opportunity for cross-learning and capacity building.
- Private operators have experience working under both lease agreements and management contracts.
- Some public kiosks are sub-contracted to local community groups to run as income-generating activities. Operators reported that this system works better than employing water point attendants directly supervised by the manager.
- Bringing together many water supplies under one management contract works in the Rwanda context because the profit margin on gravity schemes is higher and subsidises higher operation and maintenance costs on pumped schemes.

PPP activities in rural water supply are of the type of management or lease contracts to distribute water and are thus not involved in any investments in the sector. There is a need for RDB to attract PPPs like METITO that contribute not only to water treatment and transmission but also to invest in water infrastructure to treat, store and access. The Rwandan water sector needs more PPP types like the Build- Operate-Own ("BOO") schemes in which private partners finance, design, construct, own and

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[1] UNICEF, 'Study into Relative Effectiveness of Public Private Partnership (PPP) Arrangements for Rural Water Supply', 2015, https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiB4P2Zoub5AhUe8DgGHbneCQIQFnoECAQQAQ&url=https%3A%2F%2Fwww.unicef.org%2Fesa%2Fmedia%2F2161%2Ffile%2FUNICEF-2015-PPP-RWS-Study-Report.pdf&usg=AOvVaw34mdQzJeC_3oY4etZ2xSZh.

operate an infrastructure facility or other asset to provide services. In the Build-Operate- Transfer ("BOT") contracts, private partners finance, design, and construct an infrastructure facility or other assets to provide services and maintain them for an agreed period, after which a transfer of the infrastructure facility or other assets is made to the government. In addition, there is an urgent need to pursue and attract PPPs to manage urban stormwater as most Rwandan cities and towns are expanding and are mostly built on mountains. PPPs to manage stormwater in mountainous areas and urban cities will ultimately help to protect water resources.

At the same time, high levels of Non-Revenue Water (NRW) and the gap between revenues and operational costs remain challenging in Rwanda.

3.4.1.2 Establishing appropriate legal, institutional, and policy Frameworks for PPPs

The implementation of PPP is based on the enactment of new laws. However, the legal work continues as the PPP process progresses. There is a need for the regulatory regime to change oversight arrangements for pricing, customer service, operations, and market structure. Any regulatory gaps should be filled or the PPP structure should be changed. Regulatory gaps mostly include: (i) more explicit regulations and requirements for private operators; and (ii) developing actual regulatory institutions (such as the inclusion of an independent regulator).

It is important that the roles of each institution involved in performance monitoring (boards, ministries, auditors, monitors) and regulation (ministries, regulators) should be described and justified by assigned authorities. In most PPP institutional arrangements, the private sector is engaged in undertaking activities in the public domain. The public sector becomes a regulator or monitor, playing a limited role in actual service provision, if any. However, most countries initially lack the institutions and institutional capacity required to organise, manage, and implement a PPP process. Existing institutions need to build capacity to take on new roles and new institutions often have to be created. Technical specifications of the proposed PPP project are defined and documented in terms of reference, and ultimately included in the PPP contract (ADB, 2022[1]).

PPP governance requires putting into place the enabling institutions, procedures, and processes surrounding PPPs. For this to happen, the government should play a critical role in the process and involve citizens and other stakeholders. Governance matters in PPPs, along with the quality of institutions and their effectiveness in translating policy into successful implementation. The six good governance principles that are widely recognised include (UN, 2008[2]):

1. A fair and transparent selection process by which governments develop partnerships.
2. Assurance that value for money has been obtained
3. An improvement of essential public services especially for the socially disadvantaged, and adequate training for those to be involved in the new partnerships.
4. Fair incentives to all parties and fair returns for risk takers, combined with the achievement of commercial success.
5. Sensible negotiation of disputes that assures continuation of services and prevents the collapse of projects and consequent public waste.
6. Enhanced security in the face of new threats and for general improvement in the safety of services provided under PPP arrangements.

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[1] 'A Governance Approach to Urban Water Public–Private Partnerships: Case Studies and Lessons from Asia and the Pacific' (Asian Development Bank, 1 March 2022), https://doi.org/10.22617/SPR220100.

[2] United Nations and United Nations, eds., *Guidebook on Promoting Good Governance in Public-Private Partnerships* (New York ; Geneva: United Nations, 2008).

PPPs require the active participation of all partners and their successful implementation relies on the effectiveness of the national legislative and regulatory structures. Thus, the government should endeavour to safeguard the public interest and the correct use of funds. Effective legal, regulatory and contractual conditions are crucial to PPP success but can only exist if supported by an efficient institutional structure which both facilitates PPP development and provides clear boundaries to protect the interests of all parties. Two principal models of intervention exist:

- The decentralised approach, that places responsibility at the regional level and within the concerned line Ministries.
- A more centralised approach, that is based on the establishment of one dedicated national PPP unit (RDB for Rwanda).

Furthermore, an institutional framework is required to allow the public sector to change from being a direct service provider to an independent regulator, manager and monitor (UN, 2008[1]).

On an implementation level, PPPs contracts should include clear key performance indicators (KPIs) including: (i) meter installation, (ii) survey of leak detection, (iii) use of electricity, and (iv) water supply continuity. Operators should be required to finance part of capital expenditures, be willing to bear reasonable billing and collection risks, and provide a realistic leasing fee to the PPP secretariat. Penalties should sanction any failures by the private operators to observe KPIs. Rapid efficiency gains and performance improvements in water distribution can be achieved when underpinned by policy commitment, political stewardship, and public sector capacity for monitoring. It is worth recognizing that while PPPs are relatively easy to garner private investment on the promise of annuity payments (based on performance), these projects can add to the fiscal burden in the future if not adequately de-risked (Lima et al., 2021[2]).

3.4.2 Payment for Ecosystems services (PES)

3.4.2.1 Examples of PES programs

The Returning Farmland to Forests Program (RFFP) has been hailed as the world's largest and most successful PES program. Implemented in China since 1999, RFFP was intended to support the dramatic decrease in levels of Chinese rural poverty not through agricultural intensification, but through converting farmland to forests, restoring native vegetation, and improving the quality of forest management (Li et al., 2020[3]). Farmers were regularly paid to convert the land through tree plantings and afforestation ultimately creating wealth and improving livelihood, as well as achieving ecological goals of improving biodiversity, controlling erosion, and sequestering carbon. Under RFFP, farmers are encouraged and compensated to convert their farmland either into an economic forest. The latter can be an orchard or plantation, that primarily produces fruits, nuts, edible oils, spices, medicinal plants or their derivatives, and industrial raw materials. It can also be an ecological forest which can produce ecosystem services such as timber, fuel wood, biodiversity production and conservation (Trac et al., 2013[4]). Since 1999, the RFFP scheme has helped poor Chinese to replace cropland with trees across 293,700 acres, and paid 32 million households about $52 million in government investments (Zinda & Zhang, 2019[5]).

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[1] United Nations and United Nations, eds., *Guidebook on Promoting Good Governance in Public-Private Partnerships* (New York ; Geneva: United Nations, 2008).

[2] Sónia Lima, Ana Brochado, and Rui Cunha Marques, 'Public-Private Partnerships in the Water Sector: A Review', *Utilities Policy* 69 (1 April 2021): 101182, https://doi.org/10.1016/j.jup.2021.101182.

[3] Ruida Li et al., 'Rural Household Livelihood and Tree Plantation Dependence in the Central Mountainous Region of Hainan Island, China: Implications for Poverty Alleviation', *Forests* 11, no. 2 (2020), https://doi.org/10.3390/f11020248.

[4] Christine Jane Trac et al., 'Environmental Reviews and Case Studies: Is the Returning Farmland to Forest Program a Success? Three Case Studies from Sichuan', *Environmental Practice* 15, no. 3 (1 September 2013): 350–66, https://doi.org/10.1017/S1466046613000355.

[5] John Aloysius Zinda and Zhiming Zhang, 'Explaining Heterogeneous Afforestation Outcomes: How Community Officials and Households Mediate Tree Cover Change in China', *World Development* 122 (1 October 2019): 385–98, https://doi.org/10.1016/j.worlddev.2019.05.020.

Another example is the celebrated “Vittel PES for water quality” in north-eastern France. Before the PES scheme, farmers in the Vittel catchment were starting to switch to an intensive maize-based agricultural system, which threatened to increase nitrate concentration in groundwater. To implement the PES program, Vittel invested around $9 million € to purchase 1,500 hectares of land above-market prices around its water springs. It then signed long-term (18 to 30 year) contracts with fourty farmers, compensating them for (i) discontinuing maize cultivation for animal feed and adopting extensive cattle ranching instead, (ii) replacing agrochemicals with composted manure and (iii) modernising farm buildings to reduce leaching of animal waste. As a result, water quality has been maintained. Regarded by some as a near-perfect example of a PES scheme, the Vittel case study demonstrates the importance of establishing a solid relationship with ecosystem service providers through active engagement (Smith et al., 2013[1]).

A pioneering self-sufficient PES scheme for improved ecosystem water services was implemented in Costa Rica to protect the water supply of the city of Heredia and its surroundings. In the 1990s, the proliferation of unplanned urban growth and the loss of adequate forest cover in five key watersheds within the Heredia catchment area in Costa Rica hampered the ecological functioning of the catchment, including the filtration and recharge of groundwater. A socio-economic study amongst the population in that area revealed that 90 percent of the interviewed customers supported the idea of their catchment restoration and were willing to pay up to 10-12 Costa Rican colones/m3/month (about USD 0.20). Since 2000, the public utility in that area started collecting money for a green fee to protect forests, equivalent to $0.20 per m3 of water used in the monthly water bill to all end-users, including residential, commercial, social, industrial and public institutions. The fee had a low impact even for relatively poor families as it only represented 1-2 percent of the initial bill. Financial resources mobilised from this water fee were used to compensate private landowners for the lost opportunity cost of converting forests on their lands (Ottaviani, 2011[2]).

In Tanzania, a PES scheme was implemented to curb siltation levels downstream of the Ruvu river watershed, while increasing the base flow. Smallholder farmers received payment for adopting agriculture practices to control runoff and soil erosion, while improving their crop production. A combined approach was being implemented that included vegetative (reforestation, agroforestry, pineapple contour farming, and grass strips), agronomic measures (intercropping crops with fruit trees, riparian restoration, mulching and fertilising with animal manure), structural (bench terraces) to limit runoff, combat soil erosion, and increase soil moisture and productivity. Payments were made based on how many hectares of land were converted and the type of agricultural and/or land-use practice adopted. During the three years of the program, farmers were responsible for looking after their trees, although they were free to grow crops between the trees. This is a good example of how a fair estimation of the opportunity costs constitutes a key factor in the design of PES schemes to ensure farmers' participation and their long-term involvement to meet the time scale requirements to restore the functionality of ecosystem processes (Ottaviani, 2011[3]).

Lastly, another example is the Water Funds implemented by The Nature Conservancy, which is a fund from public and private sources, to finance nature-based solutions and sustainable watershed management (Figure 125). The fund is operational in Kenya, in the Tana river basin, which supplies water to Nairobi. Funding streams from the capital refill the funds, which in turn finance activities in the upstream portion of the basin.

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[1] Smith, Steven and Rowcroft, Petrina and Rogers, Heather and Quick, Thomas and Eves, Chris and White, Chris and Everard, Mark and Couldrick, Laurence and Reed, Mark (2013) Payments for ecosystem services: A best practice guide. Technical Report. DEFRA

[2] Daniela Ottaviani, *Payments for Ecosystem Services and Food Security* (Rome: Food and Agriculture Organization of the United Nations, 2011).

[3] Ibid.

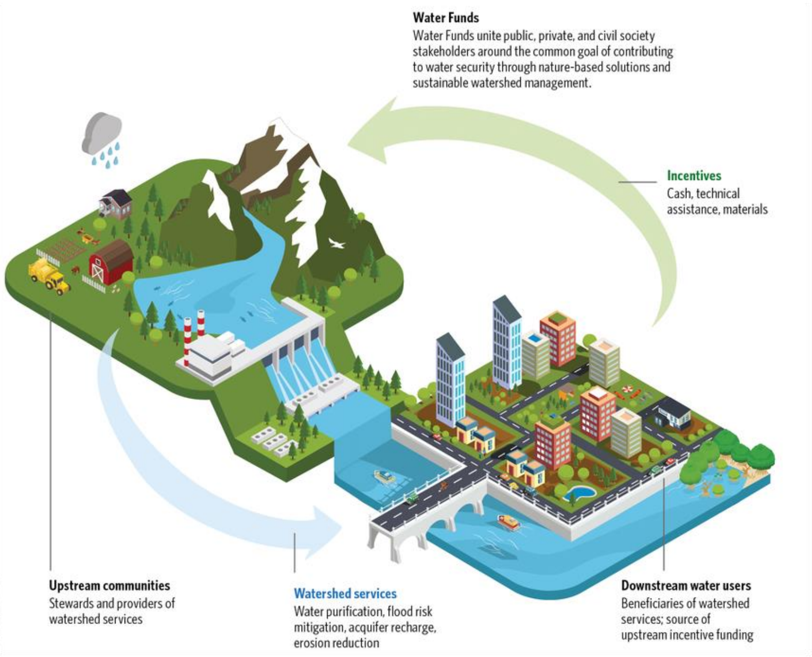

Figure 125: Scheme of the Water Funds implemented from The Nature Conservancy (source: https://waterfundstoolbox.org/)

3.4.2.2 Requirements for PES

To successfully implement PES programs, efforts should be made to reduce transaction costs associated with smallholder farmers. Local communities' institutions should play a role in facilitating participation and reducing these costs. PES programs also require ensuring institutional coordination to avoid contradictory policies or actions in land use and rural development. Studies and data collection are also needed to inform suppliers and beneficiaries about improvements to water quality due to conservation and restoration so that they can better understand and support management practices of upstream farmers. Due to the mutual interdependence between the environment and the economy, conservation programs should be integrated with economic development goals. Likewise, PES programs should be linked with rural development initiatives because the deterioration of the flow of ecosystem services will ultimately hinder economic development.

Since 2019, the GoR has put in place a plan of action and roadmap to guide the implementation of PES. This roadmap outlines how PES programs shall focus on soil conservation and landscape restoration to contribute to: (i) climate change adaptation through smart land management practices, and enhanced carbon sequestration; and (ii) reduce the losses linked to degradation and high-intensity climatic events. Achieving these objectives requires appropriate interventions in afforestation, terracing, agroforestry, marshland stabilization, and riverbank stabilisation.

Legal and institutional requirements

To facilitate the establishment of PES, an attractive legal environment for the private sector to participate, legally binding environmental standards, judicial and compliance review mechanisms, enforcement procedures and appropriate institutional frameworks should be provided.

The Government should review and, where appropriate, amend its legislation to ensure that there are no obstacles to establishing PES in all their diverse forms and scopes. Existing laws and regulations that may restrict the participation of public utilities in PES schemes should also be amended. Corporate and public laws, contracts, and procedural law should all provide a clear framework for establishing and implementing PES. The Governments should issue guidance regarding the law under which a PES management entity should most suitably be registered to be recognised as a corporate entity that can issue and administer the PES contract, the legal/institutional form(s) the entity may take, and the requirements it has to fulfil under the law.

Disputes arising in connection with the interpretation or application of legal agreements implementing PES, subject to national or international law, may be submitted to a competent court or tribunal. Therefore, PES administrators should have a legal personality to have locus standi before domestic courts or arbitral tribunals. When subject to international law, consideration should be given to the possibility of PES submitting disputes.

Provisions for the protection, restoration, and sustainable use of water-related ecosystems should be incorporated into national laws and regulations, transboundary water agreements and, where appropriate, other international agreements. Legislation should recognise the role of water-related ecosystems in water management, considering that water-related ecosystems are both water users and genuine suppliers of ecosystem services. Furthermore, legislation should help reduce fragmentation and improve coordination among government departments and institutions. It should also help to clearly define the shared responsibilities of institutions responsible for, inter alia, planning, water, environment, nature conservation, agriculture, forestry, economy and finance (UNECE, 2007[1]).

Appropriate institutional arrangements at the national and local levels and joint bodies, such as international river and lake commissions at the transboundary level should support the above legal frameworks. An institution to handle the sale of the service is necessary, as for any product sold in a market. In this regard, the first step is to identify a suitable institution with clear ownership rights to the ecosystem service. Then, it should next be considered whether the institutional and administrative capacity is sufficient.

The chosen institution to manage PES may be a government body, a local community group, an individual, or an intermediary body such as a local NGO. It is necessary to understand the governance framework in the village, group of villages, the landscape (or the potential seller) where the ecosystem service will be produced, managed and sold. Equally important is the determination of who or what body (Government, village, individual, NGO) has the legal right and capacity to govern the PES system, and whether the sale of an ecosystem service will involve more than one entity. The entity must have adequate administrative and technical capacity to manage and sell the ecosystem services. It is crucial to determine who will be the staff member or responsible person(s) to liaise on the production of the service, identification of the market and buyer, the sale itself, and the disbursement of any revenues received (IUCN, 2009[2]).

PES should be funded by different sectors benefiting from ecosystem services, proportionate to their respective financial capabilities. FONERWA would logically be the appropriate government body to receive funds from different streams and sectors to finance the different players in PES schemes.

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[1] United Nations, ed., *Recommendations on Payments for Ecosystem Services in Integrated Water Resources Management* (New York: United Nations, 2007).
[2] Thomas Greiber et al., eds., *Payments for Ecosystem Services: Legal and Institutional Frameworks*, IUCN Environmental Policy and Law Paper, no. 78 (Gland, Switzerland: IUCN, in collaboration with the IUCN Environmental Law Centre, Bonn, Germany, 2009).

Technicalities for PES design and implementation

Traditionally, PES programs have been designed based on the following ecosystem services: (i) biodiversity protection (highly efficient but very difficult to organise and maintain); (ii) watershed protection; (iii) carbon sequestration and storage; (iv) landscape beauty (e.g. ecotourism) (Wunder, 2006[1]).

PES design and implementation can be divided into five broad phases (Smith et al., 2013[2]; Fripp, 2014[3]):

1. Identify a saleable ecosystem service and the range of possible buyers and sellers of that service(s); and the prospects for trade between them (i.e. a potentially deliverable service of value to at least one buyer). Usually, the emergence of a problem, such as downstream water pollution or demand for carbon credits, drives the establishment of a PES scheme.
2. Establish the principles that will underpin the PES scheme and resolve key technical issues. For example, any PES scheme is underpinned by principles like voluntary entry; payment by beneficiaries (individuals, communities, businesses or governments acting on behalf of various parties) directly to the ecosystem service providers (or to their legal representatives); the principles of additionality, conditionality, ensuring permanence and avoiding leakages susceptible to causing degradation of ecosystem services elsewhere.
3. Negotiate and implement agreements.
4. Monitor, evaluate, and review implementation.
5. Consider opportunities for multiple-benefit PES.

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[1] Sven Wunder, 'Are Direct Payments for Environmental Services Spelling Doom for Sustainable Forest Management in the Tropics?', *Ecology and Society* 11, no. 2 (2006), http://www.jstor.org/stable/26266013.

[2] Smith, S., Rowcroft, P., Everard, M., Couldrick, L., Reed, M., Rogers, H., Quick, T., Eves, C. and White, C. (2013). Payments for Ecosystem Services: A Best Practice Guide. Defra, London.

[3] Fripp E. 2014. Payments for Ecosystem Services (PES): A practical guide to assessing the feasibility of PES projects. Bogor, Indonesia: CIFOR

4 Strategic Water Resources Management Options

4.1 Strategic water storage plan

The strategic water storage plan is built by finalising the list of prioritised dams (39 in total), identified in Chapter 3, and scheduling their implementation. The elaboration of this plan was cemented with stakeholder consultations.

4.1.1 Stakeholder consultations

The purpose of the consultations was to:

- Discuss the guidelines suggested in Chapter 3, from which strategic water resources management options are identified.
- Validate the list of prioritised dams.
- Suggest a series of flagship projects and identify three projects to be considered in this assignment, as presented in section 4.4 and 4.4.2 below.

To allow in-depth discussions and account for sectoral particularities, bilateral consultations were conducted with different organisations representing the sectors involved in water management, namely:

- RWB.
- WASAC.
- RAB.
- REG.
- MoE.
- NELSAP.

The main comment, concerning the validation of prioritised dams, is to add regulatory dams to regulate the volume of sediments in the main rivers. Stakeholders also advised scheduling the implementation of prioritised dams based on their ranking, itself function of the impact on improving the national water demand.

4.1.2 Identification of the Strategic Water Storage Plan

The Strategic Water Storage Plan is a portfolio of investments that lead to

- Augmentation of surface storage capacity through the construction of new storage dams
- Adoption of an integrated sedimentation mitigation strategy, with measures:
  - at-source: erosion control measures through NbS
  - transport and sink: regulatory dams with some desilting approach (see guidelines)
- Adoption of the other recommendations in the guidelines that relate to water and land management in Rwanda, e.g. the promotion of PES to fund NbS, multi-purpose dams, PPPs, etc).

From the Strategic Water Storage Plan, three flagship projects were distilled, after consulting with the various sectoral stakeholders. These three cases are presented in section 4.4.

The Strategic Water Storage Plan phases the potential investments in three stages. To identify the investments in these phases, from chapter 3.1, the list of 39 dams was used and ranked according to their prioritisation. The first phase assumes completion of the first set of three water storage reservoirs by 2030, a second phase entails a total of eight dams to be completed by 2035 and lastly a third phase encompassing the other 24 storage reservoir location to be finalised by 2050. Each of these phased scenarios used *WResilient_NoStorage* as a basis which represents an RCP 4.5 climate projection. This scenario serves therefore as the reference scenario to which the other studies were compared, and from which reduced unmet demand was determined (Table 65).

Each of these three phases were separately studied with the national WEAP model. In the model, a construction period of minimal five years was assumed. Hence for respectively the first, second and third phase the following construction periods were assumed: 2025 – 2030; 2030 – 2035, and 2040 – 2050. For the three scenarios, the total volume of prioritised active storage reservoirs totals 625 MCM (Figure 126). It is worth mentioning the model only assumes live/active storage, taken equal to 80% of the storage capacity. Hence, the total storage capacity commissioned by 2050 is 781 MCM (excluding four studied potential regulatory dams - 31 MCM - see section 3.1.2, p152). Also it is assumed that this active storage is maintained throughout the period of analysis, unaffected by sedimentation. In other words, this part of the analysis assumes an effective execution of the Integrated Sediment Management Plan. In the cost-benefit analysis, these assumptions are tested and the differential impact of sediment management is assessed (see Section 4.3).

Table 73. Active storage added for each of the three scenarios analysed.

[MCM]	StorDevPlan2030	StorDevPlan2035	StorDevPlan2050	Total
Active Storage Capacity (80%)	135	96	394	625
Reservoir Storage Capacity	169	120	493	781

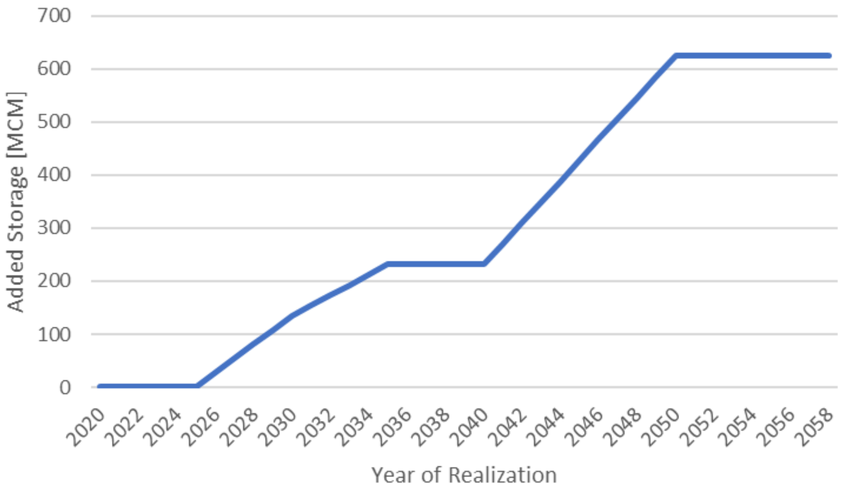

Figure 126. Active Reservoir Storage (sum) added during StorDevPlan2030, StorDevPlan2035, and StorDevPlan2050.

Besides the three phases encompassing a total of 35 storage locations, an additional analysis was done adding four selected “regulatory” dams: their usage is mainly for capturing sediments rather than providing active water storage, but still may lead to minor additional storage. The benefits of the reduced sedimentation are accounted for in the cost-benefit analysis of the Strategic Water Storage Plan, presented hereafter.

4.1.2.1 Phase 1: Completed by 2030

A total of 135 MCM active storage was added to the model by implementing the SA76, SA85, SB6 and SA14 storage locations. In this scenario, a total reduction in unmet demand of 5.7 MCM for average years, and 15.2 MCM for dry years is obtained (Table 74). It is apparent that the reduction on national level is relatively minimal, except for dry years when the impact of additional storage becomes more significant.

4.1.2.2 Phase 2: Completed by 2035

As part of this scenario, the water transfer study discussed in chapter 2.4.3 (option 6c) was considered, in addition to implementing 96 MCM active storage by realising SA3, SA105, SB26, SA96, SA35, SB30, SA41 and SA20 between 2030 and 2035. The reduced unmet demand for a dry year is found to be 36.5 MCM and for an average year 16.9 MCM.The water transfer is activated per January 2035 whereas the reservoir capascity gradually increases from 2030 upto 2035.

4.1.2.3 Phase 3: Completed by 2050

The third phase is assumed to be constructed from 2040 till 2050 and includes the remaining storage reservoirs. A total of 394 MCM of active storage is added in this scenario, on top of the already available additional active storage of 231 MCM from the previous phases. Hence this scenario accounts for a total of 625 MCM active storage. It also includes the water transfer (6c) which was part of the StorDevPlan2035 scenario.

Annexe 14 includes a table showing the WResilient_NoStorage (reference) and StorDevPlan2050 scenarios, the per capita values for both Blue Water Availability and Artificial Storage [m3/cap]. It should be noted that the storage reported for the WResilient_NoStorage scenario represents existing storage from small irrigation reservoirs and larger dams, such as Nyabarongo.

The impact of this scenario on reduced unmet demand is most significant during dry years, especially in 2057, during which the total unmet demand is reduced by 85.5 MCM. On average for the period 2020 - 2059, the unmet demand is reduced by 30.6 MCM.

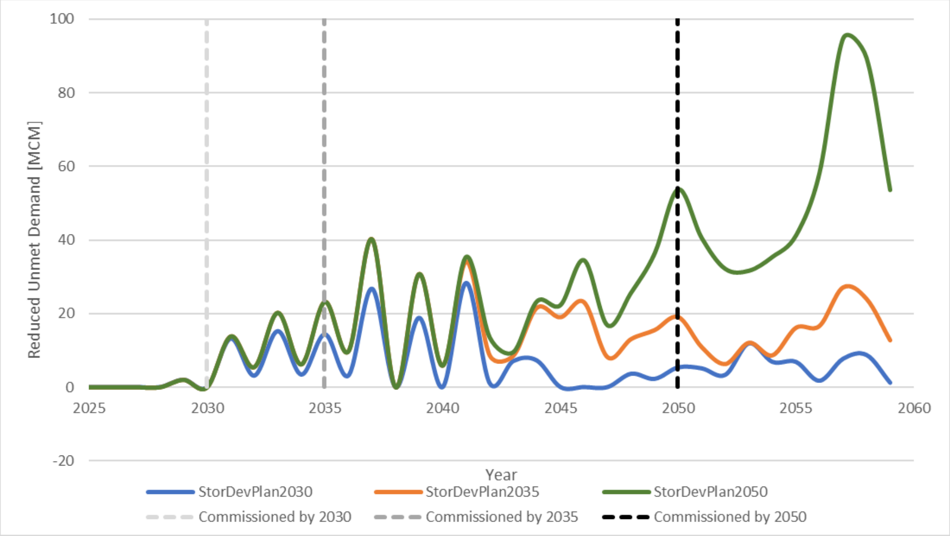

Figure 127. Reduced Unmet Demand for Water Storage by 2030, 2035 and 2050 on national level.

Hence, in summary it can be noted that as each reservoir construction phase passes, as expected, the reduction in unmet demand becomes more significant at national level (Figure 127). Table 74 further shows the general trends in total unmet demand (MCM) and coverage (fraction) for each of the five analysed scenarios. It can be noted that in general total unmet demand is highest in the reference scenario and it reduces as more storage is being commissioned for both dry and average years. Opposite to this, the coverage slightly increases with increasing storage capacity, for both dry and average years which relates to the total unmet demand numbers.

The impact of this scenario on reduced unmet demand is most significant during dry years, especially in 2057, during which the total unmet demand is reduced by 85.5 MCM. On average for the period 2020 - 2059, the unmet demand is reduced by 30.6 MCM.

Table 74. Total Unmet Demand [MCM], Reduced Unmet Demand [MCM] and Coverage (Fraction) for each of the five analysed scenarios.

Total Unmet Demand [MCM]	**Dry Year**	**Average Year**
WResilient_NoStorage (reference)	2,259	639
StorDevPlan2030	2,251	636
StorDevPlan2035	2,232	627
StorDevPlan2050	2,102	615
StorDevPlan2035+Reg	2,227	626
Reduced Unmet Demand [MCM]	**Dry Year**	**Average Year**
StorDevPlan2030	28	5
StorDevPlan2035	40	13
StorDevPlan2050	95	25
StorDevPlan2035+Reg	49	14
Coverage [%]	**Dry Year**	**Average Year**
WResilient_NoStorage (reference)	61	82
StorDevPlan2030	62	82
StorDevPlan2035	62	82
StorDevPlan2050	63	83
StorDevPlan2035+Reg	62	82

This improvement in meeting the demand predominantly benefits irrigation, hence food security, following the allocation rules set in the model, which is as per the Water Law (see sub-section 2.2, p118, and Figure 85, p131). In the model, domestic water gets the first priority, hence is supplied in baseline conditions. This is not the case for irrigation, where there are shortages in baseline conditions, hence new dams benefit irrigation.

Regarding hydropower, improving production is not an explicit objective of the plan. Therefore, impacts could be examined as possible negative or positive indirect impacts of the new dams on existing hydropower dams. Only two of the prioritised sites (SB13 and SA45) are close to planned hydropower developments, hence the benefits for hydropower of the water storage plan are assumed to be limited. Of course, in a pre-feasibility or feasibility study of the individual sites, this aspect needs to be studied further.

Figure 127 and Table 74 shows that the reduction of unmet demand is highly variable, and in the range of 30-100 MCM per year around the year 2050. This number may seem small compared to the total of additional active storage capacity of 625 MCM commissioned in the model. However, please note the following:

- The dams have over-year storage capacity to buffer multi-year drought periods. Thus benefits accumulate over several years. These multi-year benefits are not accounted for when looking at a dry year. So in reality benefits are higher
- Storage capacity has been held on purpose on the high side (within physically realistic boundaries, as explained earlier) as this study aims at prioritizing storage dams. However, dam-specific studies on the water balance may conclude that, in some cases, over-year storage capacity is not needed or cost-effective. This will need to be tackled in a pre-feasibility study of each dam location.
- The presented analysis gives a relatively high priority to dam-filling (priority 3). This causes the model to be relatively conservative in some cases, as during drought periods, dam-filling will

compete with the sectoral water demands. Dam-specific release rules may lead to more optimal regimes, causing higher benefits. Changing these allocation rules at the national level in a model is not feasible. Site-specific pre-feasibility studies need to be performed to set a more optimal priority and release regime.

- This analysis aims to assess the scope for improving water security at the national level, considering sub-catchment level data and dynamics, and prioritising investments across the sub-catchments. Site-specific benefits and optimized management operations need to be studied separately.

4.1.2.4 Regulatory Dams

As part of this analysis, four regulatory dams were scrutinized as well for which the main purpose is capturing sediments to prevent sedimentation of water storage reservoirs. From this methodology, the regulatory dams were selected within four subcatchmens of which only 1 has a significant storage capacity of 27.8 MCM (Nyabarongo 1 in NNYU_C). The other three regulatory dams are SB20 (1.9 MCM), Gikiye (0.7 MCM) and Rubagabaga (0.3 MCM) in respectively NNYU_A, NMUK_C, and NMUK_A (Table 75). As each of the four regulatory dams was prioritised in such a way that it would either be constructed in the first (by 2030) or second (by 2035) phase, the StorDevPlan2035 scenario was used as a basis and reference scenario to study the impact of these regulatory dams on the water demand. The scenario itself is referred to as StorDevPlan2035+Reg.

Table 75. Regulatory Dam characteristics as accounted for in the StorDevPlan2035+Reg scenario.

Regulatory Dam	Subcatchment	Commissioned by	Storage Capacity [MCM]
Regulatory (Giciye river)	NMUK_C	2030	0.7
Regulatory dam (Satinsyi River) [SB20]	NNYU_A	2030	1.9
Regulatory (upstream Nyabarongo 1)	NNYU_C	2035	27.8
Regulatory (Rubagabaga river)	NMUK_A	2035	0.3

As can be seen from Table 74 and Figure 128, the differences between the storage development plan scenario with and without the regulatory dams, the general impact on unmet demand is noticeable which can mostly be attributed to the regulatory dam upstream of Nyabarongo I as its storage capacity is most significant. Although the main purpose for these dams is capturing sediments rather than storing and releasing water more evenly throughout the year, it is expected they will further contribute to diminishing unmet demand. In a dry year, the unmet demand is reduced by max 39.9 MCM whereas for an average year by 17.3 MCM. For the StorDevPlan2035 scenario, these reductions were respectively 36.5 and 16.9 MCM. Note that in this analysis, the impact of the regulatory dams on sediment retention was not assessed – these were considered in the cost-benefit analysis of the Strategic Plan (see Section 4.3).

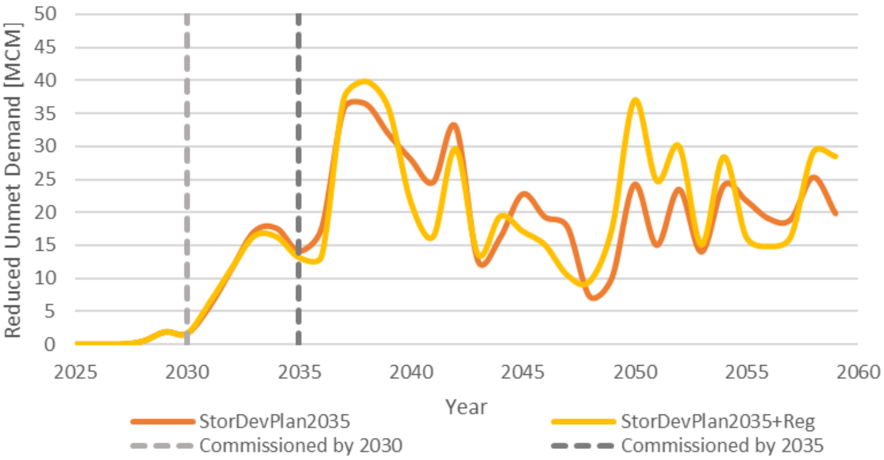

Figure 128. Reduced unmet demand (MCM) for StorDevPlan2035 and StorDevPlan2035+Reg scenarios.

4.2 SWOT analysis of management options at the national level

The SWOT analysis (draws from the Hydro-Economic Analysis and the current assignment. The items highlighted in terms of strengths, weaknesses, opportunities and threats are based on the four pathways of planning options:

- The baseline scenario: business-as-usual situation where no new policies or public infrastructure expansion are introduced, unless they are already underway with funding. This scenario allows decision-makers a contrast with other pathways of planning options,
- Vision 2050 scenario: explores the possibility of achieving the water-related goals of Vision 2050. This is a very ambitious trajectory with large shifts in the population from rural to urban areas, vast expansion of irrigated agriculture, and increased industrial and hydropower production.
- Water resilient Vision 2050 scenario: on the top of the Vision 2050 scenario, looks at adaptation measures, such as climate-smart irrigation practices, and mitigation options, such as levels of hydropower as a proportion of the overall electricity mix.
- Water resilient Vision 2050 and the Strategic water storage plan: on the top of the Water resilient Vision 2050 scenario, considers the implementation of the Strategic water storage plan defined during this assignment.

Table 76: SWOT matrix of management options at the national level, ranked by decreasing order of importance.

WRM Options	Strengths	Weaknesses	Opportunities	Threats
Baseline scenario (Business as usual with uncertain climate conditions for both rainfall and temperature)	1. Storage to be increased to almost 100 MCM; 2. Reduction of non-revenue water losses; 3. Expansion of rainwater harvesting programs; 4. Existence of several other forms of natural storage, in lakes, ponds, wetlands and groundwater;	1. No comprehensive policy approach to non-revenue water; 2. Need for a national investment plan to guide the expansion of Rwanda's water storage; 3. Expected significant water demand increase (83% increase over 2020 levels); 4. Under-utilization of groundwater; 5. Increase in irrigation water demand (accounting for 43% of total demand); 6. Need for supplemental small-scale irrigation (such as drip irrigation) targeting remote and poor communities;	1. PES can be used to preserve watershed ecosystems; 2. Reuse of treated wastewater; 3. Policies should prioritize investment in capacity to use GIS maps, and install flow rate meters to improve leak detection; 4. PPP should be increasingly used to help government financing to attain its goals 5. Use economic incentives to induce changes in water demands, including subsidies, penalties, and tariffs; 6. Legal, regulatory, and institutional strengthening (Law on Environment 2018, Water Policy 2011, Water Law 2018); 7. To use more hydropower or other renewable energy sources rather than fossil fuels;	1. Water quality, and various water infrastructures are being severely impacted by soil erosion and sedimentation 2. Climate change 3. Under this scenario, Rwanda's macro-economy is more unstable in the face of uncertain climate conditions for both rainfall and temperature, indicating a need for supply-side measures at a minimum for economic stability; 4. Large infrastructure built that falls into neglect; 5. Erosion, flooding, and other water related incidents.

WRM Options	Strengths	Weaknesses	Opportunities	Threats
			8. As the economy expands, sectors (e.g. services) that are less vulnerable to fluctuations in water supply grow in importance; 9. Increased rainfall.	
Vision 2050 scenario (very ambitious trajectory with large shifts in the population from rural to urban areas, vast expansion of irrigated agriculture, and increased industrial and hydropower production)	1. Increased water storage by an additional 300 MCM; 2. Reduction of non-revenue water losses; 3. Expansion of rainwater harvesting programs; 4. Industrial demands generally have access to both surface and groundwater supplies; 5. Existence of several other forms of natural storage, in lakes, ponds, wetlands and groundwater	1. No comprehensive policy approach to non-revenue water; 2. Expected significant water demand increase (1,140% increase over 2020 levels); 3. Shortages in domestic water is Kigali, Muhanga, Rubavu, and other large urban areas; 4. Increase in irrigation water demand (accounting for 85% of total demand) 5. Agriculture water shortages in Karangazi, Gabiro, Kirehe, and Muvumba river basins; 6. Increase in industrial water demand by 25 MCM per year; 7. Need for a national investment plan to guide the expansion of Rwanda's water storage;	1. PES can be used to preserve watershed ecosystems; 2. Reuse of treated wastewater; 3. PPP should be increasingly used to help government financing to attain its goals; 4. To use more hydropower (additional 50 MW for Rusizi) or other renewable energy sources rather than fossil fuels; 5. Policies should prioritize investment in capacity to use GIS maps, and install flow rate meters to improve leak detection; 6. Legal, regulatory, and institutional strengthening (Law on Environment 2018,	1. Climate change 2. Agriculture most vulnerable to climate given 100% dependence on the timing and amount of rainfall; 3. Water quality, and various water infrastructures are being severely impacted by soil erosion and sedimentation; 4. Large infrastructure built that falls into neglect; 5. Erosion, flooding, and other water related incidents.

WRM Options	Strengths	Weaknesses	Opportunities	Threats
		8. Need for supplemental small-scale irrigation (such as drip irrigation) targeting remote and poor communities; 9. Investments in feed processing plants; specialized chick production factories; medium scale poultry farms for egg production; and pig fattening facilities; increase in the overall herd size and in their water demand.	Water Policy 2011, Water Law 2018); 7. Use economic incentives to induce changes in water demands, including subsidies, penalties, and tariffs; 8. As the economy expands, sectors (e.g. services) that are less vulnerable to fluctuations in water supply grow in importance; 9. Increased rainfall.	
Water Resilient Vision 2050 (It involves adaptation measures, such as climate-smart irrigation practices and mitigation options, such as levels of hydropower)	1. Introduction of climate-smart agriculture; 2. Reduction of non-revenue water Losses; 3. Increased water storage by an additional 300 MCM; 4. Expansion of rainwater harvesting programs (with deeper analysis). 5. Shifts in crops towards less rice and more diversification in fruits and vegetables. 6. Industrial demands generally have access to both surface and groundwater supplies.	1. Expected significant water demand increase (740% increase over 2020 levels). 2. Increase in irrigation water demand (accounting for 77% of total demand). 3. Shortages in domestic water is Kigali, Muhanga, Rubavu, and other in large urban areas. 4. Agriculture water shortages in Karangazi, Gabiro, Kirehe, and Muvumba river basins. 5. No comprehensive policy	1. New irrigation technologies; 2. Measures to increase water productivity in the industrial sector. 3. To use more hydropower (additional 50 MW for Rusizi) or other renewable energy sources rather than fossil fuels. 4. PPP should be increasingly used to help government financing to attain its goals. 5. PES can be used to preserve watershed ecosystems.	1. Climate change. 2. Agriculture most vulnerable to climate given 100% dependence on the timing and amount of rainfall. 3. Large infrastructure built that falls into neglect; 4. Water quality, and various water infrastructures are being severely impacted by soil erosion and sedimentation. 5. Erosion, flooding, and other water-related incidents.

WRM Options	Strengths	Weaknesses	Opportunities	Threats
	7. Existence of several other forms of natural storage, in lakes, ponds, wetlands and groundwater.	approach to non-revenue water. 6. Investments in feed processing plants; specialized chick production factories; medium-scale poultry farms for egg production; and pig fattening facilities; increase in the overall herd size and in their water demand. 7. Increase in industrial water demand by 23 MCM per year. 8. Need for a national investment plan to guide the expansion of Rwanda's water storage. 9. Need for small-scale supplemental irrigation (such as drip irrigation) targeting; remote and poor communities;	6. As the economy expands, sectors (e.g. services) that are less vulnerable to fluctuations in water supply grow in importance. 7. Legal, regulatory, and institutional strengthening (Law on Environment 2018, Water Policy 2011, Water Law 2018). 7. Increased rainfall. 8. Reuse of treated wastewater. 9. Use economic incentives to induce changes in water demands, including subsidies, penalties, and tariffs. 10. Investment in capacity to use GIS maps, and install flow rate meters to improve leak detection.	
Water Resilient Vision 2050 and the Strategic water storage plan	1. Increased active water storage capacity, potentially up to 625 MCM; 2. Increased electricity generation	1. Expected significant water demand increase (740% increase over 2020 levels). 2. Increase in irrigation water	1. New irrigation technologies; 2. Legal, regulatory, and institutional strengthening (Law on Environment 2018,	1. Climate change. 2. Large infrastructure built that falls into neglect. 3. Erosion, flooding, and

WRM Options	Strengths	Weaknesses	Opportunities	Threats
	through smart association of renewables (hydro and solar). 3. Sediments control through integrated sediment management plans and regulatory dams, particularly with NbS measures to reduce sedimentation in reservoirs. 4. Promotion of PES to preserve watershed ecosystems. 5. Reduction of non-revenue water losses. 6. Expansion of rainwater harvesting programs (with deeper analysis). 7. Introduction of climate-smart agriculture. 8. Promotion of multipurpose use of reservoirs; 9. Shifts in crops towards less rice and more diversification in fruits and vegetables. 10. Increase coverage of water demands, especially in relatively water scarce catchments 11. Industrial demands generally	demand (accounting for 77% of total demand). 3. No comprehensive policy approach to non-revenue water. 4. Investments in feed processing plants; specialized chick production factories; medium-scale poultry farms for egg production; and pig fattening facilities; increase in the overall herd size and in their water demand. 5. Increase in industrial water demand by 23 MCM per year. 6. Need for small-scale supplemental irrigation (such as drip irrigation) targeting remote and poor communities.	Water Policy 2011, Water Law 2018). 3. PPP should be increasingly used to help government financing to attain its goals. 4. Measures to increase water productivity in the industrial sector. 5. Use economic incentives to induce changes in water demands, including subsidies, penalties, and tariffs. 6. As the economy expands, sectors (e.g. services) that are less vulnerable to fluctuations in water supply grow in importance. 7. Increased rainfall. 8. Reuse of treated wastewater. 9. Investment in capacity to use GIS maps, and install flow rate meters to improve leak detection.	other water-related incidents. 4. Agriculture most vulnerable to climate given 100% dependence on the timing and amount of rainfall.

WRM Options	Strengths	Weaknesses	Opportunities	Threats
	have access to both surface and groundwater supplies. 12. Existence of several other forms of natural storage, in lakes, ponds, wetlands and groundwater.			

4.3 Cost benefits analysis of the Strategic Water Storage Plan

4.3.1 Approach and assumptions

A Cost Benefit Analysis (CBA) was performed to get insight into how cost-effective the phased Strategic Water Storage Plan is. The CBA was performed in a scenario-type analysis so the accumulative impact of the subcomponents of the plan can be better understood. The CBA aims to quantify the return on investment of :

- The investments of 2030 compared to those up to 2035
- The level of erosion and sedimentation control in the upstream catchments of the investments
- The previous plus the construction of regulatory dams with the main purpose of sediment control.

The benefits included in this CBA are:

- **Reduced unmet demand, and thus increased economic water productivity.** This was analysed using the water resources system model (WEAP) outputs, based on dynamic simulations considering climate change impacts. The economic water productivity was taken from the values obtained in the literature on SDG6 economic water-use efficiency: the value added per water volume withdrawn, expressed in monetary units per cubic meter. The latest data from the SDG6 portal indicates a value of 13 US$/m3 for 2019)[1]. The latest 2019 Water Accounts for Rwanda indicate a value of 5,200 RwF/m3[2] for 2015, equivalent to about 7,3 US$/m3. Differences may be attributed to different assumptions or data on water abstractions, sectoral economic data, and currency value changes. For this study, the SDG6 portal data was used (13 US$/m3). It is assumed that the benefits become active three years after the dam construction, with a delay to to the need to fill the dam, adapt the management procedures, and build the service infrastructure around it.
- **Increased land productivity from reduced loss of fertile soil.** The costs of inaction on soil erosion were estimated by a study supported by the Dutch government and IUCN. The results show that, on average, the costs of inaction on soil erosion are 51 US$/ha (Table 166).[3]

The main cost items that were considered in the CBA are:

- **Newly built storage infrastructure**: capital costs were estimated based on earlier dam projects in Rwanda, from which unit costs (million US$/ MCM storage capacity) were estimated. Maintenance costs were estimated to be an annual 5% of the original capital costs.
- **Costs of erosion control measures (NbS):** unit costs for NbS were extracted from the 2022 State of Soil Erosion report by IUCN (on average 513 US$/ha).[4] These erosion control measures are assumed to be included in the Integrated Sediments Management Plan which need to accompany any investment project in newly built storage infrastructure (see guidelines). Maintenance costs were assumed to be negligible and compensated against the land productivity benefits.
- **Capital/maintenance of regulatory dams** to control sediment transport and sedimentation. In this case, maintenance costs are high due to the need for sediment-clearing measures. For this scoping analysis, the clearing costs were assumed to be an

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[1] https://www.sdg6data.org/country-or-area/Rwanda

[2] Government of Rwanda (NISR, Ministry of Environment). Natural Capital Accounts for Water, Version 1.0. June 2019. Kigali, Rwanda

[3] IUCN, 2022, The State of Soil Erosion Control in Rwanda

[4] Ibid.

annualized 30% of the capital costs. The capital costs were based on the same relationship with storage capacity as for the water storage dams (see first point).

Other relevant assumptions for the analysis are:

- The storage plan was analysed for investments up to 2030 and 2035. The potential investments beyond 2035 were not included, as requested by the client, given the highly uncertain socio-economic conditions on that time horizon.
- The return on investment analysis horizon is 30 years
- The scenario analysis was done with two assumptions on discount rates to calculate the Net Present value (NPV): 6% and 12%.
- There is a lack of data and understanding in Rwanda on which part of the sedimentation is due to soil erosion, and which part originates from the river bed. For this analysis, it was assumed that around two-thirds of the sediments originate from the lands and river banks, and the remainder originate from the river bed itself (70/30).
- The trap efficiency of regulatory dams depends highly on the sediment granularity, flow velocities, size of the dam, and many other factors. In this analysis, a trap efficiency of 50% was assumed. Obviously, this need to be further studied on a case-by-case basis, in case these projects are taken forward. There is the possibility of lower trap efficiencies, given the very fine sediments typical in Rwanda, and high velocities, which cause a large share of the sediments not settling before they leave the reservoir.
- The sedimentation rate of reservoirs in Rwanda is highly location-dependent, depending on land use upstream, river morphology, hydrological and hydraulic processes, and infrastructure characteristics. In this analysis, a 3% sedimentation rate was assumed in a scenario without NbS.

4.3.2 Scenario results

The analysis was done for a number of scenarios, so the marginal impact of different measures and options can be explored. The economic scenarios that were considered are (cumulative – each scenario includes all previous ones):

- **A. Storage Dams up to 2030**, with implementation of Integrated Sediments Management Plan and adoption of NbS of 100%
- **B. Storage Dams up to 2035**, with implementation of Integrated Sediments Management Plan and adoption of Nbs of 20%
- **C. Storage Dams up to 2035**, with implementation of Integrated Sediments Management Plan and adoption of Nbs of 50%
- **D. Storage Dams up to 2035**, with implementation of Integrated Sediments Management Plan and adoption of Nbs of 100%
- **E. Including regulatory dams** in the main reaches, to control sediment transport and use sinks to clear sediments from the system.

The cost-benefit indicators which are presented in the results afterwards are the following (everything expressed in million US dollars):

- Mean annual benefit from additional water productivity due to reduced unmet demand
- Mean annual benefit from land productivity due to reduced loss of fertile soil
- Return on investment (total net benefits relative to the total costs) in 2035 and 2050
- The year in which Net Present Value becomes positive for 6% and 12% discount rates

Figure 129 shows the annual values of the costs, benefits, net benefit and net present value, for the 30 years (x-axis). From this economic simulation, the above-listed cost-benefit indicators were extracted to compare the results among the scenarios. These key indicators are shown in Table 77. The Return-on-Investment indicators for 2035 and 2050 are also represented graphically in Figure 130.

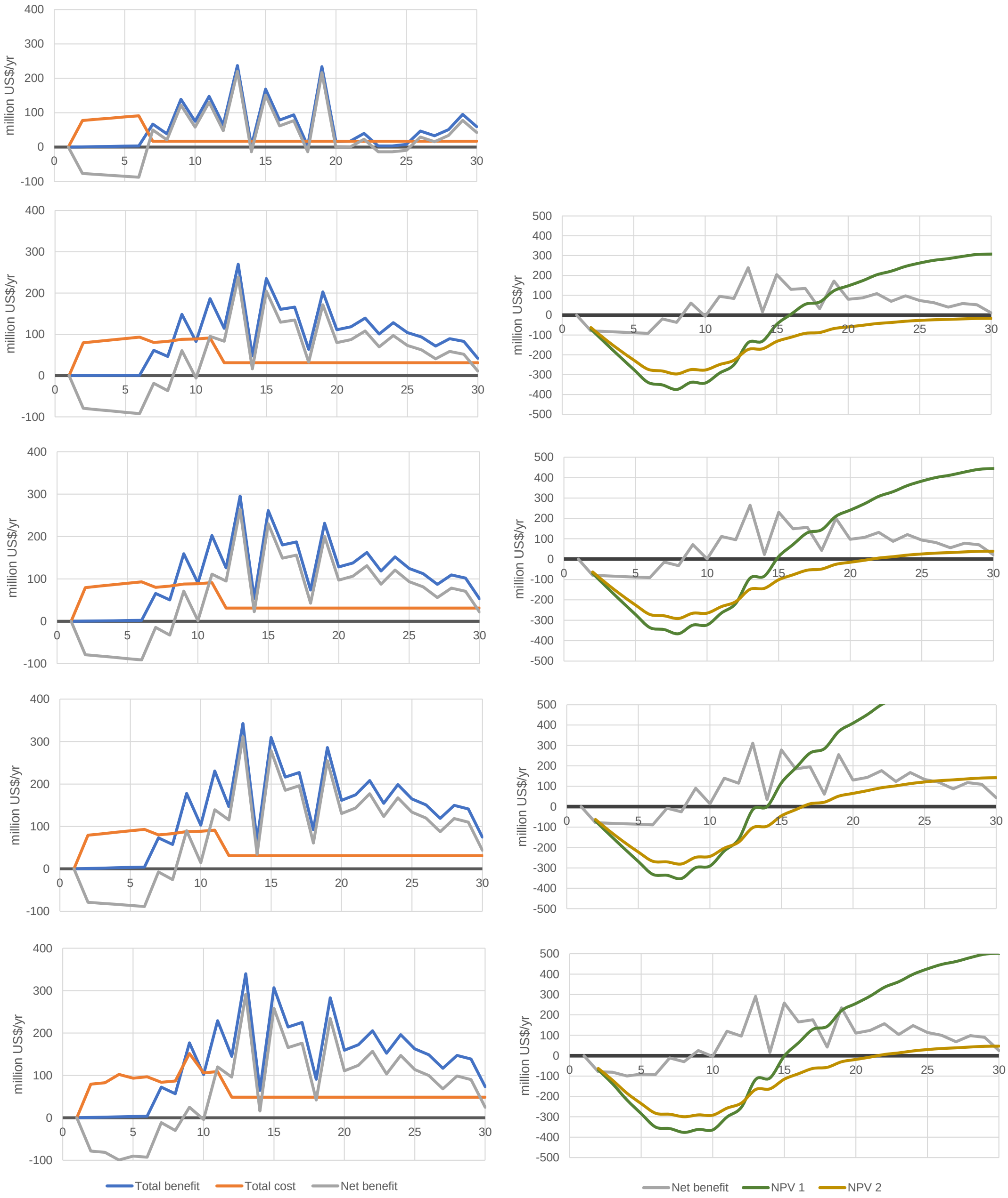

Figure 129. Costs and benefits (left) and Net Present Value (NPV, right) for the next 30-year horizon; NPV1 and NPV2 are respectively for the discount rates 6% and 12%.

Table 77. Cost-benefit indicators of the five scenarios

Cost benefit indicator		Scenario				
	Unit	A	B	C	D	E
Mean annual water productivity benefits	*M USD/yr*	69	139	155	188	187
Mean annual land productivity benefits	*M USD/yr*	3	1	4	7	6
Return on Investment in year 2035	*%*	-106%	-139%	-133%	-124%	-135%
Return on Investment in year 2050	*%*	**8%**	**-3%**	**25%**	**78%**	**8%**
Disc. rate 6%: NPV in 2050	*M US$*	204	285	412	650	462
Disc. rate 12%: NPV year 2050	*M US$*	**2**	**-22**	**32**	**131**	**38**
Disc. rate 6%: year positive NPV	*yr*	13	16	15	14	16
Disc. rate 12%: year positive NPV	*yr*	19	>30	22	17	22

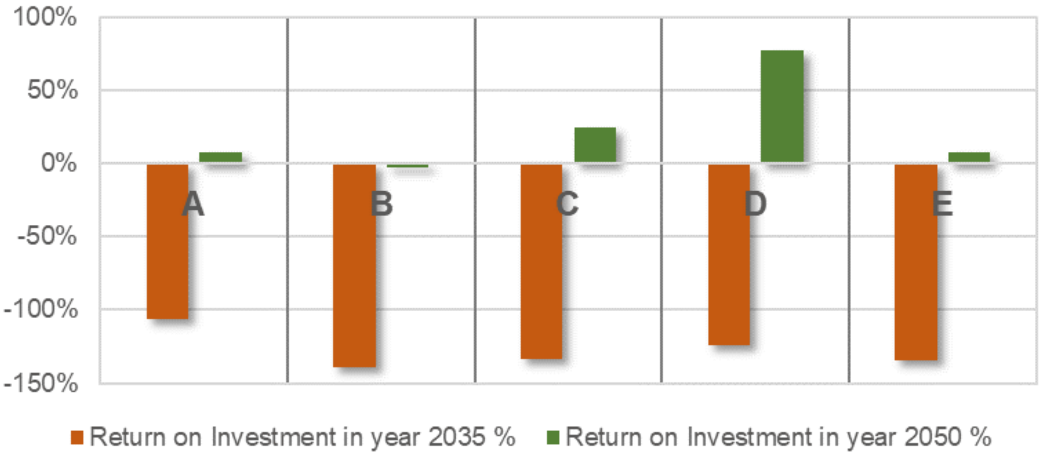

Figure 130. Return on Investment of the five scenarios for the 2035 and 2050 horizon.

From the key cost-benefit indicators presented in Table 77, the following conclusions can be drawn:

- *Scenario B vs A:* Phase 2 (investments up to 2035) of the Strategic Storage Water Plan provides substantial additional economic benefits compared to Phase 1 (up to 2030 only). The return on investment for 2035 horizon is more favourable due to the reduced investment costs, but on the long run (2050), the return on investment is much higher if Phase 2 is included. At the same time, the benefits will reduce significantly towards 2050 due to the increased sedimentation and the consequent reduced benefits progressively over time.
- *Scenario C and D*: accompanying new grey infrastructure (dams) with investments in green infrastructure (NbS for erosion control) leads to substantial additional benefits: both in terms of land productivity as well as water productivity. The returns, however depend to a large degree on the successful adoption of the NbS investments. The return on investment of a high adoption scenario (100% - Scenario D) is significantly higher than a moderate adoption scenario (Scenario C), and even more in a poor adoption scenario (Scenario B).
- *Scenario E:* complementing the investments with regulatory dams to control sediment transport and clear sediments from the system leads to slightly higher water productivity benefits. The return on investment for the 2050 horizon is positive, but less positive compared to a scenario in which these dams are not built due to their high maintenance costs (see section on assumptions for the rationale). Also the Net Present Value is lower, altogether suggesting that this complementary investment in regulatory dams is less favourable from an economic point of view.

Overall, from the cost-benefit analysis, the proposed Strategic Water Storage Plan will lead to considerable benefits for the 2050 horizon due to a portfolio of investments in grey and green (NbS) infrastructure.

4.4 Flagship projects

Flagship projects are expected to be transformative and contribute to implementing the Vision 2050. The projects should enhance water security in Rwanda and mainstream some of the strategic water resources management options identified in section 3.3 (p176).

As agreed with FONERWA and RWB, three flagship project concept notes should be developed during this assignment. The first step was to identify these three flagship projects, see sub-section below, before developing their concept note, see sub-section 4.4.2 below.

4.4.1 Identification of the flagship projects

The identification and selection of the three flagship projects were carried out in consultations with stakeholders, simultaneously with the discussion on the strategic water storage plan (see section 4.1.1 above).

4.4.1.1 Candidates

The first step was to identify candidates for flagship projects to be proposed to the stakeholders. Those were defined as follows:

1. Strategic water resources management options were extracted from the guidelines and recommendations, as summarised in Table 78.
2. Diifferent flagship projects were suggested by combining these typical management options, as summarised in Table 79.

Table 78: Strategic water resources management options to build flagship projects

Supply-side
1. Development of a multipurpose storage reservoir.
2. Development of a single-purpose storage reservoir.
3. Integrated sediments management plan (including NbS for erosion control)
4. Payment for Ecosystem Services (PES).
5. Sustainable groundwater management for rural domestic water supply, livestock and small-scale irrigation.
6. Inter-catchment transfer
Demand-side
1. Improved water productivity in irrigation.
2. Climate-smart agriculture.
3. Reuse of treated domestic wastewater for irrigation.
4. Large-scale irrigation.
5. Enhanced monitoring of water resources for enforcing control and allocation.
6. Smart association of renewables for electricity production (hydro and solar).

Table 79: Candidates for flagship project

Flagship project	Objective	Activities	Location
A	Enhance capacity to store, regulate and allocate water for water supply, energy and food security	- Development of a multipurpose storage reservoir: water supply to Kigali and irrigation in Yanze. - Smart association of renewables for electricity generation (hydro and solar) - PES and/or NbS for soil erosion control upstream of the dam (Integrated sediments management plan). - Enhanced monitoring of water resources for enforcing control and allocation.	Rulindo (Dam site SA76)
B	Development of a climate and water resilient irrigation scheme	- Development of a single-purpose storage reservoir: irrigation and livestock in Kayonza. - Smart association of renewables for electricity generation (hydro and solar) - PES and/or NbS for soil erosion control upstream of the dam (Integrated sediments management plan). - Improved water productivity for enhanced water and food security. - Climate smart agriculture. - Enhanced monitoring of water resources for enforcing control and allocation.	Kayonza (Dam site SA85)
C	Reuse treated wastewater for irrigation	- Treatment of domestic waste water (conventional and/or NbS). - Reuse of treated domestic wastewater for irrigation. - Improved water productivity for enhanced water and food security. - Climate-smart agriculture.	
D	Improved water security in Kadiridimba sub-catchment through inter-catchment water transfer	- Inter-catchment transfer from Akagera river to Kadiridimba river (option 6c). - PES and/or NbS for soil erosion control upstream of the intake area in Akagera. - Improved water productivity for enhanced water and food security. - Climate-smart agriculture. - Enhanced monitoring of water resources for enforcing control and allocation.	Kadiridimba catchment
E	Groundwater for rural domestic water supply and small-scale irrigation	- Exploitation of groundwater for rural domestic water supply and small-scale irrigation. - Sustainable groundwater management (e.g., artificial recharge, solar pumps, community groundwater management). - PES and/or NbS for groundwater recharge. - Improved water productivity for enhanced water and food security. - Climate-smart agriculture. - Enhanced monitoring of water resources for enforcing control and allocation.	
F	Development of a climate and water resilient hydropower scheme	- Development of a single-purpose storage reservoir for hydropower. - Smart association of renewables for electricity generation (hydro and solar) - PES and/or NbS for soil erosion control upstream of the dam.	

This initial definition of flagship projects was adapted further based on feedback from consulted stakeholders.

4.4.1.2 Evaluation of the projects

Participants in the bilateral consultations were asked to score the candidate flagship projects. The projects with the three best scores will be selected for drafting the concept note. The results of the scoring are summarised in Table.

Table 80: Scoring of the flagship project candidates by the sectoral stakeholders (3 is the preferred project, followed by score 2 and finally score 1)

Organisation	**Person**	**Flagship project candidates**					
		A	**B**	**C**	**D**	**E**	**F**
MoE/NELSAP	1	3		2		1	
	2			3			
	3	3	2			1	
RWB	1	2	3	1			
REG	1	1	2		3		
	2	1			2	3	
	3	2			1	3	
WASAC	1	3		1		2	
MINEFRA	1	3			1	2	
RAB	1		3	1		2	
	2		3				
	3	1	3			2	
Private sector	1	2	3				

Since the number of persons met was not the same at each organisation, these scores are summarised per organisation, to remove this bias in the number of representatives from each organisation (Table 81).

Table 81: Average scoring of the flagship project candidates per sectoral stakeholder (ranging from 3 for the preferred project to 1)

Organisation	**Flagship project candidates**					
	A	**B**	**C**	**D**	**E**	**F**
MoE/NELSAP	3.0	2.0	2.5		1.0	
RWB	2.0	3.0	1.0			
REG	1.3	2.0		2.0	3.0	
WASAC	3.0		1.0		2.0	
MINEFRA	3.0			1.0	2.0	
RAB	1.0	3.0	1.0		2.0	
Private	2.0	3.0				
Average	2.2	2.6	1.4	1.5	2.0	0.0
Count	7	5	4	2	5	0
Weighted average score	0.7	0.6	0.2	0.1	0.4	0.0

Final rank	1	2			3	

Finally, the weighted average score is calculated to identify the preferred project by weighting the average with the number of times a given project was scored. Participants were asked to score only the three best projects; therefore, projects that were not scored were the least preferred.

Eventually, project A was the most preferred, followed by B and E.

4.4.1.3 Selection of the three flagship projects

The selected flagship projects are summarised in Table 82. The discussions during the consultations suggested combining the candidate project B and D, to make the flagship project B. The latter is therefore composed of two phases: a first phase to construct the dam SA85 (candidate B) and a second phase to implement the transfer project (candidate D).

Table 82: Selected flagship projects

Flagship project	Objective	Activities	Location
A	Enhance capacity to store, regulate and allocate water for water supply, energy and food security	• Development of a multipurpose storage reservoir: water supply to Kigali and irrigation in Yanze. • Smart association of renewables for electricity generation (hydro and solar) • PES and/or NbS for soil erosion control upstream of the dam. • Enhanced monitoring of water resources for enforcing control and allocation.	Rulindo (Dam site SA76)
B	Development of a climate and water resilient irrigation scheme	<u>Phase 1:</u> • Development of a single-purpose storage reservoir: irrigation and livestock in Kayonza. • Smart association of renewables for electricity generation (hydro and solar) • PES and/or NbS for soil erosion control upstream of the dam. • Improved water productivity for enhanced water and food security. • Climate smart agriculture. • Enhanced monitoring of water resources for enforcing control and allocation. <u>Phase 2:</u> • Inter-catchment transfer from Akagera river to Kadiridimba river (option 6c). • PES and/or NbS for soil erosion control upstream of the intake area in Akagera.	Kadiridimba catchment (Dam site SA85)

Flagship project	Objective	Activities	Location
E	Groundwater for rural domestic water supply and small-scale irrigation	• Exploitation of groundwater for rural domestic water supply and small-scale irrigation. • Sustainable groundwater management (e.g., artificial recharge, solar pumps, community groundwater management). • PES and/or NbS for groundwater recharge. • Improved water productivity for enhanced water and food security. • Climate-smart agriculture. • Enhanced monitoring of water resources for enforcing control and allocation.	

The location of project E will be defined in the concept note.

4.4.2 Concept notes

The three flagship project A, B and E) are respectively renamed as:

- Multi-purpose Dam (SA76) in Rulindo (project A).
- Irrigation Dam (SA85) in Kayonza (project B).
- Groundwater for improving water security in Kirehe (project E).

Their concept notes are elaborated as separate documents accompanying this report, in which are presented the:

- Outcome and outputs.
- Location.
- Rationale for the project.
- Stakeholders to be involved.
- Activities.
- Prerequisites or assumptions.
- Identifications of costs and benefits associated with the project.
- Anticipated Environmental Impact and mitigations measures.

The cost and benefit assessment is not a complete computation, since the level of detail is insufficient at the concept note stage. The point is a first step towards this analysis by identifying the different cost items and revenue streams.

5 Revised National Policy for Water Resources Management

5.1 Implementation assessment of the 2011 National Policy for Water Resources Management

The objectives of Rwanda's National Water Resources Management Policy (2011)[1] (WRMP) were designed for direct translation into implementation activities, with indicators and associated responsibilities.

In essence, the Policy recognised that "Water is a critical resource for Rwanda's socio-economic development". Its proper management was recognised as a national development imperative, necessitating the establishment of appropriate frameworks and measures for water resource management, development, and utilisation. The country's water resources were fundamental to achieving the overarching national policy objectives outlined in Vision 2020, Economic Development and Poverty Reduction Strategy (EDPRS)[2], and other similar high-level national policies using concrete principles, objectives, and actions.

Significantly, the Policy reflected the Rwanda Government's intentions on institutional coordination, which is a significant challenge for developing economies while supporting devolution of decision-making and management to district authorities; enhancing the sustainability of service provision, regulation, and management through use-based fees as reflected in recognition of Law No. 62/2008 on the use, conservation, protection, and management of natural resources[3].

The Policy attempted to harmonise water-related functions through three key measures:

- established an institutional framework for water resource management coordination, a critical component of Integrated Water Resources Management;
- delegated management functions for water resources to appropriate district-based and user organisations, as required by the principles of subsidiarity, stakeholder and user participation; and
- established charges for water use as a critical tool for implementing the widely accepted principle that water has economic value and for financing its sustainable management, protection and conservation.

The 2011 Policy recognised water as a cross-cutting natural resource with applications across all sectors, including domestic consumption, agriculture, commerce, and industry, as well as ecological functions for environmental conservation and providing essential ecosystem services for the sustainability of nature-based resources, including forests, fisheries, and animals.

Water resource management was, therefore, to be best accomplished within a framework that allowed for integrated decision-making.

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[1] Ministry of Natural Resources, 2011 *National Policy for Water Resources, Management*, https://www.rwb.rw/fileadmin/user_upload/RWRB/Publications/Policies/National_Policy_for_Water_Resources_Management.pdf

[2] Republic of Rwanda, 2013. Economic Development and Poverty Reduction Strategy II 2013-2018, https://www.rsb.gov.rw/fileadmin/user_upload/files/EDPRS_2_Abridged_Version.pdf

[3] LAW N°62/2008 OF 10/09/2008 Putting in Place the Use, Conservation, Protection and Management of Water Resources Regulations https://www.rwb.rw/fileadmin/user_upload/RWRB/Documents/Water_law_gazetted.pdf

The Policy summarised key components and the expected contribution to national development goals for various social, economic, health, and livelihood sectors that rely on water inputs, such as agriculture, forestry, hydropower, and water supply; as well as the expected storage, protection of water quality, and sustenance of ecosystem services.

Despite a sound and well-articulated basis for the WRMP, several challenges were identified and continued to grow to become critical constraints as the population and economy as land use, agriculture, mining, and urbanisation grew.

Foremost was the continuous high level of sedimentation of rivers, dams and other storage systems, from a combination of unsuitable agricultural practices in Rwanda's steep terrains; artisanal and high levels of pollution from mining (RWB 2018), climate change, inadequate yet expensive storage and high impacts from climate-induced extreme events, particularly floods in the Western zone[1].

According to the World Bank, the El-Nino-Southern Oscillation (ENSO), an irregular, periodic oscillation in winds and sea surface temperatures over the tropical eastern Pacific Ocean that affects the climate of many tropical nations, causes floods in Rwanda due to heavy rainfall (Figure 131). The most susceptible areas to flooding are western Rwanda (Kibuye and Gikongoro), southern Rwanda (Gikongoro and Butare), and the northern part of Kigali.

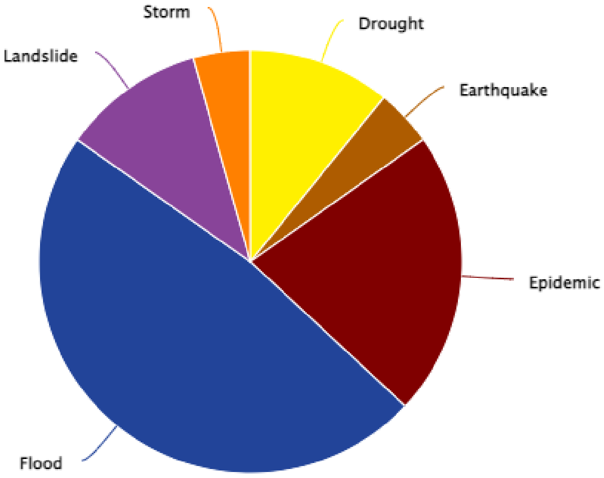

Figure 131: Average annual natural hazard occurrence 1980-2020 (World Bank Climate Knowledge Portal)

La Nina is the opposite drought calamity that frequently results in famines, animal deaths, water resource depletion, a rise in the prevalence of meningitis and other diseases, and economic losses. In addition to unpredictable rainfall, 60–90% of households in the districts of Bugesera, Nyanza, Gisagara, Huye, and Rusizi–Nyamasheke are affected by droughts.

In the short term, these challenges undermine Rwanda's economic development plans. For instance, hydropower and water utilities face a loss of reservoir storage capacity that results in a reduction in clean water and power production, forcing the utilities to turn to expensive fossil fuels to generate electricity. The destabilisation and structural damage of dams caused by the accumulation of silt, loss of investment from shortening the life span of the plant, reduced equipment efficiency, and increasing operation and maintenance costs due to unplanned shutdowns during periods when there is overwhelming siltation[2] (Kalisa, 2019[3]).

At the same time, with 72% of the working population in agriculture (FAO 2020[4]), there is a strong drive to enhance food production, which comes at the cost of increased erosion, siltation and agricultural chemicals, including fertilisers and pesticides released into water bodies.

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[1] Rwanda: Building Resilience to Flood Hazards in Northwest Rwanda through Improved National and Local Capacity https://www.gfdrr.org/en/rwanda-building-resilience-flood-hazards-northwest-rwanda-through-improved-national-and-local

[2] Eustache Hakizimana et al., 'Environmental Impact Assessment of Hydropower Plants in Rwanda: Nyabarongo I Hydropower Plant (NHPP I)', *Energy and Environmental Engineering* 7, no. 2 (June 2020): 27–37, https://doi.org/10.13189/eee.2020.070202.

[3] J. C. KALISA, 2019. Challenges in Hydro-Power Production in Rwanda https://waterportal.rwb.rw/sites/default/files/2019-04/Challenges%20in%20Hydropower%20Production%20in%20Rwanda.pdf

[4] FAO 2020. Rwanda Food and Agriculture Policy Monitoring Review 2020 Policy report. https://www.fao.org/3/cb2403en/CB2403EN.pdf

5.2 Assessment of 2050 policies and gap analysis of 2011 policy

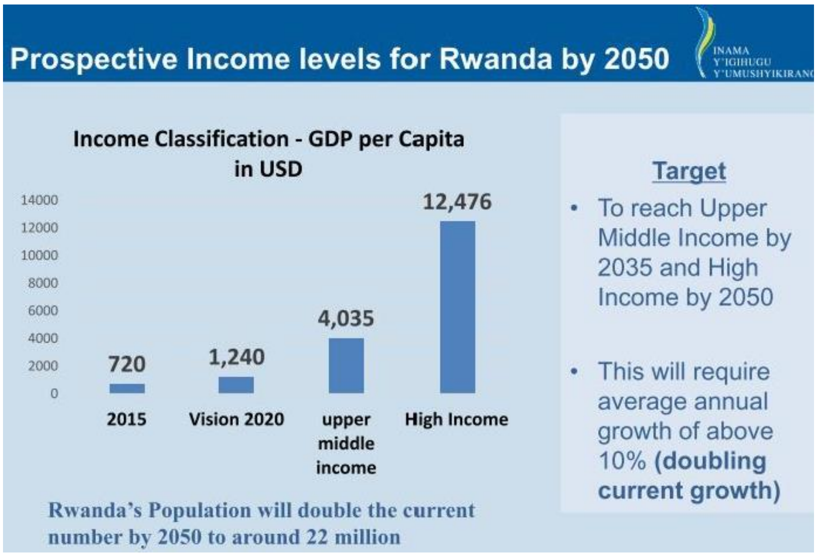
5.2.1 Rwanda's Vision 2020

Vision 2020[1] expressed the intention to invest heavily in water resources which constitute a vital asset that significantly contributes to Rwanda's socio-economic development and poverty eradication. The vision recognised land use management as an essential tool that would help to manage land efficiently and sustainably to improve the national capacity to capture and retain rainwater.

In 2000, when Vision 2020 was released, only 52% of Rwandans had access to clean water. While Rwanda has a rich hydrological network, it was estimated that the average daily water consumption in rural areas was 8.5 litres per person, way below the international standard of 20 litres per person per day.

Rwanda receives each year a net water inflow (rainfall minus evapotranspiration) of about 11.3 billion m3 to replenish its abundant water resources of lakes, rivers, streams, and groundwater, enough to satisfy various water demands from households, agriculture, industries, energy, and other ecosystem needs. Vision 2020 suggested increasing access to potable water by 2.5% annually from then coverage of 52% so that the whole Rwandan population would have access to drinkable water by 2020. The Vision is intended to pursue sustainable development through sound water and land management techniques and adequate biodiversity protection policies.

5.2.2 2050 policies



Prospective Income levels for Rwanda by 2050

Target

- To reach Upper Middle Income by 2035 and High Income by 2050
- This will require average annual growth of above 10% **(doubling current growth)**

Rwanda's Population will double the current number by 2050 to around 22 million

Figure 132: Rwanda MINECOFIN presentation (2016)

Rwanda Vision 2050, the National Strategy for Transformation (NST1), and Vision 2020 are the key guiding policy documents that define development priorities and guiding tools for the future of Rwanda.

Vision 2020 set a long-term development path for Rwanda and formulated ambitious goals to be reached by 2020. The goal was to transform Rwanda from a subsistence agriculture economy to a knowledge-based society earning 900 USD per capita to make Rwanda a middle-income country by 2020.

In Rwanda's development trajectory, the NTS1[1] is the national implementation strategy to facilitate the crossover from Vision 2020 to Vision 2050.

The water sector strategic plan outlines the sector vision, including the establishment of a comprehensive, robust framework for water supply and sanitation resulting in clear institutional roles and coordination mechanisms, adequate capacity at national and sub-national levels to plan, manage and maintain services, and adequate financing, resulting in the achievement of the sub-sector targets. The water and sanitation sector strategic plan (2018 – 2024)[2], currently being implemented, was designed based on Vision 2050 to ensure modern infrastructure, transformation for prosperity, and high standards of living for all Rwandans. The sector also operates under the context of the NST1, collaborative sector strategies and international commitments, notably the 2030 Sustainable Development Goals, Paris Declaration on Climate Change (2030), East African Community (EAC) Vision 2050 and African Union Agenda 2063. To improve public health and socio-economic development, the goal is to ensure sustainable, equitable, reliable, and affordable access to safe drinking water for all Rwandans.

Water and Sanitation Sector Strategic plan (2018 – 2024) targets

- safe and basic water supply coverage to 100% of households;
- basic water service for 100% schools, 100% health facilities and all public places;
- 80% of rainwater harvest in urban areas;
- basic household sanitation coverage to 100% by 2020 primarily by promoting hygiene behaviour change; and 100% of households have a basic hand washing facility with soap and water available;
- 80 % of domestic solid waste recycled, reused or disposed properly in urban and peri-urban areas;

The vision for the sanitation sub-sector is to ensure sustainable, equitable and affordable access to safe sanitation and waste management services for all Rwandans, contributing to poverty reduction, public health, economic development, and environmental protection. Accordingly, the strategy mission for water and sanitation is to promote, plan, build and operate water and sanitation services in a sustainable, efficient and equitable manner to ensure effective sector management.

The strategic outcome of achieving 100% coverage of safe and essential water supply services by 2024 requires, in rural area, at least a 7% coverage increase (about 700,000 people) per year. The development of provincial master plans would be critical to revealing investment needs. As for urban areas, the strategic outcome of 100% coverage will first be achieved through a mapping exercise that will establish a reliable new baseline on urban supply coverage and mapping of unserved areas, including informal settlements, to inform planning for the existing coverage gap. In addition, major strategic actions should be implemented for WASAC to increase its production and distribution capacities and considerably reduce the percentage of non-revenue water.

5.2.3 2011 Policy gap and opportunities analysis

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[1] Republic of Rwanda, *7 Years Government Programme: National Strategy for Transformation (NST1) 2017–2024* https://www.nirda.gov.rw/uploads/tx_dce/National_Strategy_For_Trsansformation_-NST1-min.pdf

[2] Ministry of Infrastructure, 2017. *Water and Sanitation Sector Strategic Plan 2018 – 2024* https://www.mininfra.gov.rw/index.php?eID=dumpFile&t=f&f=10290&token=544f18008e1ce079b163b831a26e26766d6f307b

Introduction to Water Policy Reform, 2022

- The National Policy for Water Resources Management (2011) was formulated to provide a framework for improved water allocation, development, and protection in demographic growth
- It has however been overtaken by key changes to national economic planning frameworks.
- The 2011 Policy did not anticipate the far-reaching legal, regulatory and institutional reforms, including the formation of an apex Rwanda Water Resources Board.
- It also did not predict Rwanda's significant devolution of responsibilities to district and subsidiary levels and international commitments, such as the Paris Agreement on climate change, the Bonn Challenge on the restoration of 93% of Rwanda; transboundary water issues; and biodiversity protection.
- Lastly, there is the need to improve the concomitant use and efficiency of water resources across key economic and social sectors led by water supply, hydropower and irrigation require in-depth review of related policies and programs

Policy gaps are often caused by the growing disparity between the government's broad social and economic targets against the sector agency's focus on narrowly defined outputs and targets. This section will identify the contributions expected of the water sector to the government's economic goals (such as EDPRS) and sector-specific targets (e.g., irrigation, hydropower, water quality, livestock and fisheries).

Discussions with key experts from these sectors provided useful insights on the extent of interagency coordination and collaboration required to meet the policy goals, adequacy of human, technical and financial resources, mobilisation and deployment, and the challenges of devolution given low technical capacities at district levels and the inherent misalignment between a catchment-based approach to managing water given empowerment of district authorities over social, economic development and environmental management.

Consultations with key officials from lead Ministries, State Agencies responsible for implementation and development partners suggest the following as areas of interest in the emerging new Policy (see Annexe 15 for the mapping of primary and secondary stakeholders in Rwanda and Annexe 16 for the list and feedback from these consultations):

- Sustaining the gains made for water resources management since 2010. At the institutional level, The Rwanda Natural Resources Authority gave rise to Rwanda Forest and Water Authority under the Ministry of Environment. Finally, in 2020, the Rwanda Water Resources Board, independent of any Ministry, was formed with broad powers to manage and coordinate all Ministries, agencies and sector actors, answerable to Government directly through the Prime Minister. This was based on increasing recognition of water resources' key role in underpinning environmental, economic and social development and its function in supporting Rwanda's national and global commitments to climate change and land restoration.
- Sector practitioners worry that merging the WRM Policy with the more visible water supply may jeopardise the gains made, particularly if this is followed by a similar amalgamation of the legal and regulatory framework. Decision-makers, particularly at district and local levels, frequently favour water supply due to its direct impact and support from residents.
- On the other hand, there is an opportunity to strengthen awareness of catchment protection as water quality is a key concern for users and managers, who are likely to take direct roles in watershed conservation to enhance the security and quality of the water sources.
- Actors involved in the human right to water advocacy would like to include direct mention of hygiene in the new policy title to give effect to findings of the recent Demographic and Health

Survey that indicates the issue of hygiene as lagging behind and thus needing high-level visibility to gain more attention and funding.

- Strengthening the capacity of District Authorities for management and implementation has to be core to enhanced water security and preventing degradation of landscapes essential to water quality and security while integrating the service delivery to resource sustainability.

The establishment and upgrading of the Rwanda Water Resources Board, achieved through administrative orders, was recognised as a good first step in providing a cross-sectoral governance arrangement that now needs to be institutionalised in Policy, law and regulations.

5.3 Revision of 2011 policy to incorporate Vision 2050

Vision 2050 aspires to elevate Rwanda to high living standards and quality livelihoods, focusing on five pillars: Human Development; Competitiveness and Integration; Agriculture for Wealth Creation; Urbanisation and Agglomeration; and accountable and capable State Institutions.

Under the NST1, access to water will be scaled up from 87% (2017 estimate) to 100% by 2024, with an ambition to increase household connections within premises from 9% (2017 estimate) to 95 by 2035 100% by 2050. The vision endeavours to establish a modern, safe, reliable water supply network. To contribute toward sustainable services, the production and quality of water supplied will be raised to match the increasing demand. It is expected that the relocation and resettlement of the population into densified urban and planned grouped settlement patterns will play a vital role in enhancing universal access to water and other essential services.

The Vision 2050 implementation period will also focus on sustainable management of the environment, adequate waste disposal, treatment and recycling, air and water pollution management and prudent water resource management to meet projected water demand. Its water objectives are summarised in Table 83. In addition, efforts shall be directed towards access to sanitation that will be upscaled from 86% (2016 estimate) to 100%; with adequate waste management systems. The Government of Rwanda also plans to increase onsite household access to sanitation services from 2% to 80% by 2035 and 100 by 2050.

Modern sanitation and sewer management services in urban areas to handle solid and liquid waste are expected to be established. By 2050, all households in urban areas will be connected to sewer networks where waste shall be treated at the central sewerage systems. In rural areas, all households are expected to have access to standardised onsite improved sanitary systems that respect the level of sanitation organisation chains.

In an attempt to change current farming practices, farms shall be mechanised, fully irrigated and use greater volumes of high-tech inputs.

Table 83: Vision 2050 water objectives

Objective #	References	Baseline 2016-2017	Target 2035	Target 2050
31	Land used according to the National Land Use and Development Masterplan	Agriculture: 10,949km2	Agriculture: 11,691 km^2	Agriculture: 12,433km^2
		Built-up areas and infrastructure: 2,888 km2	Built-up areas and infrastructure: 3,434km^2	Built-up areas and infrastructure: 3,980 km^2

Objective #	References	Baseline 2016-2017	Target 2035	Target 2050
		Forests: 7,242 km^2	Forests: 7,483 km^2	Forests: 7,725 km^2
		Water Bodies and their buffer zones: 1,637 km^2	Water and protected wetlands: 2200 km^2	Water and protected wetlands: 2200 km^2
		Wetlands and their buffer zones: 2,068 km^2		
32	Renewable water resource availability per capita per annum (m^3/capita/a)	670 m^3/cap/annum National Water Resources Masterplan (2015)	1000 m^3/cap/annum	1700 m^3/cap/annum
38	Percentage of households using safely managed sanitation services	86.2%	100%	100%
39	Percentage of population using improved water source	87.4%	100%	100%
40	Percentage of households with an improved water source in dwellings/ yard access to safely managed drinking water services	9.4 % (National) 39.2 % (Urban) 2.3% (Rural)	55%	99%

5.4 Implementation Plan for the revised 2011 National Policy for Water Resources Management

Following the gaps and opportunities identified for the WRMD 2011 (see section above) and to revise the first draft of the new policy merging Water Supply, Water Resources and Sanitation sectoral policies, the Consultant provided presentations and a detailed write-up to the Inter-Ministerial Task Force on the gaps, opportunities and framework for implementation of the first draft merged Water Policy (see Annexe 17 for details).

The first draft implementation plan placed a premium on the external environment in which services are delivered, which is commendable, but largely overlooked the following:

- Organisational Development to strengthen the internal capacities of the implementing agencies, which needed to be built up for efficient implementation.
- Defining institutional roles and responsibilities (including trade-offs, for instance, between economically important initiatives like agro-industry or mining that may compromise water quality).
- Effective communication and engagement. There is need to move beyond raising awareness towards effective and substantive public engagement to ensure that various stakeholders and interest groups are fully informed, able to keep pace with progress, and able to make meaningful interventions

The activities in the sanitation and water supply domains recognise the importance of subsidiarity, with actions aimed at strengthening district implementation capacity and empowering households/end users.

Engagement at the grassroots- How Rwanda contained the Covid-19 Epidemic

Gasabo District, which had the highest COVID-19 infection rates in Rwanda with more than 2,500 cases in 501 villages, served to launch the *Operation Save the Neighbour* in September 2021 with the intention of relieving the strain on over-stretched hospitals by preventing deaths from the village level, and enhancing confidence by incorporating doctors in teams providing home-based care. The home-based care strategy had a positive impact on Rwanda's reaction to the intense pandemic waves. Within two weeks of the initiative's debut, the percentage of house visits rose from 30% to 92%. 98 percent of COVID-19 confirmed cases in Rwanda were being treated at home at the end of March 2022. This initiative builds on previous, equally successful programs to contain the Ebola and the Aids epidemics. The structures for health crises management from national to village level endure, and can be harnessed to address critical challenges like restoration of common pool resources including catchments and water bodies at risk of degradation.

However, aside from mentioning public awareness, the WRM component was less explicit about this. On the contrary, WRM activities such as flood control, drought management, and soil and water conservation require household and community action.

The Consultant requested the Task Force to convene additional consultations (across the three domains of water resources, sanitation, and water services) with key implementing agencies and stakeholders to discuss the issues raised above; and assess how the proposed activities would meet the requirements for key water policy issues organised around the following key issues:

1. Policy and Strategy: Water-related policies, legislation, and strategies (including ownership rights over surface and groundwater); critical plans and agreements affecting the use of water resources, in agriculture, forestry, energy, or land use plans; regional (EAC Vision 2050, Africa Union Vision 2063 the Nile Basin Initiative, Lake Victoria basin, and Congo River) and international commitments including Climate Change, Bonn Challenge on Land Restoration[1] and others.

2. Coordination: Coordination among sectors and actors at different levels (local, landscape, river basin, national) relying on water resources for different uses (e.g., agriculture, energy, industry, domestic) and interests (e.g., economy, environment, social). The need for coordination is well illustrated in the study on the effects of upstream siltation on hydropower production at the Nyabarongo plant.[2]

3. Planning and Preparedness: Strategic and action planning to accommodate development needs through green and grey water infrastructure development; protect and rehabilitate water sources, waterways, water-related ecosystems and water resource infrastructure; implement Early Warning Systems, hazard and vulnerability assessments, including climate adaption and response planning; implement catchment disaster preparedness plans.

4. Financing Water infrastructure investment and cost-recovery; Financing (including the allocation of public funds) for rehabilitation and protection of water sources, waterways, water-related ecosystems and water infrastructure; and institutional support; public-private partnerships.

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[1] https://www.bonnchallenge.org/pledges/rwanda

[2] E. Hakizimana, U. G. Wali, D. Sandoval, Kayibanda Venant, 2020. *Environmental Impact Assessment of Hydropower Plants in Rwanda: Nyabarongo I Hydropower Plant (NHPP I)*

5. Management arrangements: allocation and distribution of water resources (e.g., licensing and permitting for water affecting/using activities); Asset ownership and management espacilly when national agencies and district authorities have similar responsibilities; Key sectoral management that affects water resource use and quality (e.g., land, forestry, agriculture and mining).

6. Monitoring, Evaluation and Learning: systematic monitoring of water quality and flow regimes, water availability, water withdrawals, and consumption; Participatory monitoring of water resources; Monitoring of progress in development and implementation of catchment management action plans; Early Warning Systems.

7. Regulation: Economic and environmental regulations such as tariff setting for bulk water, setting water abstraction limits, water discharge and ambient water quality standards and control. Defining policing procedures; Mechanisms for enforcement at different levels, including monitoring of water discharges; Mechanisms to incentivize sustainable/efficient use of water.

8. Capacity development: availability of capacity development strategies and continuous training within Ministries, Agencies and local level organizations; Continuous learning and adaptive management.

Subsequently, the Task Force held a three-day retreat to review the first draft and took into account most of the advice given by the Consultant to produce a second draft Water Policy. This second version was reviewed once more by the Consultant (see Annexe 18), and the following areas for further strengthening were emphasised:

1. There is a need for senior technical officers from departments and agencies responsible for major water resource user sectors (e.g., hydropower, mining, irrigation and the Hygiene and Environmental health sectors) to update their sector plans.

2. Rwanda has committed to several international agreements, for instance, on climate change (adaptation and mitigation) and the Bonn Challenge, where Rwanda expects to restore up to 2,000,000 hectares (81%) with 708,629 ha (29%) already underway. Since the impacts on forests, wetlands and other natural assets will imply significant demand for water resources, the Task Force needs to assess the expected impacts and identify co-benefits and tradeoffs with existing and planned projects.

3. Under the section on water supply, the Consultant requested the Task Force to institute Water Safety Plans to enhance risk management, productivity and security for the chain from catchment to household while improving water quality and protection from pollution and other factors critical in Rwanda for example. These landslides result in significant destruction of infrastructure. The Consultant provided advisory notes with specific procedures on how the water safety plans can be incorporated into the Policy and action plan utilising the WHO Water Safety Plan roadmap[1].

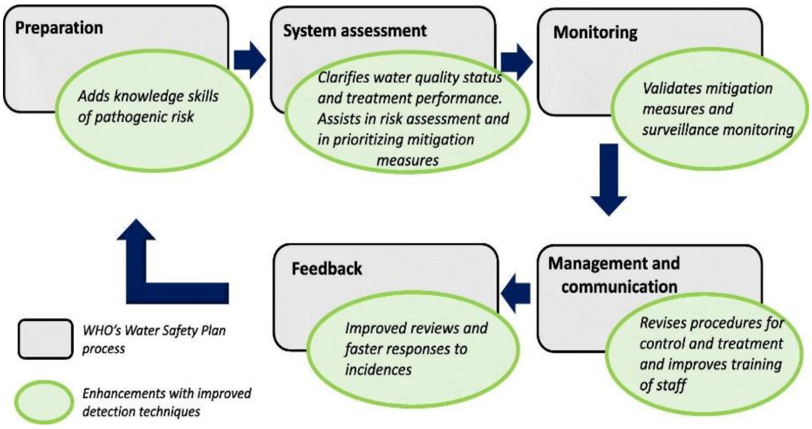

Figure 133: Water Safety Planning Process

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[1] https://www.who.int/publications/m/item/water-safety-planning-a-roadmap-to-supporting-resources

4. In the second draft, the Consultant noted that the distinction between WASAC urban utility management, support for district development and management for rural water needs to extend supporting self-supply (technology, finance) for rural households. Studies elsewhere in developing countries have demonstrated that this can significantly improve the access and affordability of water. A useful background document is the World Bank[1] review of rural water supply sustainability in 17 developing countries, which challenges and how they can be addressed were summarised through the framework below:

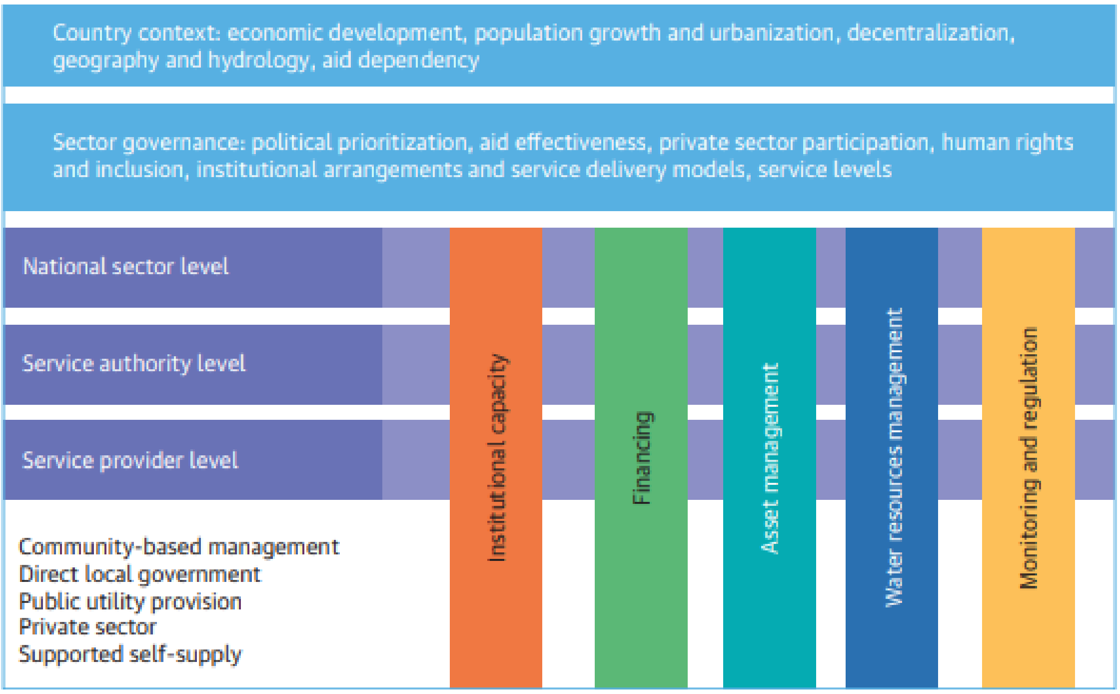

Figure 134: Analytical Framework to understand the sustainability of Rural Water

5. The second Draft noted that electronic waste has considerable damage to water quality. However, the Consultant requested the Task Force to review to what extent the draft should attempt to *"ensure safe management of e-waste, industrial waste, nuclear/radioactive waste and health-care waste"*, given the insufficient technical capacity to manage mainstream water and sanitation activities.

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[1] World Bank. 2017. *"Sustainability Assessment of Rural Water Service Delivery Models: Findings of a Multi-Country Review."*