Final Report

AUGUST 2022

A Water-Resilient Economy

A Hydro-Economic and Climate Change Analysis for Rwanda

2030 Water Resources Group

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Acronyms

BCSD	Bias Corrected Spatial Disaggregation
CCDR	Country Climate and Development Report
CMIP	Coupled Model Intercomparison Project
EDPRS	Economic Development and Poverty Reduction Strategy
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
ha	Hectares
hl	Hectoliters
HECCA	Hydro-Economic and Climate Change Analysis
HPP	Hydropower Plant
ICT	Information and Communication Technology
IPCC	Intergovernmental Panel on Climate Change
lpcd	Liters per Capita per Day
MCM	Million Cubic Meters
MINAGRI	Ministry of Agriculture and Animal Resources
MINECOFIN	Ministry of Finance and Economic Planning
MSP	Multi-Stakeholder Platform
MW	Megawatts
NAEB	National Agricultural Export Development Board
NISR	National Institute of Statistics Rwanda
OBS	Observed data (meaning historical data)
PES	Payment for Ecosystem Services
POP	Persistence Organic Pollutants
PPP	Public Private Partnership
RAB	Rwanda Agriculture and Animal Resources Development Board
RECO	Rwanda Electricity Cooperation
RCP	Representative Concentration Pathways
RDB	Rwanda Development Board
RDS	Robust Decision Support
RMB	Rwanda Mines, Petroleum, and Gas Board
RWB	Rwanda Water Resources Board
SAM	Rwanda's Social Accounting Matrices
SDG	Sustainable Development Goal
SEZ	Special Economic Zone
SRES	Special Report on Emissions Scenarios
SSIT	Small-Scale Irrigation Technology
WASAC	Water and Sanitation Corporation
WCRP	World Climate Research Program
WEAP	Water Evaluation and Planning System
WRG	Water Resources Group

Definitions

a1b	Class of climate projections Special Report on Emissions Scenarios (SRES), with a balanced emphasis on all energy sources
a2	Class of climate projections Special Report on Emissions Scenarios (SRES), with an emphasis on high emissions
b1	Class of climate projections Special Report on Emissions Scenarios (SRES), with an emphasis on global solutions to economic, social, and environmental stability
Baseline (for economic modelling)	Business as usual scenario (which is the same for WEAP)
Catchment	An area where water is collected by the natural landscape within a watershed
Clim RCP (particularly RCPs)	Representative Concentration Pathway climate projection
Demand-side interventions	Interventions that reduce the amount of water demanded by users (for example, behavioral, technical, or lifestyle changes and economic incentives)
Export demand	The demand by foreign countries for goods and services produced domestically
Historical (for economic modelling)	Historical record
Python	A programming language
RCP4.5	Class of climate projections, in which the Representative Concentration Pathway produces decreases in air temperature and increases in precipitation
RCP8.5	Class of climate projections, in which the Representative Concentration Pathway tends to reduce precipitation and increase the temperature
Scenario	A plausible representation of future climate, constructed to investigate the potential impacts of climate change
Supply-side interventions	Interventions that aim to increase the available supply of water
Water consumption	The portion of water use that is not returned to the original water source after being withdrawn
Water coverage	The percentage of water demand that is met
Water demand	The volume of water requested by users to satisfy their needs
Water supply	A source or volume of water available for use
Water use	The total amount of water withdrawn from its source to be used

Executive Summary

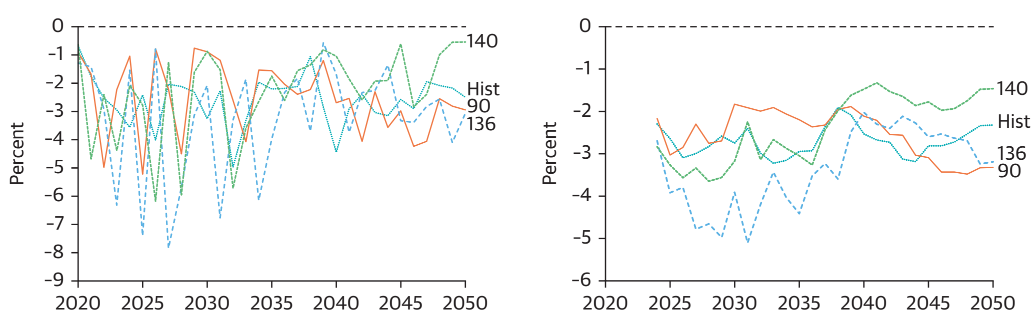
The Rwanda Water Resources Board (RWB) contacted the 2030 Water Resources Group (2030 WRG) to support a Hydro-Economic and Climate Change Analysis (HECCA) to identify concrete opportunities for investing in a more water-secure future for Rwanda and to ascertain how the private sector could be more engaged. The goal of the HECCA is to show which sectors and geographical areas are likely to experience water resource challenges that could hamper future growth and transformation in the country. This HECCA demonstrates the many intersectoral linkages in water resource management by examining the gaps between water demand and supply, and how those gaps play out in Rwanda's macroeconomy.

While, across the country, Rwanda is likely to have sufficient water to meet its economic targets, without effective planning to address seasonal and geographic variability and the uncertainty caused by climate change, there is a risk that water scarcity could hold back the country's development. There is a need for more structured investment planning and streamlined, more strategic water allocations across water catchments and economic sectors, specifically agriculture, to meet growing demand and ambitious targets.

Despite being considered at low water risk, Rwanda is vulnerable to climate change. Rwanda ranks 101st of 150 countries on the World Resources Institute's Aqueduct Water Risk Atlas,[1] placing it among the lower-risk countries. Yet this HECCA shows that Rwanda is, under baseline (status quo) conditions, relatively vulnerable to climate change at the level of the macroeconomy. This is illustrated in Figure 1, across four climate scenarios, in which "Hist" (line) depicts historical trends, climate "90" (line) presents a scenario with similar rainfall but higher temperatures, climate "136" (long dashes) presents a drier climate, and climate "140" (short dashes) presents a wetter climate than has been the case historically. Results, shown both on an annual basis and as a five-year running average, show the percentage deviation from the economy's potential gross domestic product (GDP). As depicted in Figure 1, all scenarios show considerable year-on-year variability. Ideally, Rwanda's macroeconomy would show more stability in the face of varying climatic conditions.

Rwanda has reached a point where it will be difficult to sustain high growth without greater private sector engagement and investment, and this will have important implications for water resource management. Vision 2050 aims to transform Rwanda into a dynamic global hub for business, investment, and innovation, with its growth ambitions dependent on the ability of the private sector to take the lead. While the government has made progress in improving the enabling environment for private sector engagement, several barriers still need to be addressed. The cost of doing business remains high in Rwanda, and the private sector faces high costs of transportation in almost every sector of the economy.

FIGURE 1. Deviation of GDP from estimated potential in the baseline scenario due to water constraints; left – annual; right – five-year running average



With regard to the water sector, Vision 2050 assumes a much higher share of the population in urban areas, with universal and relatively high rates of per-capita domestic water use, at 100 liters per capita, per day (lpcd) for all. It assumes an extensive increase in irrigated areas (by a factor of more than 10 times the current area), and a more modest increase in industrial activities that can be water-intensive, such as mining and manufacturing.

The central question is whether, and how, Vision 2050 can be achieved given the baseline scenario's water-related constraints and their potential impacts on GDP. Domestic use and irrigated agriculture make up over 90 percent of total current water demand. Yet industrial water demands are assumed to expand significantly over current levels, from 9 million cubic meters (MCM) to approximately 25 MCM per year in Vision 2050 and to 23 MCM per year in the water-resilient Vision 2050 (WRes2050) scenario. The lower level for WRes2050 is due to increased water efficiency in the industrial sector.

Overall, the baseline scenarios for the four climate variations project that water demands would increase by 83 percent in the 30-year period from 2020 to 2050. The full realization of Vision 2050, based on the 2015 document, would lead to an increase in water demand of 1,140 percent over 2020 levels, with major increases in water use in the agricultural sector in the form of large-scale irrigation (Figure 2). A third scenario, which combines reduced dependence on hydropower and lower water use rates in agriculture through climate-smart technologies, shows an increase in water demand of 740 percent over 2020 levels. **The strategies promoted in the water-resilient scenarios significantly reduced the overall water demand needed to achieve Vision 2050.**

Both Vision 2050 and WRes2050 assume significant increases in water storage. While water storage—a supply-side intervention—is a critical component in achieving the levels of economic growth targeted in Vision 2050, storage alone is insufficient. The country's overall economic dependence on hydropower poses a significant risk to economic growth. By combining a reduction in hydropower dependence from 40 to 20 percent with a balance of supply-side and demand-side interventions, the WRes2050 scenario implies lower GDP losses related to water constraints (Section 6.3), while maintaining overall GDP growth rates consistent with Vision 2050 (Figure 3).

The supply-side interventions considered in this analysis focus primarily on water storage. The scale of these storage solutions is mainly at the level of dams, small reservoirs, and rainwater harvesting, as well as the use of existing water bodies for fishponds. Additional options could include accessing groundwater, supplemental irrigation for rainfed agriculture, source water protection, wastewater reuse and recycling, and flood protection.

The report highlights the inconsistency of hydropower production and the great stress that will be placed on existing infrastructure as demand grows. Policy dialogue is required between the water and energy sectors to agree on targets, both for augmenting existing hydropower electricity generation (most likely through additional micro-hydropower plants) and for reducing the overall share of the country's power supply that comes from hydropower.

FIGURE 2. Annual water demands for baseline, Vision 2050, and water-resilient scenarios

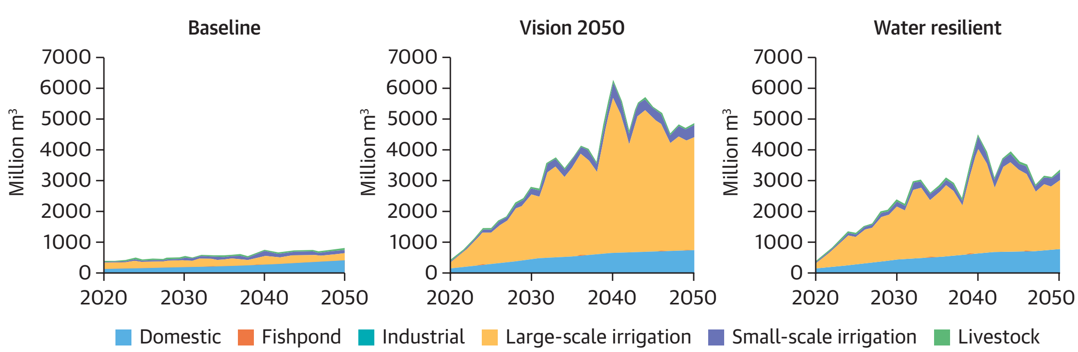
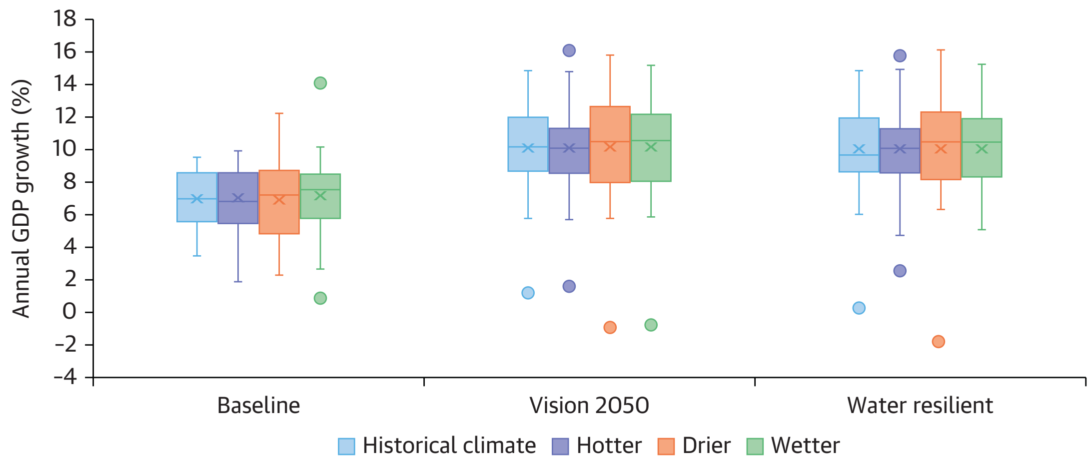


FIGURE 3. Distribution of annual GDP growth rates under different production and climate scenarios



The demand-side interventions in this analysis focus on climate-smart agriculture. This includes improvements in crop yields and reduced water use rates in industry. Additional measures could also include reducing non-revenue water through improved infrastructure and improved metering and institutional strengthening, efficient agriculture and domestic water use technologies, economic incentives, and reduced water pollution. The analysis assumes that, under both Vision 2050 and WRes2050 scenarios, environmental flows are given the highest priority, equal to that of domestic water use. All other uses are allocated water after ecosystem requirements and domestic water demands are met.

The private sector is a significant user of water resources, specifically in the agriculture sector. Planned expansion in other industrial sectors will also place more stress on water resources in urban areas and, if poorly managed and regulated, risks polluting this already scarce resource. The private sector also offers Rwanda an opportunity, however, to improve water supply and management through changes in usage patterns, the introduction and adoption of new technologies, and the financing of related infrastructure, such as water supply systems and storage solutions.

To harness this potential, Rwanda needs to better understand the private sector's needs and comparative advantages and establish stronger mechanisms to enable communication and collaboration between the public and private sectors. It has been proposed that this could be achieved through the establishment of Multi-Stakeholder Platform (MSP) that facilitates collective action and places water more deliberately and systematically at the center of strategic efforts to achieve national goals.

Moreover, without supporting governance structures in place, water infrastructure will degenerate over time and allocation decisions will be undermined, leading to a less secure water future for Rwanda. Investment in water governance is therefore just as critical as any other aspect of water planning. All of the proposed interventions require adequate and effective legal, regulatory, and institutional mechanisms. Figure 4 sets out the report's key recommendations for future policy discussion and further analysis over the short and medium-to-long term.

In summary, Rwanda is well positioned to achieve the ambitious goals set up in Vision 2050, but implementation requires careful consideration of the potential impact of water-related constraints on the overall economy. These impacts will become increasingly uncertain due to escalating changes in climate patterns as the world experiences the impacts of climate change. **Vision 2050 needs to be approached through a water-resilient lens in order for the people of Rwanda to experience the well-being aimed for in this vision for 2035, 2050, and beyond.**

FIGURE 4. Key short-term and medium- to long-term recommendations

Short-Term Recommendations	Medium- to Long-Term Recommendations
• Development of national investment plan to enhance water storage • Assesment of sedimentation in water storage infrastructure, focus on hydropower dams • Supplemental small-scale irrigation interventions • Policies to address waste from non-revenue water • Wastewater management strategies • Policy to support the expansion of payment for ecosystems services (PES) schemes • Innovative financing strategies to maximize blended finance, public-private partnerships (PPPs), and corporate social responsibility	• Ongoing tracking of the impact of climate change on agriculture • Policies to promote the development and deployment of new technologies to sustainably use groundwater • Policy dialogue between the water and energy sectors to review reliance on hydropower • Expansion of small hydropower schemes • Further research into preserving critical ecosystems to protect and promote tourism

Note

1. https://www.bloomberg.com/graphics/2019-countries-facing-water-crisis/

Chapter 1
Introduction

Rwanda's Vision 2050 is a flagship policy document that articulates the country's long-term strategic directions and the pathways to enable achievement of its ambitious goals. Rwanda aspires to become an upper-middle-income country by 2035 and a high- income country by 2050. Vision 2050 provides policy guidance and serves as the planning blueprint to guide the efforts of all players in Rwanda's development. It envisions several structural shifts in the economy, with the private sector expected to be a significant engine for change and growth to achieve this transformation.

As highlighted in Vision 2050's targets and indicators, water is a critical resource to support the country's economic, social, and environmental goals. Gaining a clearer understanding of the impacts of changing supply and demand on water sources—as well as the nexus between water, energy, and food production—will be critical to Rwanda's success in making progress toward these targets over the coming year. Approaches that enable integrated management and governance across sectors and scale can thus facilitate greater policy coherence and more efficient use of resources.

The Government of Rwanda (GoR) has recently established the Rwanda Water Resources Board (RWB) to better coordinate, empower, and mobilize all stakeholders; to properly allocate water resources among various sectors; to improve the governance of water resources; and, most importantly, to strengthen partnerships with a view to increasing financial resources and developing more extensive networks for green growth infrastructure. The RWB requested the 2030 Water Resources Group (2030 WRG)[1] to support it in fulfilling its important mandate. The 2030 WRG subsequently met with the RWB, the Ministry of Agriculture and Animal Resources (MINAGRI), and the Ministry of Environment and agreed to: (i) identify opportunities for a national Multi-Stakeholder Platform (MSP) for Water Resources Management in Rwanda (anchored at the RWB); (ii) undertake a Hydro-Economic and Climate Change Analysis (HECCA) for Rwanda; and (iii) establish an agricultural water management work stream (hosted by MINAGRI).

While there is a strong history of the government and development partners working together to achieve development goals, the private sector traditionally has not been engaged in such initiatives. The MSP for Water Resources Management in Rwanda provides an opportunity to engage the private sector more actively in assessing challenges and developing solutions. As discussed below, the private sector will play a critical role in providing technical and financial resources to support the more effective use of water resources to achieve Rwanda's development goals. To guide the establishment of the MSP and inform the private sector's role in the water and related sectors, this HECCA report, fulfilling item (ii) above, assesses the current engagement of the private sector in water use and management, reviews the enabling environment for more meaningful and sustainable private sector engagement, and discusses some of the barriers to and opportunities for streamlining and deepening that engagement.

As strategic assessment of the water sector, identifying concrete opportunities for collective action, the HECCA will serve as a foundation for initiating dialogue and project proposals to be developed under an established MSP that brings together senior government, private sector, and civil society leaders in Rwanda.

The HECCA shows which sectors and geographical areas in Rwanda are likely to experience future water resource challenges that could hamper growth and transformation in the country. This analysis aims to support dialogue with interested parties on identifying and aligning joint initiatives toward sustainable water resources management and thereby to enable long-term economic growth into 2030 and 2050.

The World Bank Group (WBG) has developed a Country Climate and Development Report (CCDR) for Rwanda, which aims to analyze how the country's development goals can be achieved in the context of the Paris Agreement and the WBG's commitment to align its portfolio with its objectives. **The CCDR provides an opportunity to further engage the Ministry of Finance and Economic Planning (MINECOFIN) in climate analytics to better understand the benefits and costs of climate action and cross-sectoral policy priorities to manage climate risks effectively. The HECCA is viewed as an important sector input to the CCDR, providing technical information to guide climate-related investments in the water sector.** This complements Rwanda's 2020 Nationally Determined Contribution (NDC) report, which sets out goals not only for mitigation but for adaptation, which are of particular relevance for water-related sectors of the economy. Factoring in the NDC, this report also contributes to the CCDR's aim of identifying near-term opportunities for private sector engagement in climate resilience and mitigation.

The first component of the HECCA is to conduct a high-level assessment of where water supply is inadequate to meet water demands over space and time. The Stockholm Environment Institute's Water Evaluation and Planning (WEAP) platform will be used for this assessment, complemented by an analysis evaluating the economic implications of the way in which WEAP simulations allocate water throughout Rwanda.

This document begins with a description of HECCA. This is followed by an overview of the private sector enabling environment in Rwanda and a review of the private sector's, current and potential roles in the country's water sector. Next, the report describes in detail the development and calibration of Rwanda's national WEAP model. This is followed by a discussion of the economic analysis methods used and the scenarios explored. **The results of the baseline, or business-as-usual, scenario are examined via 121 unique climate projections, revealing the vulnerability of Rwanda's current infrastructure and policies. Two additional scenarios are explored, Vision 2050 and Water Resilient Vision 2050 (WRes2050), to identify investment and policy pathways that are likely to lead to a more water-secure Rwanda in 2030 to 2050. Conclusions and recommendations are presented in the final section.**

Note

1. The 2030 WRG is a public-private-civil society partnership, hosted by the World Bank, that supports governments to accelerate reforms with the aim of ensuring water security for the long-term development and economic growth of their country.

Chapter 2
Methodology

2.1. WEAP

2.1.1. System capabilities

WEAP is an integrated water resources planning tool that is used to represent current water conditions in a given area and to explore a wide range of demand and supply options for balancing environmental and development objectives. WEAP is used widely to support collaborative water resources planning by providing a common analytical and data management framework to engage stakeholders and decision makers in an open planning process. Within this setting, WEAP is used to develop and assess a variety of scenarios that explore physical changes to the system, such as new reservoirs or pipelines, as well as social changes, such as policies affecting population growth or water use patterns. Finally, the implications of these various policies can be evaluated with WEAP's graphical display of results. More detailed information about the tool is provided in Annex B.

2.1.2. Spatial disaggregation

WEAP allows for a fairly high level of disaggregation to describe water supplies and demands. In practice, the model's data structure is determined by the research or policy questions that are being addressed. This commonly starts with questions pertaining to how best to allocate water to competing users, which may include different water use sectors (domestic, municipal, industrial, agricultural, environmental, and so on) as well as water users in different parts of the basin. The first level of data disaggregation thus focuses on determining which water use sectors should be included in the model. The next level of data disaggregation determines how each of these water use sectors should be disaggregated spatially. Spatial disaggregation is generally determined by water sources. For example, agricultural areas that divert water from the mainstem of a river may be considered separately from agricultural areas that divert water from a tributary flowing into the main river. Similarly, we may separate domestic demands that each take water from the same river, where downstream users are affected by the level of upstream abstraction.

These considerations are reflected in the data structure used to develop the national WEAP model for Rwanda. The Water Users and Uses Assessment in Rwanda (RWB 2020) was used as the basis for estimating water demands

in WEAP, because it provides the most recent comprehensive assessment of water use in Rwanda. For this model, we considered the following water use sectors and associated demand drivers:

- **Domestic**: Population is the main driver for domestic water use, and per-capita water use is based on information in the National Water Resources Masterplan, which estimated current rural and urban water use at 40 and 60 liters per capita per day (lcpd), respectively.
- **Irrigated agriculture**: Cropped areas for irrigated agriculture are the driver of water use in this area and are determined based on a data obtained from RWB (2020). This document indicates whether the areas are small, medium, or large. Small-scale agriculture is assumed to grow combinations of vegetables and fruits, and large-scale agriculture to include rice as well. The calculation of crop water requirements is based on the phenology of different crop types (for example, development cycle and planting and harvesting dates) and their cropped areas.
- **Rainfed agriculture**: MINAGRI publishes an annual report on cropped area and production in each of Rwanda's 30 districts. Data from the 2021 report were used to establish a baseline for rainfed crops. As with irrigated crops, crop water requirements are based on the phenology of different crop types.
- **Livestock**: The main drivers of livestock water use are the number of livestock units and their daily water usage, where one livestock unit is equivalent to one cow that consumes about 50 liters of water per day (MINAGRI 2018). Data for other animals are converted into livestock units using conversion factors obtained from MINAGRI.[1] Livestock population data for Rwanda's 30 districts were obtained from MINAGRI for the year 2018.
- **Industry, including mining, coffee washing, and manufacturing**: The primary uses of water in Rwanda for industrial purposes are coffee washing, mining, and regionally specific commercial activities, such as textiles, agro-processing, and manufacturing. Assumptions related to each sector-specific water use were developed based on information in the National Water Resources Masterplan, which provides regional estimates for per-unit water use in each sector.
- **Fishponds**: Fishponds and local aquaculture stations have been incorporated into the model using data from the National Water Resources Masterplan, MINAGRI, RWB, and the Rwanda Agriculture and Animal Resources Development Board (RAB). Water use was calculated in WEAP as the volume needed to maintain ponds at a depth of 1 meter to offset water losses to evaporation and percolation. In addition, consumption was validated using data from the National Water Resources Masterplan regionally, where estimates of current use range between 0.03 and 3.76 million cubic meters (MCM) per year.
- **Hydropower**: Hydropower generation is calculated based on flow in rivers and releases from reservoirs and aligned with Rwanda Energy Group data and analysis in the Least Cost Power Development Plan for 2020–40.
- **Ecosystems**: In-stream flow requirements are set to a fixed 30 percent of the unimpaired flow, consistent with the basic premise of the percent of flow approach established in Flannery et al. (2002). The unimpaired flow was calculated under each climate scenario, representing the hydrology without human demands or water storage, and then imposed as an environmental flow requirement in WEAP.

An example of how these demands are represented in WEAP for each sub-catchment is shown in Figure 5, where red circles represent water demands, green circles represent sub-catchments, green squares represent groundwater, blue dotted lines represent rainfall runoff and groundwater recharge, blue solid lines represent rivers and streams, green lines represent surface water diversions and/or groundwater pumping, and red lines represent return flows.

Rwanda is divided into nine high-level hydrological catchments. These are referred to as Level 1 catchments (Figure 6; Table 1).

When considering the spatial gap, it is important to take into consideration the level of detail. Rwanda's hydrology currently has three levels of disaggregation: Levels 1, 2, and 3 (Figure 7).

Level 1 has nine catchments, Level 2 has 21, and Level 3 has more than 300. For this HECCA, an intermediate level between Level 2 and Level 3 was determined to be most appropriate for water planning purposes. We term this approach "Level 2.5," and it divides Rwanda into 88 hydrological sub-catchments (Figure 8). Figure 9 shows how the water supply and demand structure is implemented in WEAP for each of the Level 2.5 sub-catchments.

More details on the WEAP model are found in Appendix B: WEAP.

FIGURE 5. Example of Level 2.5 disaggregation of demands

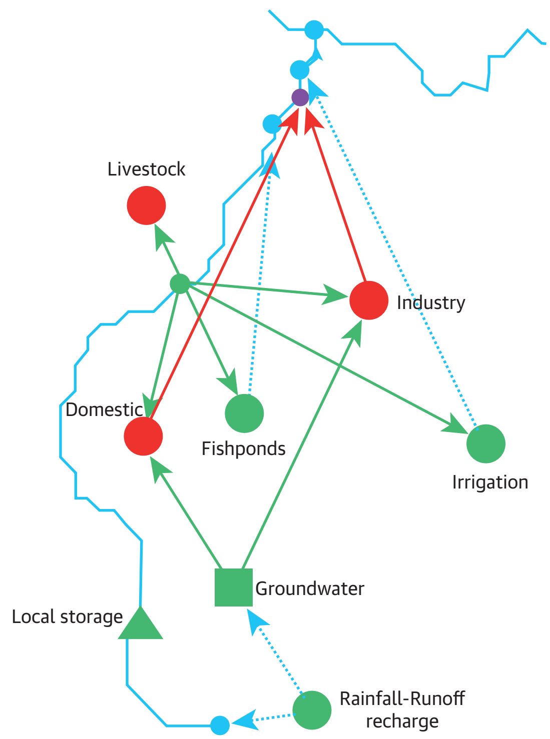
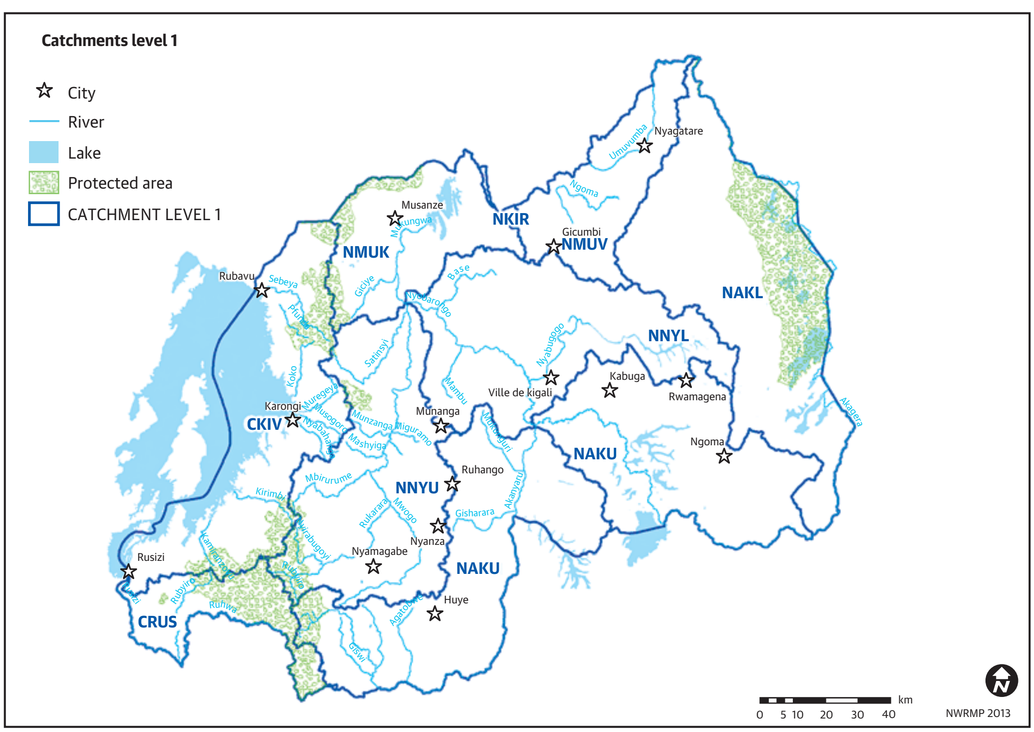


FIGURE 6. Location of the nine Level 1 sub-catchments for Rwanda (Republic of Rwanda 2014), where the first letter of each catchment indicates whether it is in the Nile (starting with N) or the Congo (starting with C). NAKL is the Lower Akagera catchment



Source: Republic of Rwanda (2014)

TABLE 1. Summary of Level 1 Catchments (adapted from NWRMP 2013)

Code	Basin	Catchment Name	Surface Area (km²)
CKIV	Congo	Lake Kivu	2,425
CRUS	Congo	Rusizi	1,005
NNYU	Nile	Nyabarongo upper	3,348
NMUK	Nile	Mukungwa	1,887
NNYL	Nile	Nyabarongo lower	3,305
NAKN	Nile	Akanyaru	3,402
NAKU	Nile	Akagera upper	3,053
NAKL	Nile	Akagera lower	4,288
NMUV	Nile	Muvumba	1,565

FIGURE 7. Levels of hydrologic analysis for Rwanda, with Level 1 on the left, Level 2 in the middle, and Level 3 on the right

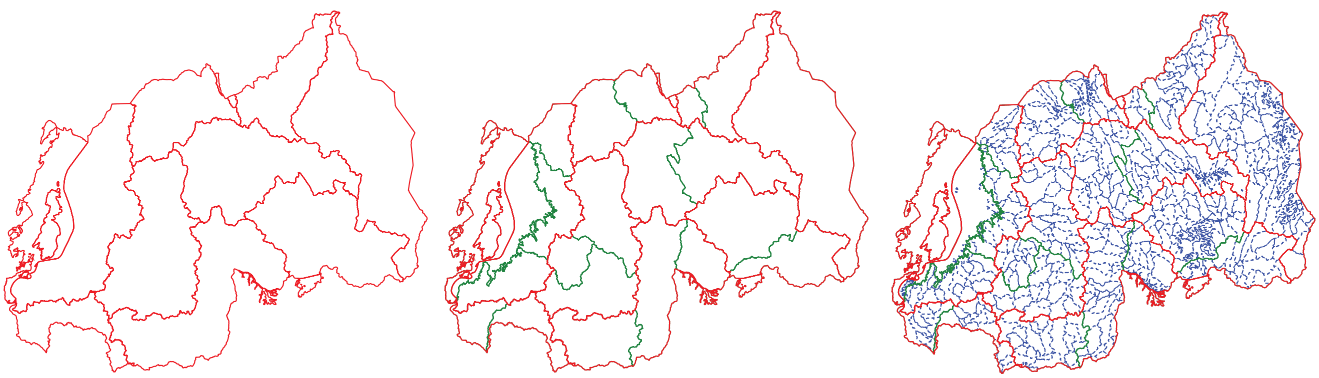


FIGURE 8. Catchment level 2.5 with shaded areas at Level 1, and sub-catchments labelled with letters within each Level 1 catchment

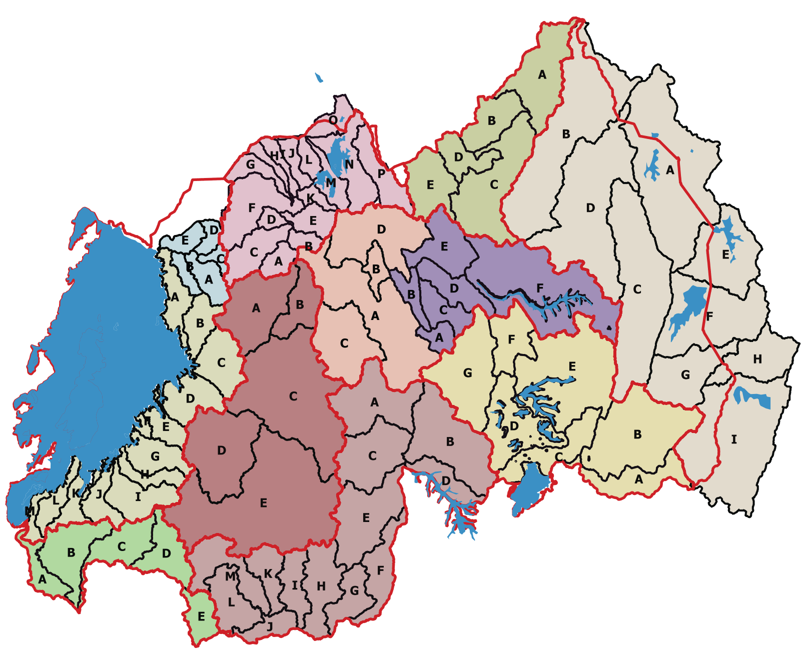
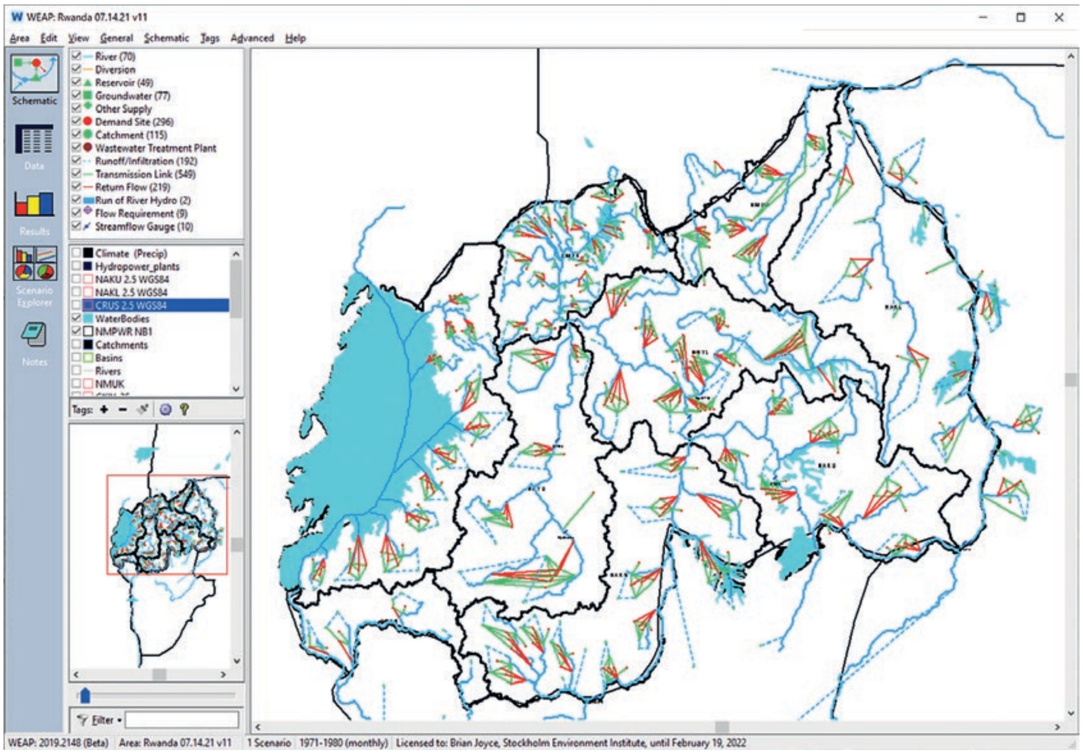


FIGURE 9. **WEAP Schematic for catchment level 2.5**



2.2. Economic Analysis

The economic analysis within the broader HECCA aims to: *(1) provide analytical tools for understanding the role of water-dependent sectors in the economy, and (2) generate scenarios of deviations in economic output due to water constraints on domestic production*. The analysis focuses on the structure of the economy that is, on interconnections between economic sectors to represent, as mentioned above, how water-constrained production from one sector can cascade through the economy to affect other sectors. The resulting model can be used to estimate the impact on gross domestic product (GDP) from water constraints. The model is then used to estimate "costs of inaction" by comparing GDP under a production scenario aligned with Vision 2050, with and without water storage and supply. These calculations will inform a later section on investment opportunities.

There are, broadly, two ways in which one sector can have an impact on others. First, if as a result of lower production, the sector makes less use of inputs from upstream sectors in the economy, it will lower demand from other sectors (and, perhaps, from imports). In the context of this research this is called a *backward* linkage. Second, if outputs from the sector are used by downstream sectors, then it might constrain output from other sectors (and, perhaps, lower exports), which is referred to as a *forward* linkage. The macroeconomic analysis takes both effects into account.

2.2.1. Sectors in the analysis

The choice of sectors for the economic analysis (Figure 10) is informed by both the needs of water resources analysis in WEAP and the content of national and sectoral plans for Rwanda. It is constrained by the structure of Rwanda's Social Accounting Matrices (SAMs). There are 26 sectors, which have been aggregated from the 74 activities and 78 commodities of the Rwandan SAM for 2017. Most of the sectors were chosen because they are water-dependent and therefore tracked within WEAP. Three of the sectors knowledge-based services, textiles, and tourism are mentioned in the Vision 2050 document but are not particularly water-intensive. Other sectors are present because of their role in broader economy.

FIGURE 10. Aggregate sectors based on SAM 2017. From the Rwanda Statistical Yearbook 2012, the value of consumption for electricity was around 10 times the value of consumption for water (values for natural gas were not available). For this reason, we consider "electricity, gas, and water" to predominantly reflect electricity production

Sector	Export share	Linkages Forward	Linkages Backward	Motivation WEAP	Motivation Vision 2050	Motivation Other
Mining, oil and gas	14%			x	x	
Electricity, gas, and water	0%			x	x	
Rice	1%			x		
Other cereals	0%			x		
Tubers and root crops	0%			x		
Bananas	0%			x		
Fruits	0%			x		
Pulses	0%			x		
Vegetables	0%			x		
Coffee and tea	14%					Forward linkages into agro-processing
Other crops	0%					
Livestock	1%			x	x	
Forestry	0%			x		
Fishing	0%			x		
Agro-processing	9%			x	x	
Textiles and garments	3%				x	
Other manufacturing	7%					
Construction	2%					Labor-intensive input to investment expenditure
Wholesale and retail trade	0%					Key intermediate sector
Transportation	9%					Key intermediate sector
Tourism and hospitality	22%				x	
Knowledge-based services	3%				x	
Other services	0%					
Public administration	14%					Public sector balance
Education	0%					Public sector balance
Health	0%					Public sector balance, COVID-19

Figure 10 shows some metrics that are based on the aggregated SAM. The export share shows the importance of the water-dependent mining and food processing sectors for exports. The measures of forward and backward linkages[2] show the degree to which the rest of the economy depends on the sector as a source of either upstream supply or downstream demand. For example, coffee and tea are delivered to the agro-processing sector, so coffee and tea have high forward linkages, while agro-processing has high backward linkages. Economic development plans, even if the general strategy is export-oriented, seek broadly to increase both forward and backward linkages. For example, the tourism and hospitality sectors bring foreign exchange into the country and provide direct employment for restaurant and hotel employees. However, their broader impact is evident from the relatively high backward linkage measure; the tourism sector has a high demand for goods produced elsewhere in the economy, particularly agricultural processing, livestock, transport, and manufacturing.

Aggregate SAMs were constructed using the Rwandan SAMs for 2006 and 2011, each of which had 54 sectors. After aggregating to the 26 sectors used for this study (from SAM 2017), the forward and backward linkage indices were computed. Setting aside possible issues with compatibility between the exercises in the different years, the data show a tendency toward both higher forward and higher backward linkages. This is a characteristic development pattern, in which interactions and exchanges between sectors become strengthened. By linking expanding sectors to the rest of the economy, increasing integration supports broad-based growth. At the same time, it increases interdependency between sectors, and therefore potential vulnerability. For water-dependent sectors, storage helps to offset that vulnerability. Given the substantial impact of storage at both watershed and macroeconomic scale, it is a particular focus of the modeling exercises. Other interventions are explored to different degrees, including different cropping patterns and technologies, and changes in the overall energy mix.

2.2.2. Economic analysis methodology

Details of the methods used for the economic analysis are provided in Appendix E, in mathematical form. As explained in the appendix, the economic analysis requires a set of parameters, listed in Table 2. Most of the parameters are derived from Rwandan statistics, except for longer-term trends, which are based on scenarios.

Two parameters that must be specified to execute the model are "domestic dependence" and "input sensitivity". These determine the degree to which water constraints or reduced production affect sector output. The calibration procedure is explained below.

2.2.3. Calibration

Calibration was carried out on a scenario with baseline economic assumptions and historical climate trends. The description of the baseline scenario is given in Section 5.1 below but represents a future that assumes "business as usual," with no major new policies or infrastructure. As indicated in Table 2, growth in final domestic demand and exports in each sector was prepared based on recent trends and was then assumed to approach a long-run value. For most sectors, the long-run growth rate of final demand in the baseline scenario was set to the general (that is, not sector-specific) growth rate of final demand in recent years, at around 7.1 percent per year. However, given the tendency for demand for food to rise more slowly than for other goods (Engel's Law), the long-run growth rate for final demand for agricultural products was assumed to be lower than in other sectors, at 3 percent per year for non-livestock sectors and 5 percent per year for livestock. Further details of the calibration are set out in Annex D, including how the methodology has addressed the availability of foreign exchange, domestic dependence, and the impact of power outages.

TABLE 2. Parameters, purpose, and source of assumptions

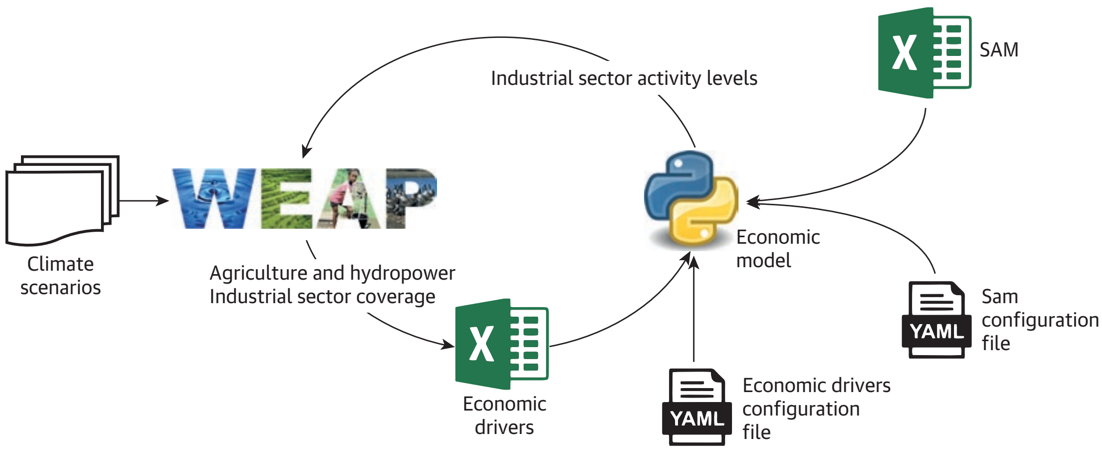
Input	Purpose	Source
Technical coefficients	Relate production in one sector to demand for another sector's product	Rwanda SAM
Final demand	Differentiate changing levels of domestic demand for different sectors' outputs	Rwanda SAM; near-term growth based on recent patterns from National Institute of Statistics Rwanda (NISR); long-term growth based on scenario
Export demand	Differentiate changing levels of foreign demand for different sectors' outputs	Rwanda SAM; near-term growth based on recent patterns from NISR statistics; long-term growth based on scenario + (for the baseline) calibration
Specified production	Set production levels in specific water-dependent sectors	WEAP
Non-hydropower electricity generation	Hydropower production is generated by WEAP. The production index for total electricity generation comes from a LEAP[3] exercise carried out as part of an earlier study.	Technical report: "Narratives, data and assumptions used to model development scenarios and climate sub-scenarios for Rwanda"
Import propensities	For production levels solved by the model, determine how much of domestic demand is supplied by imports	Rwanda SAM
Price indices	Take relative prices into account while computing sectoral activity levels	Near-term growth based on recent patterns from NISR and Food and Agriculture Organization statistics (FAOSTAT); long-term change based on scenario
Domestic dependence	One of two factors, associated with an upstream product, that expresses the degree to which upstream supply constraints affect downstream production	Domestic production divided by the sum of domestic production and imports
Input sensitivity	One of two factors, associated with a downstream producer, that expresses the degree to which upstream supply constraints affect downstream production	World Bank Enterprise Survey + assignment + calibration (see text)

2.3. Connecting WEAP and the Macroeconomic Analysis

The HECCA is carried out using multiple models. The core modeling tool is the WEAP system. It interacts with the economic model via a set of "soft" links. The economic model, which is written in the open-source language Python, is being built for the HECCA project.

The models are described in detail in Section 2 on the WEAP model and in Section 3 on the economic analysis. In this section, the relationships between the models are explained. Selected WEAP outputs are used as economic drivers—physical production of agricultural goods and hydropower[4]—and "coverage" of water needs in water-dependent sectors (Figure 11). The economic aspects of the scenarios are effectively specified in the economic drivers' workbook,

FIGURE 11. Relationships between model components (note that the economic model is implemented in Python)



while the scenarios in WEAP are determined by detailed internal assumptions, drivers from the economic model, and climate scenarios. The economic model takes three input files in addition to the economic drivers: a SAM, a configuration file to aggregate the SAM, and a configuration file describing the economic drivers' workbook.

After an initial run of the economic model, simulated industrial sector activity levels are passed back as inputs to WEAP. This calculation is carried out once, so there is only a single iteration of the models. After passing the activity levels from the economic model to WEAP, WEAP is run again, and the updated economic drivers are passed to the model for a final run.

2.4. Scenario Pathways

Scenarios are a common approach to help understand the consequences of different planning options, as well as critical uncertainties that is, factors outside the control of decision makers that can affect outcomes. The methodological approach is described below, followed by a description of the three scenario pathways explored in the analysis.

The method proposed for exploring alternative investment opportunities and policies is to use a Robust Decision Support (RDS) scenario process, which is based on a framework for theoretical decision making under uncertainty, referred to as Robust Decision Making.[5] The motivation for RDS is that traditional decision-making systems and approaches do not factor in deep uncertainties, like climate change, where there is no consensus about the likelihood of specific climate futures.

The scenario process centers on pathways to achieve Vision 2050, using the macroeconomic analysis, subject to external critical uncertainties, starting with climate change. The central feature of the RDS practice is to acknowledge and intentionally incorporate the analysis of external factors, such as climate change, as well as other factors, such as population growth and economic development, into the evaluation of the potential trade-offs and synergies associated with specific water management actions. While grappling with the uncertainty associated with these external factors, decision makers engage in a process of identifying actions that can be taken at the national and catchment levels to reduce vulnerability and increase the resilience of water systems.

Three core components in formulating the scenarios are:

- Measures of success or indicators of achieving goals.
- Critical uncertainties, or things that are outside the control of decision makers; and
- Planning options, or things within the control of decision makers, such as gray and green infrastructure, policies, and behavioral change.

Each of these is elaborated below in more detail.

Based on these inputs, a draft set of scenarios has been prepared. WEAP and macroeconomic analyses have been applied to explore these scenarios, including the impacts of climate change (with 120+ climate projections) to identify which investments and policies are likely to promote the greatest resilience for the measures of success for water management for Rwanda (Section 2.4.1).

2.4.1. Measures of success

The resilience of a system is expressed through performance metrics that are of the greatest interest to stakeholders. Metrics derived from WEAP, or the associated macroeconomic model include:

Coverage of demands by sector (percent of demand met)
Unmet demands by sector (m^3/year)
Hydropower production (tJ/year)
Rainfed and irrigated production (millions of kg)
Industrial outputs (varies by sector)
Impacts on the macroeconomy (percent change in GDP).

Additional metrics can be added based on stakeholder inputs.

2.4.2. Critical uncertainty: climate change

Rwanda will need to develop strategic water plans that consider the deep uncertainty around climate change. While Rwanda faces other types of critical uncertainty, this analysis focuses on climate change as one of the most dominant with respect to water and the macroeconomy. This analysis draws upon climate projections developed by an earlier World Bank project on increasing the resilience of Africa's infrastructure in 2015 (Cervigni et al. 2015), which included both the Congo and Nile River basins. A detailed description of methods for developing these projections is given in Chapter 3 of this report. A total of 121 climate projections are used in this analysis (Figure 12), which aligns with the projection used in the CCDR.

FIGURE 12. Historical rainfall and temperature relative to the 121 climate projections

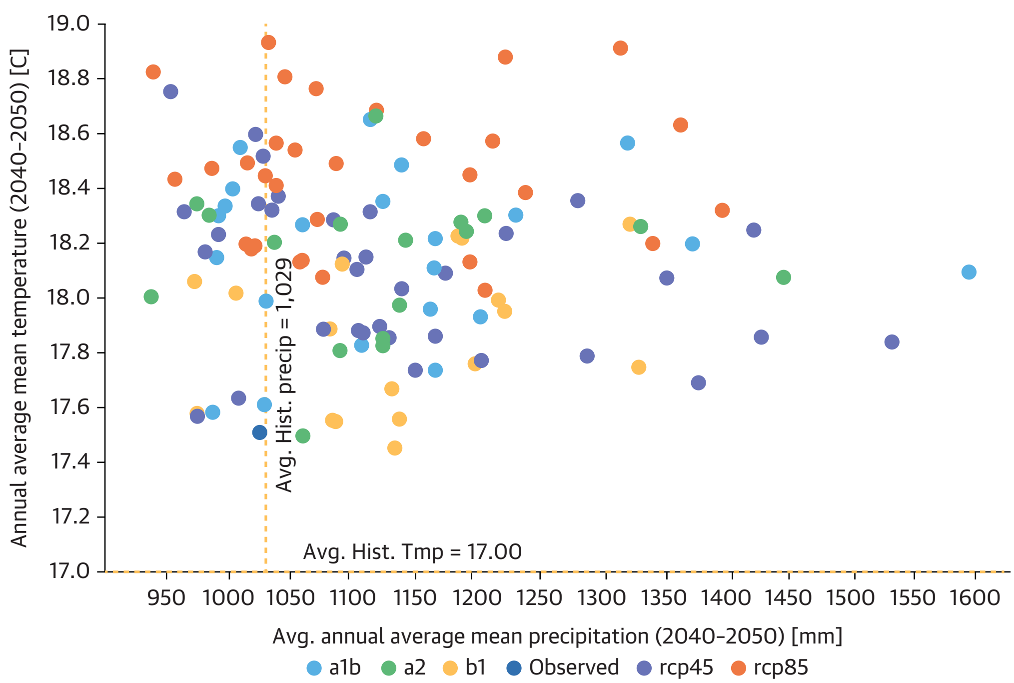
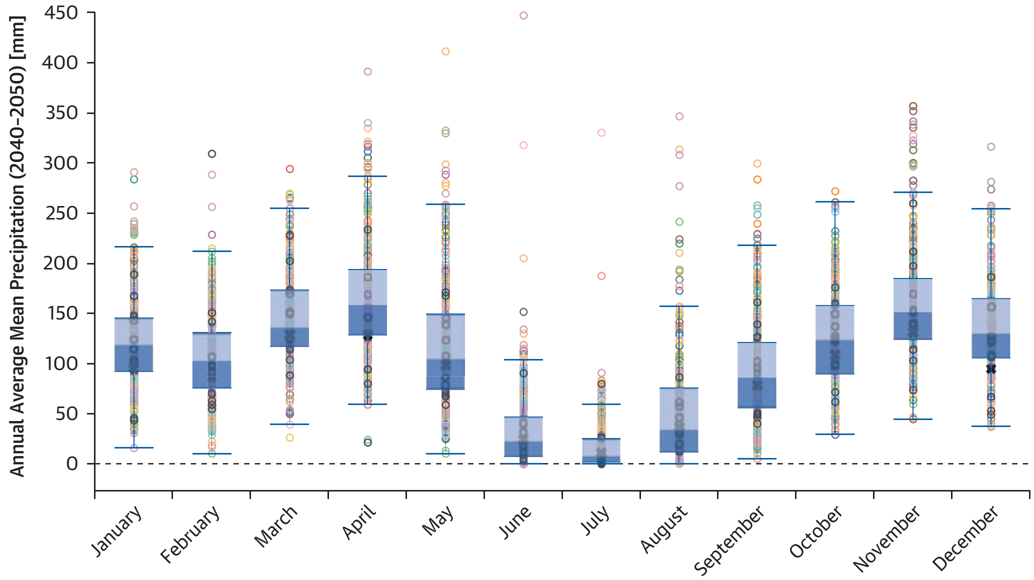


FIGURE 13. Monthly average precipitation (2040–50)



The average annual temperature historically is 17.0 degrees Celsius, and annual precipitation is 1,029 mm. As shown in Figure 12, the majority of climate projections in the decade 2040–50 are at least 1 degree hotter. While the majority of precipitation projections show higher levels, not all do, indicating a need to prepare for both wet and dry years.

Figure 13 shows average monthly precipitation across the climate projections from 2040–50 in the form of a box plot, which gives a quick indication of the distribution of data and identify the presence or possibility of outliers. The gray-shaded box around the mid-point of each vertical bar gives the median (50^{th} percentile) in the middle. The top of the light gray box captures the 75^{th} percentile, and the bottom of the darker gray box represents the 25^{th} percentile. The bar at the top captures 99.65 percent of the values, and the lower bar is 0.35 percent of all the values. Figure 13 shows that the greatest number of outliers are found for precipitation during the months of May, June, July, and August. Given that these are the driest months, this indicates that some planning options need to consider seasonal droughts as well as year-to-year droughts.

2.5. Methodological Limitations

The methods outlined in Sections 2.1–2.4 provide a solid basis for an initial understanding of the role of water in Rwanda's macroeconomy. Several limitations of this approach are important to consider, however. Any quantitative modeling inherently has limits, including a lack of adequate data, bias in the data, and simplifying assumptions. All of those limitations are true in this modeling effort, and two are particularly important. The first is on storage and the second is around the macroeconomic modeling.

With storage in the WEAP model, the catchments are disaggregated at Level 2.5, but the stream gauge data required to calibrate at that level do not exist. This is particularly problematic in the representation of storage and irrigated agriculture, as the amount of surface water flow into storage at that scale is based on calibration that is largely at Level 1 and Level 2 gauges. The results associated with storage therefore need to be examined with more data collected at that scale before any decisions are made with respect to the sizing and placement of storage facilities. Using sensitivity analyses on the model for storage will not adequately capture this type of error. It requires additional collection of field data.

Some limitations of the analysis should be noted. Most of these were due to data limitations, although some were deemed out of scope for this project.

Investment in climate-smart agriculture. There is a wide range of climate-smart techniques for agriculture. For each of those, cost-benefit ratios can be computed, as was done in this report for large-scale storage. That analysis was not carried out in this report for multiple reasons; first, because the model is only sensitive to interventions that have an impact on the macroeconomy, as opposed to farm-level economic impacts; second, because the available techniques vary considerably from one crop to another; and third, because the same technique will have different cost-benefit ratios in different locations.

To take one example, alternate wetting and drying of rice has been found to be cost-effective in South, East, and Southeast Asia (Ishfaq et al. 2020, 15). The benefits come from lower labor requirements, lower energy use (for pumping), and lower water costs. However, the estimated cost-benefit ratios depend on local costs for those inputs and need not transfer to the Rwandan context. Moreover, the costs may vary across Rwanda.

These observations suggest that options for climate-smart agriculture should be evaluated with local conditions in mind.

Climate damages. Physical damage and migration arising from climate change will affect economic outcomes. Damage to physical infrastructure not only results in lost output, but also requires investment in hardening infrastructure against increasingly severe climate impacts and in rebuilding. The Ministry of Emergency Management (MINEMA) reports around 3,309 disasters between 2011 and 2019. Responses to prolonged droughts are more complex, ranging from food aid to migration. Droughts can be accompanied by wildfires, which add to the economic damage.

Such damages were out of the scope of the analysis presented in this report. These additional impacts would add to those identified through our analysis on the potential vulnerability to variable water supply and water stress.

Notes

1. Each livestock unit is equivalent to seven goats, seven sheep, two pigs, 70 chickens, and 70 rabbits.
2. The backward linkage measure is calculated from the Leontief inverse matrix, while the forward linkage measure is calculated from the Ghosh inverse matrix.
3. LEAP: Long-range Energy Alternatives Planning.
4. Hydropower is not yet represented in the model, pending a specification of the electricity generation mix in the scenarios.
5. RDM emerged from a program on strategic decision making under conditions of deep uncertainty within the RAND Corporation.

Chapter 3
Key Findings from the Scenario Pathways and Economic Analysis

3.1. Scenario Descriptions and Comparison

Given the goals of water planning and the context of critical uncertainties, this chapter explores planning options that could be implemented to help achieve the country's water sector goals in the face of climate change. Three planning pathways are explored.

Baseline

In this scenario, no new policies or public infrastructure expansion are introduced, unless they are already underway with funding. This scenario represents business as usual, offering decision makers a contrast with other potential planning pathways. Overall growth in demand is specified, combining household, government, and investment expenditure. Final demand and exports are initially assumed to grow in line with recent patterns, as reported in the Open Data database of the National Institute of Statistics Rwanda (NISR).[1] Where the sectors in the NISR statistics do not align with the sectors in the HECCA macroeconomic analysis, the closest corresponding value, or the aggregate trend, is assumed. In the baseline scenario, both final demand and export growth rates in all sectors are assumed to converge by 2036 toward common levels, in which most demands grow at around 7 percent per year. The exception is final demand for food, which grows more slowly than consumption overall.

Vision 2050

This scenario explores the possibility of achieving the water-related goals of Vision 2050, including in areas such as agriculture, mining, tourism, ecological preservation, and poverty reduction. The overall goal of Vision 2050 is to achieve upper-middle income status by 2035 and high-income country by 2050. Specifically, the scenario takes into account the following stated objectives in Vision 2050: #1 (population growth rate); #4 (GDP per capita); #24, 25, and 38 (industry, services, and agriculture value added); #26 (investment as a share of GDP); #29 (urbanization); #30 (proportion of the urban population living in slums); #31 (land use); and #32 (availability of renewable water resources).

Water Resilient Vision 2050

The WRes2050 scenario identifies pathways that are consistent with the intentions of Vision 2050, but factor in the potential impacts of climate change on water availability. This scenario looks at adaptation measures that are consistent with Rwanda's NDC, such as climate-smart irrigation practices, improved water management, and mitigation options, including with regard to the proportion of hydropower in the overall electricity mix.

Various aspects of the quantitative models are discussed below, including how the data entered differs across the three scenario pathways. Where possible, levels of investment are indicated, which draw heavily on the 2020 National Irrigation Master Plan. A comparison of the baseline, Vision 2050, and WRes2050 scenarios is presented in Table 3. More detailed descriptions are given in Appendix E.

TABLE 3. Comparison of scenarios for HECCA for Rwanda

Scenario element	Baseline	Vision 2050	Water Resilient Vision 2050	Assumptions
Population growth	United Nations (UN) World Population Prospects mid-range projection: 2.15 percent per year starting in 2025, 1.98 percent per year in 2030, 1.83 percent per year in 2035, and 1.52 percent per year in 2045.	Following Indicator #2 in Vision 2050, the rate drops to 1.7 percent per year in 2035 and 1.4 percent per year by 2050 (Republic of Rwanda 2015).	Following Indicator #2 in Vision 2050, the rate drops to 1.7 percent per year in 2035 and 1.4 percent per year by 2050.	The baseline assumption uses a globally accepted set of projections, and Vision 2050 sets out its own projections (Republic of Rwanda 2015).
Rate of urbanization	UN Urbanization Prospects is used, with a transition to an urbanization rate of 31percent by 2050.	Population estimates in the Land Use Master Plan of 2020 (Republic of Rwanda 2020, 34) are used.	The SSP[2] database used World Urbanization Prospects 2009 (WUP2009), which gave a higher number than the revised WUP2018. Following the high estimate (for SSPs 1, 4, and 5), the original value in 2050 is 56 percent. A revised value, simply shifting everything down to match the 2020 WUP2018 figure, is 47 percent. Based on that, we assume a value of 50 percent in 2050.	The baseline uses UN standard projections and the Land Use Master Plan, which follows Vision 2050 as a basis for the assumptions (Republic of Rwanda 2020). National urbanization rates are downscaled to catchment level through an algorithm that assumes: (a) urban and rural population growth rates are the same as at the national level; and (b) catchment-level urbanization rates follow an "s-shaped" curve that keeps the rates between 0 percent and 100 percent and that assumes fully rural areas to remain rural in the future. (Appendix E, section on urbanization).
Domestic water use rates[3]	Average rural water use rates start at 30 lpcd and rise to 40 lpcd by 2050. Average urban water use rates start at 45 lpcd and rise to 90 lpcd by 2050. (Annex F)	Both rural and urban domestic demands reach 100 lpcd by 2040 and stabilize there until 2050.	Both rural and urban domestic demands are at 100 lpcd by 2040 and stabilize there until 2050. Rainwater harvesting is introduced to cover the gap in meeting domestic demands in Vision 2050.	The baseline scenario assumes little progress in rates of water use per capita, and the Vision 2050 scenario assumes the same level of consumption in rural and urban areas by 2050 (Republic of Rwanda 2015).
Rainfed agriculture	Current levels are maintained at 1.4 million hectares (ha), with crop yields determined based on climate impacts modelled by WEAP.	Following the National Land Use Master Plan, total agricultural area will be reduced to 1,242,400 ha by 2040. The balance of rainfed agriculture will be based on small-scale ag and medium- and large-scale ag below (Republic of Rwanda 2020, 54).	Following the National Land Use Master Plan, total agricultural area will be reduced to 1,242,400 ha by 2040. The balance of rainfed agriculture will be based on the small-scale ag and medium- and large-scale ag below (Republic of Rwanda 2020, 54)	A large part of Rwanda's population is dependent on rainfed agriculture. This will continue in both scenarios, but with the two Vision 2050 scenarios there is a reduction in rainfed agriculture as more investment in irrigation occurs.

table continues next page

TABLE 3. continued

Scenario element	Baseline	Vision 2050	Water Resilient Vision 2050	Assumptions
Expansion of small-scale agriculture	Small-scale agriculture will expand from the current level of 5,200 ha to 24,000 ha by 2040, based on projections in the 2020 Irrigation Master Plan, with crop yields determined based on climate impacts modeled by WEAP (Minagri 2020).	Small-scale agriculture will expand from the current level of 5,200 ha to 84,552 ha by 2040, based on projections in the 2020 Irrigation Master Plan, with yields increasing by 25 percent over the 30-year period, but also affected by climate as modeled in WEAP (Minagri 2020).	Small-scale agriculture will expand to 84,552 ha, but different cropping patterns are assumed to reduce water use by 25–50 percent in vegetables.	Small scale irrigation expansion is assumed under the baseline scenario through private investment. Crops are either fruits or vegetables, with percentages according to Feasibility Study for the Identification of Potential Small Scale Irrigation Areas in Rwanda (RAB 2018).
Expansion of medium- and large-scale agriculture	Current levels, at approximately 30,000 ha, will be maintained with current yields, but affected by climate as modeled in WEAP.	Medium- and large-scale agriculture will expand to almost 400,000 ha by 2040, with additional high-value crops introduced. Yields increase by 25 percent by 2040, although still affected by climate, as modeled in WEAP.	Medium- and large-scale agriculture will expand to 400,000 ha, but different cropping patterns (such as alternate wet-dry cycling with rice) reduces water use by 25–50 percent.	The significant boost in irrigation requires public investment, which is not considered in the baseline scenario, but is assumed to take place in the Vision 2050 scenario. The National Irrigation Master Plan 2020 states that, on average, crop yields in Rwanda are 25 percent below potential, and it is assumed that crops can meet potential yields by 2040, although that may not be achievable under climate change (Minagri 2020).
Livestock[4]	See Annex F section on livestock.	See Annex F section on livestock.	See Annex F section on livestock.	Scenario values are calculated assuming that livestock units and kg of meat per livestock unit each follow an "s-shaped" pattern that eventually saturates. Differences between scenarios are based on the range of possible fits of the s-shaped pattern to historical data, with the baseline scenario based on the midline and the Vision 2050 scenario based on the 97.5th percentile.
Expansion of mining	Driven by the macroeconomic model	Driven by the macroeconomic model	Driven by the macroeconomic model	Mining sector activity levels are based on runs of the macroeconomic model; water intensities are assumed to rise at half the rate of the increase in activity.

table continues next page

TABLE 3. continued

Scenario element	Baseline	Vision 2050	Water Resilient Vision 2050	Assumptions
Expansion of fishponds	Production levels will reach those projected in the 2011 Fish Master Plan, reaching 230,000 tons by 2040 (Minagri 2011).	Production levels reach 1 million tons by 2040.	Production levels reach 1 million tons by 2040, but 50 percent of the target is met through the use of existing water bodies, such as lakes and ponds, to achieve the same production with less water diverted.	The Master Plan for Fisheries and Fish Farming (Minagri 2011) suggests that with an investment of US$71 million, 230,000 tons of fish could be produced. Vision 2050 states that Rwanda's lakes will be "fully exploited" for fish production (Republic of Rwanda 2015); according to page 51 of the master plan, using a maximum of 2 percent of lake reservoir area would make possible more than a million tons of production.
Expansion of manufacturing and other industrial water use	Driven by the macroeconomic model	Driven by the macroeconomic model	Driven by the macroeconomic model	Manufacturing sector activity levels are based on runs of the macroeconomic model; water intensities are assumed to rise at half the rate of the increase in activity. This increase can include on-site reuse.
Storage	Current storage levels plus dams at Nyabarongo II (846 MCM), Akanyaru (333 MCM), and Muvumba (35 MCM).	Baseline storage levels plus planned new dams, and expansion of local storage at a rate proportional to large-scale irrigation, for a total of 279 MCM.[5]	Baseline storage levels plus planned new dams, and expansion of local storage at a rate proportional to large-scale irrigation, for a total of 279 MCM.	Expansion is based on the planned/funded dams, and possible additional local storage is based on estimates in the 2014 and 2020 Irrigation Master Plans. The investment for storage is embedded in the irrigation expansion numbers.
Environmental flows	Assumed to be 30 percent of historical average monthly flows	Assumed to be 30 percent of unimpaired flows	Assumed to be 30 percent of unimpaired flows	Assumes Rwanda will follow international standards
Hydropower	Includes expansion due to the dams listed above under storage	Small increase, with two additional dams; non-hydropower electricity given by the reference scenario in a prior study using LEAP (Johnson et al. 2018).	Small increase with two additional dams; non-hydropower electricity given by the optimistic scenario in the LEAP[6] study.	The more rapid expansion of non-hydropower electricity in the optimistic LEAP scenario leads to a lower share of hydropower in the total electricity mix.

Source: Rwanda Agriculture and Animal Resources Development Board

3.2. Scenario Results

The goal of water planning is to achieve water security. The performance metrics described above are indicators of how well any given plan, including an array of demand-side and supply-side options, performs across the range of deep uncertainties considered.

Following an overview of how water demands vary across the three scenarios, the baseline scenario is presented first. The baseline includes no new interventions (other than what is already funded) or new strategies. Next, the Vision 2050 scenario is compared with the WRes2050 scenario to highlight the impact of different supply-side and demand-side strategies. Both scenarios are evaluated against 121 climate projections to explore the impact of climate change. Outcomes from the performance metrics are described below, followed by a section on the economic outcomes.

3.2.1. Projection of water demands across the three scenarios

Annual water demands are expected to increase ***740 %*** *under WRes2050.*

Annual water demands are expected to increase significantly over 2020 levels for all scenarios: 83 percent under the baseline, 1,140 percent under Vision 2050, and 740 percent under WRes2050 (Figure 14). Domestic use and irrigated agriculture currently make up over 90 percent of total water demand in Rwanda. The expected increase in water demand with the expansion of irrigation (particularly large-scale irrigation) is likely to skew this proportion even further, with irrigation (medium-/large- and small-scale) accounting for 43 percent of total demand under the baseline, 85 percent under Vision 2050, and 77 percent under WRes2050.

3.2.2. Baseline results

The baseline scenario provides a point of comparison for the more optimistic visions of the future, under which the well-being of the people of Rwanda improves significantly relative to current conditions. It is not, however, an aspirational vision of the future. As highlighted in Section 7.3 below, Rwanda's macroeconomy will face volatility due to its current dependence on water - not only in the parts of the economy that use water directly, such as agricultural production, but due to its dependence on hydropower for 40 percent of its electricity generation.

The overall supply - demand gaps under the baseline scenario, under both relatively wet and relatively dry climate scenarios, are shown in Figure 15 below. With the exception of the NAKL sub-catchment, at the level of annual averages, demands are within the annual supplies.

However, these overall gaps mask the intra-annual (seasonal, for example) shortfalls experienced across all sectors. Even the highest-priority sector, domestic water demand, sees consistent shortfalls during June through October (Figure 16).

FIGURE 14. Annual water demands for baseline, Vision 2050, and WRes2050 scenarios

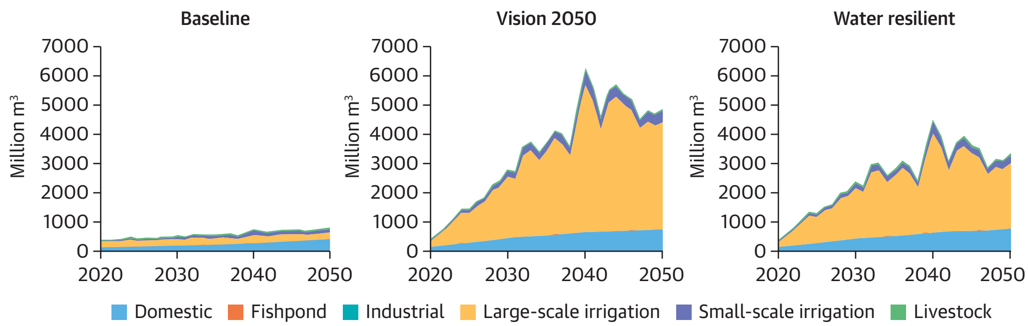
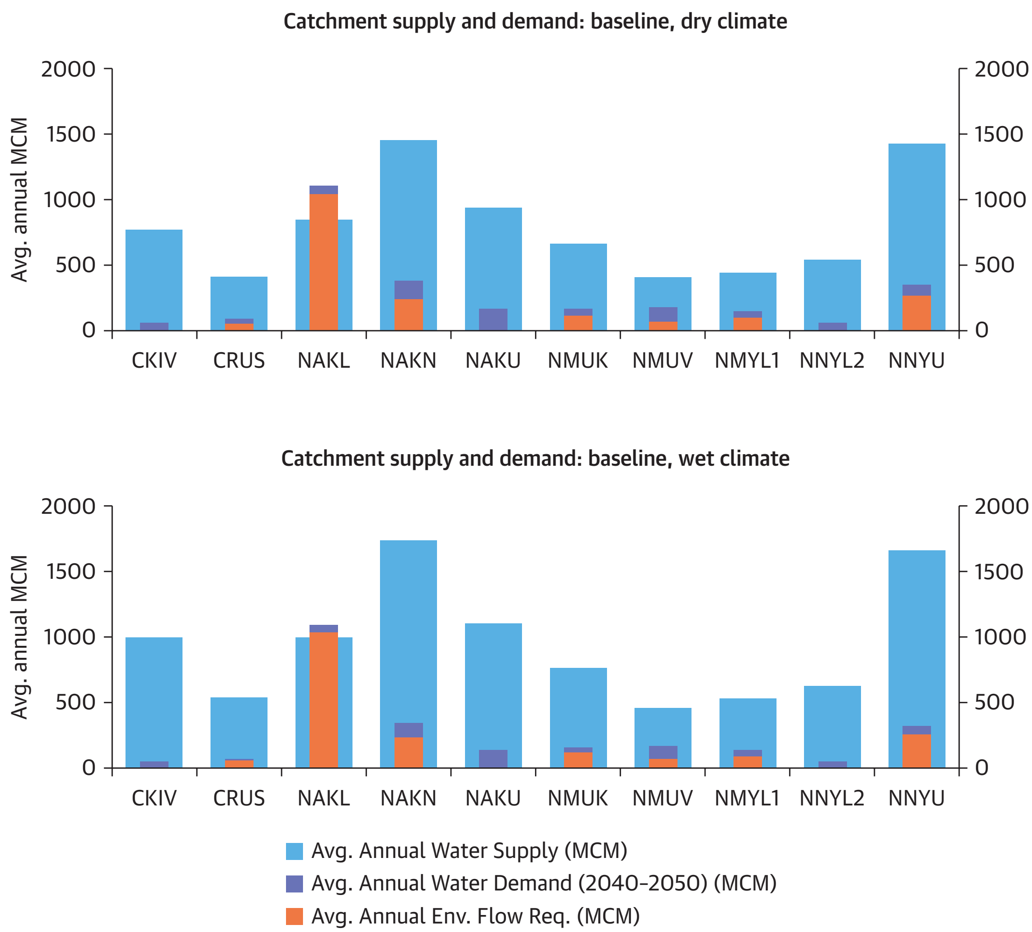
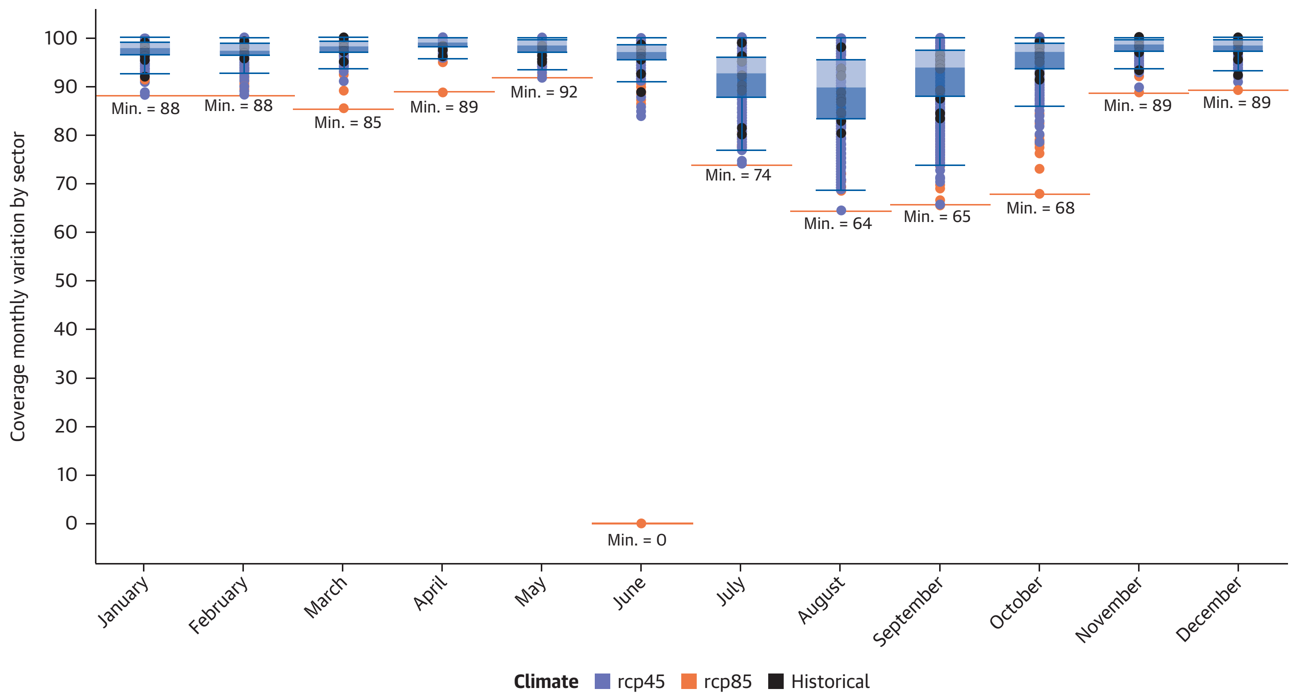


FIGURE 15. Comparison of average annual water supply and demand across all sectors in the nine Level 1 sub-catchments for the decade 2040–50



Note: The environmental flow requirements for the NAKL sub-catchment include flows from upstream catchments in the Nile portion of Rwanda.

FIGURE 16. Expected shortfall in meeting domestic water demands under the baseline scenario for the decade 2040–50 under all 121 climate projections



Average of DN_Cov for each Date Month. Color shows details about Climate. Details are shown for Date Year and Clim Names. The data is filtered on Exclusions (Climate Sim, MONTH(Date)), Decades, Exclusions (Climate Sim,MONTH(Date), YEAR(Date)) and Scenario. The Exclusions (Climate Sim, MONTH(Date)) filter keeps 45,383 members. The Decades filter keeps 2040-2050. The Exclusions (Climate Sim,MONTH(Date),YEAR(Date)) filter keeps 45,383 members. The Scenario filter keeps Baseline. The view is filtered on Climate and Clim Names. The Climate filter keeps multiple members. The Clim Names filter has multiple members selected.

The seasonal unmet demands under the baseline scenario are consistent with a lack of investment in storage, which can have significant positive impacts, as discussed below.

3.2.3. Comparison of results for Vision 2050 and WRes2050 scenarios

This section provides an overview of the assumptions on which the Vision 2050 and WRes2050 scenarios are built, as outlined in Table 3, along with a comparison of results from the perspective of water supply and demand gaps. In addition, the section will discuss how the interventions considered in WRes2050 would be expected to reduce the gaps. The discussion covers four key water uses: domestic; agricultural, including crops, livestock, and fishponds; industrial; and hydropower.

Domestic

Domestic water demands are essentially identical for the Vision 2050 and WRes2050 scenarios. They assume the same rate of population growth and water use rates of 100 lpcd in both rural and urban areas. The share of the population in urban areas is different, with 70 percent of the population assumed to be in urban areas under Vision 2050, as compared to 50 percent under WRes2050.

Domestic water demands (both urban and rural) are given the highest priority for water, resulting in generally high coverage for these demands. Where shortages are expected, however, they are not experienced uniformly throughout Rwanda. Rather, the WEAP model suggests that shortages may be most pronounced in the portions of the country around large urban areas, such as Kigali, Muhanga, and Gisenyi (Figure 17). These areas should be the focus of possible interventions, including reduction of non-revenue water (NRW) losses and expansion of rainwater harvesting programs. With rainwater harvesting added under WRes2050, domestic demands can be met (Figure 17, right side).

Agriculture

A key sector for Rwanda is agriculture, which includes rainfed and irrigated agriculture, livestock, and fishponds. Water plays a critical role in each of these areas, with rainfed agriculture most vulnerable to climate variations given that is is 100 percent dependent on the timing and amount of rainfall during any given season. Each sub-category is discussed below.

Rainfed agriculture

Rainfed agriculture is inherently vulnerable to climate (Figure 18). The increased rainfall expected across climate projections suggests that, on average, rainfed agriculture will be more productive. But there are many projections in which rainfed agriculture shows significant losses, and without some intervention, given the country's dependence on subsistence agriculture, there could be significant impacts on rural and impoverished populations.

Moderating this impact, there is expected to be substantial movement of labor out of agriculture into other sectors in the coming decades. Through that movement and the consolidation of farms, social vulnerability to variable rainfall in the agriculture sector is likely to decline.

FIGURE 17. Water supply coverage for domestic water in each Level 2.5 catchment for Vision 2050 and WRes2050 scenarios

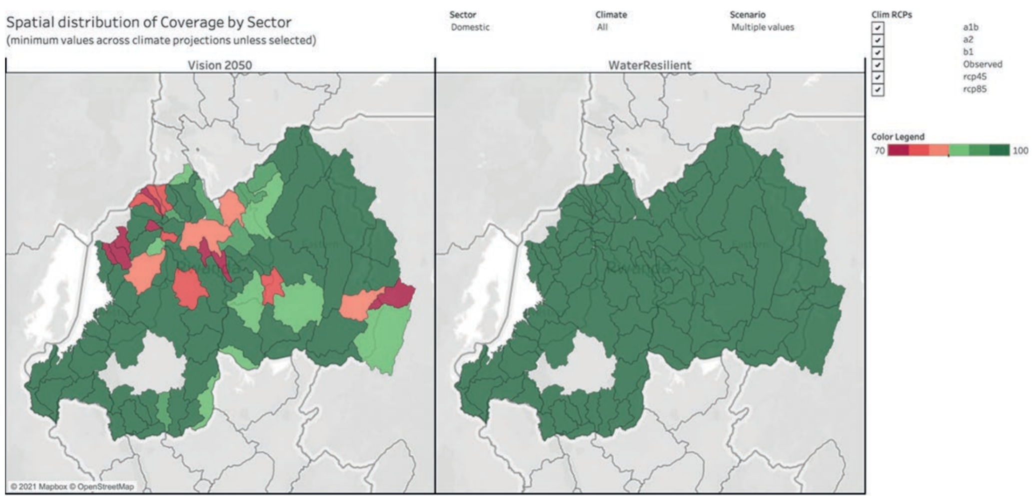
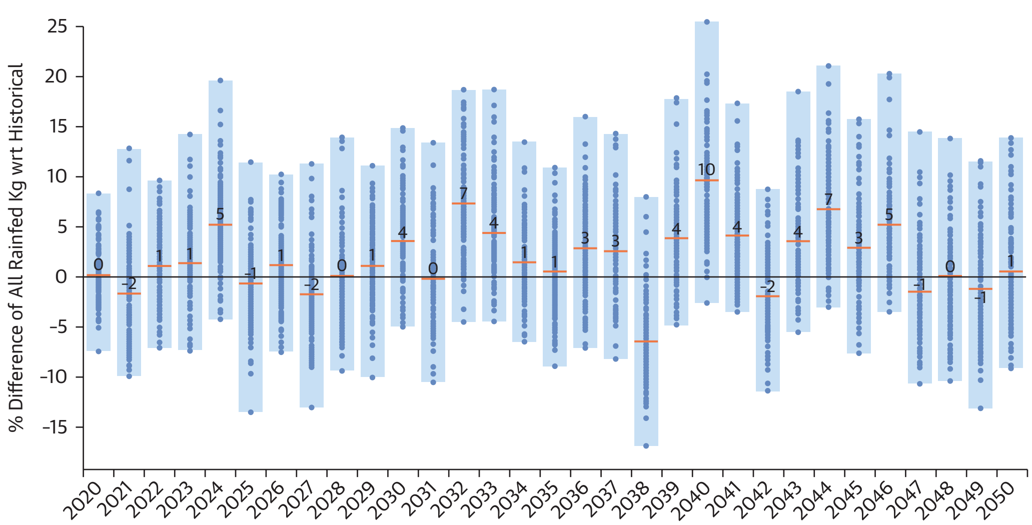


FIGURE 18. Change in rainfed crop production relative to historical climate



The assumption under the Vision 2050 and WRes2050 scenarios is that the total area devoted to rainfed agriculture, together with the associated population, would shift increasingly toward urban areas and away from subsistence farming. If these goals were achieved, it would alleviate the potential negative impacts of variable rainfall on rural and poor populations.

Irrigated agriculture

Irrigated agricultural land area is assumed to increase significantly for small, medium, and large enterprises under both Vision 2050 and WRes2050 scenarios, by approximately 84,000 ha in small-scale irrigation and 400,000 ha in medium- and large-scale irrigation. The distinction between the two scenarios is the introduction of climate-smart agriculture under WRes2050, which would reduce the volume of water demanded per unit of area through new irrigation technologies (such as wet and dry cycling), shifts away from water-intensive crops such rice, and greater diversification in fruits and vegetables. This would reduce water requirements by 40 percent overall and would reduce, to some extent, the need for additional storage under the WRes2050 scenario.

Introduction of climate-smart agriculture would reduce water requirements by ***40 %*** *under WRes2050*

The regions of Rwanda where these shortages are most likely to occur are in the eastern part of Rwanda, in the Karangazi, Gabiro, and Muvumba river basins (Figure 19). On the other hand, model results indicate that water demand coverage improves in some parts of western Rwanda, owing to increased water storage.

For example, the initial design for the Muvumba multipurpose dam was 35 × 106 m³ of storage capacity, whereas the ongoing new design for is aiming for 50 × 106 m³ of storage capacity. Similarly, in the first phase of the Gabiro irrigation project, a 120,000 m³ reservoir is being built, which will irrigate 5,600 ha. Phase 2 targets 10,000 ha, requiring a reservoir with storage capacity of 210,000 m³.

While this may imply the need for additional storage, the model results indicate that expanding storage does not improve demand coverage, because the areas experiencing shortages are limited by the required environmental flows for Akagera National Park under NAKL. This creates a deficit in water supply for potential planned large-scale irrigation projects, namely Karangazi, Muvumba, and Gabiro (Figure 20). There is not enough local runoff to augment water storage beyond what is already included in Vision 2050, given the environmental flows requirement.

FIGURE 19. Water coverage for large-scale irrigation in each Level 2.5 catchment for Vision 2050 and WRes2050 scenarios

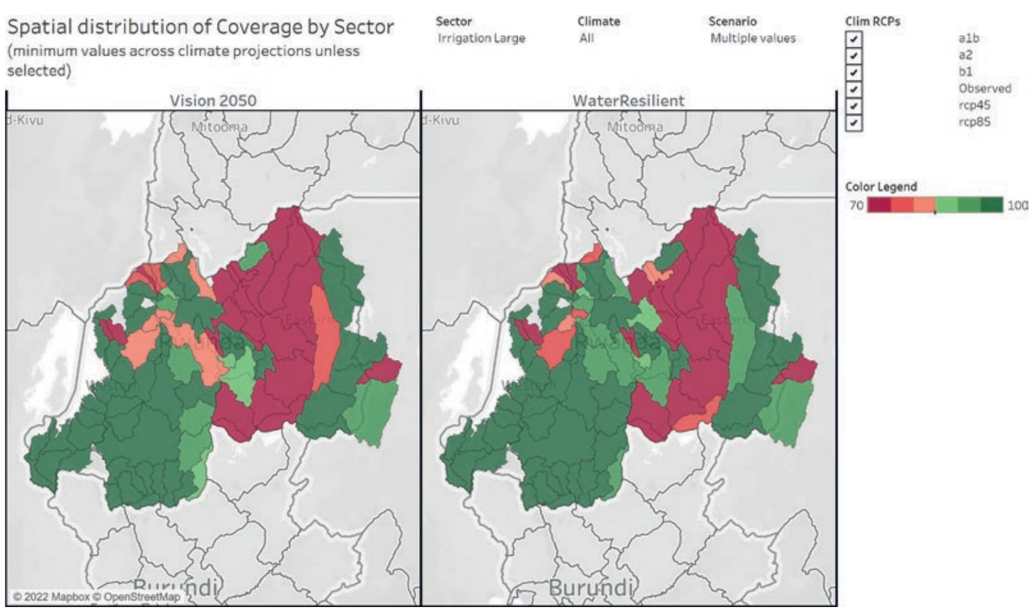
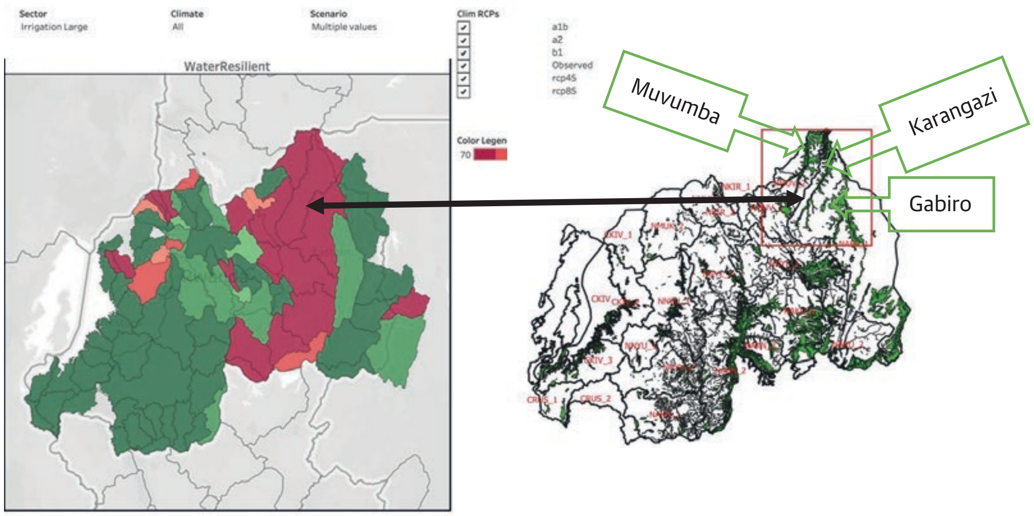


FIGURE 20. Location of Karangazi and Gabiro irrigation schemes and Muvumba catchment



According to the 2020 Rwanda Irrigation Master Plan (MINAGRI 2020), the hotspot catchments shown above coincide with the highest potential irrigation areas for marshland development and river potential irrigation in NAKU, as well as shallow lake irrigation potential under the NNYL catchment. On the other hand, reduced coverage for the Umuvumba catchment (Figure 20) can be attributed to the transboundary flows. The river flows from Rwanda to Uganda, and then back to Rwanda. According to the 2020 Rwanda Irrigation Master Plan, the amount of water required for large-scale irrigation would necessitate additional damming and storage. As of today, only the Umuvumba multipurpose dam is planned for construction in the near future.

Livestock and Fishponds

Livestock and fishponds are an important part of the culture and livelihoods for many people in Rwanda, yet their water demands account for less than 1 percent of total consumptive demand.

It is reasonable to expect that the Vision 2050 scenario would support a higher number of livestock units relative to the baseline scenario due, for example, to proposed investments in feed processing plants, specialized chick production factories, medium-scale poultry farms for egg production, and pig fattening facilities. The Vision 2050 and WRes2050 scenarios consider that compositional changes may also be accompanied by an increase in overall herd size. Despite this increase in demand, however, livestock water demands would still remain below 1 percent of total water demand for these two scenarios, with relatively high coverage.

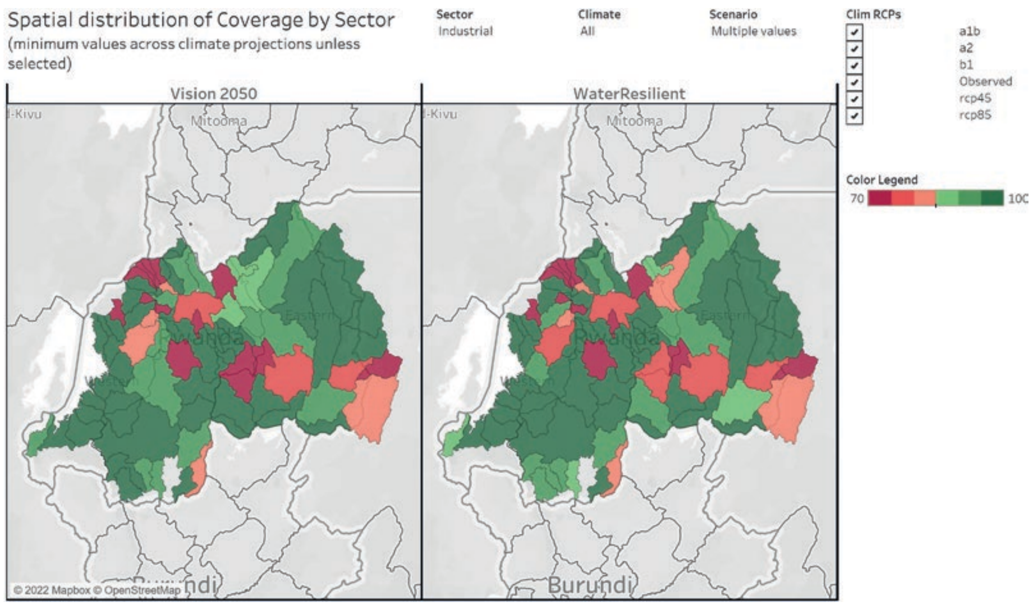
Similarly, there is an expected increase in fishponds over the next 30 years, with Vision 2050 setting a goal of 1 million tons by 2040. The WRes2050 scenario assumes that this level will be reached with half of the production taking place in existing water bodies, rather than establishing new ponds. Given the priority for fishponds, and their relatively low water demands, coverage is relatively high, except in the more water-scarce regions of Rwanda.

Industry

While industrial water demands comprise a small part - less than 1 percent of total water usage in Rwanda, industrial outputs make an important contribution to the economic sector. Industrial water demands are assumed to expand from an existing 9 MCM to approximately 25 MCM per year under Vision 2050 and to 23 MCM per year under WRes 2050. The lower level for WRes2050 is due to increased water efficiency in the industrial sector.

Industrial water demands expected to increase to ***23 MCM*** *per year under WRes2050.*

FIGURE 21. Comparison of average annual percent coverage of industrial demands under the Vision 2050 (left) and WRes2050 (right) scenarios



Note: Red indicates more vulnerable sub-catchments and green indicates less vulnerability. The threshold for "vulnerable" is set at 70 percent coverage on an annual average basis.

Industrial demands generally have access to both surface and groundwater supplies, which allows them to largely cover their water demands. As with other demands, however, the dry period from July to October occasionally constrains their ability to fully meet water demands (Figure 21). **The majority of hotspots correlate with larger urban areas in Rwanda. With the higher rate of urbanization planned under Vision 2050, additional focus should be given to the provision of urban and peri-urban water supply for domestic and industrial water use. Under the WRes2050 scenario, measures to increase water productivity in the industrial sector, combined with rainwater harvesting, would alleviate some of the water stress seen in Vision 2050, but this aspect of water planning needs deeper analysis.**

Hydropower production

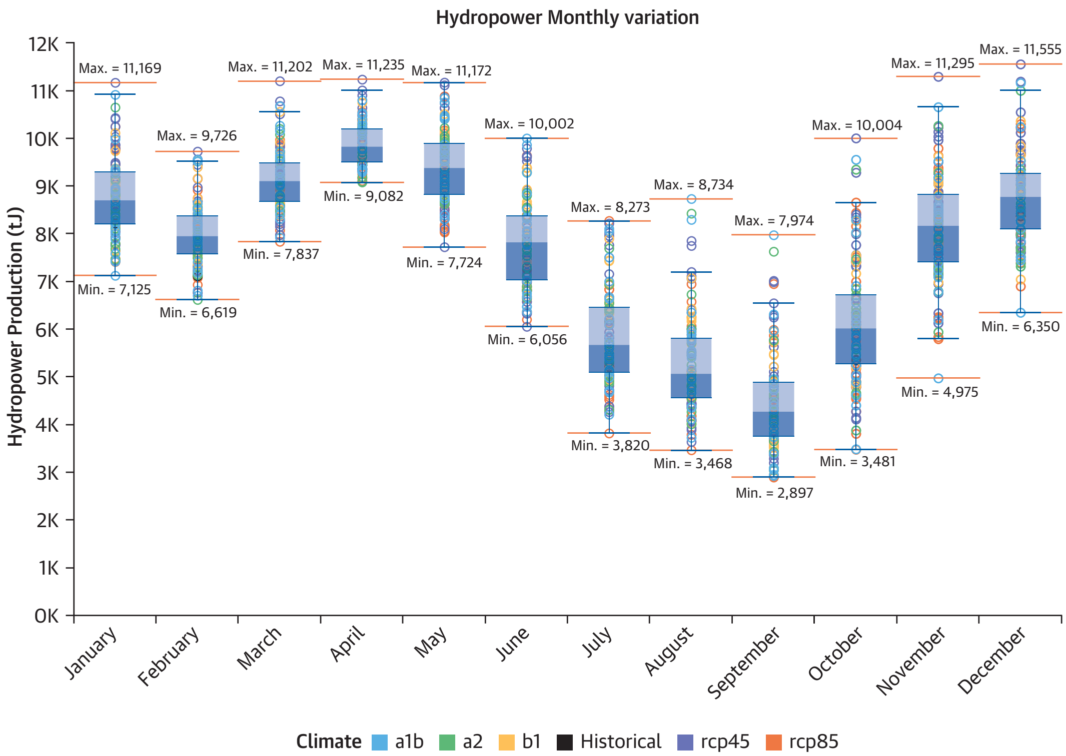
With climate change, an increasing emphasis for Rwanda will be to use hydropower or other renewable energy sources rather than fossil fuels. Expansion of hydropower was assumed under all scenarios, with the Vision 2050 and WRes2050 scenarios including an additional 50 megawatts (MW) of new hydropower on the Rusizi River. **All scenarios show similar patterns of hydropower production and indicate much greater production than is currently the case because of expanded capacity. However, there is substantial variability in hydropower production throughout the year, with median monthly production ranging from 3,000 to 12,000 tJ per month (see Figure 22).** Given that existing hydropower production is largely run-of-river, it is not surprising that production decreases during the historically drier months of July through October, and this continues to be the case under the various climate projections.

3.3. Results from the Economic Analysis

The WEAP model has been run using a large ensemble of climate scenarios, in an automated process. The link between the WEAP model and the macroeconomic model includes some manual steps, which prevents the use of the full ensemble. This section focuses on a few characteristic climate scenarios to draw some broader conclusions. The scenarios chosen are:

- **Climate scenario 0:** Historical climate (average temperature: 17.5° C; average rainfall: 1,023 mm)
- **Climate scenario 90:** Hotter climate with precipitation close to historical patterns (average temperature: 18.2° C; average rainfall: 1,021 mm)

FIGURE 22. Monthly hydropower production (tJ) under the WRes 2050 scenario



Sum of Hydropower Production (tJ) for each Date Month. Color shows details about Climate. Details are shown for Clim Names. The data is filtered on Scenario, which keeps Vision 2050. The view is filtered on Climate and Clim Names. The Climate filter keeps multiple members. The Clim Names filter keeps no members.

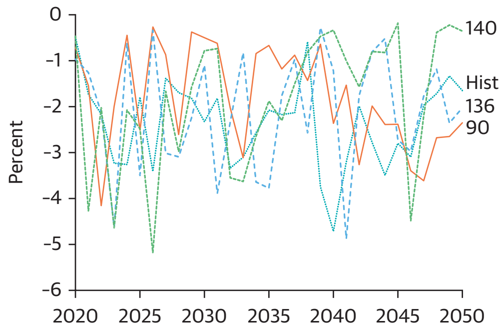
- **Climate scenario 136:** Drier climate compared to historical patterns (average temperature: 18.5° C; average rainfall 1,014 mm)
- **Climate scenario 140:** Wetter climate compared to historical patterns (average temperature: 18.2° C; average rainfall 1,340 mm)

Results for the estimated deviation of GDP from the maximum potential are shown in Figure 23 for the four climate scenarios and baseline economic assumptions, both on an annual basis and as a five-year running average. Maximum potential GDP is never met, as there are always some constraints in the system, so negative values are expected. The deviations show considerable year-on-year variability across the wide range of possible future climate projections. Ideally, the macroeconomy would show more stability in the face of varying climatic conditions. The non-historical, projected climate scenarios, moreover, show non-stationary behavior, with deviations late in the scenario period different from those earlier in the period. **This sensitivity to climate indicates the macroeconomy's vulnerability to water-related aspects embedded in the overall economy.**

Figure 24 shows results for the distribution of annual GDP growth rates for the four selected climate scenarios, as well as the baseline, Vision 2050, and WRes2050 production scenarios. **Under all production scenarios, GDP growth rates are much more variable for the comparatively dry climate scenario (136), while the wetter climate scenario (140) shows less variability. Variability is more similar between climate scenarios for the Vision 2050 scenario, due in part to the expansion of sectors—such as business services—that are not highly dependent on water.**

The long-run growth trends of the Vision 2050 and WRes2050 production scenarios - that is, after 2035 or so - are essentially identical, indicating that the reduction in water use does not affect the resilience of the overall economy (Figure 24, climate scenario 136). The reason is that, as the economy expands, sectors that are less vulnerable to

FIGURE 23. Deviation of GDP from estimated potential under the baseline scenario due to water constraints, annual (left) and five-year running average (right)



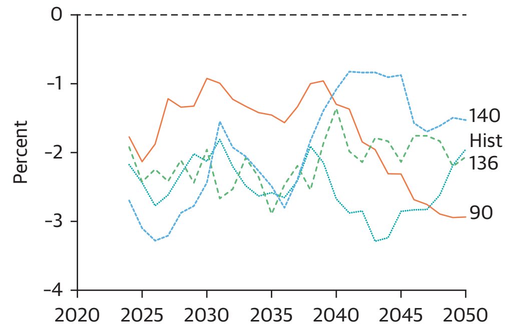
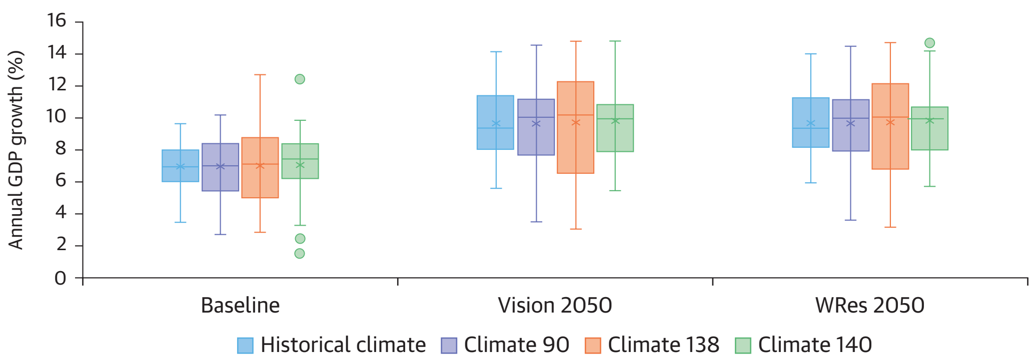


FIGURE 24. Distribution of annual GDP growth rates under different production and climate scenarios



fluctuations in water supply grow in importance. As a result, the difference between the Vision 2050 and the WRes2050 scenarios is largest in the early years of the simulation and shrinks as the simulation continues. Nevertheless, as explained below, despite the greater importance of non-water-dependent sectors in the Vision 2050 scenario, investment in water storage is justified. **Moreover, the WRes2050 scenario shows that combining supply-side and demand-side interventions provides a more robust set of water investments for water security for Rwanda.**

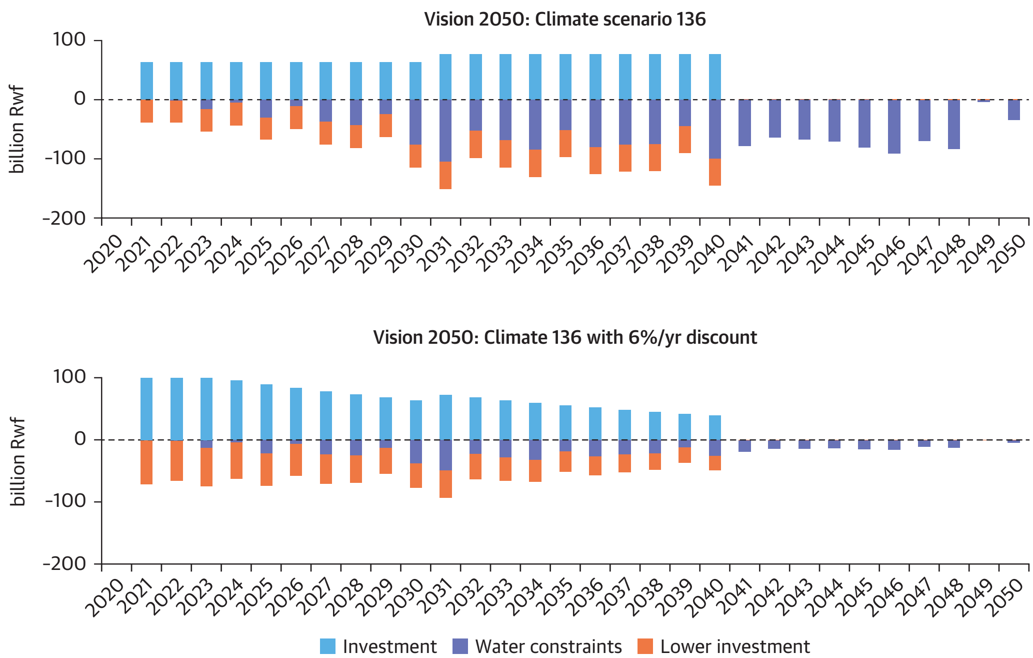
3.3.1. Cost-benefit analysis

Storage reduces fluctuations in water availability and thus fluctuations in water-linked economic output. Without sufficient available storage, economic output is lower. In other words, investing in storage, which incurs a cost, results in avoided loss of GDP, which is a benefit. The linked WEAP and economic models were run to compare the discounted benefit of avoided GDP loss against the discounted cost of investment. A further potential benefit is the economic activity stimulated by the expenditure on investment.

To carry out the analysis, planned investments for irrigation, drinking water and sanitation, and industrial water use were taken from existing planning documents. The focus of the analysis is on storage, because of its significant impact on fluctuations in water availability at a level that can affect aggregate economic output - that is, GDP. The cost of storage was estimated at half the estimated cost of investment in irrigation, as reported in the Rwanda Irrigation Master Plan.

The cost-benefit analysis results are presented graphically for one climate scenario, 136 (Figure 25. Both panels show three trends: the difference in GDP between Vision 2050 with storage implemented and Vision 2050 with no storage (orange bars); the cost of investment spread over time (blue bars); and the simulated stimulus effect of investment in storage (gray bars). The stimulus captures indirect expenditure associated with the investment, assuming that it

FIGURE 25. Investment costs, avoided GDP loss, and investment effect over time under climate scenario 136, with undiscounted values (left) and discounted values (right)



does not substantially crowd out other investment opportunities. The left-hand panel shows the directly calculated values as generated by the model. The right-hand panel shows the same values discounted at a discount rate of 6 percent per year over a characteristic time period of 17 years.

In the right-hand side panel, the total size of all the orange and gray bars combined exceeds the total size of the blue bars. That means that the discounted benefits (avoided GDP loss plus the stimulating effect of investment) exceed the discounted costs (of investment), so that the investment is justified if this climate scenario were to occur.

The results are similar for each of the climate scenarios (Table 4, Table 5). Table 2 shows results for a 6 percent per year discount rate, the same assumption as in Figure 25 and a standard World Bank assumption. Table 5 shows results for a 10 percent per year discount rate, a typical value for Rwandan analyses that is close to the average official discount rate for Rwanda for the period 2010-19, as reported by the International Monetary Fund.

3.3.2. Sensitivity analysis

The calculations depend on the choice of technical coefficients and baseline demand levels, and therefore on the vintage of the social account matrix (SAM) used. As a check on the sensitivity of results to the choice of SAM, the baseline scenario was run for historical climate with the 2006, 2011, and 2017 SAMs (Figure 26). There were significant changes

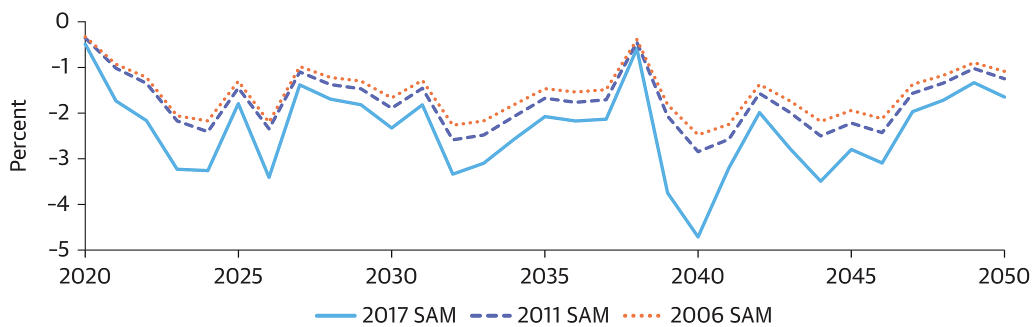
TABLE 4. Estimated costs and benefits of investment in storage, assuming a 6 percent per year discount rate (RF billions)

	Climate scenario		
	90	136	140
Investment cost	(691)	(691)	(691)
Avoided GDP loss	455	514	429
Investment stimulus	415	413	413
Total	**178**	**236**	**151**

TABLE 5. Estimated costs and benefits of investment in storage, assuming a 10 percent per year discount rate (RF billions)

	Climate scenario		
	90	**136**	**140**
Investment cost	(534)	(534)	(534)
Avoided GDP loss	285	336	272
Investment stimulus	321	320	320
Total	**71**	**122**	**58**

FIGURE 26. Deviation of GDP from estimated potential due to water constraints for three historical social accounting matrices under the baseline scenario with climate scenario 140



in Rwanda's economic structure in the five years between 2006 and 2011. However, the changes were much more substantial between 2011 and 2017. As discussed above, a key change was increasing the interrelatedness among sectors, as evidenced by growing backward and forward linkages. Consistent with that change, the depth of the deviation becomes progressively larger when using the 2006, 2011, or 2017 SAM.

In contrast to the increasing variability reflected in the SAM, the scenario analysis finds declining vulnerability to water-related constraints on production. In that case, a different process is driving the change: as the mix of productive activities shifts away from those that depend directly on water - in particular, increasing the share of non-hydropower sources in electricity generation - the variability of GDP due to variable water supply declines gradually. In contrast, increasing interrelatedness might be expected to stabilize. One indicator of interrelatedness, the intensity of intermediate production, is the largest eigenvalue of the inter-industry matrix. The largest eigenvalues for the 2006, 2011, and 2017 SAMs were 0.37, 0.38, and 0.59, respectively. The most recent value is characteristic of upper and middle-income countries (Xu and Yan 2011), suggesting that the intensity of intermediate production tends to plateau with economic development. The most recent SAM indicates that Rwanda is near that plateau.

3.4. Summary of Results

The hydro-Economic analysis evaluated three scenario pathways against 121 climate projections. Under the baseline scenario, Rwanda's macroeconomy is more unstable in the face of uncertain climate conditions for both rainfall and temperature, indicating a need, at a minimum, for supply-side measures to boost economic stability.

The Vision 2050 scenario sets out an ambitious trajectory for Rwanda, with large shifts in the population from rural to urban areas; vast expansion of irrigated agriculture at small, medium, and large scales; and increased industrial and hydropower production; among other aspects of development. All of these have implications for water, human welfare, and the economy as a whole.

Even in the wettest of climates, there are often unmet water demands across all sectors during the months of June to October, suggesting a need for additional storage to bridge the gap between demands and supplies during these months. When storage is added to the Vision 2050 scenario, there are clear economy-wide benefits relative to the costs, with discount rates ranging from as low as 2 percent to as high as 7 percent. Yet major water demands are not met, particularly for irrigated agriculture, in the eastern part of Rwanda, where the climate is generally drier, and rainfall is insufficient to store enough water to consistently meet irrigation demands.

When looking at average gaps in annual water supply and demand, it is clear that under a relatively dry climate projection (Figure 27 left) demands either exceed or approaching the limits of available supply. While this is less likely to be the case overall under a wet scenario, there are drier sub-catchments, largely in the Nile, that indicate stress.

The WRes2050 scenario adds several demand-side interventions focusing on the agricultural sector and hydropower. This scenario assumes widespread adoption of climate-smart agriculture, which combines a diversification of crops with more advanced irrigation technologies to bring about a 25 to 40 percent reduction in water demands. In addition, the share of hydropower in the overall electricity mix is reduced from 40 percent to 20 percent, reducing the economy's vulnerability to rainfall for run-of-river hydropower in any given year. The combination of supply-side and demand-side measures increases Rwanda's overall water security (Figure 28), while achieving the level of GDP growth set out in Vision 2050.

Adoption of climate-smart agriculture brings about upto ***40 %*** *reduction in water demands under WRes2050*

FIGURE 27. Comparison of water supply and demand gaps under Vision 2050 under dry (left) and wet (right) climate projections by Level 1 sub-catchments

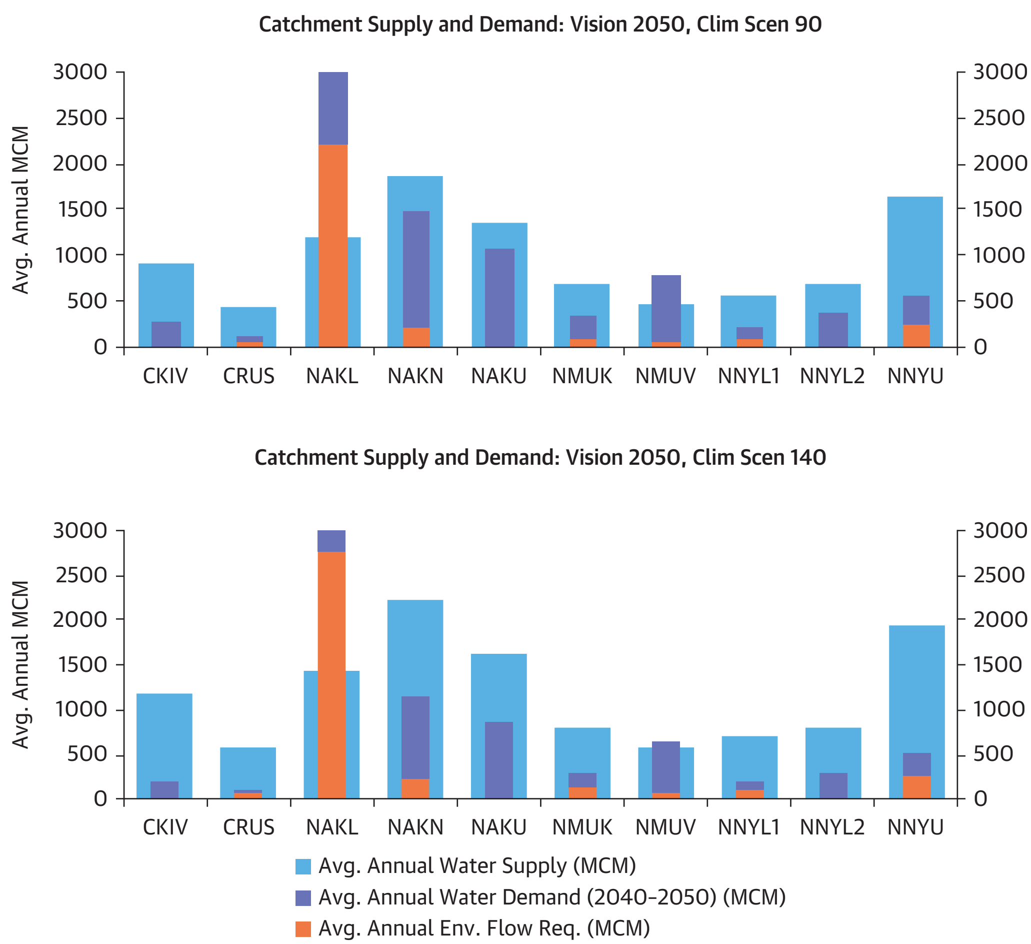
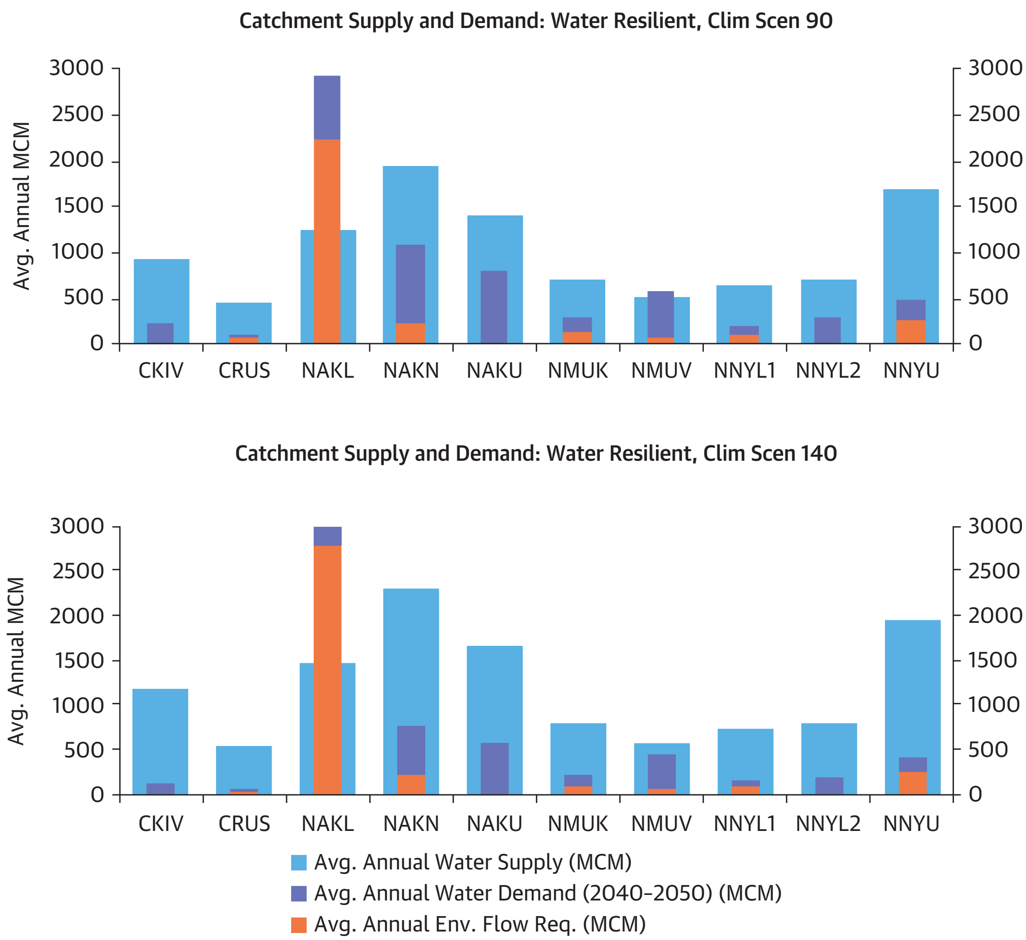


FIGURE 28. Comparison of water supply and demand gaps under the WRes2050 scenario under dry (left) and wet (right) climate projections by Level 1 sub-catchments



Rainfed agriculture increases overall production, on average, under both scenarios, but remains vulnerable in years of low rainfall. The assumed increase in productivity under the Vision 2050 WRes2050 scenarios shows more consistent resilience in production relative to the baseline scenario across all climate projections.

Notes

1. See https://nso.rwanda.opendataforafrica.org/speris/national-summary-data-page-nsdp.
2. Shared Socioeconomic Pathways
3. This analysis does not factor in non-revenue water losses.
4. Livestock feeding in grasslands is another form of water consumption. It is not explicitly reported but is captured in the overall water budget.
5. To test for the sensitivity of results to this assumption, the Vision 2050 scenario was run with half and twice the amount of storage. Aggregate values across all catchments were then calculated for crop production, hydropower production, and coverage of the water requirements of industry, livestock, and fishponds. The largest deviations were for hydropower production, with a maximum deviation of 7 percent. Thus, a 300 percent variation in this parameter resulted in a maximum 7 percent deviation in total hydropower production, suggesting that the results are comparatively insensitive to the specific value chosen.
6. LEAP: Long-range Energy Alternatives Planning

Chapter 4
The Private Sector and Its Role in Water Supply and Management

Vision 2050 prioritizes investments in enhanced human capabilities, strong innovation and technological capabilities, socioeconomically integrated forms of urbanization, and effective and accountable institutions of governance. To achieve these goals, Rwanda needs to continue to reduce its trade deficit by growing exports. While trade deficit reductions have been achieved since 2015, this has been driven largely by a reduction in imports, while export growth continues to be slow. Rwanda's economy remains heavily dependent on agriculture. To achieve its planned growth, increase exports, and expand productive job creation, Rwanda needs to continue the process of structural transformation, whereby industry and high-end services take up increasingly larger shares of the economy and workforce. This will require increased private sector participation in the economy, particularly in sectors with high job-creation potential, to reduce the dependency of growth on public sector investments.

4.1. Enabling Environment for Private Sector Engagement and Investment

Despite continuing efforts, the ineffectiveness of the private sector remains a major risk to Rwanda's growth outlook. Insufficient involvement of the private sector in some areas has affected the quality of policy dialogue and engagement of the private sector in implementation. The Economic Development and Poverty Reduction Strategy (EDPRS) required that every sector identify private sector players and engage them in developing their respective strategies. This was broadly achieved and taken forward as a principle for the EDPRS II, which also aimed to refine public-private dialogue and to adopt private sector investment targets for line ministries.

Like most developing countries, Rwanda faces an infrastructure gap that is hindering its economic transformation. Despite heavy public investments over the past two decades to improve access to affordable electricity, water, sewage, and internet across the country, private sector firms have still faced constraints in accessing critical services. Other infrastructure that is currently lacking is improved trade and logistics facilities and serviced land, which is often cited by foreign investors as one of the biggest challenges to setting up operations in Rwanda. As a solution to this challenge, and to facilitate investment in priority sectors, the GoR established the Special Economic Zone (SEZ) Program in 2006, initially with 278 ha in Kigali and expanded in 2013 to over 1,000 ha in eight additional locations across the country.

While fiscal expansion is necessary to achieve the country's targets for expanding access to infrastructure, it also risks increasing debt and crowding out the private sector's access to finance, which will in turn undermine long-term growth. If the trend continues, Rwanda may have difficulties in financing its growth over the medium term. Rwanda's commitment to concessional borrowing and monetary stability significantly reduces the risks to macroeconomic stability, but reliance on the public sector for achieving growth targets raises the fiscal risks. Rwanda has reached a point where it will be difficult to sustain high growth without greater private investment.

Vision 2050 aims to transform Rwanda into a dynamic global hub for business, investment, and innovation, with growth ambitions that depend on the private sector's ability to take the lead. While the government has tried to prioritize public investments that can crowd in private investments, more effort is still required to improve the allocation of economic resources through the markets to achieve sustainable and productivity-led long-term growth.

The GoR has enacted laws[1] and developed guidelines on public-private partnerships (PPP) to improve the enabling environment for the private sector and set out clearer modalities for engagement. In addition to marketing itself aggressively as a location for investment and working to better understand the constraints faced by the private sector and external investors, Rwanda has sought to involve private sector representatives more actively in policy discussions.

The Rwanda Development Board (RDB) is the multiagency governmental department tasked with creating the enabling environment to achieve deeper private sector engagement, promoting private investment, and encouraging private-sector-led exports. The RDB's role includes overseeing the privatization of government assets, negotiating contracts with the private sector, helping investors to secure concessions, and settling disagreements.

Analysis has shown that, by regional standards, Rwanda's policies toward the private sector are well coordinated (Booth et al. 2017). Ministries and other agencies are run under a well-functioning cabinet, coordinated by an Economic Cluster and several interagency bodies, including the Industrial Development and Export Council. However, these bodies appear to lack adequate engagement with the private sector or the required experience in management investment coordination. While the RDB has played an important role in streamlining investment registration, it has not had responsibility for setting or coordinating the industrial policy agenda. The RDB has worked effectively to coordinate cross-cutting topics but often lacks sufficient in-depth sector-specific knowledge, such as on the issue of water management, to add value to the private sector and anticipate problems that investors might face. Strengthening the RDB's policy-making role and sectoral capabilities might support future engagement with the private sector and promote more successful efforts to secure private investment.

While Vision 2050 lays the foundation to help meet the SDGs and propel Rwanda to middle-income and high-income status over the longer term, available resources fall far short of what will be needed to realize the country's longer-term development objectives. Fiscal discipline has been complemented by efforts to bolster domestic revenue mobilization and improve fiscal transparency, but more progress is needed. **Attracting private sector investment for critical development sectors is expected to play a pivotal role in delivering economic growth by promoting PPPs and joint venture modalities. More could also be done to leverage existing resources to attract significant private sector funding and the technology transfer that would follow from private sector investments.**

Rwanda still needs to address several barriers to improving private sector engagement and investment. The cost of doing business remains high in Rwanda, with the private sector facing high costs of transportation in almost every sector of the economy. Furthermore, despite efforts to remove bureaucracy, the high cost of finance, energy, and infrastructure means poses challenges for cutting the cost of doing business.

4.2. The Private Sector in the Water Sector

4.2.1. Managing scarce water resources and conflict

As mentioned above, the lack of access to water continues to hamper private sector engagement and investment. The private sector has cited a diverse range of challenges related to water supply, including poor construction of drainage channels in built-up areas, conflicts around multiple uses of water (for people, animals, crops, and so on), and pollution from upstream activities like mining or poor agriculture practices.[2] **As Rwanda implements its Vision 2050 plan, economic growth and further industrialization will increase the private sector's demand for water and potentially place further pressure on existing supply and infrastructure. A lack of additional investment to supplement supply or poorly coordinated responses to this challenge could hamper growth across the economy, specifically in the agriculture and hydropower sectors, whose water footprints are already high and expected to grow.**

Conflict over water and related coping strategies are already being witnessed, both within the private sector and between the private sector and public sector. For example, the Water and Sanitation Corporation's ongoing expansion to the Gihira water treatment plant has resulted in the use of a substantial amount of water that was supposed to be used by the downstream hydropower plant of Rwanda Mountain Tea. This has affected the productivity of the hydropower plant, and the private operator is not able to produce the agreed output in megawatts of electricity. Private firms are also leading the way in adaptation and water management. Inyange Industries, for example, which produces milk, juices, and bottled water, has sought greater efficiencies through the reuse of water for activities in its factories where clean or treated water is not necessary.[3]

While it is reported that water for the private sector is currently prioritized to support economic activities, there is a growing realization that increasing demand and changing supply as a result of climate change impacts could increase conflict in the future. Climate change could also contribute to an increase in instances of flooding and drought, posing higher economic risks and costing the economy as much as US$19 billion per year by 2050 if unmanaged (UNISDR and Cima Foundation 2018).[4] There is a growing consensus, therefore, that mechanisms need to be in place to allocate water resources (and related financial resources) more effectively to meet basic needs and maximize economic development.

While scarcity of water remains a threat for Rwanda, in the short to medium term, issues related to water quality will probably be the main water-related challenge that will need to be addressed by the private sector. Poor agricultural and industrial practices are resulting in significant water contamination, which is having a negative impact downstream, resulting in conflict between users. Water-polluting sectors (such as mining) have a negative knock-on impact on the economy through increased water treatment costs and impacts on specific industries, such as tourism and tea production in the Rukeri catchment.

Water quality is also affected by soil erosion and sedimentation. These issues pose a problem for farmers and other economic activity and often contribute to increases in flash flooding, which can have a significant impact on housing, livelihoods, transport, and other infrastructure. Siltation and sedimentation also bring increasing costs for hydropower production by necessitating additional maintenance. The Nyabarongo Hydropower Plant is a case in point, as its output has been affected by high sedimentation. **Water quality issues need to be tackled through both stronger enforcement of existing laws and collaborative initiatives to identify solutions and reduce conflict.**

4.2.2. Private sector role in water supply and management

*Over **50 %** of rural water supply systems are now managed by private operators*

In addition to using water responsibly, the private sector has an important opportunity to play a greater role in the management and provision of water in Rwanda. The national water policy sets out a role for the private sector in providing water services through additional technical and managerial capacity as well as financing. While private operators are not yet operating urban drinking water supply systems, the rural water supply sub-sector has switched in recent decades from a community management model to a PPP model, with over 50 percent of rural water schemes now managed by private operators.

In the agriculture sector, private and commercial farmer-led irrigation schemes are rare in Rwanda. There are two prominent farmer-led irrigation development ventures in the Eastern District of Rwanda. One is Bramin Corporate Ltd., a joint venture between Bralirwa Brewery and the maize processing company, Minimex Ltd. The second is a joint venture between Rwanda's National Agriculture Export Development Board and the Rwandan company, ProDev Bugesera. The relatively low cost of farmer-led irrigation development is a significant benefit that should support its expansion across the country. Scaling up these experiences could bring additional financing and new technologies, while reducing the burden on the public sector.

Private sector water users have demonstrated a willingness to invest in addressing water supply and quality issues to support their business needs. This has included source water protection and moving intakes upstream to ensure adequate supply. Where water scarcity is a significant problem and the cost of delivering water is high, as in remote locations, the private sector has focused its resources on ensuring greater efficiency through water reuse. Such approaches can have the dual benefit of addressing both the scarcity and quality of water and should be expanded within and outside of SEZs.

Such proactive measures by the private sector are driven by financial and business pressures. These include requirements to ensure a reliable water supply, initially to address risks identified by investors and, subsequently, to prevent the interruption of business activities. Insurers may also require interventions, such as protection against erosion and flooding, to address future risks and forestall significant payouts from water-related incidents. While the uncertainty brought about by climate change and more extreme weather events will likely increase insurers' risk management demands in the future, this can be seen as an opportunity to engage with the private sector more actively. **Understanding these financial incentives for and business pressures on private sector firms operating in the water sector is essential to better dovetail public investment and harness the comparative advantage of public and private actors in the sector.**

While documentation is limited, there is some evidence of private sector support for water supply and management through corporate social responsibility activities in Rwanda. These have included the provision of water supply to local communities and environmental interventions, such as wetlands management and erosion control. While not strictly corporate social responsibility, some new business license agreements have included requirements that the private sector provide support for water management in the areas in which they operate. Further regulatory tools could incentivize the private sector to share water sources and wastewater treatment infrastructure with society more broadly or use legal mechanisms to encourage Payment for Ecosystem Services (PES). **With the right incentives, there is scope to encourage the private sector to invest more in wider water infrastructure and related environmental interventions.**

The private sector has the potential to provide significant additional investment into the sector to support water and related infrastructure. GoR policy sets out options for leveraging private capital investments by providing low-interest loans, including through co-financing arrangements. Global evidence points the potential of blended finance (combining grants with loans and equity from public and private sources) and pooled financing mechanisms based on PPPs, and these should be explored further. **Such mechanisms can support the sharing of risks to encourage private sector actors to engage.**

Furthermore, credit guarantees can encourage lending by reducing the losses that a lender experiences when a borrower defaults or by reducing the risk of default on a loan. They are designed to give commercial lenders greater comfort in lending and can encourage additional lending, extend loan tenures, and reduce collateral requirements. Guarantees usually cover part of the risk (partial credit guarantee) and often impose a fee and certain project requirements or commitments. **The feasibility of applying such arrangements at scale in Rwanda's water sector still needs to be established, however.**

4.2.3. Public–private sector collaboration

There is a perception in the water sector that there is currently no clear rationale for allocating and pricing water for different uses. This also applies to the allocation of financial resources to increase water supply, build related infrastructure, and address water-related challenges such as erosion, sedimentation, and flooding. The analysis in this report and the proposed interventions in Chapter 6 aim to contribute to the evidence base to guide decision makers by highlighting where water scarcity might emerge in the country, which sectors are likely to see the greatest impacts, and where there is economic value in allocating resources to provide water and support government goals and strategies.

To maximize the utility of this evidence base, it will be important to put in place mechanisms at the national and subnational levels for discussing emerging findings and ground them in water users' real experiences. To bring diverse actors together in a constructive manner requires both leadership and a willingness to collaborate effectively in the pursuit of shared goals. This needs to start with government departments, such as RAB, MINAGRI, and others, where conflict over water and financial prioritization is evident. Furthermore, more delegated authority at the local level would support improved decision making to address catchment and local issues. Some efforts in this regard are underway, as the RWB is in the process of setting up decentralized catchment committees to help coordinate and streamline water allocation for various sectors.

Collaboration, including both more inclusive decision making and collective action, needs to reach beyond the public sector to development partners and the private sector. Incentives are greater for development partners to engage in such a process, whereas the private sector's voice is not often heard, and its capacity and resources therefore not leveraged. **In line with the GoR's wider strategy of enhancing public-private dialogue, a new sector mechanism is required to establish an environment in which the private sector can contribute more effectively to a coordinated response to water-related challenges.**

It has been proposed that this would take the form of a Multi-Stakeholder Platform that facilitates collective action and places water more deliberately and systematically at the center of efforts to achieve the goals and targets of the first National Strategy for Transformation (NST-1) and Vision 2050. **A primary role of an MSP could be to identify the most appropriate solutions, using cost-effectiveness as a key parameter. Another key role would be to determine appropriate government incentives (financial or otherwise) to bring different stakeholders to the table and to engage them in water security measures.** For the private sector, the MSP should reflect the operational and commercial incentives that would support businesses in running more efficiently and ultimately becoming more profitable. The incentives that are most likely to attract the private sector and encourage its engagement include ensuring the consistency of water supply within supply chains and reducing operation or resource costs.[5] Other incentives relate to clearer regulation and licensing procedures and to commercial interests, such as expanding the customer base and promoting product innovation.

Notes

1. N.14/2016 of 02/05/2016.
2. 2030 WRG virtual Partnership Strategy Meeting, "Strengthening public-private collaboration for sustainable water resource management in Rwanda," November 2021.
3. 2030 WRG virtual Partnership Strategy Meeting, "Strengthening public-private collaboration for sustainable water resource management in Rwanda," November 2021.
4. This assumes that no action has been taken to reduce risk.
5. 2030 WRG virtual Partnership Strategy Meeting, "Strengthening public-private collaboration for sustainable water resource management in Rwanda," November 2021.

Chapter 5
Investment and Intervention Opportunities

The HECCA has shown that Rwanda's economy has vulnerabilities related to the water sector, looking forward to 2030 and 2050 under the three scenario pathways considered. Each of these pathways assumes a set of investments and policies, with the baseline scenario assuming business as usual, the Vision 2050 scenario meeting ambitious development goals with a focus on growth, and the WRes2050 scenario considering the potential limitations of those ambitions due to climate change. Several interventions are considered, some quantitatively and some qualitatively, in this analysis. The interventions are categorized briefly as follows, then discussed in more detail below:

Supply-side measures:
Multi-scale storage, from rainwater harvesting to small reservoirs and large dams
Groundwater access
Supplemental irrigation
Source water protection and payment for ecosystem services
Wastewater treatment and reuse
Flood protection and erosion control
Demand-side measures:
Increased water productivity in irrigation via technologies and choice of crops and industrial systems
Reduction of non-revenue water (NRW) losses, including physical and institutional aspects
Economic incentives
Reduced water pollution

Legal, regulatory, and institutional strengthening

For supply-side and demand-side interventions to succeed in strengthening Rwanda's long-term water security, effective legal, regulatory, and institutional mechanisms must be in place, together with the capacity to operate and maintain the infrastructure that is built. There is a long history of large infrastructure projects falling into neglect and disrepair after initial construction is completed. Building grey infrastructure is not sufficient.

5.1. Supply-Side Interventions

5.1.1. Storage

As discussed above, the HECCA has demonstrated that the benefits of increasing water storage capacity outweigh the costs on an aggregate macroeconomic level. Investment in storage has positive benefits for discount rates ranging from 2 to 7 percent over a 30-year time horizon (Section 3.3.1).

Current surface water storage in Rwanda is less than 30 MCM per year. Under the baseline scenario, the level of storage is assumed to increase to almost 100 MCM with the addition of three large dams. The Vision 2050 and WRes2050 scenarios assume an additional 300 MCM in increased storage by 2050.

Changes in storage for irrigated agriculture via small and large reservoirs have substantial impacts, both on individual catchments and at the macroeconomic level. Yet, even with added surface water storage, the driest parts of Rwanda show unmet demands (Section 3.2.3).

Rwanda also has several forms of natural storage in lakes, ponds, wetlands, and groundwater. Natural storage clearly has the potential to be more cost-effective, where feasible. Rwanda's existing water storage capacity is being reduced, however, by the effects of erosion and sedimentation and addressing these factors is likely to introduce costs (Section 5.1.6).

To ensure long-term benefits from the creation of new or expansion of existing water storage infrastructure, these initiatives will need to be accompanied by interventions to reduce erosion and resulting sedimentation in reservoirs and other water bodies. **Rwanda's NDC has earmarked US$ 164.3 million to support Intervention 1 in the plan, which aims to support national water security by expanding storage, as well as through water conservation practices, wetlands restoration, and efficient water use.**

5.1.2. Groundwater access

Groundwater has the potential to address some of the gaps in water supply and demand. While its full potential is not well understood, it is likely that groundwater is underutilized. As in most of Sub-Saharan Africa, the potential may be very large (Cobbing and Hiller 2019; Xu et al. 2019). Estimates of groundwater storage/potential range from 6 billion cubic meters per year (REMA 2015) to more than 10 times that amount, at over 60 billion cubic meters (Republic of Rwanda 2014, 12). There is a need to invest in research to establish the potential that can be exploited (Xu et al. 2019), with a focus on the safe yields or sustainable renewable groundwater available in geographically specific contexts.

As a form of natural storage, groundwater has the possibility of lowering capital costs, especially relative to large dams, with reduced evaporation losses and more localized access (Pavelic et al. 2012). Groundwater can be an affordable option, particularly when considering the possibility of solar pumping, if initial capital costs can be subsidized for the poor.

The sustainable extraction of groundwater would need to be accompanied by efforts to enhance groundwater recharge. This can be linked to the planned expansion of storage infrastructure. In addition to dams and reservoirs associated with large storage interventions, sand and surface dams, recharge facilities, and a variety of agricultural soil and water management interventions can support groundwater recharge.

Source: Rwanda Agriculture and Animal Resources Development Board

The private sector might have a role to play in understanding both potential groundwater yields and the economic potential of using groundwater. The private sector could also bring technical capacity and financial resources to support the extraction of groundwater and the maintenance of pump and other infrastructure required to extract and transport groundwater. Where groundwater offers a more accessible and reliable supply to private firms, whether they are operating in industry or mining, it is an attractive option. **However, expansion of groundwater would also need to be accompanied with strong licensing and monitoring systems to ensure that withdrawals remain sustainable.** The sector has made significant progress in satellite and mapping technologies to track and monitor groundwater extraction and recharge, and this is another area where private sector partnerships could add significant value to Rwanda's sustainable use of this resource.

5.1.3. Supplemental irrigation for rainfed agriculture

Rainfed agriculture forms a significant part of the overall economy and is likely remain so in the coming years. Moreover, it can have a substantial impact on livelihood security in dry areas and, therefore, on patterns of migration. **Rwanda's NDC has earmarked US$2.26 billion to support Intervention 8 in the plan, which aims to expand irrigation and improve water management.**

Supplemental irrigation can be used to help bridge dry spells during critical stages in the life cycle of rainfed crops. This can be done via rainwater harvesting, where rainfall is collected in small storage structures (typically 100-1,000 m^3). Given that much of rainfed agriculture is at the subsistence level, this technique can provide some degree of insurance against short dry periods and shifts in rainfall patterns due to climate change. Studies in dry regions within Rwanda have shown that supplemental irrigation can lead to higher maize yields (Kannan et al. 2011; Uwizeyimana et al. 2018).

Irrigation development can support farmers' climate adaptation efforts by helping them overcome dry spells and boost crop yields. In Rwanda, however, irrigation development is typically not demand-driven; the majority of existing irrigation developments result from government-led initiatives and donor support. Few irrigation projects have been initiated by private commercial farmers and smallholder farmers. On the other hand, farmer-led irrigation development (FLID) is not new in the country. In 2015, the GoR launched the Small-Scale Irrigation Technology (SSIT) subsidy program, with the aim of supporting 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 portion 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 through which 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 irrigated small-scale land by 2024, with an annual budget of around RF 1.15 billion (MINAGRI 2018), and to increase the total irrigated area to about 600,000 ha by 2050 (MINECOFIN 2020). Between 2015 and 2021, the program supported the development of 17,000 ha of small-scale irrigation (World Bank 2021).

***8,000 Ha** - increase in newly irrigated smallscale land by 2024*

To facilitate access to SSIT kits, the GoR concluded contracts with private equipment suppliers operating across the country. Drip irrigation is one of the small-scale irrigation technologies promoted through the SSIT subsidy program. It is a low-cost technology whose introduction can help to mitigate the impact of rainfall variability on small-scale farmers. It applies water directly to the roots of crops, minimizing runoff and evaporation and thereby conserving water. Compared to surface irrigation and sprinkler systems, which can provide 60 percent and 75 percent water-use efficiency, respectively, drip irrigation can provide as much as 90 percent water-use efficiency (Gillet and Biancalani 2022). Adopting drip irrigation more widely could therefore boost the efficiency of water use in Rwanda if steps were taken to ensure that farmers had the technical capacity to use, manage, and maintain drip kits.

5.1.4. Source water protection and nature-based solutions

Water security - ensuring that the 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 source water protection efforts require a clear understanding of the potential risks to the drinking water supply, as well as the motivations and incentives that influence civil society stakeholders, private sector actors, service providers, and public institutions to prioritize, plan, and implement source water protection.

Nature-based solutions (NBS) - refers to the sustainable management and use of natural features and processes to tackle socio-environmental challenges. These challenges include issues such as climate change, water security, water pollution, food security, human health, biodiversity loss, and disaster risk management. Nature-based solutions, which include Payment for Ecosystem Services (PES), constitute a key pillar of Rwanda's Vision 2050. Rwanda and Costa Rica recently signed a Memorandum of Understanding on environmental cooperation that will focus specifically on exchanging experiences with nature-based solutions. In many cases, the effectiveness of funding modalities for source water protection depends on stakeholder buy-in and willingness to pay, as well as fund management (that is, how resources are raised and allocated). In the institutional context of East Africa, Namirembe et al. (2018) 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. Successful funding schemes for source water protection for urban drinking water include the Nature Conservancy's Water Fund Model in Nairobi, Kenya, and Peru's use of utility tariffs to support green infrastructure investments.

Most farmers in Rwanda currently use few inputs and are highly susceptible to droughts, with limited market access (Andrew et al. 2010). This gives farmers limited options to increase incomes. PES can help famers gain a sustainable income, while also sustaining the surrounding environment. PES requires strong regulatory support to be effective. There are successful cases in Africa, but PES programs alone cannot reduce poverty among rural farmers in Rwanda. PES programs should therefore be integrated with other rural development initiatives to increase incomes, with a particular emphasis on restoring or preserving ecosystems and raising awareness of the importance of ecosystem services.

Mining is another sector in which nature-based solutions should be explored further. Small-scale mining in Rwanda has local impacts on water quality, with the potential for heavy metals (such as lead, cadmium, zinc, and copper) to accumulate in soils and enter the food chain, especially in floodplains used for agriculture and irrigation. For example, open cast mining, such as at Bijyojyo, Mbobo, and Gatumba (in the Upper-Nyabarongo catchment), is associated with environmental impacts on water and river streams, including siltation due to soil erosion and sedimentation. **Addressing these impacts requires stronger monitoring and accountability mechanisms, and PES can be a useful tool for incentivizing positive change, rather than just punishing poor practices.**

PES and other nature-based solutions could help shape a private sector response that incorporates land use practices to manage erosion and flooding and that provides some water storage solutions. **It will be importance for the GoR to reflect on the different "stick and carrot" strategies that might lead both to more efficient use of water and to better management of water sector investments. The proposed MSP could be an ideal forum for exploring these different approaches and reaching some consensus on the best way forward.**

Source: Rwanda Water and Sanitation Corporation

5.1.5. Water supply and wastewater reuse

Rapid population growth in urban areas is placing increased pressure on drinking water supplies, requiring the expansion of existing infrastructure and better management of existing systems. Water management and demand issues, such as NRW, are addressed in Section 5.2. Rwanda has begun to look beyond traditional sources of investment in new infrastructure, such as government and donor financing. In Kigali, for example, a build-operate-transfer arrangement was designed in which a private investor financed the design, construction, and operation of water production and treatment facilities.

The Metito consortium was successful in winning the contract and agreed to invest US$75 million in developing the scheme and operating it for a 25-year period. Such innovative schemes have demonstrated both the viability of PPPs and the availability of commercial finance to support water delivery in Rwanda. Additional learning is needed to support the expansion of such initiatives to other cities and, where applicable, other water-related infrastructure and service delivery in Rwanda.

Rwanda's NDC prioritizes improvements in human settlement, with a specific focus on high-density building and informal settlements. **The plan allocated US$400 million to improve urban infrastructure, including water and sanitation, and an additional US$400 million has been allocated to improve storm water management.** The reuse of treated wastewater is an additional potential means to increase water supply, especially in urban areas. Reused water can be both cost-effective and reliable but requires adequate monitoring to ensure that safety standards are met. While wastewater treatment plants are often the responsibility of local governments or water utilities, there is increasing interest within the private sector to recycle water. This approach would address pollution issues and, in some cases, reduce reliance on intermittent public water supply.

Bralirwa Plc. has constructed a new wastewater treatment plant for its brewery, which is expected to have a production capacity of over 2 million hectoliters (hl) per year by 2021, resulting in up to 2,200 m^3 wastewater every day. The new treatment plant cost €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 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 be discharged back into Lake Kivu in compliance with Rwandese environmental legislation.

5.1.6. Flood protection and erosion control

Climate change is likely to affect flooding patterns into the future. More extreme events are likely, and the degree of damage from these events can create a vicious cycle affecting 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. Thomas et al. (2021) examined the connection between rainfall-induced flooding and increased uncertainty where first-mile transportation infrastructure is limited. In Rwanda, 90 percent of the population below the poverty line lives in rural areas that are typically mountainous, with frequent flooding (Thomas et al. 2021). To reduce the transportation barriers that result from increased flooding, the non-profit organization Bridges to Prosperity plans to construct hundreds of trail-bridges in Rwanda between 2018 and 2023. Thomas et al. (2021) examined households living near 12 trail-bridge sites and 12 comparison sites during February 2019 - March 2020. The team found that labor market income increased by 25 percent, as a result of the trail-bridges. They did not observe any significant effects on agricultural income, education, or health outcomes; however, given the small sample and short duration of this study, they anticipate observing additional impacts as a result of the recently launched four-year trial with 200 sites.

Investment in flood-mitigating infrastructure in Rwanda is crucial, as the climate continues to change. In a second study, which examined flood risk in Rwanda, Icyimpaye et al. (2021) aimed to forecast the Nyabugogo River flood risk and to propose mitigation measures to reduce flood impacts using hydrological and hydraulic models. They found that the medium to high flood vulnerability in the river region was in cropland, open grassland, open shrubland, settlements, sparse forest, and wetlands. The simulation showed that the 100-year return period gives a water depth of 3.24 meters, pointing to the need for flood mitigation measures in the region. With reference to this study, although traditional flood-mitigating infrastructure construction may be beneficial, **thought should also be given to the role that natural landscapes, such as forestland, can play to help mitigate, or at least lower, the risk of extreme flooding in Rwanda.**

Source: Rwanda Agriculture and Animal Resources Development Board

5.2. Demand-side interventions

5.2.1. Increased water productivity in irrigation and industrial systems

It is possible to achieve higher rates of production in irrigated and industrial systems than currently seen in Rwanda using water-efficient technologies, such as drip irrigation, as discussed above, and other climate-smart agricultural practices. Rice, for example, is typically irrigated in furrows, but with alternate wet-dry irrigation methods, water usage can be reduced by 25-70 percent at the same level of production (Ishfaq et al. 2020). In general, with proper incentives around water pricing and enforcement, increasing water productivity can be cost-effective. **Conservation agriculture could play a key role in reducing total water losses, as well as enhancing soil health and crop productivity. This could connect to source water protection opportunities, as suggested in Section 5.1.4.**

Within industry, water productivity can be raised through process changes, but a great deal can also be accomplished through recycling and reuse (Klemeš 2012). A wide range of technologies are available today for recycling and reuse, many of them well-established, with prospects for a future shift in perspective to viewing wastewater as a resource (Ranade and Bhandari 2014).

5.2.2. Non-revenue water reduction

Loss of water in municipal systems can result from physical losses, such as leaky pipes, as well as from water diverted from the system for productive use. Revenue can be lost even when water is delivered to its intended use, through poor billing and collection systems or poorly maintained meters. In March 2020, the Rwanda Utilities Regulatory Authority Statistics reported **NRW losses on the order of 44 percent, so that for every cubic meter of water delivered, 1.8 cubic meters are abstracted.** This recent figure is **comparable to the estimated 41 percent NRW losses** reported by Karamage et al. (2016) using data for 2013-14. **Revenue losses are substantial, at an estimated US$8.7 million** (Karamage et al. 2016). **NRW losses of this magnitude have an important impact on water security, as well as energy consumption for pumping, transport, and treatment.**

In economic terms, under Vision 2050, the domestic portion of Rwanda's overall water demand is dominated by irrigation agriculture, but for the utility NRW reduction is likely to be a worthwhile investment. A pricing model developed by Wyatt (2010, 20) showed that the optimal level of NRW prevention increases with the tariff rate. Rwanda increased tariff rates substantially in 2019 for some customers, so, while keeping in mind that financial objectives must be balanced against social objectives (Marson and Savin 2015), it is worth exploring whether significant NRW reduction may be more cost-effective under the new rates.

5.2.3. Economic incentives

Changes in water demands can be encouraged through a wide range of economic incentives, including subsidies, penalties, and tariffs to incentivize more water-efficient technologies across sectors. Adoption of the user-pays 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.

It is important to find the "right" water pricing for household use in order to balance the basic right to water with the need to cover the cost of providing services. Rwanda has lowered its water tariffs in recent years, which may help improve equity in access to water while also raising questions about cost recovery for water treatment and delivery by commercial water suppliers, such as the Water and Sanitation Corporation and Aquavirunga.

Given its potential impact on water use, the pricing structure for irrigation is arguably more important. There are several options for pricing irrigation water to achieve water use efficiency: (i) without the transfer of water rights, which could promote technical efficiency; (ii) with the transfer of water rights, which could promote allocative efficiency; and (iii) incorporating environmental costs, which could promote ecological efficiency. Moreover, the productivity of water is not constant over the growing season and, consequently, the economic value of water varies widely. **The accepted basis for pricing irrigation water is to consider water as one "input," among others, in the agriculture production system and charge for it based on the quantity used. Another approach is to charge for irrigation water based on output per area, such that irrigators pay a certain water fee for each unit of output they produce.**

The GoR recognizes the need for revenue to be generated for wider water management and protection activities, including pollution and downstream impacts. **Taxes and fees for the use of water and other natural resources create incentives to use the resource efficiently and improve its management.** Conversely, taxes or fees placed on discharges to the environment can create disincentives 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 the supply of drinking water, wastewater treatment, irrigation, aquaculture, mining, hydropower generation, and industrial production (such as coffee, tea, and other beverages).** Such a fee structure would be implemented in conjunction with a more comprehensive water use permit system. Currently, only a small portion of existing water abstraction sites and wells are officially registered in the permitting system.

5.2.4. Reduced water pollution

A comprehensive water quality monitoring report for Rwanda (IWRM Programme Rwanda 2019) identified the pollutant and water quality measures that are almost always at unacceptable levels: dissolved oxygen, fecal coliform, Escherichia coli (E. coli), total suspended solids, and turbidity. It is likely that this pollution arises as the result of the sedimentation/siltation of water bodies caused by soil erosion, as well as poor sanitation systems and practices. **Source water protection can be an effective way to address soil erosion, while appropriate sanitation can address the problem of microbial contaminants.**

Improved water quality is an essential tool to boost countries' economic growth and aid in poverty alleviation. Many components, including watershed protection, forests, use of pesticides, and wastewater treatment, affect the quality of water. In Rwanda, there are still opportunities for improvement in wastewater treatment. Theoneste et al. (2020) evaluated the performance of Kacyiru Sewage Treatment Plant and its effluent impacts on the receiving wetland, measuring influent and effluent wastewaters as well as receiving wetland water quality from April to September 2019 at Kacyiru Estate. It was found that the wastewater treatment at this plant did not comply with 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. Water quality in the region is also affected significantly by pest management practices. Umulisa et al. (2020) evaluated the occurrence, residue levels, spatial distribution, and sources of persistent 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 Rwandan urban areas.

A more recent study on Rwandan water quality by Umwali et al. (2021) assessed the spatio-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 poor water quality 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/land cover.

These changes include the removal of forests, increases in cropland, substitution of grasslands, and large-scale urban expansion. **Land-use change plays a critical role in water quality outcomes and must be considered as Rwanda continues to implement its development strategy.**

5.3. Legal, Regulatory, and Institutional Strengthening

All of the above interventions require adequate and effective legal, regulatory, and institutional mechanisms. Without supporting governance structures, infrastructure will degenerate over time and water allocation decisions will be undermined, thereby compromising the security of Rwanda's water future. **Investment in governance is as critical as any other aspect of water planning.** The effective delivery of Vision 2050 will require strengthening the 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 on the part of the private sector.**

Rwanda's regulatory environment is not sufficiently robust to optimally engage the expanding number of stakeholders in the water sector or to maximize wider economic development. The Rwanda Utilities Regulatory Authority has a mandate to regulate the provision of water and sanitation services to promote fair competition, as well as oversee the efficient use of resources and the quality of water services. The authority is also tasked with developing regulatory tools, licensing service providers, monitoring compliance by licensees, and reporting on sector performance.

Barriers need to be removed at several levels, including the lack of rules and enforcement mechanisms to guide water use and management. The absence 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 need to be put in place to facilitate wider engagement in policy discussions so that stakeholders feel engaged in decision making processes. **Platforms, such as the proposed MSP, can share knowledge and experiences and create a collaborative environment to promote innovation and maximize 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, based on their responsibilities and roles in the sector. This will require a range of tools and indicators. While the wider adoption and mainstreaming of the WEAP tool within 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 whether or not it is being priced effectively. **To do 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 mobilization, targeting, and monitoring of resources in the sector. Vision 2050 provides a platform for the government to make strategic investment decisions and optimize scarce financial resources. Advancements in water-related data collection and management could 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 terms of skills, innovation, and resources. Rwanda's NDC has earmarked US$10 million to support Intervention 2 in the plan, which aims develop water resource models, water quality testing, and improved hydro-related information systems.**

Chapter 6
Recommendations for Policy Discussion and Further Analysis

This report has aimed to provide insights into the water sector challenges that Rwanda faces as it moves ahead with its economic expansion and deals with the uncertainties that climate change brings. The report has focused in particular on the current and future role that the private sector can play as a critical partner in the water sector. **Good progress has been made in both broadening private sector participation in the sector and increasing meaningful dialogue, but there is more to be done to recognize and maximize the private sector's contribution.** Although addressing the wider economic barriers to private sector engagement in the water sector is beyond the scope of the sector itself, it does need to continue to articulate how these challenges manifest for private sector water users and suppliers to inform future policy.

The proposed MSP will be constituted primarily as a platform for stakeholder dialogue to ensure that water remains a top priority on the political agenda. It will serve as an advisory group for both the proposed National Water Consultative Committee on policy matters and the RWB on policy and implementation aspects. **The MSP, which would bring together public and private sector actors on a common platform, would offer an opportunity to strengthen synergies and partnerships between the public and private sectors. This platform could also provide a mechanism to review the recommendations in this report and to develop and prioritize concrete proposals to harness PPPs to tackle the issues raised.** Furthermore, through ongoing consultation and dialogue, water sector policies should continue to be updated to improve the private sector enabling environment.

Effective regulations, laws, policies, human capacity, and financing all need to be in place to enable actors to work together to achieve Rwanda's water security goals. The public sector should place specific focus on strengthening the implementation of regulations and legal frameworks to improve clarity for the private sector, promote good business practices, and encourage investment. **The private sector is encouraged to take advantage of new technologies and management practices, especially in the agriculture, energy, and mining sectors, as an opportunity to increase profitability and, at the same time, contribute to improving management of the country's water resources. There is also a need for the public at large to be aware of the value of water and its role in both day-to-day life and the broader economy, so that water is given prominence in decision making at all levels.**

Set out below are several areas in which Rwanda should consider strengthening policies and financing options to address the supply-side and demand-side challenges that the country faces, together with the additional analysis needed to inform this effort. Rwanda faces a range of challenges and opportunities to maximize its water resources in the coming years, and these will present themselves over different time scales. **Rwanda therefore needs to balance interventions to address short-term impacts while preparing for those that may emerge over the longer term.** Hence, the remainder of this report presents key recommendations for policy discussion, organized around short-term as well as medium- to long-term priorities.

Short-Term Priorities

The main short-term challenges in Rwanda's water sector are related to the lack of water infrastructure to support basic drinking needs, the risks that rainfed agriculture poses for farmers' livelihoods and the economy, and the impact of growing urban centers and increased industrial production on water quality. **Actions taken to address these issues over the next five years will also need to create a conductive policy environment to address medium- and long-term challenges.** This includes mechanisms to manage conflicts and tradeoffs in water use and to facilitate private sector engagement and the mobilization of needed financing.

- **A national investment plan is needed to guide the expansion of Rwanda's water storage,** targeting initiatives in both rehabilitation and protection of existing storage (natural and manmade) and the construction of new storage infrastructure. This plan should focus on areas where scarcity has been identified and has the potential to have the most negative economic impact.
- While reliance on rainfed agriculture is likely to decline as economic development continues, this will not happen quickly and those who continue to follow this practice are often from the poorest communities with limited other options. **Supplemental small-scale irrigation interventions (such as drip and sprinkler irrigation) are therefore needed while larger-scale irrigation systems and related storage infrastructure are put in place.** Furthermore, small-scale irrigation interventions can target the remote and poor communities that are most vulnerable to the impact of changing weather patterns caused by climate change, and less likely to benefit from large-scale schemes. These smaller irrigation interventions can reduce risk (and thus promote investment), allow the cultivation of more water-consuming crops, add cropping in the dry months of June-August, and overall get more "crop per drop" than rainfed agriculture.
- **A stronger and more comprehensive policy approach to address waste from NRW can reduce the stress on water supplies, especially in urban areas.** Policies should prioritize investment in capacity to use Geographic Information System (GIS) maps, undertake hydraulic analysis, and install flow rate meters to improve leak detection. In addition, investment in soft infrastructure, such as billing and metering systems, can further boost

cost-effectiveness. There are examples across the continent of using private sector capacity and innovation to outsource the maintenance of systems, including fixing pipes, to improve functionality and reduce losses from leaks and theft.

- **Wastewater management strategies should be prioritized to set out both sewered and non-sewered solutions for growing urban centers.** Such strategies will need to look at reducing pollution from household and industrial waste to preserve existing water resources and, where appropriate, look to install circular solutions to maximize reuse and reduce the burden on increasingly scarce water resources. Proposals to build new hard infrastructure should be balanced with investment in soft infrastructure to promote the infrastructure management, regulation, and monitoring/accountability systems that are critical to minimize water pollution.

Source: Rwanda Water and Sanitation Corporation

- **To strengthen the economic case for investing in basic water and sanitation infrastructure, there is a need for further analysis of the role of piped water supply and sanitation in improving the basic health and well-being among the people of Rwanda, allowing them to engage in education and productive livelihoods.** The country's current macroeconomic model does not, for example, consider the development impacts associated with women and children carrying water for long distances. According to the United Nations Children's Fund (UNICEF), only 57 percent of Rwanda's population has access to safe drinking water within 30 minutes of their home. This affects children's ability to attend school and women's ability to do other productive activities, thereby keeping families in cycles of poverty. Benefit-cost ratios have been reported to be significant for basic water and sanitation services in developing countries, with valuable impacts on quality of life and the overall economy.
- **There is a need to assess current water storage and the level of sedimentation, especially with regard to storage linked to hydropower dams.** Some existing storage is close to reaching its dead level, a comprehensive program to desilt existing dams would improve the life span of existing dams.
- **Policy should support the expansion of PES schemes to enable the improved functioning of water management structures and provide another entry point for private capital into the sector.** Policy emphasis should be placed on

creating an enabling environment for water-related investments through PES mechanisms, where local institutions, farmers, and the private sector can be incentivized to undertake activities that support water management, address flooding within catchments, and promote sustainable land management to address sedimentation. **Policies should also incorporate ecological compensation and be harnessed as an opportunity (or obligation, when required by law) for companies to compensate for their negative impacts on water bodies and related ecosystems, and this compensation can be used to support improvements.**

- **New policy tools and interventions to address the challenges discussed here will require additional investment and capacity in the sector.** Financial resources will need to be mobilized from a range of sources, including the government's own budget, donor support, and private sector investment. Innovative funds, such as the Rwanda's National Fund for Environment (FONERWA), should explore how to promote community-level incentives to build resilience and sustainable grassroots institutions to support water management.
- **The private sector offers an alternative source of funding to meet funding gaps.** Rwanda's PPP policy recognizes the deficiencies in government financing to attain its economic goals and the need for greater engagement of the private sector. The water sector has started to explore some more creative financing approaches, including blended financing approaches that aim to harness concessional finance from development partners to leverage private sector finance.
- There are a growing number of examples of the use of development finance to de-risk water investments, thus making the investment more attractive to the private sector. **Financially de-risking investment opportunities needs to be accompanied, however, by greater engagement with the private sector to build trust and to develop a clear, joint, long-term vision of the private sector's role in the sector.** Private investment in establishing the necessary capacity and infrastructure to play a larger role in the sector requires a viable business case, built on a stable and enabling operating environment.
- In addition to promoting private investment for business purposes, **the policy framework should encourage private companies to allocate funds to water management through corporate social responsibility (CSR) initiatives.** This can be done by integrating water management in operational funds so that it becomes mainstreamed in business operations and value chains as part of a long-term business strategy.

Medium- to Long-Term Priorities

As Rwanda moves beyond 2030 and toward its 2050 targets, pressure on water resources will increase. Research indicates, moreover, that the impacts of climate change are likely to exacerbate this pressure. **Conflict over water resources will increase, and the food–energy–water nexus will see critical trade-offs to achieve economic growth and maximize water resources.** As highlighted above, this will be especially true if Rwanda's ambitious expansion in irrigated land is achieved, as this will require significant new infrastructure, including additional storage. Below are interventions that should be considered for the medium to long term, five to 20 years into the future.

- **For both irrigated and rainfed agriculture, climate impacts need to be examined in more detail** as climate pathways evolve and knowledge of impact increases, particularly as temperatures will continue to rise, with significant and to some extent unknown consequences. Which crops will be best suited and most profitable for Rwandan famers 10, 20 and 30 years from now? While climate resilience is mentioned in the Irrigation Master Plan, specific crops that could be more climate-resilient are not identified.
- As water scarcity increases after 2030, groundwater offers a supplementary supply that has yet to be tapped effectively in Rwanda. **Policies should be put in place to promote the development and deployment of new technologies,** both to reduce the cost of extraction (such as solar pumping) and to sustainably manage extraction. The planned expansion in storage can also contribute toward groundwater recharge, which would need to be carefully planned and regulated.

- The scenarios explored in this report point to the need to reduce Rwanda's reliance on hydropower, which will struggle to meet energy requirements consistently as demand grows over the medium to long term, especially if Rwanda meets it ambitious economic growth targets. **Policy dialogue between the water and energy sectors will be needed to establish a set of agreed targets and strategies for expanding Rwanda's hydropower resources while developing supplementary energy production options.**

Source: Rwanda Energy Group

- Expanding large hydropower infrastructure is expensive, technically challenging, and time consuming. By contrast, smaller hydropower schemes have proven to be a cost-effective means of supplementing energy resources in high-demand areas. Examples already exist of private sector investment in this area in Rwanda, including the investment mobilized by Rwanda Mountain Tea through loans from the Belgian Investment Company for Developing Countries for the construction of a 4 MW hydropower plant in Nyabihu District. The generated electricity is sold to Rwanda Energy Group. The favorable policy and regulatory framework in the energy sector has engaged in three more such schemes, including the Giciye II Hydropower Plant (4 MW) and Rwanda Mountain Tea's rehabilitation of the Rugezi (2.6 MW) and Gihira (1.8 MW) hydropower plants. **Exploring opportunities for further PPPs and the mobilization of private finance in this sector offers an opportunity to expand hydropower in Rwanda.**
- Another aspect not fully covered in this report, which is worth further investigation, is the ability to preserve critical ecosystems that could affect tourism – a key economic sector for Rwanda, much of which is focused on its unique ecosystems and biodiversity. Much of the ecological health of Rwanda is connected to water, aspects of which are dependent on decisions on how to manage water. **Meeting ecological flow requirements, and how that might affect the tourism-dependent parts of Rwanda' ecosystem landscape, is an important aspect of the macroeconomy that could be explored.**

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Appendix A
Data Sources

DATA	SOURCE
Hydrology (Soil Moisture Model)	
Land use/Land cover	Rwanda Natural Resources Authority2018 land cover map of Rwanda
Meteorological data – precipitation, temperature, relative humidity, wind speed	Terrestrial Hydrology Research group at Princeton University (http://hydrology.princeton.edu/home.php)
Historical streamflow	Rwanda Water Portal (https://waterportal.rwb.rw/data/surface_water)
Domestic Water Use	
Total Domestic Water Use	2020 Water Use Assessment
Population	2012 Census (National Institute of Statistics Rwanda). Supported by Level 1 data from National Water Resources Master Plan
Per capita water use	National Water Resources Master Plan
Agricultural Water Use	
Total Agricultural Water Use	2020 Water Use Assessment
Cropped areas by crop type	Ministry of Agriculture. 2021 Crop report
Estimated irrigation efficiency by crop type	Ministry of Agriculture
Livestock Water Use	
Number of livestock units	2018 Report
Water use per livestock unit	National Water Resources Master Plan
Industrial Water Use	
Total Industrial Water Use	2020 Water Use Assessment
Total Mining Water Use	2020 Water Use Assessment
Hydropower	
Location of facilities	2020 Water Use Assessment
Installed capacity	Rwanda Energy Group
Maximum turbine flow	Rwanda Energy Group
Fixed head (run-of-river) or Tailwater elevation (reservoir)	Rwanda Energy Group

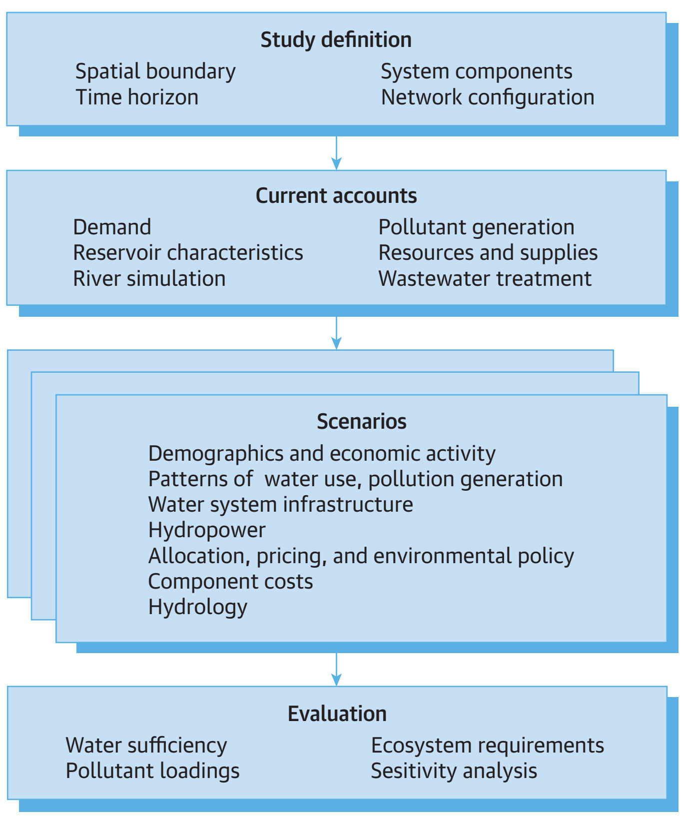
Appendix B
WEAP

WEAP is a widely used modelling platform for water security studies. It takes into consideration supplies and demands, with many built-in models around hydrology, water quality, groundwater and climate. WEAP can links to external models as well. But WEAP is not designed to address hydraulic models of pipelines, for example, nor is it an optimization tool, unless linked to an external platform, such as GAMS or Excel.

Modelling Approach

The development of all WEAP applications follows a standard approach, as illustrated in Figure 29. The first step in this approach is the *Study Definition*, wherein the spatial extent and system components of the area of interest are defined and the time horizon of the analysis is set. The user subsequently defines system components (e.g., rivers, agricultural and urban demands) and the network configuration connecting these components. Following the study definition, the *Current Accounts* are defined, which is a baseline representation of the system - including existing operating rules to manage both supplies and demands. The current accounts serve as the point of departure for developing *Scenarios*, which characterize alternative sets of future assumptions pertaining to regulations, infrastructure, water demands, and water supplies. Finally, the scenarios are *Evaluated* regarding water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables. In this context, scenarios represent evaluations of water management alternatives under uncertain future conditions. The steps in the analytical sequence are described in greater detail in the following sections.

FIGURE 29. Steps in Developing and Applying a WEAP model



One of the main strengths of WEAP is its flexibility in the way in which it can be adapted to the needs of a particular water system. Starting with the *Study Definition*, WEAP can be set up to consider a range of spatial and temporal scales. It has been used to evaluate daily water usage patterns at the municipal scale in Bangalore, India as well as to evaluate the impact of long-term climate change and the implications on trans-boundary water sharing agreements in the Nile River basin.

This flexibility carries through to the data types that are used to define the *Current Accounts*. This step typically begins with defining water supplies, which can be entered into the model in a variety of ways, including constant inflows, reading in historical streamflow values from files, or using climate inputs to simulate watershed hydrology (i.e. rainfall-runoff, infiltration, groundwater recharge, stream-aquifer interactions, etc.). Similarly, WEAP demand nodes can be set up to consider a range of water users, including domestic, industrial, agriculture, livestock, inter=basin transfers, etc. Additionally, each water use type can be disaggregated to best represent water use dynamics. For example, domestic demands are often defined based on population and per capita water use rates. However, in situations where it is important to consider the drivers of household water use, it is possible to disaggregate demands such that these drivers (e.g. toilets, showers, washing machines, outdoor watering, etc.) are explicitly considered. This is also common for agricultural demands, where agricultural areas can be divided between different crop types, and crop types may be further refined to reflect different irrigation practices.

Another way in which WEAP offers flexibility is through its ability to link to external models. This linkage can be either a ‘soft’ linkage, in which the models are run independently and then outputs are shared such that they become inputs to the other, or a ‘dynamic’ linkage, in which the models are run concurrently, and data is passed between models at regular intervals during simulation.

Model Setup

WEAP models are constructed using a collection of model objects (Figure 28) to represent the water system. Each object is programmable, allowing users to specify rules that control patterns of water supply and usage.

WEAP Calculation

At each time step, WEAP first computes the hydrologic flux, which it passes to each river. The water allocation is then made for the given time step, where constraints related to the characteristics of reservoirs and the distribution network, environmental regulations, and the priorities and preferences assigned to points of demands are used to condition a linear programming optimization routine that maximizes the demand “satisfaction” to the greatest extent possible. All flows are assumed to occur instantaneously; thus a demand site can withdraw water from the river, consume some, and optionally return the remainder to a receiving water body in the same time step. As constrained by the network topology, the model can also allocate 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 HECCA study.

Water Allocation

WEAP is a demand-driven model, which uses a hierarchical priority structure to determine the order in which water supplies are allocated to different water users. Two user-defined priority systems are used to determine allocations of water supplies to meet demands (modelled as demand sites and as catchment objects for irrigation), instream flow requirements, and for filling (or draining) reservoirs. These are: (1) demand priorities, and (2) supply preferences.

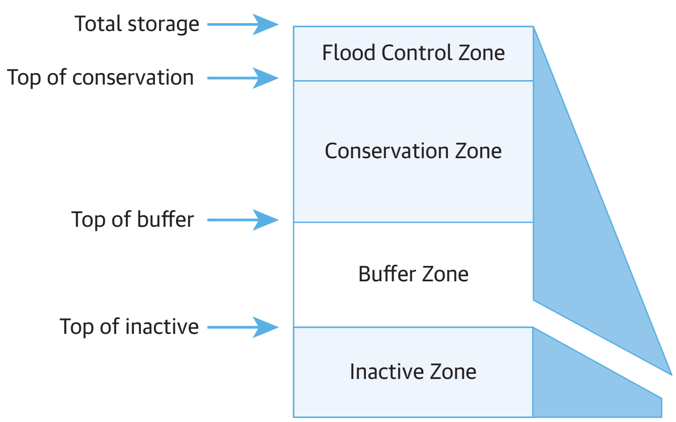
A demand priority is attached to a demand site, catchment, reservoir, or flow requirement, and may range from 1 to 99, with 1 being the highest priority and 99 the lowest. Demand sites can share the same priority, which is useful in representing a system of water rights, where water users are defined by their water entitlement and/or seniority. In cases of water shortage, higher priority users are satisfied as fully as possible before lower priority users are considered. If priorities are the same, shortage will be shared equally (as a percentage of their water demands).

When demand sites or catchments are connected to more than one supply source, supply preferences determine the order of withdrawal. Like demand priorities, supply preferences are assigned a value between 1 and 99, with lower numbers indicating preferred water sources. The assignment of these preferences usually reflects economic, environmental, historical, legal, and/or political realities. Several water sources may be available when a preferred water source is insufficient to satisfy all of an area's water demands. WEAP treats additional sources as supplemental supplies and will draw from these sources only after it encounters a capacity constraint (expressed as either a maximum flow volume or a maximum percent of demand) associated with a preferred water source.

WEAP's allocation routine uses demand priorities and supply preferences to balance water supplies and demands. To do this, WEAP must assess the available water supplies each time step. While total supplies may be sufficient to meet all the demands within the system, it is often the case that operational considerations prevent the release of water to do so. These rules are usually intended to preserve water in times of shortage so that long-term delivery reliability is maximized for the highest priority water users (often indoor urban demands).WEAP can represent this controlled release of stored water using its built-in reservoir routines.

WEAP uses generic reservoir objects, which divide storage into four zones, or pools, as illustrated in Figure 30. These include, from top to bottom, the flood-control zone, conservation zone, buffer zone, and inactive zone. The conservation and buffer pools together constitute a reservoir's active storage. WEAP always evacuates the flood-control zone, so that the volume of water in a reservoir cannot exceed the top of the conservation pool. The size of each of these pools can change throughout the year per regulatory requirements, such as flood control rule curves.

FIGURE 30. WEAP Reservoir Zones



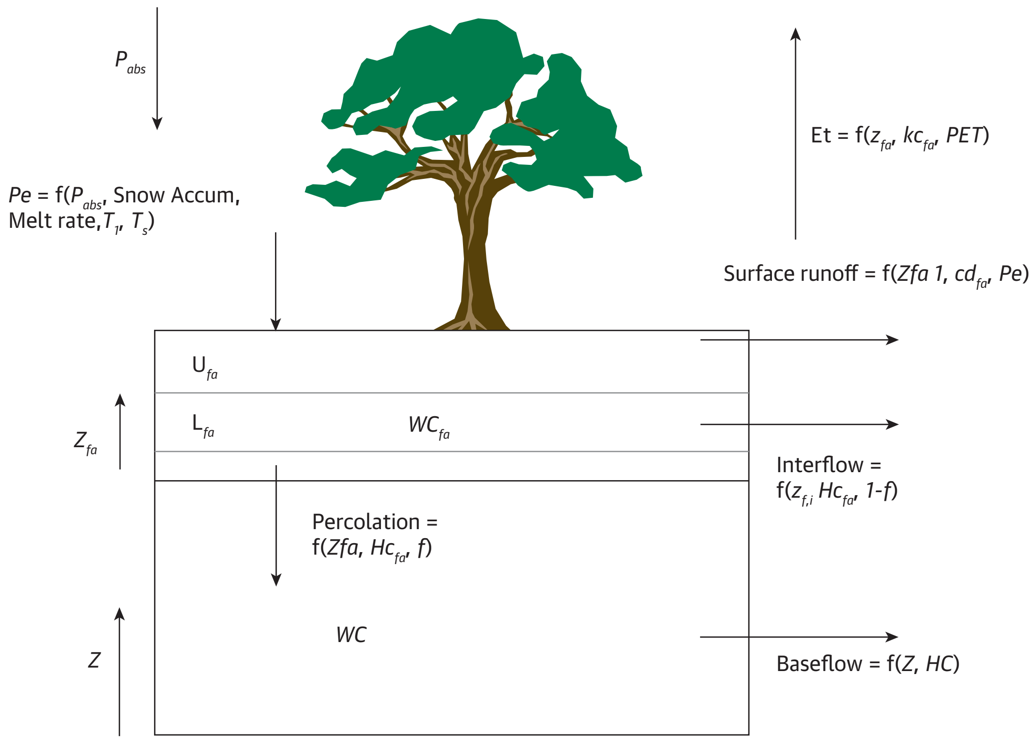
WEAP allows reservoirs to freely release water from the conservation pool to fully meet downstream requirements. Once the reservoir storage level drops into the buffer pool, the release is restricted according to the buffer coefficient, to conserve the reservoir's dwindling supplies. The buffer coefficient is the fraction of the water in the buffer zone available each month for release. Thus, a coefficient close to 1.0 will cause demands to be met more fully, while rapidly emptying the buffer zone. A coefficient close to zero will leave demands unmet while preserving the storage in the buffer zone. Alternatively, the conservation zone and buffer zone may be assigned different priorities to represent changing priorities as storage reserves dwindle. Water in the inactive pool is not available for allocation, although under extreme conditions evaporation may draw the reservoir below the top of the inactive pool.

Rainfall-Runoff

WEAP's Soil Moisture module is used to simulate basin hydrology. This module configures a basin as a contiguous set of sub-catchments that cover the entire extent of the river basin. This conceptual model for each sub-catchment is show below in Figure 31. This continuous representation of the river basin is overlaid with a water management network topology of rivers, canals, reservoirs, demand centres, aquifers and other features. A unique climate-forcing dataset of precipitation, temperature, relative humidity, and wind speed is uniformly prescribed across each sub-catchment.

A one-dimensional, quasi-physical water balance model depicts the hydrologic response of each fractional area within a SC and partitions water into surface runoff, infiltration, evapotranspiration, interflow, percolation, and baseflow components (see Equation 1 and Figure 31). Values from each fractional area within the SC are then summed to represent the lumped hydrologic response, with the surface runoff, interflow and baseflow being linked to a river element and evapotranspiration being lost from the system.

FIGURE 31. Diagram of WEAP's Soil Moisture Hydrology Model



Source: Yates et al. 2006a.

Equation 1.

$$RD_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)\left(\frac{5z_{1,j} - 2z_{1,j}^2}{3}\right) - P_e(t)z_{1,j}^{RRF_j} - f_j k_{s,j} z_{1,j}^2 - (1 - f_j)k_{s,j} z_{1,j}^2$$

Groundwater

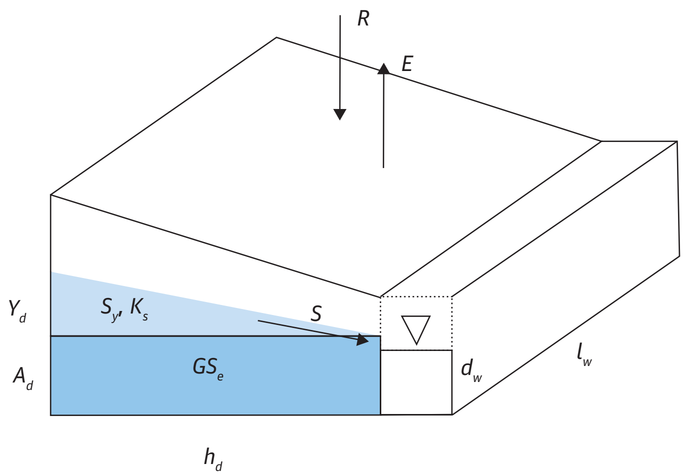
The WEAP model uses a simplified, physically based approach for simulating groundwater levels and lateral flows between the aquifer and the river. This is represented as a wedge that is symmetrical about the river, such that recharge or extraction from one side of the wedge represents half of the total rate (Figure 32).

Calibration to historical groundwater levels used a GIS assessment to set the length of the stream-aquifer interface (l_w) and set the specific yield (S_y) uniformly to 0.2, which is generally suitable to groundwater in the region. The wetted depth of the stream-aquifer (d_w), the horizontal distance from the stream to the centroid of the contributing area of the aquifer (h_d), and the hydraulic conductivity (K_s) were adjusted until groundwater storage levels were consistent with available data and local knowledge for the historical period of simulation.

Application for Rwanda

In line with previous analysis in Rwanda, this assessment used the WEAP platform to review the supply and demand of water in Rwanda to identify potential scarcity and conflict between different users. The WEAP software has been under development by Stockholm Environment Institute for nearly 20 years. The software provides a comprehensive suite of tools for simulating water resources systems including rainfall-runoff hydrology, water resources infrastructure, agricultural, urban, and environmental demands, and the ability to apply complex operating rules and constraints to the water allocation problem. The water allocation problem is solved using linear programming (LP) defined

FIGURE 32. WEAP's groundwater wedge model



by user-specified demand priorities and water supply preferences. The software is well-documented and has a well-developed training tutorial provided on the WEAP21 website. Comprehensive information on the software and download links are available at www.weap21.org. The data sources for this application are given in Annex A.

Rwanda's NDC has earmarked US$ 360 million to support Intervention 3 in the plan, which aims to develop and implement catchment management plan for all Level 1 catchments. GoR, through the Water for Growth Rwanda programme, has commenced the development of catchment plans, which requires an extensive modelling exercise. The WEAP framework has been used to develop catchment models for four selected demonstration catchments and subsequently used to develop a water balance and water allocation tool for the entire country. Hence this study has aligned it methodology and is using the WEAP framework, however while the previous WEAP models have been considered in this analysis due to inconsistent data sets much of the previous analysis has not been used in this report.

Water Demands

WEAP is a demand-driven model and, as such, provides a lot of flexibility in how data can be structured to characterize water use. This can range from highly disaggregated end-use oriented data structures to highly aggregate analyses. Typically, the data will be organized around water use sectors, including households, industry, and agriculture, each of which might be broken down into different subsectors, end-uses and water-using devices. You can adapt the structure of the data to your purposes, based on the availability of data, the types of analyses you want to conduct, and your unit preferences. WEAP also allows for the creation of different levels of disaggregation in each demand site and sector. All of the demand data sources are given in Annex B.

The Water Users and Uses Assessment in Rwanda (RWB, 2020) was used as the basis for estimating water demands in WEAP, because it provides the most recent comprehensive assessment of water use in Rwanda. These data are summarized at Level 1 in Table 6. The assessment includes a georeferenced database for water use within each demand sector that enables these data to be apportioned to each Level 2.5 catchment.

The WEAP model uses a hierarchical priority structure for allocating water among competing users. This system assigns an integer value between 1 and 99 to each consumptive (i.e. domestic, irrigation, livestock, and industry) and non-consumptive (i.e. storage and environmental flows) water demand to indicate its priority, with a value of one indicating highest priority and 99 indicating lowest priority. As described in further detail in Appendix B: WEAP, water can be released from any upstream location to satisfy a downstream demand. This situation, however, does not reflect the local nature of water management throughout Rwanda. In the upper parts of a watershed, local dams are used strictly for local purposes, not to store water to be released in the lower reaches of a watershed. As such, a tiered priority structure was implemented, with a tier for upstream and mainstem priorities within each catchment. This structure that takes into account that storage in tributaries can only be used locally and not called upon by water users downstream. Additionally, storage along mainstem river branches can only be called upon by downstream water users within the same level 1 catchment, but not from any other level 1 catchments downstream. To set this up, the priority structure shown below in Table 7 shows the relative priority of the water user types within a given tier. The relative priorities follow what one would expect, with first priority going to domestic demands, followed by environmental flows (level 2), followed by livestock (level 3), followed by fishponds and industry (level 5), then irrigation. The storage is assigned level 9.

TABLE 6. Summary of water use for each demand sector. at catchment level 1 in millions of cubic meters per year.

Catchment	Domestic Water Supply	Irrigation	Coffee Washing	Fishponds	Industrial/ Manufacturing	Mining	Sub-catchment Total
CKIV	18.23	16.05	0.28	0.08	0.12	0.47	**35.24**
CRUS	11.70	8.30	0.08	0.00	0.04	0.06	**20.17**
NAKL	8.01	59.92	0.05	0.03	0.01	0.66	**68.68**
NAKN	6.38	84.11	0.19	0.26	0.05	0.39	**91.39**
NAKU	18.74	62.97	0.07	0.15	0.38	0.00	**82.3**
NMUK	47.39	5.65	0.01	0.01	1.26	0.82	**55.14**
NMUV	9.15	55.46	0.01	0.16	0.34	0.31	**65.42**
NNYL	77.98	43.34	0.16	0.24	0.00	1.50	**123.22**
NNYU	37.27	27.60	0.03	0.14	1.01	1.02	**67.06**
Demand Sector Total	**234.85**	**363.4**	**0.88**	**1.06**	**3.21**	**5.22**	**608.62**
% of Total	**38.6**	**59.7**	**0.1**	**0.2**	**0.5**	**0.9**	

TABLE 7. Demand priority structure in WEAP

Water User	Priority	
	Upstream	Downstream
Domestic	1	11
Environmental flow	1	11
Livestock	2	12
Industry	3	13
Irrigation	3	13
Fishponds	3	13
Storage	10	20

Domestic

The main drivers for domestic water use are population and per capita water use. Additionally, per capita water use is generally higher in urban than in rural areas because the increased prevalence of piped water networks improves access to water while also increasing losses.

Population data were based on 2012 census and growth rates since then. Per capita water use was based on information in the National Water Resources Masterplan that estimated current rural and urban water use at 40 and 60 liters per capital per day, respectively. The masterplan also suggests that economic development and improvements in living conditions will lead to increases in water usage such that both urban and rural water users will consume about 100 liters per capital day by the year 2040.

For the purpose of this assessment, the proportional split between urban and rural population was considered within each Level 2.5 catchment. This was determined by overlaying data from the 2012 census at Level 1 catchments (Table 8) with a 2015 map of population density[1]. The Level 2.5 data are presented in Appendix C.

Land Cover and Cropped Agriculture

For each sub-catchment in Rwanda the WEAP model considers the total land cover in the hydrologic calculations (see more in the section on rainfall-runoff below), and the water consumption and production of cropped agriculture, both of which vary from year-to-year based on climate and agricultural practices. For this reason, the WEAP model uses a catchment object to represent crops, which requires climate inputs to estimate crop water requirements. Calculation of crop water requirements is based on the phenology of different crop types (i.e., development cycle and planting and harvesting dates) and their cropped areas.

Crop yields are calculated based on how much of the crop water requirement is satisfied. For each crop, WEAP considers the 'potential yield' as the maximum yield achievable with an optimal amount of water. Yields are reduced according to crop yield response factors when the actual evapotranspiration of the crop is less than the potential evapotranspiration.

TABLE 8. 2012 Census population data for 9 Level 1 catchments

Catchment	2012 Census	Percent Urban	Percent Rural
CKIV	1,415,418	7	93
CRUS	318,048	6	94
NNYU	1,425,492	10	90
NMUK	1,048,631	18	82
NNYL	2,181,940	38	62
NAKN	1,447,480	21	79
NAKU	1,318,379	27	73
NAKL	725,068	7	93
NMUV	725,068	12	88

TABLE 9. Irrigated cropped areas (ha)

	Small-Scale	Medium to Large-Scale	
	Vegetable/fruit mix	Rice	Vegetable
CKIV	39	863	939
CRUS	84	1,016	0
NAKL	956	1,274	961
NAKN	634	4,261	795
NAKU	1,424	2,079	2,585
NMUK	188	977	102
NMUV	699	1,199	131
NNYL	78	1,705	1,172
NNYU	179	2,522	1,115
Total	**4,988**	**15,896**	**7,801**

Irrigated

Cropped areas for irrigated agriculture were determined based on a data obtained from the Water Users and Uses Assessment report (RWB, 2020). This included georeferenced locations and estimates of irrigated area for large- and small-scale operations. For small-scale irrigation (under 10 ha), vegetables and fruits are the predominant crops, whereas medium (between 10-100 ha) to large-scale (over 100 ha) operations are divided between rice and vegetables according to year 2020 cropping reports from MINAGRI (Table 9).

Rainfed

The Rwanda Ministry of Agriculture publishes an annual report on cropped area and production within each of Rwanda's 30 districts. The data from the year 2021 report were used to establish a baseline for rainfed crops. The data include information on 22 different crop types. For consideration within the WEAP model, these were grouped into eight crops as follows (where underlined crops indicate the reference for the crop group):

- Cereals: Maize, Sorghum, Paddy Rice, Wheat, Other
- Tubers and Roots: Cassava, Sweet Potatoes, Irish Potatoes, Yams & Taro
- Bananas: Cooking Banana, Dessert Banana, Banana for Beer
- Legumes and Pulses: Bush Bean, Small Red Bean, Climbing Bean, Peas, Ground Nuts, Soya Beans
- Vegetables

- Fruits
- Fodder Crops
- Other Crops

These cropped areas are summarized at Level 1 in Table 10.

The table below (Table 11) compares reported crop yield in Rwanda from MINAGRI (2021) and FAO STAT (2000-2019) to WEAP's internal calculations of potential yield. In general, the yields are close to potential - even above potential for tubers and roots, bananas and vegetables - with the exception of cereals (67 percent) and legumes and pulses (65 percent).

Livestock

The main drivers for livestock water use are the number of livestock units and their daily water usage, where one livestock unit is equivalent to one cow, which consumes about 50 liters of water per day (MINAGRI, 2018). Data for other animals are converted into livestock units using conversion factors obtained from the Ministry of Agriculture (MINAGRI)[2].

Livestock population data for the 30 districts in Rwanda were obtained from MINAGRI for the year 2018. These data were assigned to the Level 2.5 catchments by overlaying the catchment and district boundaries and assuming uniform distribution of livestock across districts. These data are presented in greater detail in Appendix B: WEAP

TABLE 10. Rainfed cropped area (x1000 ha)

	CVIK	CRUS	NAKL	NAKN	NAKU	NMUK	NMUV	NNYL	NNYU	Total
Bananas	19.64	3.31	22.72	48.92	28.43	24.51	26.81	37.15	38.11	249.61
Cereals	31.45	11.28	14.48	49.29	34.39	17.10	7.40	34.51	33.12	233.02
Fodder	1.28	0.36	0.75	1.01	0.63	1.08	0.88	1.58	0.65	8.22
Fruit	0.65	0.36	1.10	1.76	1.59	0.49	0.38	2.32	1.62	10.27
Legumes Pulses	44.30	9.98	27.43	69.14	52.81	39.42	25.68	56.46	66.28	391.50
Tubers & Roots	24.13	8.44	29.60	63.73	47.26	30.33	36.10	60.43	47.83	347.86
Vegetables	1.37	0.90	0.97	3.44	1.86	2.40	3.73	4.81	1.95	21.43
Other	2.10	2.54	3.36	133.13	78.24	6.24	5.02	35.45	53.12	319.18
Total	**124.9**	**37.16**	**100.4**	**370.4**	**245.2**	**121.6**	**106.0**	**232.7**	**242.7**	**1,582**

TABLE 11. Rainfed crop yields (kg/ha)

Crop	MINAGRI 2021 Average Yield (Kg/ha)	FAOSTAT 2000-2019 Maximum Yield (Kg/ha)	WEAP Potential Yield
Cereals	1,683	2,501	2,500
Tubers & Roots	14,220	13,544	13,500
Bananas	10,926	9,606	9,600
Legume & Pulses	665	1,026	1,000
Vegetables	7,912	7,375	7,350
Fruit	5,495	7,377	7,350
Fodder	14,226	Not reported	15,000
Other Crops	8,700	Not reported	9,000

Fishponds

Fishponds and local aquaculture stations have been incorporated into the model using data from the National Water Resources Masterplan, MINAGRI, RWB, and the Rwanda Agriculture and Animal Resources Development Board (RAB). Fishponds are a key component of the local economy in Rwanda, particularly in wetland areas with low rates of water flow. Primary concerns for fish farming include water quality deterioration due to seepage and percolation problems, though in practice wastewater treatment has prevented these from impacting overall water quality for each catchment. Surface area for each level 2.5 sub catchment was estimated by overlaying the map of individual fishponds with the level 2.5 map, then aggregating surface area within each sub catchment. Water use was then calculated in WEAP as the volume needed to maintain ponds at a depth of 1 meter to offset water losses to evaporation and percolation. In addition, consumption was validated using data from the National Water Resources Masterplan regionally, where estimates of current use ranging between 0.03 and 3.76 MCM per year.

Industry

The primary uses of water in Rwanda for industrial purposes are coffee washing, mining, and regionally specific commercial activities such as textiles, agro-processing, and manufacturing. Assumptions related to each sector-specific water use were developed based on information in the National Water Resources Masterplan, which provides regional estimates for per unit water use in each sector.

Coffee Washing

Water used for coffee washing is reported by MINAGRI as predominantly non-consumptive: most of the water required is treated and returned to the water source after use. As such, the Masterplan considers coffee washing a relatively small contributor to the water balance for Rwanda. Still, given its relevance for the Rwandan economy and non-consumptive water use, spatial and water demand data from the National Agricultural Export Development Board of Rwanda (NAEB) and RWB were included in the model. Water use for each level 2.5 sub catchment was calculated by overlaying the map of individual coffee washing stations with the level 2.5 map, then aggregating water use data for each sub catchment. In addition, consumption was estimated by the National Water Resources Masterplan regionally for current values, with estimates of current water use ranging between 0.001 and 5.1 MCM per year, depending on the catchment.

Mining

Mining is a more consumptive use than coffee-washing, yet still not a major use. Mining activity, which includes cassiterite, coltan, wolfram, gold, nickel, and precious stones, poses important problems for local environments, namely sedimentation/erosion and pollution with toxic substances (such as mercury, lead, zinc, and arsenic). Nevertheless, the Masterplan emphasizes the impact on water use by mining, rather than its pollution-related concerns; consequently, the analysis focuses on determining spatial and water use data for each level 2.5 sub-catchment. Spatial and water use data for mining sites in Rwanda were provided by the Rwanda Mines, Petroleum and Gas Board (RMB) and the RWB. Water use for each level 2.5 sub catchment was again calculated by overlaying the map of individual mining sites with the level 2.5 map, then aggregating water use data for each sub catchment. In addition, the National Water Resources Masterplan estimates consumptive water use for mining at 1 liter per production unit per day for 2012, with projected growth between 4 and 10 liters per production unit per day by 2040.

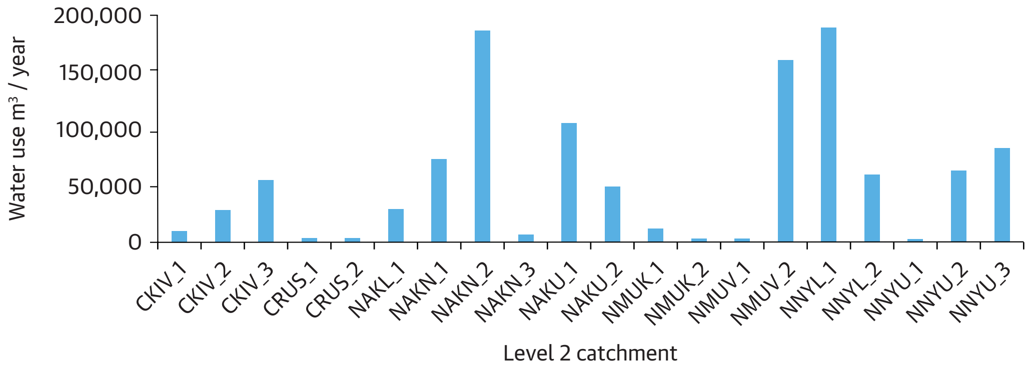
Other industrial water use

According to the Water Users and Uses Assessment in Rwanda report of 2020, industrial water use is quite low, representing 0.53 percent of total water use, or 3.2 MCM per year. This includes industries such as agro-processing, manufacturing, tourism, and knowledge-based services and ICT. The distribution of water use across the Level 2 catchments is shown in Figure 33 below. These data were disaggregated to level 2.5 sub catchments based on population density.

Environmental flows

The in-stream flow requirements are set to a fixed 30 percent of the unimpaired flow, consistent with the basic premise of the percent of flow approach established in Flannery, et al., 2002.[3] The unimpaired flow was calculated under each

FIGURE 33. Industrial water use per year across the Level 2 catchments in Rwanda, taken from the Water Users and Uses Assessment in Rwanda report of 2020



Source as indicated: Water Users and Uses Assessment in Rwanda report (2020)

climate scenario, representing the hydrology without human demands or water storage, and then imposed as an environmental flow requirement in WEAP.

Water Supplies

WEAP uses a climate-driven approach for estimating water supply that relies on hydrological routines to estimate rainfall-runoff, evapotranspiration, soil water storage, and groundwater recharge. This approach integrates hydrology into water allocation such that the implications of climate change or variability can be easily considered as part of the water systems analysis.

Climate

The WEAP models was developed and calibrated using a reconstruction of the historical climate data, 1948-2008, developed by the Terrestrial Hydrology Research Group at Princeton University (Sheffield et al., 2006). These data include climate sequences of monthly temperature and precipitation, spatially averaged for each hydrologically connected catchment.

These data also served as a baseline climate for the scenario analysis, in which they are referred to as the *Historical* climate condition. The model also includes three sets of climate projections that are used to represent plausible future climate conditions. The first set included 56 Bias Corrected Spatial Disaggregation (BCSD) downscaled GCM simulations from the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project - Phase 3 (Coupled Model Intercomparison Project, (CMIP)3, (Meehl et al., 2007))—*Projected CMIP$_3$, BCSD*. The second set includes 43 sequences derived from BCSD GCM simulations from the CMIP5 archive. The third set includes 22 CMIP5 simulations downscaled using the University of Cape Town Climate Systems Analysis Group (CSAG) methodology (Hewitson & Crane, 2006)—*Projected CMIP5, UCT-CSAG*.

Broadly speaking, the Intergovernmental Panel on Climate Change (IPCC) created a standard set of scenarios that allowed for comparisons across researchers. The first set of scenarios were the Special Report on Emissions Scenarios (SRES). Those have been updated to the Representative Concentration Pathways (RCPs). The rationale for the change is RCPs provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. Both SRES and RCPs are included in the analysis. In total, 122 simulations were used, 1 historical and 121 climate projections. These data are organized as numbered subdirectories that accompany the data files for each WEAP model. These climate scenarios are summarized below, with the subdirectory numbers in parentheses:

1. Historical
2. Projected CMIP3, BCSD (22 SRES a1b; 17 SRES a2; and 17 SRES b1)
3. Projected CMIP5, BCSD (23 RCP 4.5 and 20 RCP 8.5)
4. Projected CMIP5, UCT-CSAG (11 RCP 4.5 and 11 RCP 8.5)

Rainfall-runoff

For the Rwanda national model, WEAP sub-catchments were created for each of the 88 Level 2.5 catchments. These were subdivided into a unique set of independent land use/land cover classes based on land cover maps (Rwanda Natural Resources Authority, 2018).

The land cover map indicates that agriculture is the predominant land cover, account for approximately 63 percent of the surface area in Rwanda (see Figure 34 below). This suggests that agriculture largely controls the hydrological response within most catchments. As such, the calibration of the hydrological model focused mainly on adjusting parameters related to agriculture. Details of the calibration are presented in Appendix C.

Groundwater

Groundwater is an important water source and contributor to streamflow. The national WEAP model includes groundwater nodes that represent shallow, unconfined aquifers that are physically linked to catchments, which act as a source of percolation to the water table, and to rivers, which can either be a source of groundwater recharge in the case of a losing river reach or be a sink for groundwater outflow when groundwater levels exceed the height of the river reach's height above riverbed. Groundwater nodes are linked by way of transmission links to water demands to represent groundwater pumping.

Groundwater storage capacities were estimated using a simplified approach that considered the surface area of the overlying catchment, the usable depth of groundwater, the specific yield of the aquifer, and an area correction factor that acknowledges that boundary of the overlying catchment may not be consistent with the aquifer boundaries. The area correction factors were adjusted such that the total storage volumes matched groundwater storage estimates from the Masterplan. These aggregate values are presented in Table 12, adding up to almost 70 billion cubic meters. These values were fractionally divided among the Level 2.5 sub-catchments based on their surface area.

Only limited data exist to adequately calibrate groundwater levels. As such, we calibrated the model such that storage levels reflect the general understanding of groundwater trends over the historical period.

With existing demands and supplies, taking the country as a whole, there is sufficient supply to meet demands. The limitation is not water availability, but water infrastructure for storage, pumping, treatment, and transport, and supporting policies.

FIGURE 34. Land cover within each Level 1 catchment (Km² and % of total)

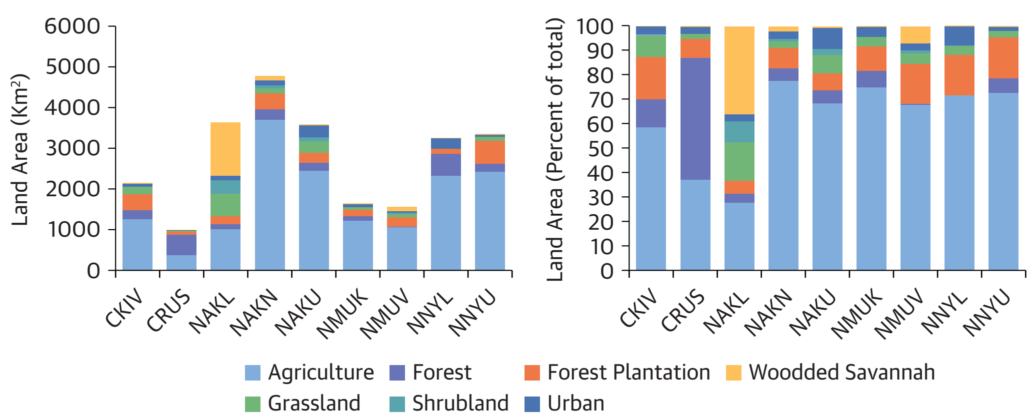


TABLE 12. Groundwater storage capacity for Level 1 catchments

Catchment	Groundwater Storage (Million m^3)
CKIV	5,806
CRUS	4,999
NAKL	4,822
NAKN	7,056
NAKU	6,593
NMUV	1,564
NMUK	4,872
NNYL	8,672
NNYU	25,111
TOTAL	**69,495**

Notes

1. Linard, C., Gilbert, M., Snow, R.W., Noor, A.M. and Tatem, A.J., 2012, Population distribution, settlement patterns and accessibility across Africa in 2010, PLoS ONE, 7(2): e31743. Downloaded from https://energydata.info/dataset/rwanda-population-density-2015/resource/803e037b-9652-4af9-86d7-855b9da0a33e
2. 7 goats per livestock unit, 7 sheep per livestock unit, 2 pigs per livestock unit, 70 chicken per livestock unit, and 70 rabbits per livestock unit.
3. Flannery, Michael S., Ernst B. Peebles, and Ralph T. Montgomery. "A percent-of-flow approach for managing reductions of freshwater inflows from unimpounded rivers to southwest Florida estuaries." *Estuaries* 25, no. 6 (2002): 1318-1332..https://www.jstor.org/stable/1352860

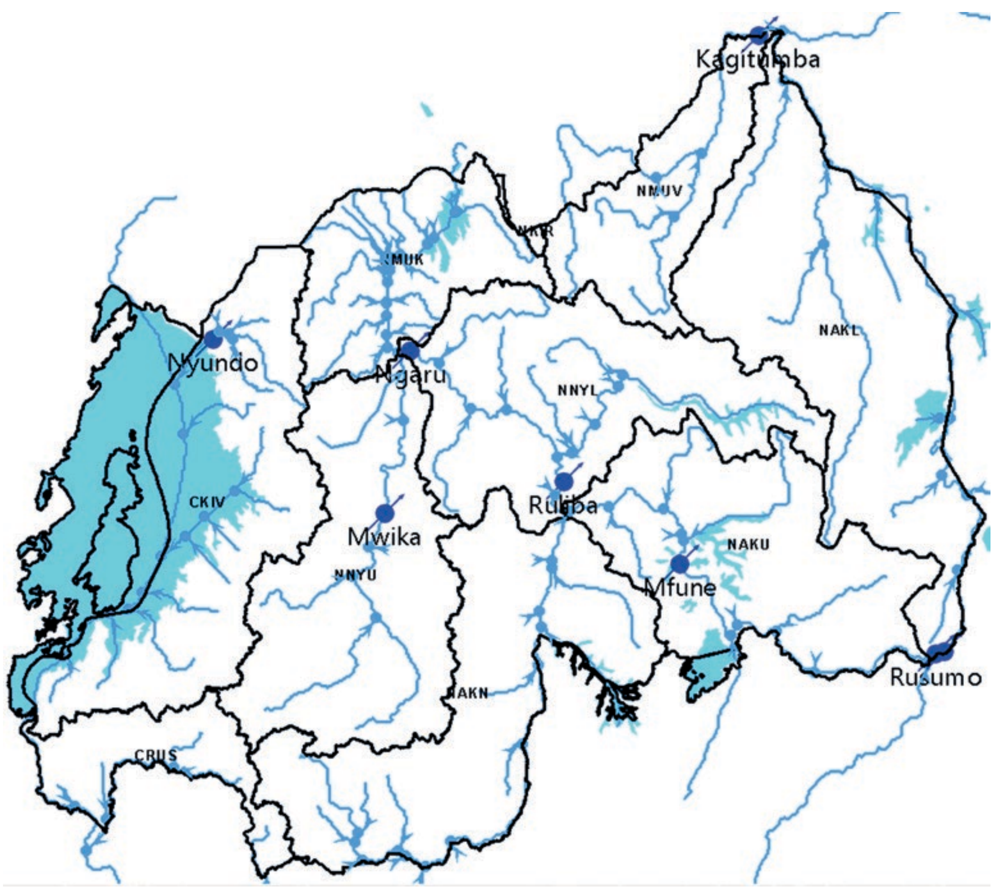
Appendix C
WEAP Calibration

Before using the model to evaluate the performance of water supply reliability Rwanda, it was necessary to first calibrate and validate the hydrological routines to ensure that it can adequately estimate flows in Rwanda's rivers.

The first step in calibrating any model is to select a historical period of record that includes concurrent input and observation data that cover a period long enough to capture the range of conditions (wet and dry) within a basin. In this case, the main input data for the WEAP model include climate data and the observation data are gaged streamflow. We selected the forty-year period from 1961 to 2000, during which there were multiple stream gauges containing several years of flow data. These included the following locations:

- Nyabarongo River at Mwika
- Nyabarongo River at Ngaru
- Nyabarongo River at Ruliba
- Nyabarongo River at Mfune
- Akagera River at Rusumo Falls
- Muvumbu River at Kagitumba
- Sebeya River at Nyundo

FIGURE 35. Stream gauge locations



The WEAP model was calibrated to historical streamflows at each of these locations using a combination of manual methods and computer algorithms, such as the PEST software (Doherty, 2002). Five land use parameters were adjusted to achieve calibration to streamflow at various locations. The parameters are the evapotranspiration coefficient (Kc), soil water capacity (SWC), runoff resistance factor (RRF), root zone conductivity (RZC), and the preferred flow direction (PFD). Model simulations are most sensitive to SWC, RZC, and RRF. Thus, initial calibration focused on these three parameters. Further refinement to the shape and timing of the resulting hydrographs was accomplished by adjusting Kc and PFD.

FIGURE 36. Observed and Simulated Discharge – Nyabarongo River at Mwika

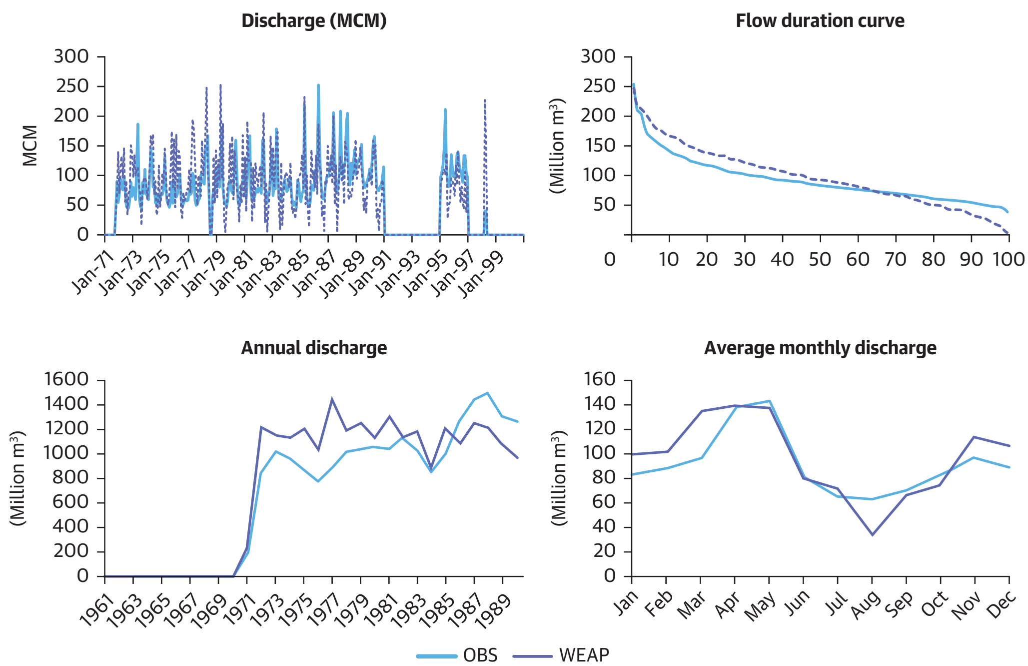


FIGURE 37. Observed and Simulated Discharge – Nyabarongo River at Ngaru

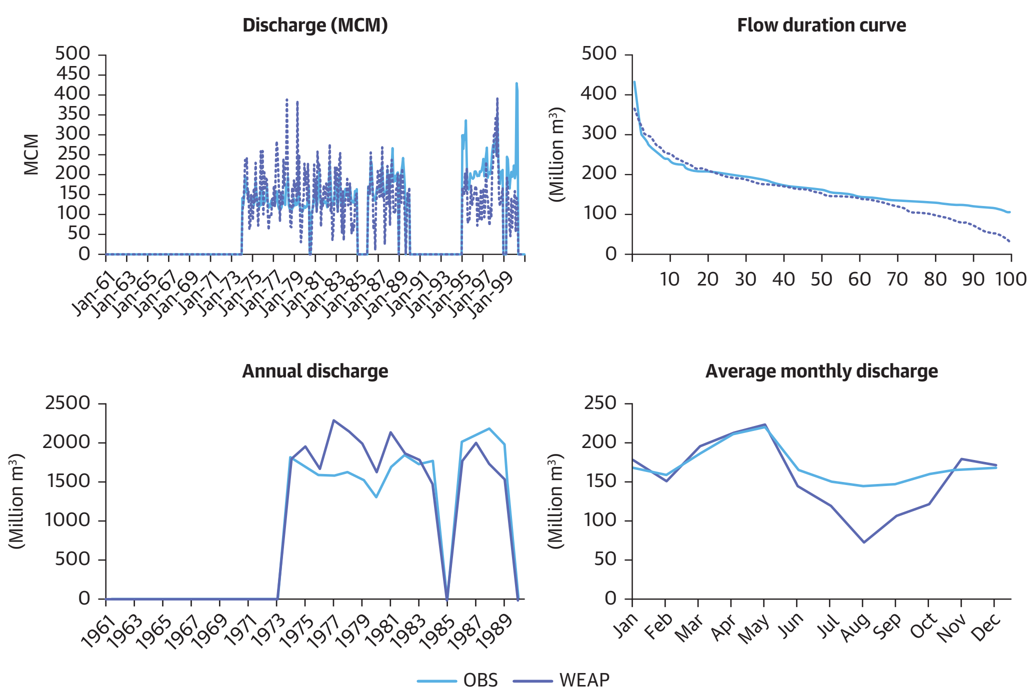


FIGURE 38. Observed and Simulated Discharge – Nyabarongo River at Ruliba

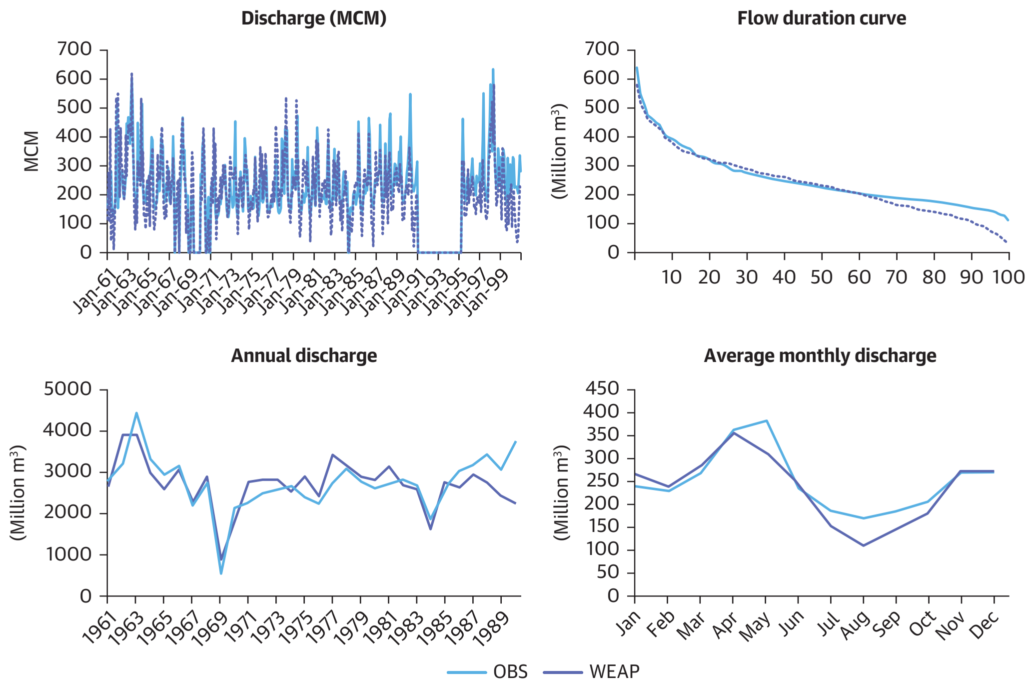


FIGURE 39. Observed and Simulated Discharge – Nyabarongo River at Mfune

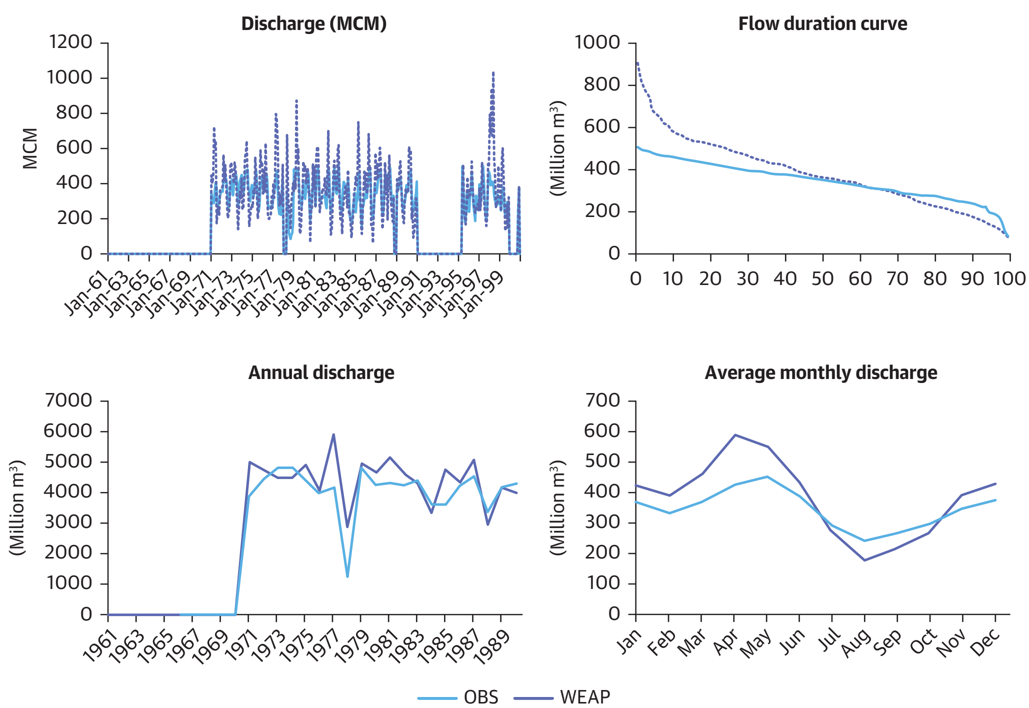


FIGURE 40. Observed and Simulated Discharge – Akagera River at Rusumo Falls

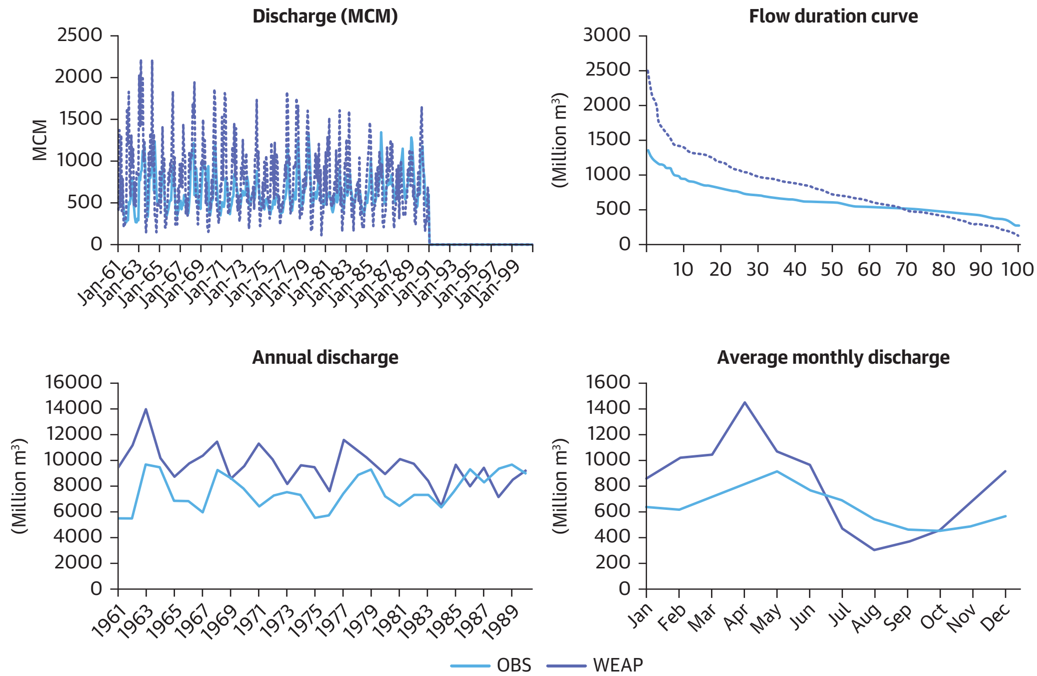


FIGURE 41. Observed and Simulated Discharge – Muvumubu River at Kagitumba

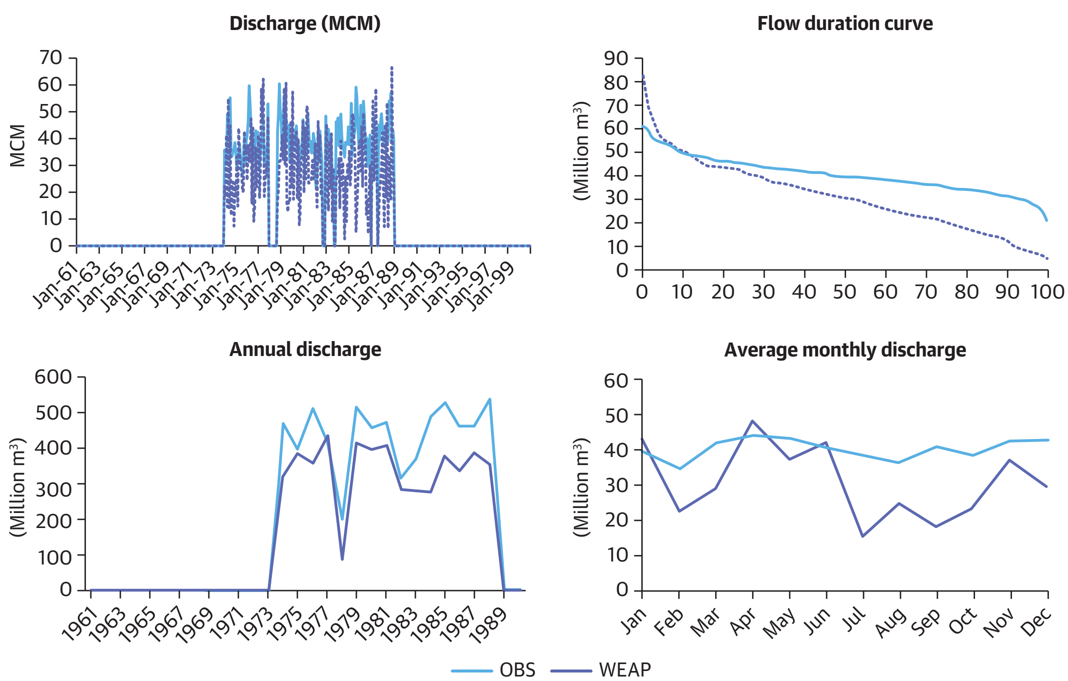
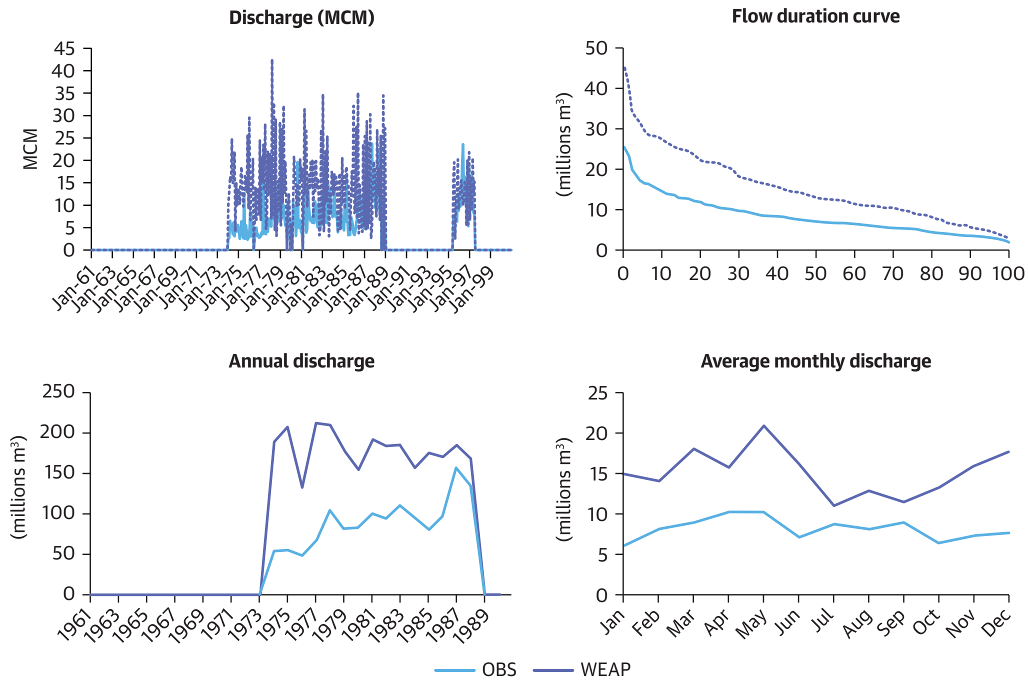


FIGURE 42. Observed and Simulated Discharge – Sebeya River at Nyundo



Appendix D
Algorithms for the Economic Model

This appendix summarizes key algorithms used in the economic modelling exercise in mathematical form.

The input-output system

The basic set of equations for the production system says that total domestic supply from sector i, Y_i, is equal to the sum of intermediate demand Z_{ij} for good i from all other sectors j; final household, government, and investment demand F_i; and export demand, X_i, net of imports M_i, and margins marg_i. For n sectors,

$$Y_i = \sum_{j=1}^{n} Z_{ij} + F_i + X_i - M_i - \text{marg}_i .$$

The model makes the common assumption from input-output analysis that intermediate demand can be expressed as the product of a technical coefficient a_{ij} and output Y_j,

$$Z_{ij} = a_{ij} Y_j .$$

Unconstrained production

Given values for F_i, X_i, and M_i, substituting this equation into Equation gives a matrix equation that can be solved for production through the Leontief inverse, without taking constraints into account. For this purpose, it is convenient to use matrix notation. For example,

$$\mathbf{A} = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}.$$

Furthermore, margins are expressed as a matrix multiplying the sum of domestic supply and imports through a matrix $\boldsymbol{\mu}$,

$$\text{marg}_i = \sum_{j=1}^{n} \mu_{ij} \left(Y_j + M_j \right).$$

Then combining Equations, and give

$$\mathbf{Y} = \mathbf{A} \cdot \mathbf{Y} + \mathbf{F} + \mathbf{X} - \mathbf{M} - \boldsymbol{\mu} \cdot \left(\mathbf{Y} + \mathbf{M} \right).$$

The combination of imports and the margin matrix applied to imports is denoted $\mathbf{N}$,

$$\mathbf{N} \equiv \left(\mathbb{I} + \boldsymbol{\mu} \right) \cdot \mathbf{M}.$$

where a double-stroke I represents the identity matrix, with ones along the diagonal.

The solution to equation is

$$\mathbf{Y} = \left(\mathbb{I} + \boldsymbol{\mu} - \mathbf{A} \right)^{-1} \cdot \left(\mathbf{F} + \mathbf{X} - \mathbf{N} \right),$$

This is the standard Leontief analysis (aside from the introduction of margins), but the analysis for this project allows some production to be set exogenously. In particular, WEAP provides production indices for agriculture. Each matrix and vector can then be split into sectors where production is "fixed" exogenously, with subscript F, and where production is "variable"; that is, determined by the input-output system in Equation, with subscript V. For example,

$$\mathbf{A} = \begin{pmatrix} \mathbf{A}_{FF} & \mathbf{A}_{FV} \\ \mathbf{A}_{VF} & \mathbf{A}_{VV} \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} \mathbf{F}_F \\ \mathbf{F}_V \end{pmatrix}.$$

The output of WEAP is production that has taken water constraints into account. What is needed for unconstrained production is *potential* fixed production $\mathbf{Y}_{F0}$. That is not calculated in WEAP. For example, for agriculture, land may be gradually brought into or out of production, so the potential can vary over time. The analysis assumes that potential production follows an adaptive scheme, with time constant τ_{pot}, in which:

$$Y_{F0,i}(t) = \max\left[Y_{F,i}(t), Y_{F0,i}(t-1) + \frac{1}{\tau_{\text{pot}}}\left(Y_{F,i}(t) - Y_{F0,i}(t-1)\right)\right].$$

To solve for unconstrained production, Equation can be written as two matrix equations,

$$\left(\mathbf{I}_{FF} + \boldsymbol{\mu}_{FF}\right)\cdot \mathbf{Y}_{F0} = \mathbf{A}_{FF}\cdot \mathbf{Y}_{F0} + \left(\mathbf{A}_{FV} - \boldsymbol{\mu}_{FV}\right)\cdot \mathbf{Y}_{V0} + \mathbf{F}_F + \mathbf{X}_F - \mathbf{N}_F,$$
$$\left(\mathbf{I}_{VV} + \boldsymbol{\mu}_{VV}\right)\cdot \mathbf{Y}_{V0} = \mathbf{A}_{VV}\cdot \mathbf{Y}_{V0} + \left(\mathbf{A}_{VF} - \boldsymbol{\mu}_{VF}\right)\cdot \mathbf{Y}_{F0} + \mathbf{F}_V + \mathbf{X}_V - \mathbf{N}_V.$$

For the second of these equations, the model takes as an input an import share (corrected for margins) of total domestic demand for goods from sector *i*, m_i, so that

$$N_{V,i} = n_i\left[\sum_{j=1}^{n} a_{VV,ij}Y_{Vj} + \sum_{j=1}^{n} a_{VF,ij}Y_{Fj} + F_{V,i}\right].$$

Using a tilde over a vector to denote a diagonal matrix with the vector as entries along the diagonal, this can be written in matrix form as

$$\mathbf{M}_V = \tilde{\mathbf{n}}\cdot\left(\mathbf{A}_{VV}\cdot \mathbf{Y}_V + \mathbf{A}_{VF}\cdot \mathbf{Y}_F + \mathbf{F}_{V0}\right).$$

Substituting into Equation gives the system

$$\left(\mathbb{I}_{FF} + \boldsymbol{\mu}_{FF}\right)\cdot \mathbf{Y}_{F0} = \mathbf{A}_{FF}\cdot \mathbf{Y}_{F0} + \left(\mathbf{A}_{FV} - \boldsymbol{\mu}_{FV}\right)\cdot \mathbf{Y}_{V0} + \mathbf{F}_F + \mathbf{X}_F - \mathbf{N}_F,$$
$$\left(\mathbb{I}_{VV} + \boldsymbol{\mu}_{VV}\right)\cdot \mathbf{Y}_{V0} = \left(\mathbb{I} - \tilde{\mathbf{n}}\cdot\right)\cdot\left(\mathbf{A}_{VV}\cdot \mathbf{Y}_{V0} + \mathbf{A}_{VF}\cdot \mathbf{Y}_{F0} + \mathbf{F}_V\right) - \boldsymbol{\mu}_{VF}\cdot \mathbf{Y}_{F0} + \mathbf{X}_V.$$

This can be solved in a two-step process. First, solve for $\mathbf{Y}_V$,

$$\mathbf{Y}_{V0} = \left[\mathbb{I} + \boldsymbol{\mu}_{VV} - \left(\mathbb{I} - \tilde{\mathbf{n}}\right)\cdot \mathbf{A}_{VV}\right]^{-1}\cdot\left[\left(\mathbb{I} - \tilde{\mathbf{n}}\right)\cdot\left(\mathbf{A}_{VF}\cdot \mathbf{Y}_{F0} + \mathbf{F}_V\right) - \boldsymbol{\mu}_{VF}\cdot \mathbf{Y}_{F0} + \mathbf{X}_V\right].$$

Then, substitute into the first of the equations, which implicitly determines $\mathbf{N}_F$. Solving the system therefore requires:

- The matrix of technical coefficients $\mathbf{A}$;
- Fixed production $\mathbf{Y}_F$ (which is converted into the potential level of fixed production $\mathbf{Y}_{F0}$ using Equation);
- Final demand $\mathbf{F}$;
- Exports $\mathbf{X}$;
- Import coefficients $\mathbf{m}$ for the variable sectors.

The result of solving the system is the level of unconstrained production

$$\mathbf{Y}_0 = \begin{pmatrix} \mathbf{Y}_{F0} \\ \mathbf{Y}_{V0} \end{pmatrix}.$$

Constrained production

When water constraints are present, production might be below the unconstrained level. The relevant system is again given by Equation, but for convenience the sum of final domestic demand and net exports will be denoted by $\mathbf{G}$,

$$G_i = F_i + X_i - M_i.$$

The notation is chosen because GDP in nominal terms G_{nom} – that is, not corrected for inflation - is given by the sum of the G_i multiplied by a price level for the sector,

$$G_{\text{nom}} = \sum_i p_i G_i.$$

Constraints on production lead to a (negative) deviation ΔY_i away from the fixed production level for at least some sectors, so that

$$Y_i = Y_{0,i} - \Delta Y_i.$$

When WEAP indicates either a coverage constraint or limited exogenously specified production, it determines a minimum gap. For coverage c_i, the following expression is used,

$$\Delta Y_i \geq \left(1 - c_i^{s_i}\right) Y_i,$$

where s_i is the "input sensitivity" for sector i. If the sector is entirely dependent on its inputs, including water, then s_i = 1; in that case, capacity utilization is equal to coverage. If it entirely insensitive, then s_i = 0; in that case, water supply constraints have no impact on output from the sector. For exogenously specified (fixed) output, the deviation satisfies

$$\Delta Y_i \geq Y_{F0,i} - Y_{F,i}.$$

Note that, from this equation, the calculated output might be below that produced by WEAP. That degree of flexibility helps to ensure a solution exists for production in all sectors. Together, these expressions can be written

$$\Delta Y_i \geq \Delta Y_i^{\min}.$$

The basic macroeconomic balance implies that the deviation must satisfy

$$\Delta Y_i = \sum_j \Delta Z_{ij} + \Delta G_i.$$

Moreover, holding technical coefficients fixed, the change in intermediate demand is equal to

$$\Delta Z_{ij} = a_{ij} \Delta Y_j.$$

However, some sectors may be supply-constrained. In that case, a Ghosh-type supply-driven analysis (Ghosh, 1958), rather than the Leontief-type demand-driven analysis is called for.[1] The relevant technical coefficient is the Ghosh coefficient

$$b_{ij} = \frac{1}{Y_{0,i}} a_{ij} Y_{0,j}.$$

The Ghosh coefficient says how an input (multiplied on the left) translates to an output. It is relevant when production is input limited. However, that limitation is rarely absolute. The model allows for some short-term substitution by incorporating the "input sensitivity" s_j for sector j that was introduced above, and adding a "degree of domestic dependence" d_i is for product i. If the input can be readily imported, then d_i can be set to zero, but if imports are constrained, d_i might be closer to one. If the input is not critical to production, then s_j might be close to zero, whereas if it is essential, then s_j might be closer to one. For example, construction is often entirely dependent on domestic supply and strongly constrained if inputs are not available, whereas manufactures can be imported and might have some potential for substitution. With these, definitions, the gap in intermediate use must pass a threshold value,

$$\Delta Z_{ij} \geq d_i s_j \Delta Y_i b_{ij}.$$

The model minimizes the negative deviation of nominal GDP, given these constraints. That gives the system

$$\min \sum_i p_i \left(\Delta Y_i - \sum_j a_{ij} \Delta Y_j \right) \quad \text{w.r.t.} \quad \Delta Y_i,$$

subject to

$$\Delta Y_i \geq \Delta Y_i^{\min},$$
$$a_{ij} \Delta Y_j \geq d_i s_j \Delta Y_i b_{ij}.$$

The solution to this equation is the deviation from unconstrained output, which then gives the deviation from potential GDP.

This algorithm has introduced the following additional parameters:

- The vector of price indices $\mathbf{p}$;
- Constrained production levels based on WEAP coverage $\mathbf{c}$ or physical output $\mathbf{Y}_F$ (for agriculture and hydropower[2]);
- Degree of domestic dependence $\mathbf{d}$;
- Inputs sensitivity $\mathbf{s}$.

Price index

Price indices per sector are an exogenous input into the model. For the price index in sector i, p_i, an inflation rate π_i is calculated as

$$\pi_i(t) = \frac{p_i(t)}{p_i(t-1)} - 1.$$

Then, an average inflation rate is constructed by weighting the inflation rates by sectoral value of output,

$$\bar{\pi}(t) = \frac{\sum_{i=1}^{n} p_i(t-1)Y_i(t-1)\pi_i(t)}{\sum_{j=1}^{n} p_i(t-1)Y_i(t-1)}.$$

Finally, a general price index $P(T)$ for time T is calculated as

$$P(T) = \prod_{t=1}^{T}\left(1+\bar{\pi}(t)\right).$$

Urbanization

While not strictly within the economic model, there is a need to downscale national-level assumptions for population growth and urbanization to the catchment level. The strategy is as follows.

The urbanization rate for catchment c is denoted u_c, while the percent rural population is $r_c = 1 - u_c$. Urbanization rates are updated each time step using the following expression:

$$u_c(t) = u_c(t-1) + \frac{1}{\tau_{\text{urb}}} u_c(t-1) r_c(t-1),$$

so that

$$r_c(t) = r_c(t-1) - \frac{1}{\tau_{\text{urb}}} r_c(t-1) u_c(t-1).$$

The time constant τ_{urb} is set to 10 years in the Baseline scenario. This formula has the following features:

- Urbanization always increases or stays the same;
- Catchments that are 100 percent rural in the current accounts remain that way throughout the simulation, because $u_c = 0$ in the current accounts;
- As catchments become more urbanized, from a low level, their pace of urbanization increases;
- However, because urbanization must saturate at 100 percent, the pace of urbanization slows as the urbanization rate approaches 100 percent.

A second assumption is that urban and rural population growth rates in each catchment are equal to the national growth rates, γ_u and γ_r. However, the distribution of that change between overall population growth and shifting from rural to urban differs between catchments. To derive the expression and demonstrate how it works, it is helpful to use a more compact notation in which a "prime" indicates an updated variable, e.g.

$$u_c' = u_c(t), \quad \text{while} \quad u_c = u_c(t-1).$$

The requirement for uniform urban and rural population growth rates can then be written

$$u_c' P_c' = (1+\gamma_u) u_c P_c,$$
$$r_c' P_c' = (1+\gamma_r) r_c P_c.$$

Because urban and rural shares sum to one, adding these together gives

$$P_c' = \left[(1+\gamma_u) u_c + (1+\gamma_r) r_c\right] P_c,$$

but

$$\frac{P_c'}{P_c} - 1 = \gamma_c,$$

the population growth rate of the catchment. From Equation , this can be seen to equal

$$\gamma_c = u_c \gamma_u + r_c \gamma_r.$$

That is, the catchment population growth rate is simply the sum of the national urban and rural population growth rates, weighted by the previous-period urban and rural population shares.

Economic Anlaysis Calibration

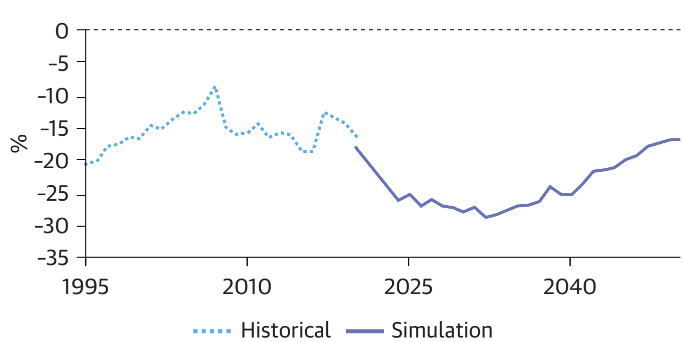
Further to what is set out in Section 2.2.3, the following was considered during the economic calibration process. A potential constraint on growth is the availability of foreign exchange. The analysis reported in this document does not take into account deviations in prices, aside from an exogenous sector-specific inflation rate (see Table 2). In particular, it does not attempt to capture changes in the exchange rate. That assumption is most plausible if the trade deficit does not depart substantially from current levels. For the calibration, export growth rates were set to the minimum of the initial growth rate and a common long-run rate. The near-term trends, which are based on Rwandan statistics, suggest an increasing trade deficit. The long-run rate was then adjusted to ensure that over the longer run, the trade deficit as a share of GDP begins to fall. This trend is illustrated in Figure 43.

The sector-specific "domestic dependence" parameters in Table 3 were set equal to the ratio of domestic production to domestic production plus imports as calculated from the SAM. The "input sensitivity" parameters were adjusted so that the variability in GDP growth attributable to fluctuations in water availability, as measured by the standard deviation of the annual growth rate across scenario years, closely matched the residual variability in historical GDP growth that could not be explained by the annual growth rate of final consumption demand.

For the input sensitivity calibration, NISR data were used to calculate residual variability as the standard deviation of the residuals of a linear regression of annual GDP growth rate against annual growth in final demand, both the in same year and lagged by one year. The regression was carried out on data from 2004-2019, excluding recession years. The standard deviation was found to be 1.5 percent per year.

A further source of data is the World Bank Enterprise Survey database[3]. The surveys ask, "If there were [electricity] outages, [what are the] average losses due to electrical outages (% of annual sales)?" They also ask for the average number and duration of outages per month. Multiplying the number of outages/month

FIGURE 43. External balance of goods and services as a share of GDP, historical (from World Bank WDI), and for the Baseline scenario with historical climate



by the duration of outages in hours gives an estimate of the total time without electricity per month. These data can then answer how loss of electricity supply translates into reduction of sales. An electricity input sensitivity measure can then be calculated as the percent reduction in sales divided by the total time without electricity. In the 2019 survey for Rwanda, the estimated electricity input sensitivity for services was around half that for manufacturing.

Input sensitivity parameters were calibrated against a model run with baseline scenario conditions and historical climate. Following from the Enterprise Survey results, input sensitivity in service sectors was set to one-half that in all other sectors. Both were then scaled so that the standard deviation of GDP was 1.5 percent per year. The resulting scaling factor was found to be 0.35.

Notes

1. This analysis does not make use of the Ghosh model itself, in which value added drives activity through Ghosh coefficients. That model has been criticized for lacking a clear interpretation of its outputs due to the inevitable mixing of price and quantity variables (de Mesnard, 2009). However, in the model presented in this paper only the coefficients are used, and in a quantity-based calculation.

2. Hydropower is not currently implemented because the electricity generation mix is not yet implemented.

3. https://www.enterprisesurveys.org/en/enterprisesurveys

Appendix E
Description of Scenarios and Assumptions

Population growth rates and domestic demands

Current population growth rates are on the order of 2.6 percent per year. For the Baseline scenario, this rate gradually declines in line with UN World Population Prospects mid-range project, to 2.15 percent/year starting in 2025, 1.98 percent/year in 2030, 1.83 percent /year in 2035, and 1.52 percent/year in 2045. For Vision 2050, following Indicator #2 in the Vision 2050 Indicators Table, the rate drops to 1.7 percent/year in 2035 and 1.4 percent/year by 2050. Starting from a 2020 population of 13 million, each trajectory translates into a population of 22 million by 2050.

At present, Rwanda's population is approximately 20 percent urbanized, with 80 percent in rural areas. The Baseline scenario assumptions are based on the UN Urbanization Prospects but shifted upward to match the base-year value from Rwandan national statistics. Under that scenario, the urbanization rate is 31 percent in 2050 (see Table 13). Under the Vision 2050 scenario, Indicator #29 is adopted, which essentially flips the current percentages by 2050, to 70 percent urban and 30 rural.

As described in Table 10 above, the Water Resilient Vision 2050 scenario assumes a rate between the other two scenarios, at 50 percent.

For per capita water use rates, see Annex F for detailed assumptions in the Baseline, which are based on type of access. Vision 2050 and Water Resilient Vision 2050 assume all people have access to 100 l/c/day.

Note that non-revenue water losses are not incorporated into this analysis, but there is some indication that losses are as high as 44 percent. This should be factored into future analysis and is discussed in more detail below.

Domestic water use

Domestic water use is supplied by a variety of sources in both rural and urban areas. According to the most recent (5^{th}) wave of the Integrated Household Living Conditions Survey (EICV5), which was carried out between 2016 and 2017, 39.2 percent of urban and 2.3 percent of rural households had water piped to their home. A further 41.5 percent of urban and 33.9 percent of rural households had access to a public standpipe. The remaining 19.3 percent of urban and 63.8 percent of rural households used another source (borehole, well, spring, rain-water, surface water, tank truck, or other).

Water use is affected by household size. Household consumption tends to rise with household size, but less than one-to-one (Arbués, García-Valiñas, and Martínez-Espiñeira 2003). For this reason, water consumption per person tends to decline with household size. Regression estimates for European countries give elasticities of around −0.6 (Höglund 1999; Schleich and Hillenbrand 2009). This is consistent with the practice in the OECD report *Divided We Stand* to calculate person-equivalent poverty measures by taking the square root of the household size (OECD 2011).

TABLE 13. Percent of population living in urban areas assumed under the baseline

	2015	2020	2025	2030	2035	2040	2045	2050
Assumed	18.2	18.6	19.5	20.8	22.6	25.1	27.8	30.8

Water use is always affected by water price. In 2015, Rwanda increased the tariff rate above the lowest block on the advice of UN Habitat, with the goal of full cost recovery.[1] In 2019 the tariff was raised even more sharply,[2] and one effect was to drive down demand. The tariff structure and water price per cubic meter at different levels of household use are shown in Figure 1. The WEAP model contains a full specification of the tariff structure, but uses it only to calculate the price at 100 liters per capita per day. The equivalent line in cubic meters per household depends on household size and is shown for 4.4 people per household in Figure 44.

For the model, piped water supply, but not other sources, water consumption per person q_{piped} is assumed to decline with the square root on the household size h and the (real) volumetric price at 100 L/cap/day p to a power,

$$q_{\text{piped}} = A\frac{p^{\varepsilon}}{\sqrt{h}}.$$

The elasticity was estimated by looking at the difference in consumption between the 2017/2018 and 2018/2019 household survey rounds, dividing residential water supply by the number of customers. Per capita consumption fell by 17 percent as the price at 100 L/cap/day rose by 76 percent, suggesting an elasticity of $\varepsilon = -0.33$. This is the parameter value used in WEAP.

References

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Höglund, Lena. 1999. "Household Demand for Water in Sweden with Implications of a Potential Tax on Water Use." *Water Resources Research* 35 (12): 3853-63. https://doi.org/10.1029/1999WR900219.

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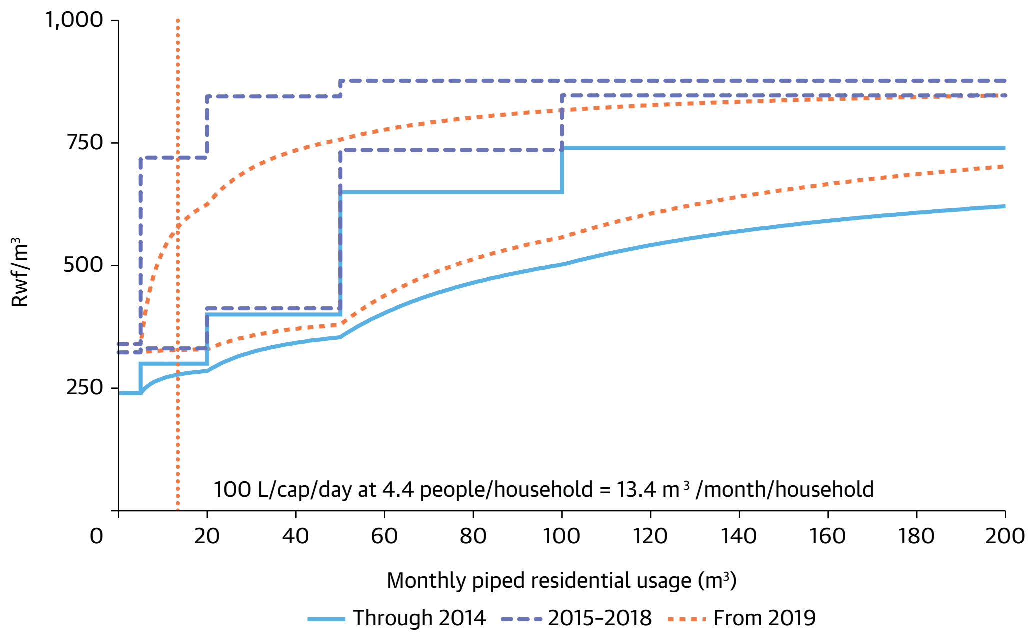
Schleich, Joachim, and Thomas Hillenbrand. 2009. "Determinants of Residential Water Demand in Germany." *Ecological Economics*, Eco-efficiency: From technical optimisation to reflective sustainability analysis, 68 (6): 1756-69. https://doi.org/10.1016/j.ecolecon.2008.11.012.

FIGURE 44. Water tariff in Rwanda: Step structure is incremental tariff from Rwandan statistical yearbooks of different years; curves give the average per cubic meter per month per household; vertical lines shows 100 L/cap/day, used as an indicative value for calculations in WEAP



Industrial demands and investments

Mining

Mining is not specifically mentioned in Vision 2050, but is in NST1, which outlines a plan to upscale mining by completing exploration of potential mineral areas to establish the extent of national resources and reserves, in terms of quantity and quality with the aim of exporting USD 800M by 2020 and 1.5B by 2024. This would represent an extraordinary increase in a short span of time. We assumed that mining would expand as assumed for the overall economy, at a rate of 6.8 percent.

The activity level for this sector in WEAP is taken from the mining sector in the economic model. At present, water use is assumed to rise at one-half the rate of increase of output in the Baseline scenario. However, a sector-specific figure is expected to be used in future revisions to the Baseline scenario. Water is required in mining, but the level needed varies considerably by type of mining product, type of ore, and technology. The potential for efficiency gains thus needs to be carefully evaluated.

It is expected that the private sector will make any necessary investments to obtain water, but that there will be public sector investment by 2030 to ensure water pollution standards are being met.

Coffee Washing

Coffee production is envisioned to increase with Vision 2050, with an expectation that exports of coffee and tea will double in volume and quadruple in value to generate $230 million per year, but without significantly increasing the land area under cultivation. The investment needed for this would be borne by the private sector, so no public investment is envisioned.

Coffee washing is a subsector within the agri-food processing sector. The activity level for this sector in WEAP is taken from the agri-food processing sector in the economic model. The sector is highly water-intensive. At present, water use is assumed to rise at one-half the rate of increase of output in the Baseline scenario. However, in future revisions to the Baseline scenario the HECCA modeling team anticipates using figure that reflects the potential for water efficiency gains in the sector within Rwanda.

Other industry

This is a catch-all category that includes a highly heterogeneous list of sectors. The activity level for this sector is taken from the "other manufacturing" sector in the economic model. At present, water use is assumed to rise at one-half the rate of increase of output in the Baseline scenario. However, in future revisions to the Baseline scenario the HECCA modeling team anticipates using a typical figure for water efficiency improvement rates in manufacturing.

Agricultural demands and investments

Cropped areas: rainfed and irrigated agriculture

As with the assumptions around crop production for the calibration, calculation of crop water requirements is based on the phenology of different crop types (i.e. development cycle and planting and harvesting dates) and their cropped areas. Crop yields are calculated based on how much of the crop water requirement is satisfied. For each crop, WEAP considers the 'potential yield' as the maximum yield achievable with an optimal amount of water. Yields are reduced according to crop yield response factors when the actual evapotranspiration of the crop is less than the potential evapotranspiration.

Rainfed agriculture will continue to play a major role in food production in the Baseline and Vision 2050. Rainfed agriculture currently accounts for more than 60 percent of the land area in Rwanda, constraining the ability for significant expansion. As such, these areas were kept stationery over the 2020-2050 time horizon for the Baseline, but is reduced as investment in irrigation reduces the land in rainfed.

For the Baseline scenario, it is assumed that there will be continued private investment in small scale irrigation (less than 10 ha) that will increase to 24,000 ha by 2050[3], and for Vision 2050 the full potential of 84,552 ha will be reached, based on the Feasibility Study for the Identification of Potential Small Scale Irrigation Areas In Rwanda (Final Report, September 2018). Currently there are only 5,000 ha of SSI.

For Vision 2050, the basis for expanded irrigated agriculture is the 2020 report on Improving and Updating Rwanda Irrigation Master Plan. The total potential foreach catchment is given in Table 13 below in hectares. The total area is on the order of 500,000 hectares.

For the Water Resilient Vision 2050, more diversified crop varieties and irrigation techniques will be considered, as well as increases in the water productivity of existing irrigated crops.

As noted in the report, the up-front investment and operation and maintenance costs vary widely depending on where the source of water is relative to the land, type of irrigation technology, and other factors. However, an estimate of these costs were presented in the Irrigation Master Plan, as shown below in Table 14.

This table combined with the added areas will form the basis of expansion of irrigated agriculture and investment costs.

Livestock

Baseline projections for livestock are calculated assuming that livestock units and kg of meat per livestock unit each follow an "s-shaped" pattern that eventually saturates. Differences between scenarios are based on the range of possible fits of the s-shaped pattern to historical data, with the Baseline based on the midline and Vision 2050 and Water Resilient Vision 2050 based on the 97.5th percentile.

TABLE 14. Total potential for irrigation in hectares for each Level 1 catchment

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**

TABLE 15. Investment and O&M costs by water source, technology and the need for pumping or not, in US$ per hectare

Domain	Investment costs $/ha	O&M costs $/ha
Marshland, diversion, gravity	1,500-4000	50-100
Marshland, dam, gravity	16,000-20,000	150-200
Hillside, dam, gravity	20,000-30,000	200-300
River/lake, pumped	6,000-10,000	300-500
Groundwater, pumped	4,000-10,000	400-600
SSIT	3,500-6,000	600-800

Livestock production and water demand are defined in terms of livestock units (LSUs), which are "feed energy equivalents" used to combine population statistics on livestock into a meaningfully comparable number. Typically, a cow is defined as 1 LSU and then other animals' feed energy needs are calculated relative to that standard. The LSU-per-animal conversion factors are shown in Table 16. They are based on the ratios used by MINAGRI (7 goats or sheep per livestock unit, 2 pigs per livestock unit, 70 chickens per livestock unit, and 70 rabbits per livestock unit).

TABLE 16. Livestock units (LSU) per animal

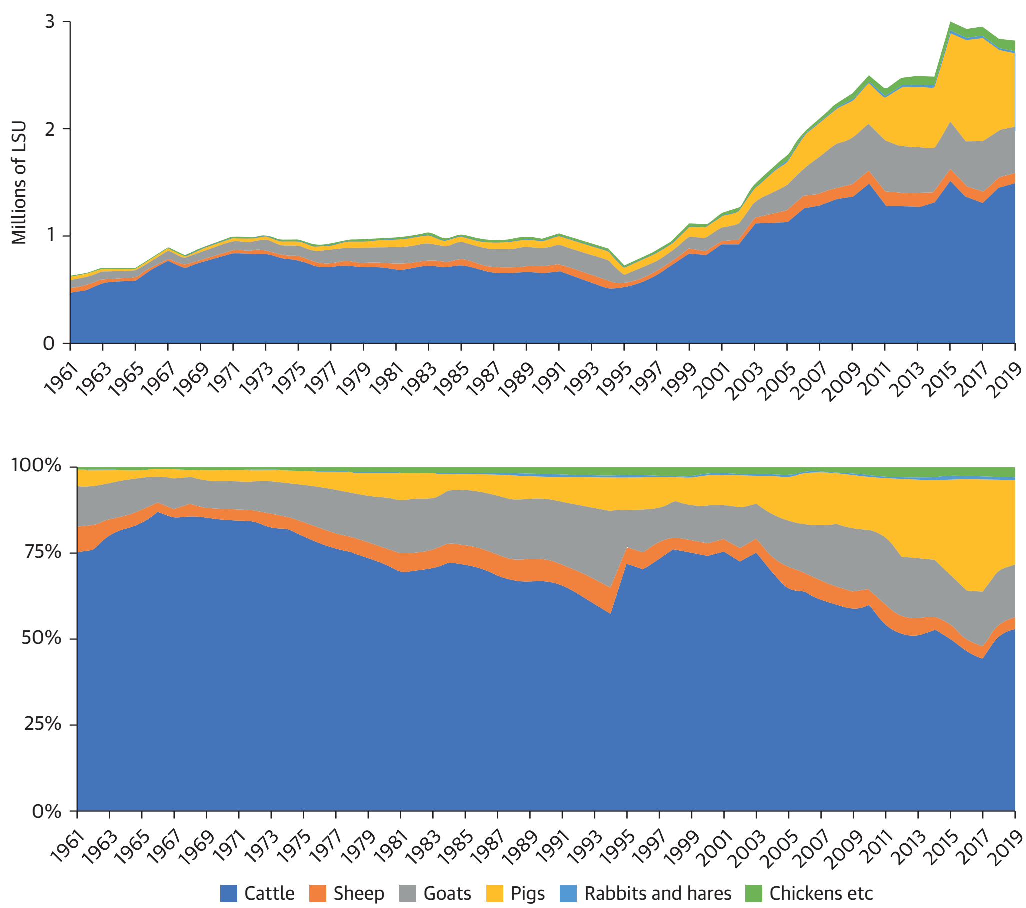
Livestock type	LSU/HECCAd
Cattle	1.000
Pigs	0.500
Sheep & goats	0.143
Chickens, ducks, geese & guinea fowl	0.014
Rabbits and hares	0.014

The values from Table F-1 were applied to time-series statistics from FAOSTAT for Rwanda from 1961 to 2019. The animal population in livestock units, both total and as a share, is shown by type of animal in Figure 45.

Because livestock units express feed energy demand, the maximum number of livestock units that can be supported depends on the feed resource. That can be based on grazing or forage, but can also depend on feed concentrates, which can be imported. Thus, the total number of livestock units can be increased through changed practices. Figure 1 shows a dramatic rise in the livestock population after around 1997. That rise has slowed recently.

Given certain of the plans within Vision 2050, it is reasonable to expect that a higher number of livestock units will be able to be supported relative to a Baseline case. These include proposed investment in: feed processing plants; specialized chick production factories; medium scale poultry farms for egg production; and pig fattening facilities.

FIGURE 45. Livestock population in Rwanda in livestock units (top: number; bottom: share of total)



Moreover, the yield per animal could rise (reflected in kg of meat produced per LSU). Pig fattening facilities could contribute to this, as well as: domestic production of veterinary inputs and feed micronutrients; milk collection centers and slaughterhouses; and animal product processing facilities.

To generate the scenarios, historical time-series data x_t was fit to an "s-shaped" curve of the following form,

$$x_t = x_{\min} + \left(x_{\max} - x_{\min}\right)\frac{1}{1+e^{-(t-t_0)/\delta}}.$$

Here, t is a year. When t is much less than the parameter t_0, where the meaning of "much" less is determined by the parameter δ, then x_t is approximately $x_{\min}$. When t is much more than t_0, then x_t is approximately equal to $x_{\max}$. The curve was fit to data for total population in livestock units (Figure 46) and kg of meat per LSU (Figure 47). The central fit is shown in the figures with a dashed line, and the 95percent confidence interval is illustrated with dotted lines.

For the Baseline scenario, values for total LSU and kg/LSU are assumed to approach the center line over time. For Vision 2050, the values are assumed to approach the upper (97.5^{th} percentile) line. The time scale over which that convergence takes place is 5 years, based on an examination of the autocorrelation functions of the residuals of the fitted curves shown in Figure 46 and Figure 47. The autocorrelation functions are shown in Figure 48.

Fishponds

Fishponds are an important water-related sector. Some fishponds are non-consumptive, but some are. Physical fish production is a driver within the economic model, just as crop production. The Master Plan for Fisheries and Fish Farming dates from 2011, with an investment of $71M, 230,000 T of fish could be produced; Vision 2050 states that Rwanda's lakes will be "fully exploited" for fish production; according to page 51 of the master plan, using a maximum of 2percent of lake reservoir area, more than a million tons of production are possible. For the Baseline, 230,000 T of production is reached by 2040. This reaches 1M T in Vision 2050 and Water Resilient Vision 2050, with the assumption that half of that production will take place in existing bodies of water in the latter scenario.

FIGURE 46. Fit of the s-shaped curve for total LSU and scenario trajectories

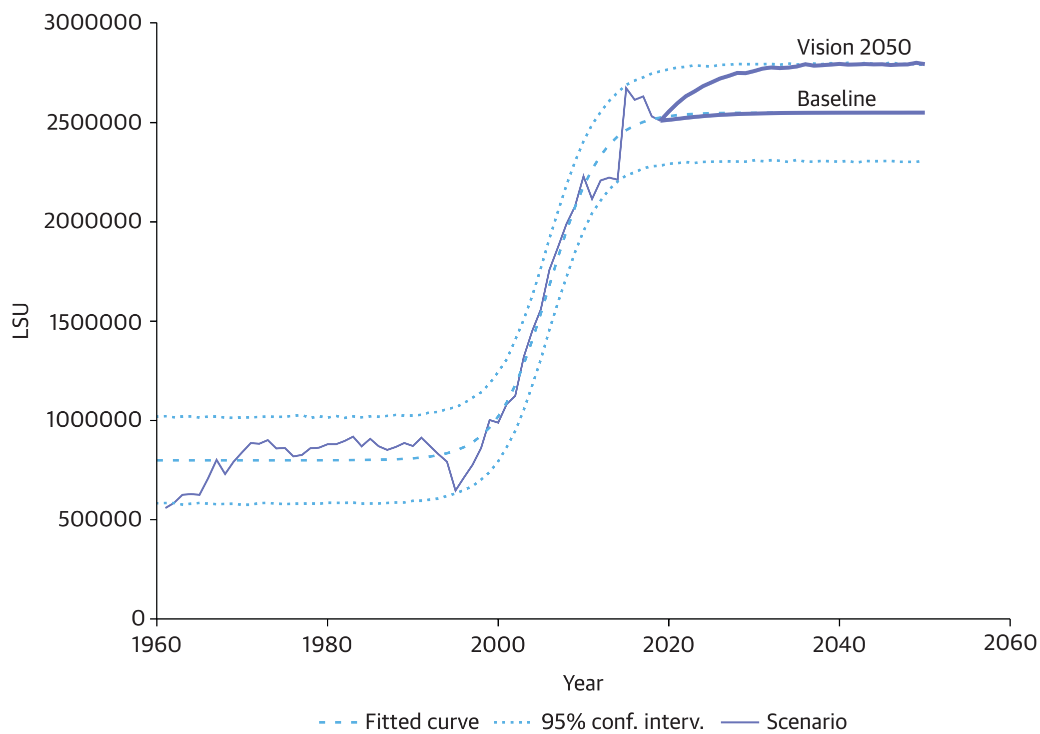


FIGURE 47. Fit of the s-shaped curve for kg of meat per LSU and scenario trajectories

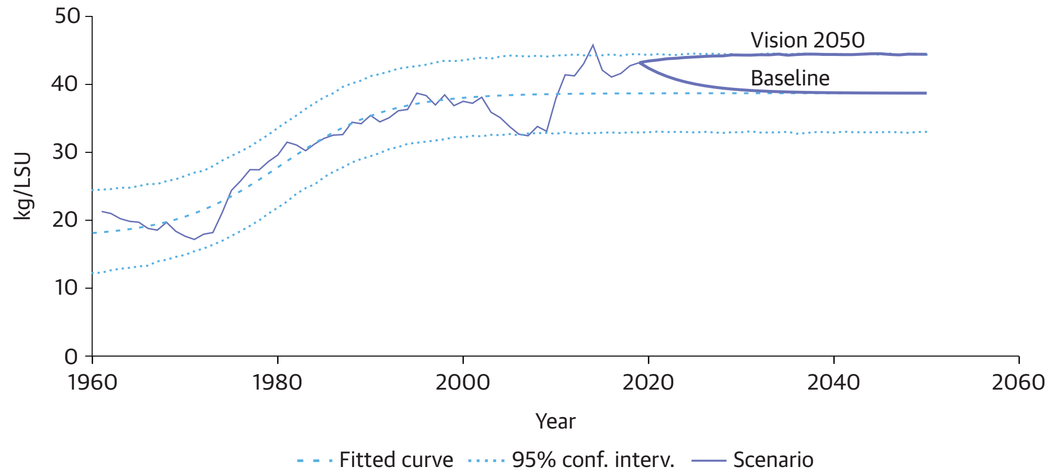
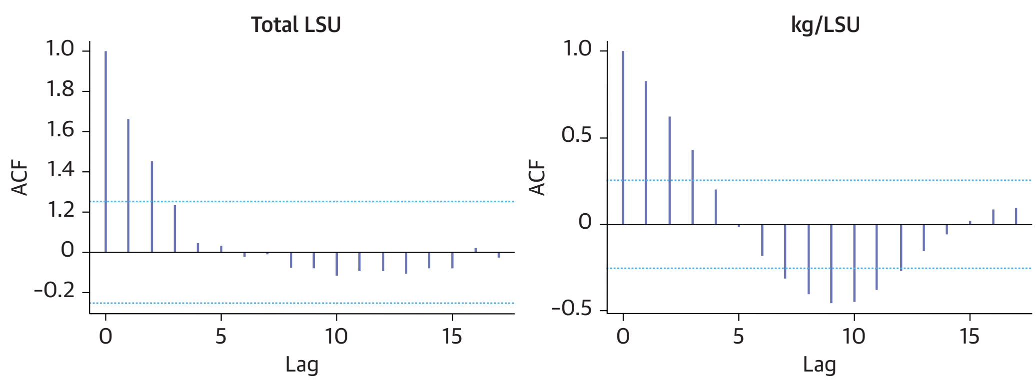


FIGURE 48. Autocorrelation function plots



Hydropower

Hydropower generation is calculated within WEAP based on streamflow and storage, depending on the type of dam. The electricity generation mix expected over the scenario period is specified in the economic model. Assumptions were reviewed with REG data and models.

The Baseline scenario assumes that the construction of the Nyabarongo II (846 MCM), Akanyaru (333 MCM), and Muvumba (35 MCM) dams is completed.

The Vision 2050 and Water Resilient Vision 2050 scenarios assume that Rusizi III, the third phase of hydropower development on the Rusizi River, will be constructed, which benefit the countries of Burundi, DRC, and Rwanda. The first two phases are operational as of 2017. The third phase is expected to contribute 50 megawatts of hydropower to Rwanda.

Environmental flows

Current representation of ecological flow requirements will be maintained in the Baseline at 30 percent of flow and 30 percent of unimpaired flows in Vision 2050 and Water Resilient Vision 2050 scenarios. The latter is considered a more ecologically protective approach, in the absence of detailed ecological surveys.

The figures and assumptions used align with those set out in Rwanda Energy Group's Least Cost Power Development Plan (December 2020).

Storage

New dams already financed are included in the Baseline scenario. Two additional planned dams are included in Vision 2050, as well as realistic estimates of potential storage drawn from the Catchment Management Plans.

2030 Water Resources Group

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