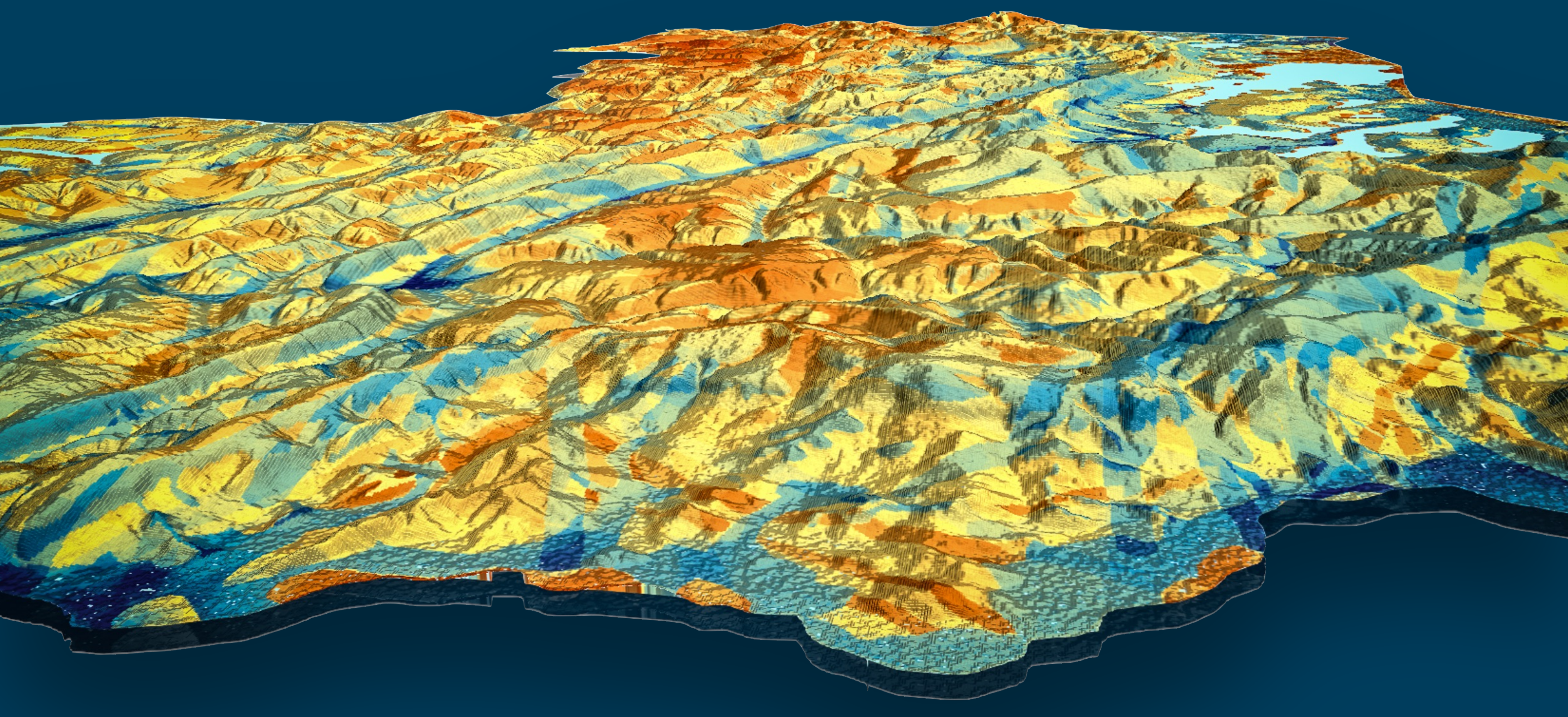
Republic of Rwanda
Rwanda Water Resources Board

Prepared for UNICEF, in cooperation with the Rwanda Water Resources Board

Mapping of Groundwater Potential in Southeastern Rwanda



Consultancy to Provide Technical Services for Groundwater Mapping in Rwanda

Deliverable 2 (D-2), Groundwater Potential Map Report

30 September 2022

HydroNova

WEconsult

Cover: Oblique view from south of southeastern Rwanda, showing the land-surface topography and the configuration of the groundwater potential. Land-surface elevation is derived from a 30-meter resolution digital elevation model. Groundwater potential is derived from modeling multiple criteria and using remote sensing imagery processed to represent the development potential of groundwater. Vertical scale is exaggerated 1.2X.

Mapping of Groundwater Potential in the Water-Scarce Areas of Southeastern Rwanda

By Kenneth Hardcastle and Casey Walther

Prepared for UNICEF, in cooperation with the Rwanda Water Resources Board

Deliverable 2 (D-2), Groundwater Potential Map Report
Draft version 30 September 2022

Consultant Team	Hydro Nova s.r.l. Viale IV novembre 82/A, 31100 Treviso – Italy Email: info@hydronova.tech www.hydronova.tech
	WE Consult Uganda Plot 57 Lake Drive, Luzira PO Box 22856 Kampala, Uganda Email: contact@we-consult.ug www.we-consult.info

Client	UNICEF
Contract No.	43347441
Client's Authorized Representative	Juliana Lindsey, UNICEF Representative
Client's Project Coordinator	Denis Mupenzi, Supply/Procurement & Logistics Specialist
Beneficiary	Rwanda Water Resources Board

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Mapping of Groundwater Potential in the Water-Scarce Areas of Southeastern Rwanda

By Kenneth Hardcastle and Casey Walther

Abstract

Reliable information describing the development potential of groundwater in the southeastern region of Rwanda is needed to resolve a variety of water resource issues including evaluation of target areas for groundwater development, prospecting for borehole sites, planning water supply systems, and monitoring. This report presents the method for estimating groundwater potential through multicriteria analysis and modeling, and presents maps of groundwater potential for the southeastern part of Rwanda to answer these needs.

The method of analysis used to determine groundwater potential in southeastern Rwanda relied on two types of readily available information: (1) raw satellite and processed data from remote sensing, and (2) ancillary data from official maps. Expert judgement also guided the development of key derived thematic layers and drove analysis, drawing from over 30 years of real-world successful application of the methods for groundwater exploration in similar hydrogeological settings.

Twelve thematic parameters related to the favorable conditions that make groundwater 'available' for development were developed, which form the building blocks of the groundwater potential model. Two component models—hydrogeologic favorability and recharge favorability – were combined for use in the indexation of the groundwater potential model.

The Groundwater Potential Map aims to make groundwater exploration in southeastern Rwanda as efficient as possible. The map is a first-level approximation of conditions favorable for a water supply system to be built and operated. It tells the hydrogeologist where to go to focus field exploration that will enable a new well or borehole to be sited. In the fractured bedrock setting of southeastern Rwanda, areas with favorable groundwater potential are those where constructing a productive, sustainable water supply well is most likely to succeed and carries lower risk. By contrast, areas with less favorable groundwater potential are those where conditions for installing a new well are less than optimal and pursuing development carries higher risk.

The results of the GWP model show variation across the study region, with notable differences between the western area (Kamonyi, Ruhango, Nyanza and Gisagara Districts) and the eastern area (Bugesera, Ngoma, Kirehe, Kayonza Districts). Overall, the study region has 18% favorable- to very-favorable GWP, with less favorable areas accounting for about 8%. The areas with the highest potential appear to correlate with low-lying drainage network areas, unsurprising for this more arid region.

Introduction

Groundwater is an important natural resource, especially in southeastern Rwanda, where limited annual rainfall and water demands for agricultural and domestic use can strain existing water supplies. Water utilities in the region serve a population of about 1.86 million (Rwanda National Institute for Statistics, 2015), while distribution to another 800,000 (35%) is inadequate, demonstrating the need for sustainable water management and a better understanding of local and regional groundwater resources.

There is a renewed need for reliable information on the potential of groundwater resources in the southeastern region of Rwanda for a multitude of purposes. This information typically is used in planning focused field surveying, targeting locations for new water supply sources, designing boreholes and wells and designing monitoring programmes to protect groundwater resources. However, recent failures to develop productive water points in the complex geological setting and the planned expansion of new groundwater-based water supply wells have raised concerns regarding the lack of adequate prospecting capabilities and have emphasized the need for practical information about the potential of groundwater to support development. The goals are to improve project sustainability and protect groundwater resources. However, information is needed regarding the favorability of groundwater to help determine the appropriate location and design of new water supply systems and guide planning and investments in groundwater prospecting.

To help provide this information, UNICEF engaged a consortium of Hydro Nova and WE Consult to determine the Groundwater Potential zones (GWP) in the drought-affected areas of southeastern Rwanda in order to provide insights and tools for field-based groundwater exploration in an efficient manner. The study developed a groundwater potential model (GWPM) based on an indexed composite of ranked overlay analysis and using an Analytical Hierarchy Process (AHP) to assign weights to the different factors. The assessment of the GWP factors is based on publicly and freely available remote sensing and ancillary datasets.

Purpose and Scope

The purpose of this report is to present estimated groundwater potential maps for the southeastern region of Rwanda. The study area comprises a portion of Eastern and Southern Provinces, where an increasing need for information on the development potential of groundwater resources has come to the forefront. The area faces increasing water scarcity and climate related food shortages, renewing the focus on exploring for and developing groundwater as a strategy for safer and more reliable source of water. The objective of this study is to generate a new regional map of groundwater potential that will guide the planning of effective boreholes and other groundwater-based water supply projects.

The method of analysis used to map groundwater potential in southeastern Rwanda relied on a model that predicts groundwater potential developed from processing of remotely sensed and ancillary datasets.

Definition of Groundwater Potential

Though no universal definition exists for 'groundwater potential', it can be broadly defined as the hypothetical degree to which, or probability that, subsurface water can be developed for a specific purpose (Diaz-Alcaide, 2019). Groundwater potential is thought of as the unrealized availability. In the context of development, realizing the full groundwater potential at a given location depends ultimately on technical and engineering solutions in the form of expert exploration and adequately constructed boreholes or wells. High groundwater potential is generally defined as a location where constructing a productive, sustainable water supply well is most likely to succeed and carries lower risk. By contrast, low groundwater potential is where conditions for installing a new well are less than optimal and pursuing development carries higher risk.

Groundwater potential mapping

Mapping groundwater potential requires the ability to combine a series of indirect indicators into a single measurement of suitability—hydrogeologic and recharge favorability. The groundwater potential map, therefore, is defined as a spatially distributed estimate of the physical capacity of the terrain to yield enough groundwater for a given use. Over a regional scale, like southeastern Rwanda, the primary purpose of the groundwater potential map is to make exploration as efficient as possible. As a tool for pre-feasibility analysis of options for developing water supply, the groundwater potential map is a first-level approximation of conditions favorable for a water supply system to be built and operated. It tells the hydrogeologist where to go to focus field exploration. Within the process of regional groundwater exploration, the groundwater potential map is an expert best estimate of optimal zones for groundwater development.

Previous Investigations

Groundwater hydrology of the southeastern portion of Rwanda has been the focus of numerous studies, although many of the studies are limited in scope. The most notable early geological investigations were those by Baudin et al. (1982), who studied and mapped geological units at national scale, and Verdoodt et al. (2006), who mapped and digitized soil classes across the country. Kabalisa (2006) provided a first generalized groundwater potential for Rwanda based primarily on soil classifications. Groundwater potential of the Eastern Province was further studied by JICA (2010) and Sloots (2019).

Description of the Study Area

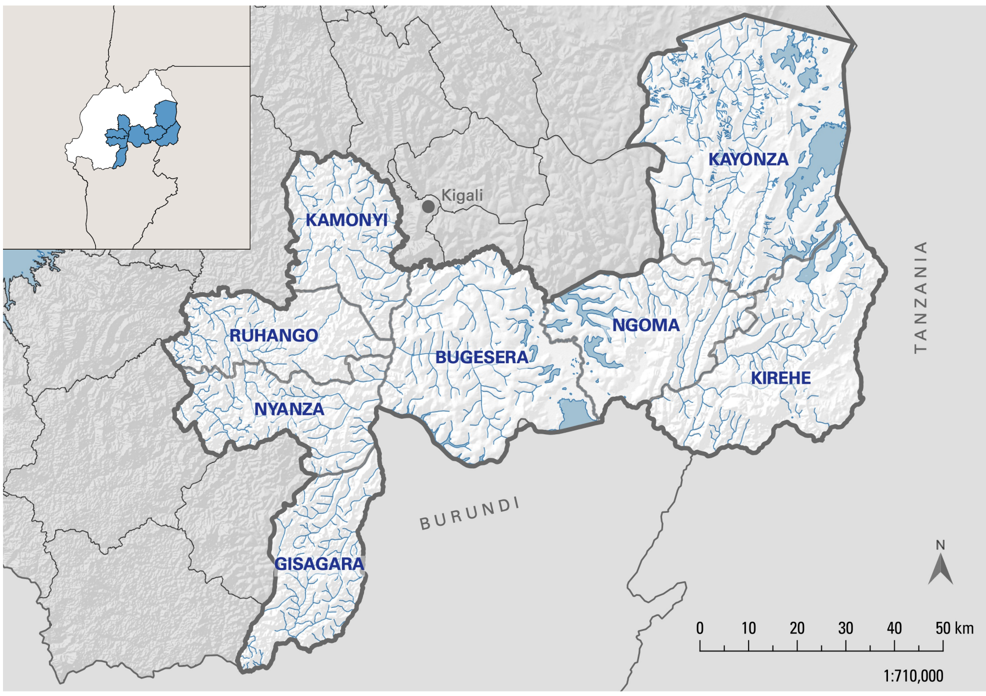
The primary study area, consisting of a region in southeastern Rwanda, includes the eight districts of Kayonza, Ngoma, Kirehe, Bugesera (Eastern Province), Kamonyi, Ruhango, Nyanza and Gisagara (Southern Province, Amayaga Region) and covers an area of about 7,852 km^2 (Figure 1). The study area has an estimated population of about 2.6 million (NISR, 2012). The region is relatively flat with altitudes well below 1,500 m, draining entirely into the Nile Basin, through a network of three major rivers (Nyabarongo, Akanyaru and Kagera) and several major lakes (Cyohoha, Rwehu, Migesera, and Ihema). The region is the warmest and most arid in Rwanda, with temperatures rising to 30°C in February and July-August and is often affected by prolonged droughts.

Hydrogeologic Setting

The study area is considered to be tectonically active, belonging to the East African Rift System, and located between its Western Branch, the Albertine Rift, and Lake Victoria. A set of normal faults with NE–SW orientation are spread on the central plateau, starting from the Miocene Age. The geology of southeastern Rwanda is characterized by three major lithological groups: the quartzite, tectono-metamorphic, Fm1-3 unit group; the crystalline and granite Gr1-3 unit group, the recent alluvial deposits (Qal) along rivers and lakes, and a minor class of Dolerite and Gabbro (Geologic Map of Rwanda, 1:250,000 scale).

Two main types of aquifer systems are found in this southeastern part of Rwanda: shallow alluvial aquifers which are typically underlain by fractured bedrock aquifers. In principle, the hills act as recharge areas and water flows to the valleys either as surface water or as sub-surface flow. Where fractures are spread and /or surface soil is less permeable, water infiltrates deeper, outcropping where slope gradient changes or there is the contact between two formations of dissimilar permeability. Springs may be isolated or arrayed depending on the type of contact.

Figure 1. Location of the study area in southeastern Rwanda



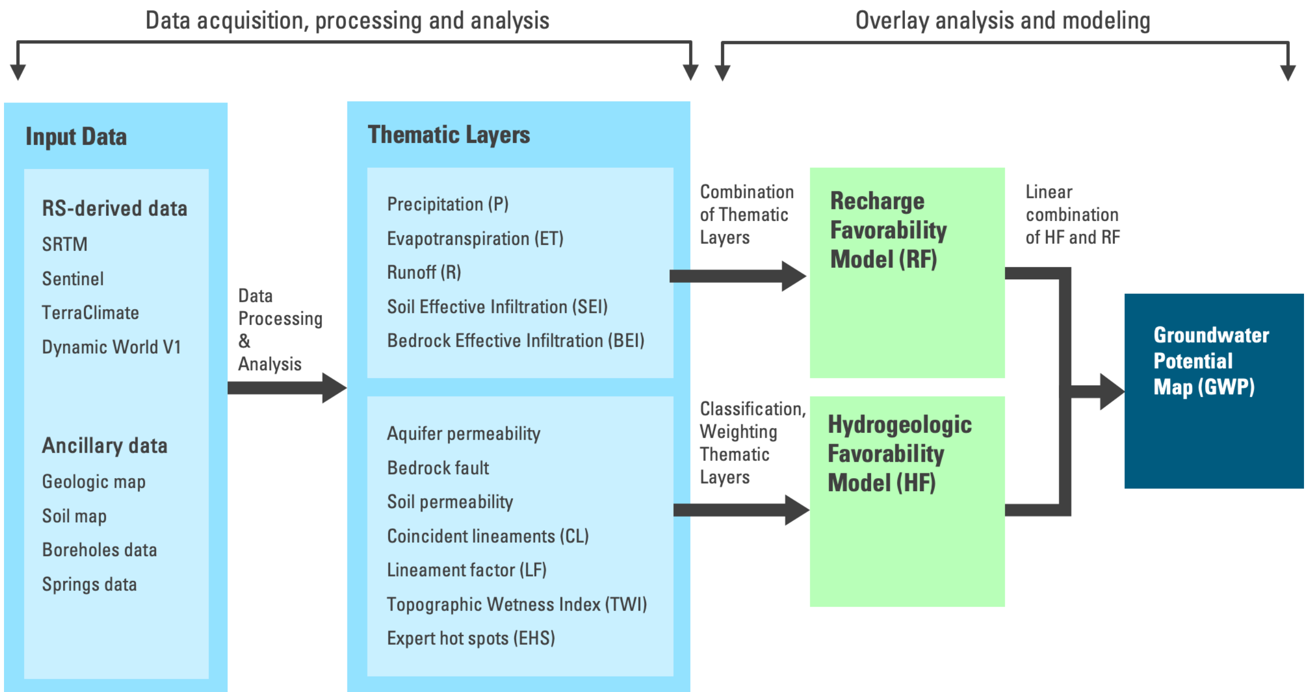
Study Methods

Approach

A tried and field-tested approach to remote sensing has been applied that provides useful insight on groundwater potential and occurrence over a large region. The approach establishes and rigorously analyzes robust hydrogeologic and remote sensing databases. Our approach is 'reverse engineered,' whereby results of previous drilling results advise next exploration efforts. This is a continually focusing approach to make sure all available pertinent data are incorporated and evaluated. This practical approach has been the foundation of over 30 years of successful exploration drilling, resulting in hundreds of high-yield wells. The inherent bias in existing borehole data does not advise on the potential sustainable yield of accurately targeted and drilled wells, and therefore are inappropriate to guide or test the exploration approach or groundwater potential model. Successful drilling, testing and sustained use of new groundwater resources will be the ultimate confirmation of this study, as it has been in all previous investigations.

The approach relies on a combination of twelve thematic layers derived from remote sensing and ancillary data and the amalgamation of two primary component models to generate an indexed groundwater potential model (GWPM). See schematic diagram of the approach below in Figure 2. Component models for hydrogeological favorability (HF) and recharge favorability (RF) are generated independently through separate weighted and mathematical processes to discern the most important conditions for groundwater potential in a fractured bedrock setting, including zones that could have higher yield, potable water quality and overall promising for sustainable development. A groundwater potential model is indexed through a mathematical combination of HF and RF models.

Figure 2. Procedures used to develop groundwater potential maps



Validation

The primary goal of the GWP model is to make exploration of groundwater over a region more efficient. It provides an expert best estimate of a first-level approximation of optimal zones for field exploration and the level of risk associated with drilling and installing new water supply boreholes and wells. The model results should be verified with a robust sample of resulting field surveys and new boreholes and wells. The limited scope of the current project does not allow fully testing the model results, which plans only for a limited number of (5) site surveys located in only one type of groundwater potential, "highly favorable", and no new boreholes drilled.

Still, this study plans to make a cursory spot check of the model in specific target areas by comparing new information on lithology and water bearing formations interpreted by ten (10) geophysical surveys with the GWP model predictions for groundwater potential. This will provide an indirect spot check of a few 'high potential' areas of the model at a specific linear location and near-surface depth; however, these few geophysical surveys will not test GWP at deeper depths, at regional scale or other GWP classes ('moderate' and 'low favorability'), since the aim of the geophysical surveys is to site boreholes in high potential areas.

Also, conducting a statistical based analysis with old data from existing near-surface boreholes, as some recent studies have used (Shabani et al. (2022), Kahn et al. (2022), Kolli et al. (2020), Serele et al. (2020)), cannot corroborate the results of the GWP model in this particular project. Data from existing water points in the study region do not give an adequate reference for actual groundwater potential, given they lack necessary information about groundwater potential, ie. yield, depth, water level; have poor regional distribution; and are inherently biased towards the goal of drilling to shallowest depths and using the most economic pumping method—often a handpump.

A preliminary validation has been done *a priori* through an expert judgement process to create a reasonable first approximation of a model of groundwater resource potential for the study region. Unlike most other similar studies, the GWP model has been 'reverse engineered' based on extensive application to site and construct over 1,000 wells in similar hydrogeologic environments, which has guided the development of key datasets and weighting of model parameters. Due to the lack of details on bedrock characteristics and structures in the study region, emphasis was placed on specific enhancements of satellite data and remote sensing efforts. A robust and thorough lineament mapping effort, followed by advanced lineament analyses, provides a powerful surrogate for such otherwise lacking critical data. The significant experience of use of this model approach in different settings gives confidence of the usefulness of the model in the study area.

Sensitivity

Our approach to estimating the robustness of the GWP model, ie. sensitivity, was to expertly evaluate numerous trial models, and converge on a balanced model through an iterative process of varied weightings. The final model brings to bear all parameters without being weighted too heavily on any single parameter.

Sources and Description of Data

Original datasets were collected from remote sensing and conventional data. The table below provides the sources of data, spatial resolution, and products derived thereof for the production of models in this study.

Data Limitations

As is the norm for remotely sensed datasets used for estimating a composite model, such as groundwater potential, limitations can lead to increased errors and, therefore, larger uncertainty in the results. These include uncertainty in the spatial distribution of the data points, both lateral and vertical, and bias introduced as a result of the temporal distribution of the imagery. Uncertainty resulting from the lateral spatial distribution of available data is a function of the number and location of data of features used for analysis, and is discussed further in section, 'Assumptions.' The vertical spatial estimations related to geology and deeper horizons can only represent an expert first-level approximation of groundwater potential at reasonable depth, from surface down to known viable geological formations.

Table 1. Sources of remote sensing data and derived products

Source	Resolution	Derived products
Shuttle Radar Topography Mission (SRTM)	30m, 90m	Digital elevation model (DEM), Slope, Topographic wetness index (TWI), Lineaments (coincident lineaments, lineament factor), Expert Hot Spots
Sentinel-2	10-m	False-Color Index, Transformed Normalized Vegetation Index (tNDVI), Normalize Difference Water Index (NDWI), Soil-Adjusted Vegetation Index (SAVI), Principal Component Analysis (PCA), Lineaments (coincident lineaments, lineament factor), Expert Hot Spots
TerraClimate	4,638.3m (~4 km)	Precipitation (P), Evapotranspiration (ET), Runoff (R)
Dynamic World V1, based on Sentinel-2 L1C	10m, near-real-time	Land cover

Thematic Layers

Thematic layers were generated from original factors using remote sensing and conventional data in a GIS environment. Enhanced imagery products and derived products were converted to raster format and, if necessary, resampled to 10-m and 30-m spatial resolutions and reprojected to the World Geodesic System (WGS-84), UTM zone 36S.

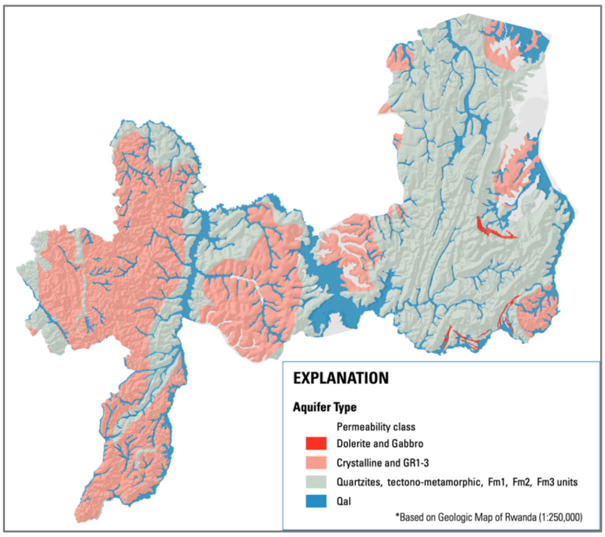
Aquifer Permeability

A primary thematic layer of hydrogeological favorability is aquifer permeability, which has been adapted from the Geologic Map of Rwanda collected from the Rwanda Water Resources Board, 2022, (scale 1:250,000). Values of aquifer permeability have been assigned by experts to the classes of geology, given in the table below. The resulting thematic layer of aquifer permeability is shown in the Figure 3.

Table 2. Values of classes of aquifer permeability

Value	Class	Legend
20	Qal	Blue
10	Quartzites, tectono-metamorphic, Fm1, Fm2, Fm3 units	Gray
3	Crystalline and GR1-3	Pink
1	Dolerite and Gabbro	Red

Figure 3. Aquifer permeability thematic layer



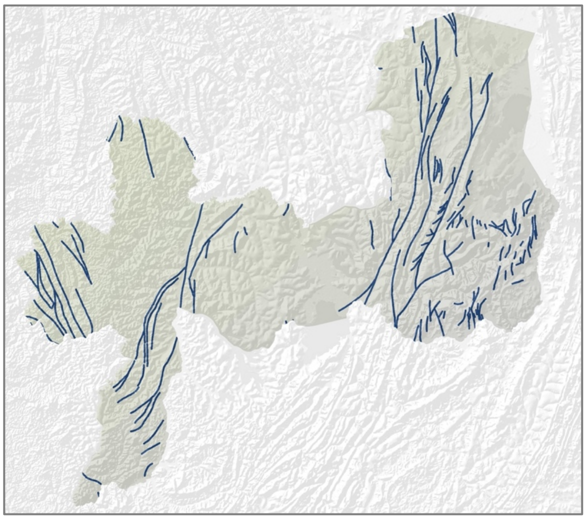
Bedrock Faults

A primary thematic layer of hydrogeological favorability is bedrock faults, which has been adapted from the Geologic Map of Rwanda collected from the Rwanda Water Resources Board, 2022, (scale 1:250,000). Such structures can have highly varied characteristics across the study region and have similar varied impact on groundwater potential. A simple numerical value has been assigned to each class of bedrock fault – 'fault' and 'no fault', given in the table 3 below. The resulting thematic layer of bedrock faults is shown in Figure 4 below.

Table 3. Values assigned to bedrock faults

Value	Class	Legend
1	Fault	Dark blue
0	No fault	Gray

Figure 4. Bedrock fault thematic layer



Coincident Lineaments (CL)

A thematic layer critical to calculating hydrogeological favorability is Coincident Lineaments (CL), which CL is where at least three raw lineaments are spatially proximal and approximately parallel (Maybe et al., 1994). A base lineaments layer was processed, comprised of 9,280 raw lineament features detected through expert analyses of 11 different, enhanced remotely sensed images based on SRTM DEM (30 and 90m) and SENTINEL (10m) multispectral images (Figure 5).

A total of 628 CL were computed from the base lineament layer with buffering of 250 m and ranked by their orientation relative to regional extensional stress of NW-SE. Table 4 below provides the rank value assigned. The resulting CL thematic layer is provided in Figure 6.

The stress-ranked CLs are rasterized and, where overlapping lineament buffers occur, their rank values are added. The occurrence of more than one CL is considered more favorable than areas where no overlap occurs. Values range from 0 – 6 (table 5). Resulting stress-ranked CL layer seen in Figure 7 below.

Table 4. Values assigned to Coincident Lineaments (CL)

Value	Class	Legend
1.25	90+-10 degrees off or about perpendicular to regional extensional stress and therefore more likely to be open	Violet
0.75	0+-10 degrees off or about parallel with regional extensional stress and therefore least open	Green
1.00	All others	Light blue

Figure 5. Base lineaments layer

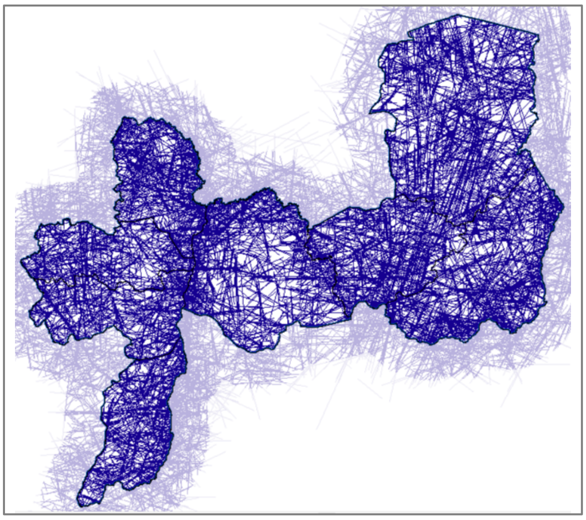


Figure 6. Coincident Lineaments (CL) thematic layer

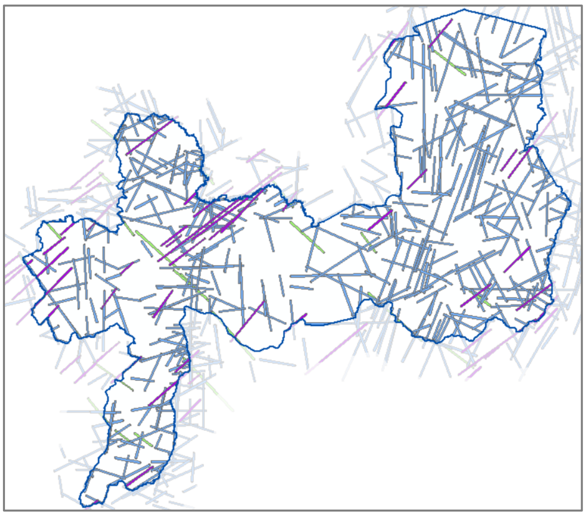
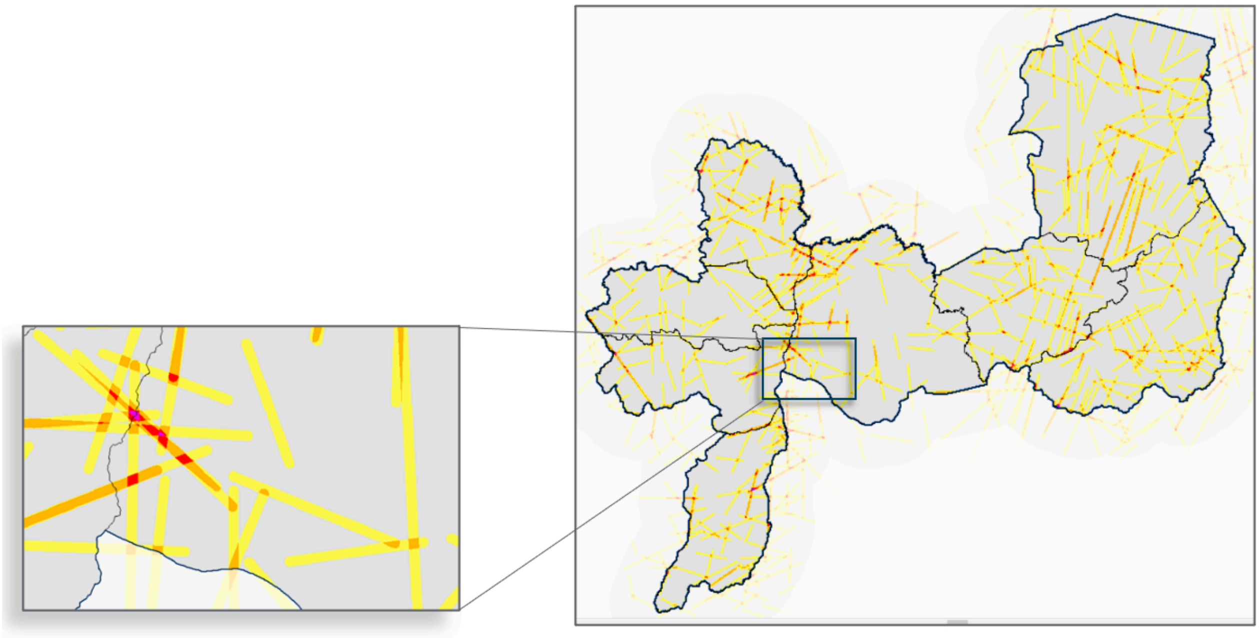


Table 5. Factor values assigned to CL raster layer

Value	Class	Legend
0	No CL	Gray
1	One CL, no overlapping	Yellow
2	Two CL overlapping	Light orange
3	Three CL overlapping	Mid orange
4	Four CL overlapping	Dark orange
5	Five CL overlapping	Red
6	Six CL overlapping	Dark red

Figure 7. Stress-ranked CL thematic map



Lineament Factor (LF)

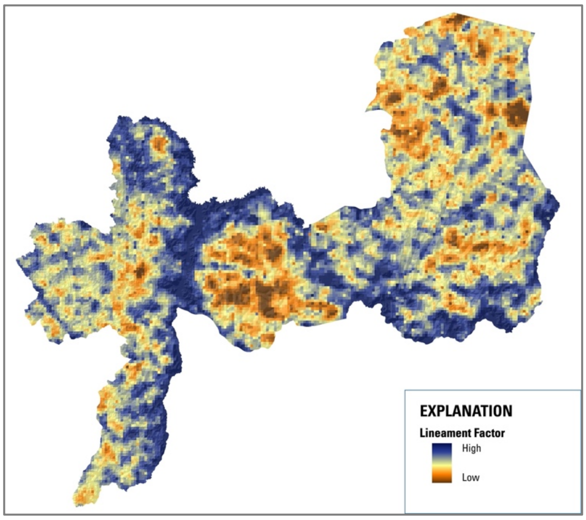
Another key thematic layer for computing hydrogeologic favorability (HF) is Lineament Factor (LF), a composite index of lineament conditions related groundwater potential in bedrock settings. LF is a proxy for the degree of disruption in the bedrock and therefore the likelihood of the ability of the bedrock to store and transmit groundwater. LF is a combination of three parameters: (i) the total number of lineaments, (ii) the total length of lineaments, and (iii) the number of statistically significant lineament families (Hardcastle and others, 1995).

Based on the base lineament layer, LF values were computed for these parameters in a 750-m grid with 1000-m overlapping circles. LF values are recast over a spectrum of ranking ranging from low to high, as seen in Table 6 below. The resulting LF thematic layer is provided in Figure 8 below.

Table 6. Values assigned to Lineament Factor (LF)

Value	Class	Legend
4.22974	Low LF	Red
78.1543	High LF	Blue

Figure 8. Lineament Factor (LF) thematic layer



Topographic Wetness Index (TWI)

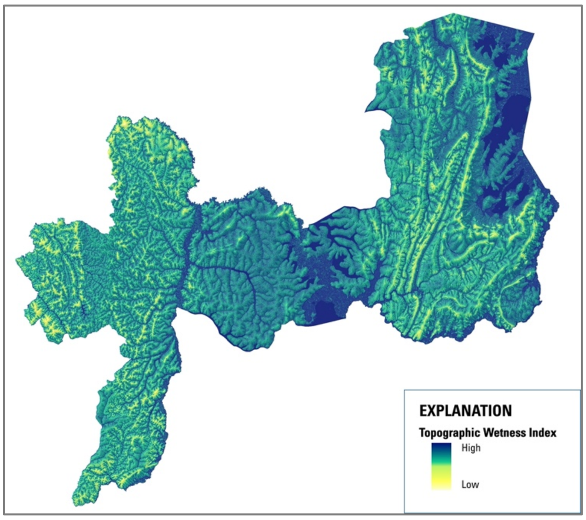
Another important thematic layer for modeling HF is the Topographic Wetness Index (TWI), a standard derived product used for the study of soil moisture and surface area drainage. This index can be viewed as a proxy for depth-to-water table and, therefore, the drawdown potential in a borehole. Higher TWI values are therefore more favorable for groundwater resource development than lower values.

TWI has been processed from a DEM derived from SRTM, 30-m resolution, computing a TWI value for every pixel in a 30-m grid. Normalized values assigned to the TWI layer range from 0 to 1, given in Table 7 below. The resulting TWI thematic layer is shown in Figure 9.

Table 7. Normalized values assigned to TWI

Value	Class	Legend
0	Low TWI	Yellow
1	High TWI	Blue

Figure 9. Topographic Wetness Index (TWI) thematic layer



Soil Permeability

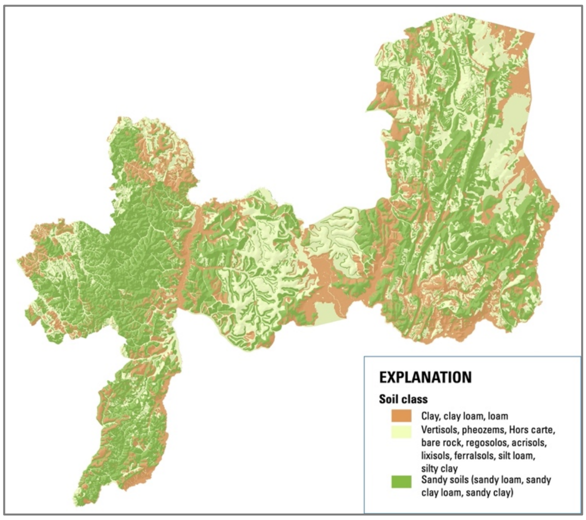
Permeability of soils is a key thematic layer for computing HF. Soil permeability is an important control on shallow aquifers due to variability of composition. Soil permeability has been based on the digital Soil Map of Rwanda collected from Ministry of Agriculture and Animal Resources (MINAGRI) (Verdoodt, A. Van Ranst, E., 2006) with 1:250,000 scale.

Permeability values have been assigned to soil class by experts, provided in Table 8 below. The resulting soil permeability thematic layer is shown in Figure 10.

Table 8. Values assigned to soil permeability

Value	Class	Legend
10	Sandy soils (sandy loam, sandy clay loam, sandy clay)	Green
5	Vertisols, pheozems, Hors carte, bare rock, regosols, acrisols, lixisols, ferralsols, silt loam, silty clay	Pale yellow
1	Clay, clay loam, loam	Orange

Figure 10. Soil permeability thematic layer



Expert Hot Spots

HF is also dependent upon conditions potentially favorable for hosting a productive well. Expert hot spots (EHS) are generalized locations that are considered by expert exploration judgement to have potentially favorable conditions for exploration. A total of 344 EHS have been identified based on expert judgement and analysis of remotely sensed datasets (bedrock geology, structure, topographic models, enhanced multispectral satellite images). Data layers used to identify EHS in the study region include:

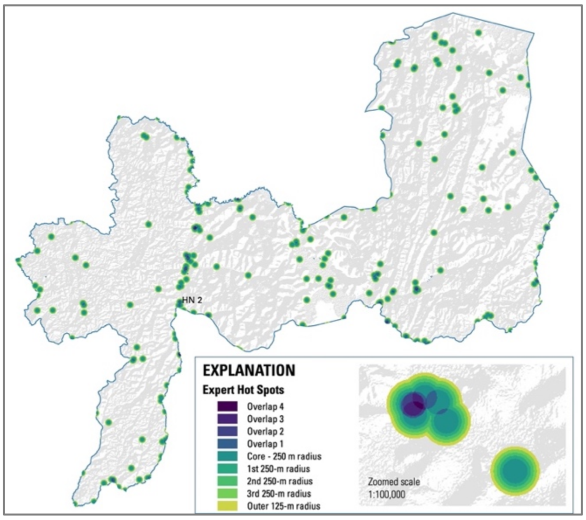
- Bedrock geology (1:250,000) and structure maps
- Topographic models based on 30-m and 90-m SRTM data
- Enhanced Sentinel-2 multispectral images at 10-m resolution

EHS points have been buffered to a 1-km circle with a graded value at five intervals including a 500-m core. The values assigned to EHS zones are provided in Table 9 below. Where EHS overlap, values are added. The resulting EHS thematic layer is shown in Figure 11 below.

Table 9. Values assigned to EHS

Value	Class	Legend
1.00	500-m diameter core	Medium-dark green
0.75	next 125-m radius	Green
0.5	next 125-m radius	Bright green
0.25	next 125-m radius	Light green
0.05	outer 125-m radius	Pale yellow-green

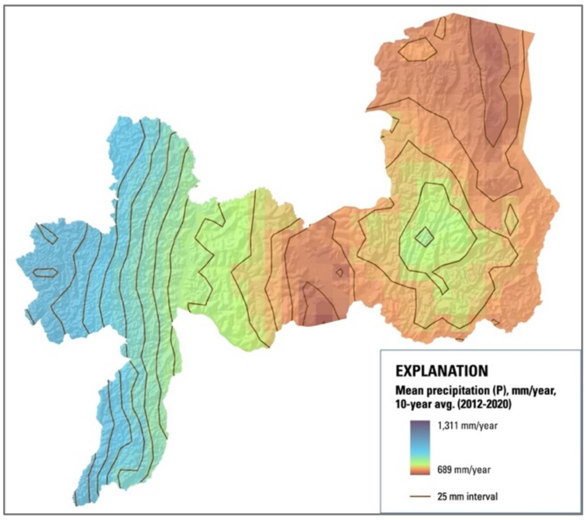
Figure 11. Expert Hot Spots (EHS) thematic layer



Precipitation

One of the five principal thematic layers of recharge favorability (RF) is precipitation (P). Imagery from TerraClimate v1 were compiled at 4-km resolution for 10 year monthly means calculated for average year of P. P values range from 689.1 (red) to 1,311.5 (blue) mm/year. The resulting raster thematic layer for precipitation is provided below, shown with 25-mm contours.

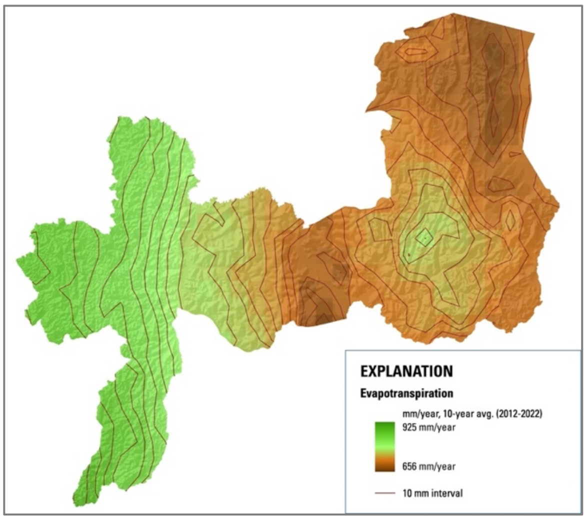
Figure 12. Precipitation thematic layer



Evapotranspiration

A second thematic layer of recharge favorability (RF) is precipitation (ET). Imagery from TerraClimate v1 were compiled at 4-km resolution for 10 years monthly means calculated for average year of ET. ET values range from 655.9 (green) to 925.0 (brown) mm/year. The resulting raster thematic layer for ET is shown in Figure 13 with 10 mm contours.

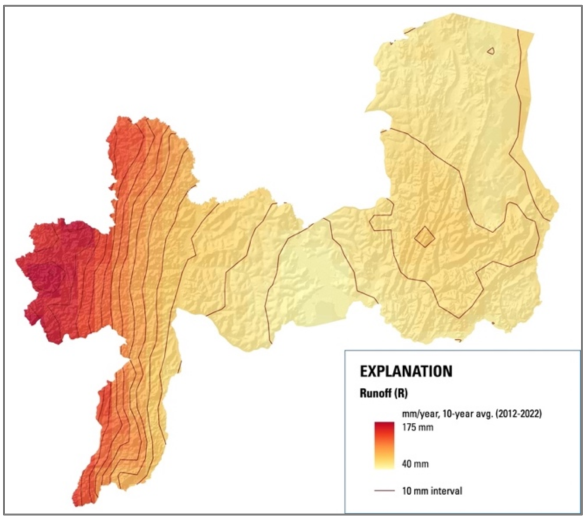
Figure 13. Evapotranspiration (ET) thematic layer



Runoff

A third thematic layer of recharge favorability (RF) is runoff (R). Imagery from TerraClimate v1 were compiled at 4-km resolution for 10 years monthly means calculated for average year of R. R values range from 40.9 (yellow) to 444.4 (red) mm/year. The resulting raster thematic layer for runoff is provided in Figure 14 with 10-mm contours.

Figure 14. Runoff (R) thematic layer



Soil Effective Infiltration (SEI)

A fourth primary thematic layer of RF, and an important parameter of infiltration, is captured as soil effective infiltrating (SEI). SEI helps to capture the nature of the surficial soil materials that the recharge enters and affects the true groundwater recharge. SEI has been based on the digital Soil Map of Rwanda, 1:250,000 scale, Nzeyimana, Innocent; E. Hartemink, Alfred; Geissen, Violette (2015). SEI values have been assigned to geology class by experts, provided in Table 10 below. The resulting SEI thematic layer is shown in Figure 15.

Table 10. Assigned values for soil effective infiltration (SEI)

Value	Class	Legend
0.05	Clay and silt units	yellow
2.00	Sandy units	blue

Figure 15. Soil Effective Infiltration thematic layer

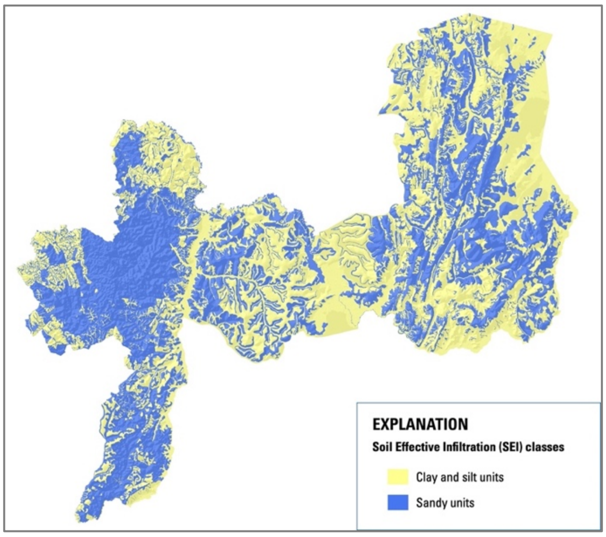
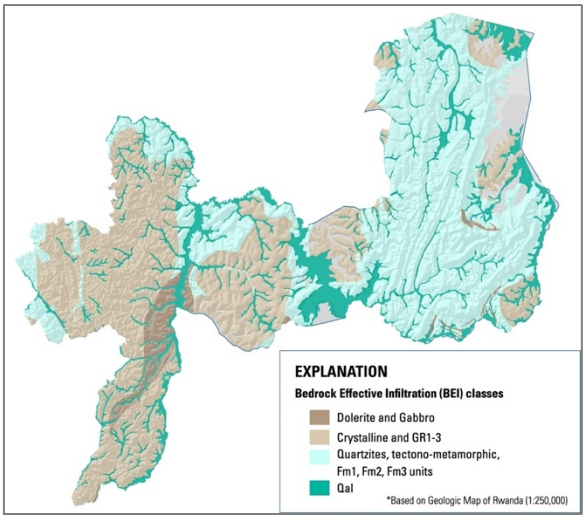


Figure 16. Bedrock Effective Infiltration (BEI) thematic layer



Bedrock Effective Infiltration (BEI)

The last of the primary thematic layers of RF and another important parameter of infiltration, is captured as bedrock effective infiltrating (BEI). BEI helps to capture the nature of the subsurface bedrock material that the recharge enters and affects the true groundwater recharge. BEI has been based on the digital Geologic Map of Rwanda (1:250,000 scale). BEI values have been assigned to geology class by experts, provided in Table 11 below. The resulting BEI thematic layer is shown in Figure 16.

Table 11. Assigned values for bedrock effective infiltration (BEI)

Value	Class	Legend
0.1	Dolerite and Gabbro	Dark brown
0.2	Crystalline and GR1-3	Light brown
0.3	Quartzites, tectono-metamorphic, Fm1, Fm2, Fm3 units	Light green
0.5	Qal	Green

Component Models

Modeling groundwater potential (GWP) combines two core component models—that of hydrogeological favorability (HF) and that of recharge favorability (RF).

Hydrogeological Favorability (HF)

Hydrogeologic favorability is an index model representing the ability of the subsurface to store and transmit groundwater. In fractured bedrock settings such as the study region, HF is dependent upon the factors such as soils, bedrock geology, faults, lineaments, terrain morphology, drainage patterns, etc. For this specific survey region, modeling HF has been adapted to combine seven (7) thematic layers: (i) aquifer permeability, (ii) bedrock faults, (iii) Coincident Lineaments (CL), (iv) Lineament Factor (LF), (v) topographic wetness index (TWI), (vi) soil permeability, and (vii) expert hot spots (EHS). Both ancillary and satellite-based data were collected and processed for the HF model (Table 12).

Table 12. Parameters and derived products of the hydrogeological favorability (HF) model

Thematic layer	Parameter	Data source [spatial resolution]
Geology	Aquifer permeability Bedrock faults	Geologic Map of Rwanda [1:250,000]
Soil type	Soil permeability	Soil map of Rwanda [1:250,000]
Structural geology	Coincident Lineaments Lineament Factor	SRTM [~30 m, ~90m], Sentinel-2, 13-band [10m]
Topographic controls on hydrologic processes	Topographic Wetness Index (TWI)	SRTM [~30 m]
Hydrogeology	Expert hot spots	SRTM [~30 m, ~90m] Sentinel-2, 13-band [10m] Aquifer map (permeability) Fault map Coincident Lineaments Lineament Factor

For the HF model, each layer, once ranked, was then normalized to have values from 0 to 1 and then weighted following a pair-wise comparison and weighting process.

Developing a balanced model

Our approach to sensitivity was to expertly evaluate numerous models, and through an iterative process of varied weightings, converge on a balanced model. The final model brings all parameters to bear without being weighted too heavily on any one parameter.

Pairwise

Through an Analytical Hierarchy Process (AHP), we take the ranked layers and go through a Pairwise comparison to develop weights for each layer. The pairwise comparison is guided by expert judgment, in our case, based on many decades of installing numerous high yield fractured bedrock wells, in addition to the typical theoretical and literature-based decision matrix. For this study area, the resulting pairwise comparison resulted in the matrix and weighting below (Figure 17).

Comparison matrix

The ranking from pairwise were normalized to derive weightings that would be applied to the indexation of the layer images in the GIS environment (Figure 18).

These weights make sense in this study's setting of variably weathered, complexly deformed, heterogenous crystalline bedrock overlain by different types and thicknesses of recent alluvium. The key to storing and transmitting water in the bedrock is dependent upon the occurrence of disruptions within the otherwise very low permeability to impermeable crystalline rock. Such disruptions are detected as remotely sensed lineaments and therefore both the Coincident Lineament and Lineament Factor Values have high weightings. The ability of experts to integrate many different parameters dictates that the Expert Hot Spots also have a high weighted value. The bedrock geology and TWI are also very important to the model. Because of their highly variable nature, the faults are to be addressed in the site-specific detailed investigations of Target Areas and are therefore only moderately weighted for this regional model. The soils, which are at the very surface and therefore of minor impact on deeper sustainable groundwater resources, are the lowest weighted layer.

Hydrogeological Favorability model

The resulting HF model is given in Figure 19. Unitless HF values are recast over a panchromatic spectrum (ROYGB), with higher HF in indigo blue and lower HF in red. In the HF model for southeastern Rwanda, we begin to get a sense of a roadmap of veins of more favorable groundwater.

Figure 17. Pairwise ranking of thematic layers of the hydrogeological favorability model (HF)

Pairwise Ranking

	Aquifer permeability	Bedrock faults	Coincident Lineaments	Lineament Factor	TWI	Soil permeability	Expert Hot Spots
Aquifer permeability	1.00	3.00	0.50	0.80	1.00	5.00	0.40
Bedrock faults	0.33	1.00	0.20	0.50	0.80	5.00	0.50
Coincident Lineaments	2.00	5.00	1.00	1.20	1.20	5.00	1.00
Lineament Factor	1.25	2.00	0.83	1.00	1.00	5.00	0.80
TWI	1.00	1.25	0.83	1.00	1.00	5.00	0.80
Soil permeability	0.20	0.20	0.20	0.20	0.20	1.00	0.20
Expert Hot Spots	2.50	2.50	1.00	1.25	1.25	5.00	1.00
TOTAL	8.28	14.95	4.57	5.95	6.45	31.00	4.70

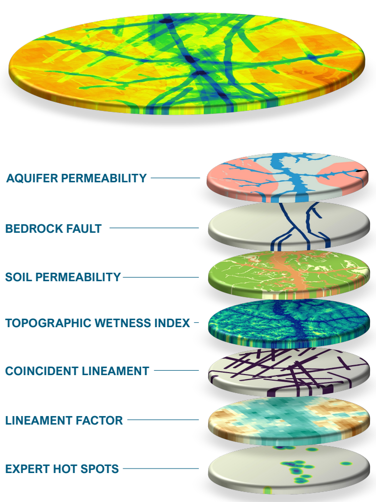
Figure 18. Weighting of thematic layers for calculating Hydrogeologic Favorability (HF)

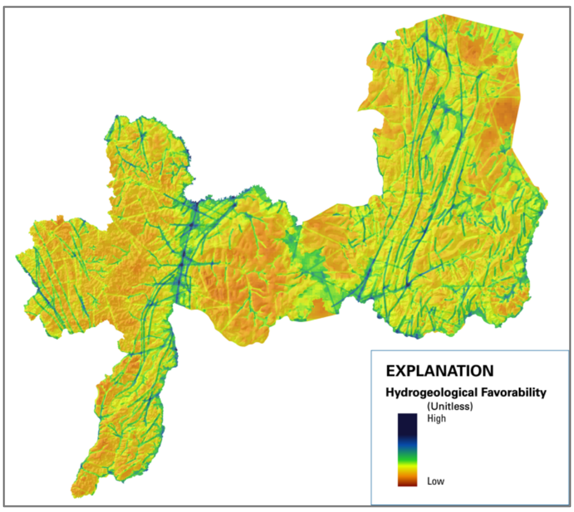
Normalized Comparison Matrix*

	Aquifer permeability	Bedrock faults	Coincident Lineaments	Lineament Factor	TWI	Soil permeability	Expert Hot Spots	WEIGHT
Aquifer permeability	0.12	0.20	0.11	0.13	0.16	0.16	0.09	**0.14**
Bedrock faults	0.04	0.07	0.04	0.08	0.12	0.16	0.11	**0.09**
Coincident Lineaments	0.24	0.33	0.22	0.20	0.19	0.16	0.21	**0.22**
Lineament Factor	0.15	0.13	0.18	0.17	0.16	0.16	0.17	**0.16**
TWI	0.12	0.08	0.18	0.17	0.16	0.16	0.17	**0.15**
Soil permeability	0.02	0.01	0.04	0.03	0.03	0.03	0.04	**0.03**
Expert Hot Spots	0.30	0.17	0.22	0.21	0.19	0.20	0.21	**0.21**

*Each parameter divided by the sum of Pairwise Ranking total

Figure 19. Hydrogeological Favorability (HF) model





Recharge Favorability (RF)

The other primary component model of the GWPM is recharge favorability (RF), an index model representing the recharge conditions in the study region and surroundings. The key RF categories of layers developed for this study include infiltration and groundwater recharge. Both ancillary and satellite-based data were collected and processed for the RF model. See table below. RF comprises five main thematic layers: (i) precipitation (P), (ii) evapotranspiration (ET), (iii) runoff (R), (iv) soil effective infiltration (SEI), and (v) bedrock effective infiltration (BREI, or BEI). Raster images for P, ET and R were computed from cumulative mean monthly values for 10-year period (2012 – 2022) to give a robust dataset. The source of data for P, ET and R was TerraClimate v1 at 10-m spatial resolution. SEI and BEI were derived from the digital Geologic Map of Rwanda (scale 1:250,000).

Indexation

The RF model adapts the standard hydrogeological equation for groundwater recharge and integrates a factor of infiltration:

$$RF = (P - ET - R) \times (SEI + REI)$$

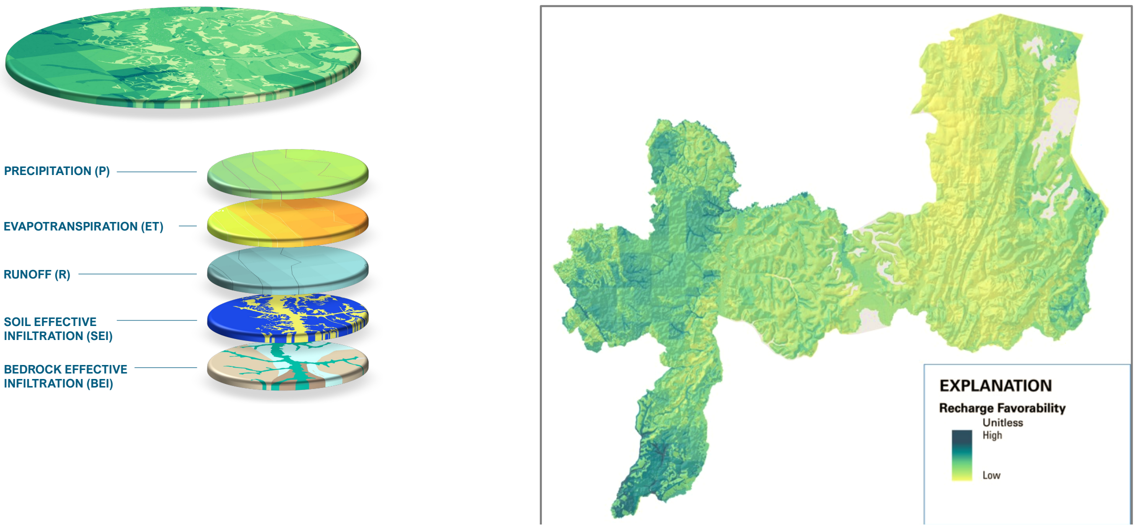
Recharge Favorability model

The resulting RF model (Figure 20) has unitless values, which are recast over a chromatic spectrum (BGY), with higher RF in indigo blue and lower RF in yellow. In the RF model for southeastern Rwanda, we see varied RF across the study region, and generally higher RF in the western area and lower RF in eastern area.

Table 13. Parameters and derived products of recharge favorability (RF) model

Thematic layer	Parameter	Data source [spatial resolution]
Infiltration	a) Soil Effective Infiltration (SEI) b) Bedrock Effective Infiltration (BEI)	Geologic Map of Rwanda [1:250,000]
Groundwater recharge	c) Precipitation (P) d) Evapotranspiration (ET) e) Runoff (R)	TerraClimate, monthly data between 2012 and 2022 [4,638.3m (~4 km)]

Figure 20. Recharge Favorability (RF) model



Groundwater Potential (GWP) Model

Modeling the unrealized development potential groundwater resources in a fractured bedrock setting is affected by a number of key variables, including bedrock geology, structural setting, coincident lineaments, recharge setting, discharge area and land use, and requires the ability to combine them into a single measurement of suitability. The GWP model developed for southeastern Rwanda is a simulated prediction of regional groundwater potential, representing a composite of hydrogeological and recharge favorability parameters. The model combines the two component models, HF and RF, into an indexed composite of groundwater potential.

Calculated GWP

GWP was calculated using the following equation:

$$GWP = (Sum\ Factor) - (Difference\ Factor)$$

More specifically, the equation for calculating GWP was:

$$GWP = (HF + RF) - (HF - RF)$$

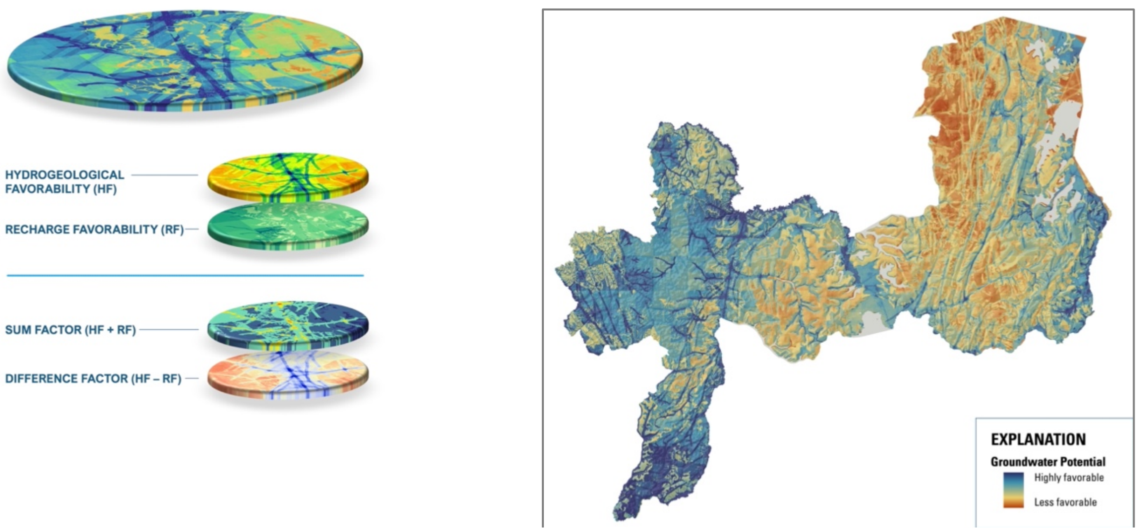
The resulting model is represented in Figure 21 below.

Assumptions

The accuracy of the groundwater potential maps depends on various factors pertaining to the data, the method of combining parameters, and the conditions of groundwater in the study region. Some of these factors have been discussed in the section, 'Data Limitations.' The following assumptions are made with regard to the datasets used for modeling groundwater potential:

- Structural, recharge, permeability and geology are representative of hydrogeological conditions in the study area
- Spatial positions of the lineaments and fracture traces are accurately known
- The surface features that were used for modeling were assumed to be the features that represent the nature and position of groundwater potential; spatial positions of the features are accurately known; and land-surface elevations of the features are accurately assessed.

Figure 21. GWP model



Groundwater Potential

In the fractured bedrock setting of southeastern Rwanda, areas with favorable groundwater potential are those where constructing a productive, sustainable water supply well is most likely to succeed and carries lower risk. By contrast, areas with less favorable groundwater potential are those where conditions for installing a new well are less than optimal and pursuing development carries higher risk.

Groundwater Potential Map

The groundwater potential map is a spatially distributed estimate of the physical capacity of the terrain to yield enough groundwater for a given use. The primary purpose of the groundwater potential map is to make regional exploration as efficient as possible. The map, therefore, gives users a first-level approximation of conditions that are favorable and unfavorable for a water supply system to be built and operated.

A combined Groundwater Potential model reveals the nature and spatial distribution of both shallow and deep aquifers, subsurface conditions and recharge conditions that impact the availability, quality, and sustainability of groundwater resources. The GWP model for southeastern Rwanda predicts the presence of sustainable groundwater resources, offering a promising and provide a clear guide to the location and nature of groundwater resources over the region. The next section demonstrates examples of maps demonstrating the capabilities of the GWP model.

Example Variations of the Groundwater Potential Map

The groundwater potential map provides information to determine optimal zones for field surveying, targeting locations for new water supply sources, designing boreholes and wells and designing monitoring programmes to protect groundwater resources. The GWP map does not indicate precise sites where new boreholes can be built. It indicates where additional field exploration and investigation would be best conducted which can determine the final site and design of a new water supply borehole or well.

Example 1: Groundwater Potential Base Map – spectral chromatic scheme

The base visualization of the GWP model (Figure 22) is the spectrum mode recasting the model as a seamless gradient color scheme, ranging from dark blue ('highly favorable') to red ('less favorable').

Example 2: Groundwater Potential Zones Map – blue scheme

The GWP model can be recast to show four discrete zones of favorability, ranging from 'less favorable' to 'highly favorable' (Figure 23). The below example shows the 4-class mode in sequential shades of blue to best show the order of magnitude for GWP. Zones with less favorable groundwater potential may still yield boreholes, but typically at a lower production rate and much higher risk of failure or loss of investment.

Example 3: Groundwater Potential Zones Map – chorochromatic scheme

For a quick discretion and comparison of zones with favorable and less favorable groundwater potential, the 4-class mode of the GWP model is recast using a chorochromatic red-yellow-green-blue (RYGB) color scheme (Figure 24). This GWP zone map example is useful for demonstrating categories and differences in zones and can be a useful guide for high-level planning of groundwater projects.

Example 4: High Groundwater Potential Zones Map

For a more targeted application of GWP, the model can be visualized to isolate the best classes of GWP—favorable and highly favorable areas (Figure 25). Based on the '4-class mode–blue', the 'moderate' and 'less favorable' zones are filtered out, leaving only the most important information for more rapid decision making. This example of the GWP zone map can be useful to planners and hydrogeologists to determine quickly where to prospect for larger scale water supply projects, such as high-yield water supply wells intended to deliver larger volumes to more people. This map example also helps identify optimal zones for small scale projects.

Figure 22. Groundwater Potential Map, base map example

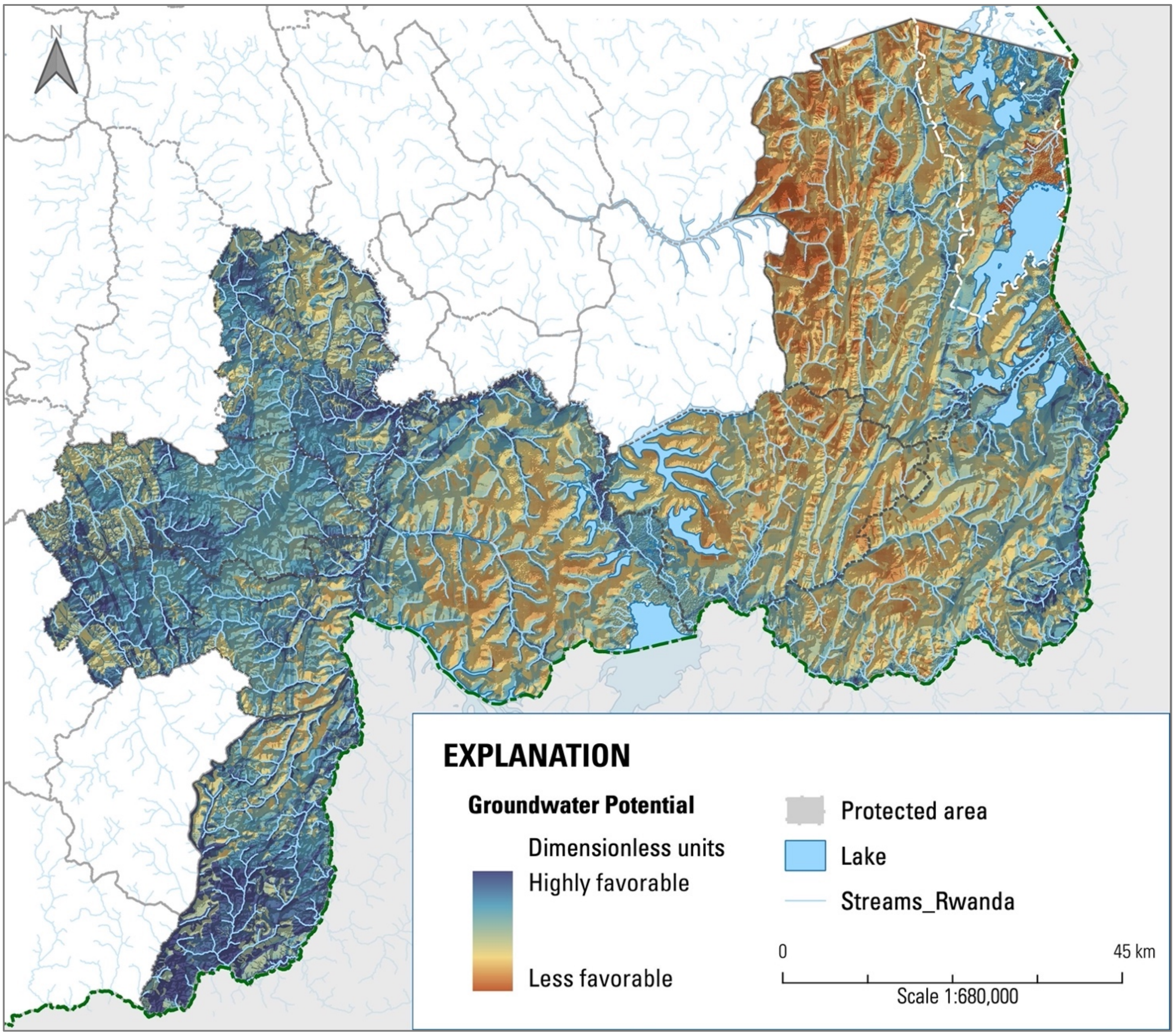


Figure 23. Groundwater Potential Zones Map, 4-class mode, blue scheme

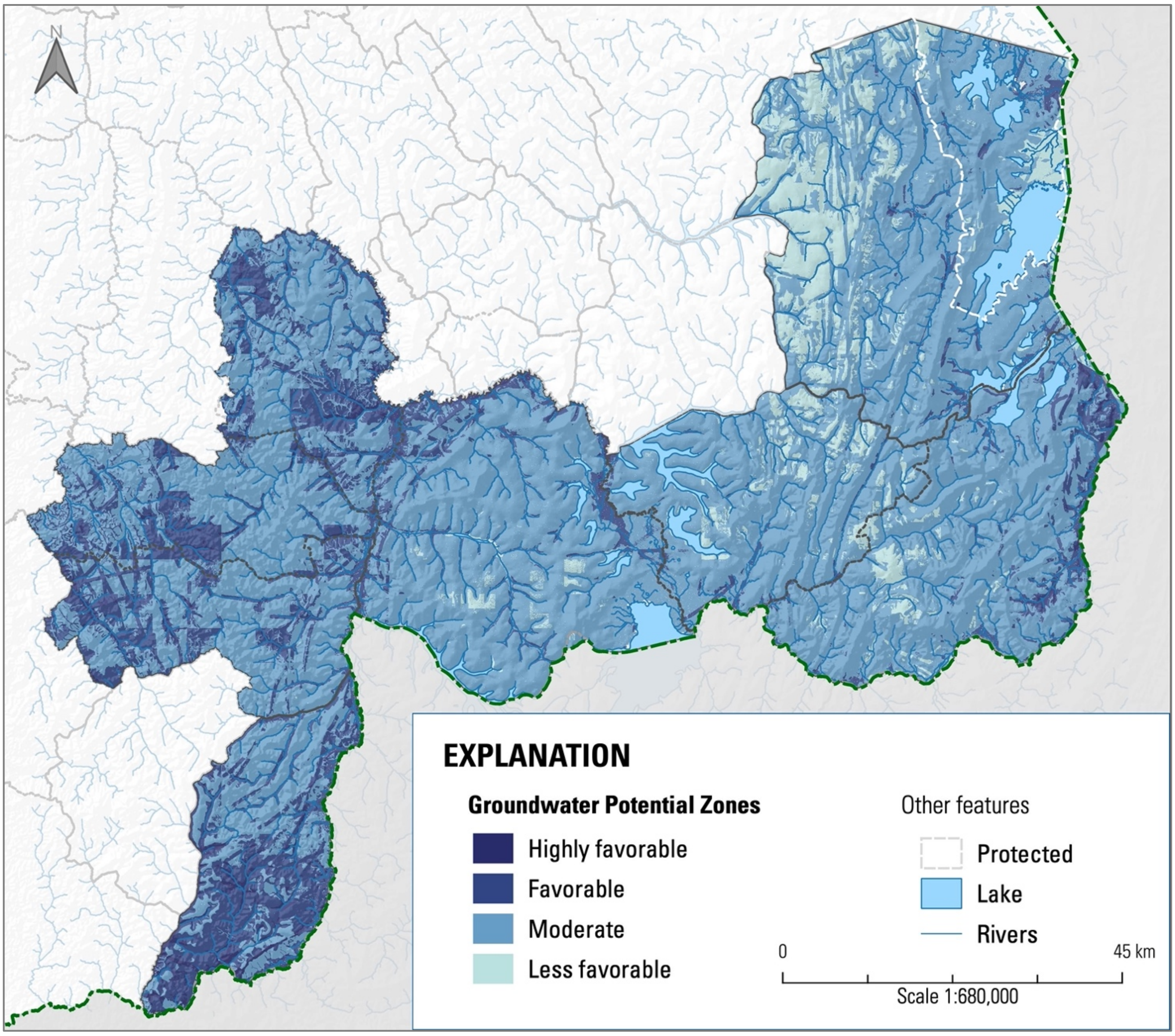


Figure 24. Groundwater Potential Zones Map, 4-class mode, RYGB scheme

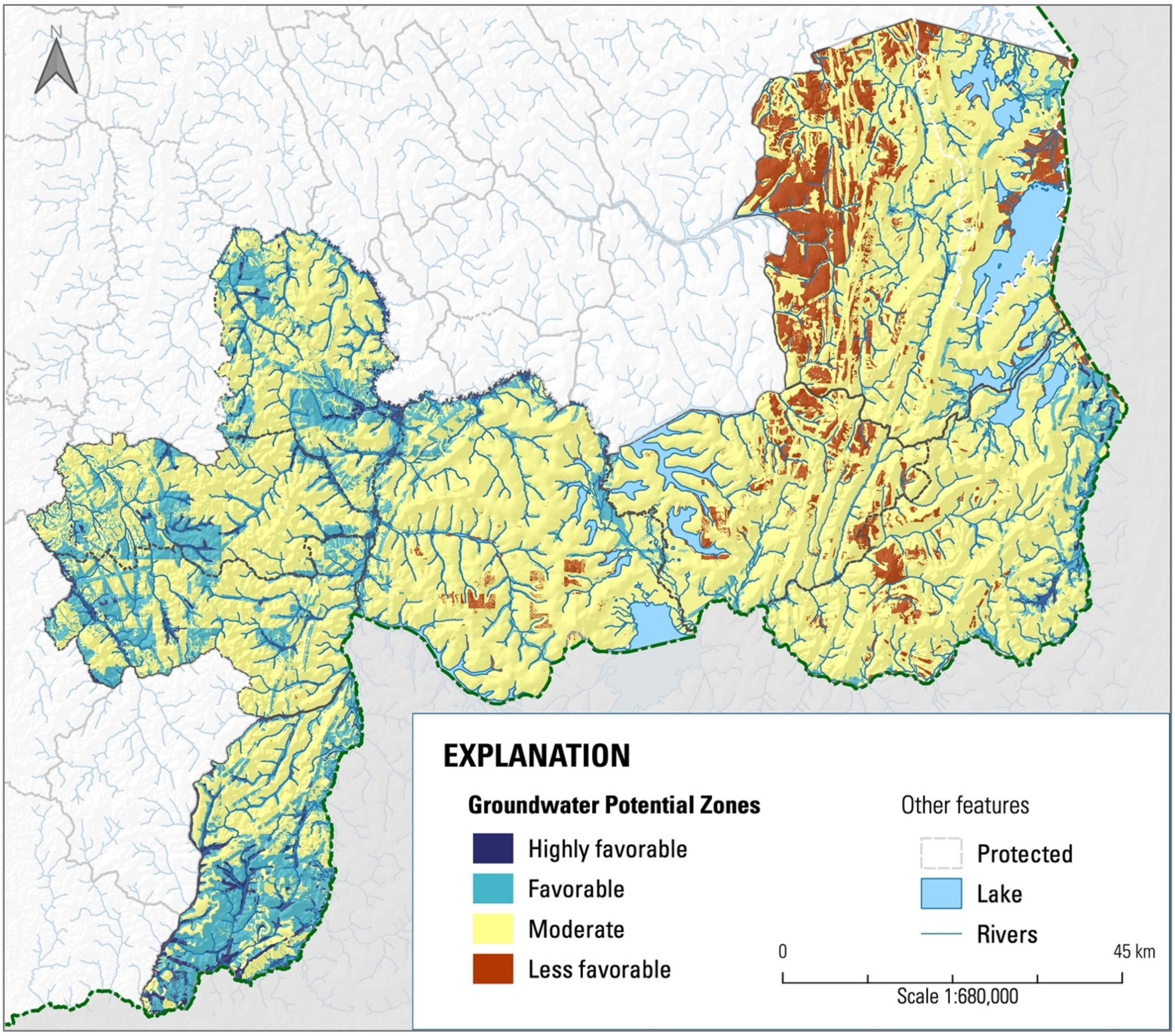
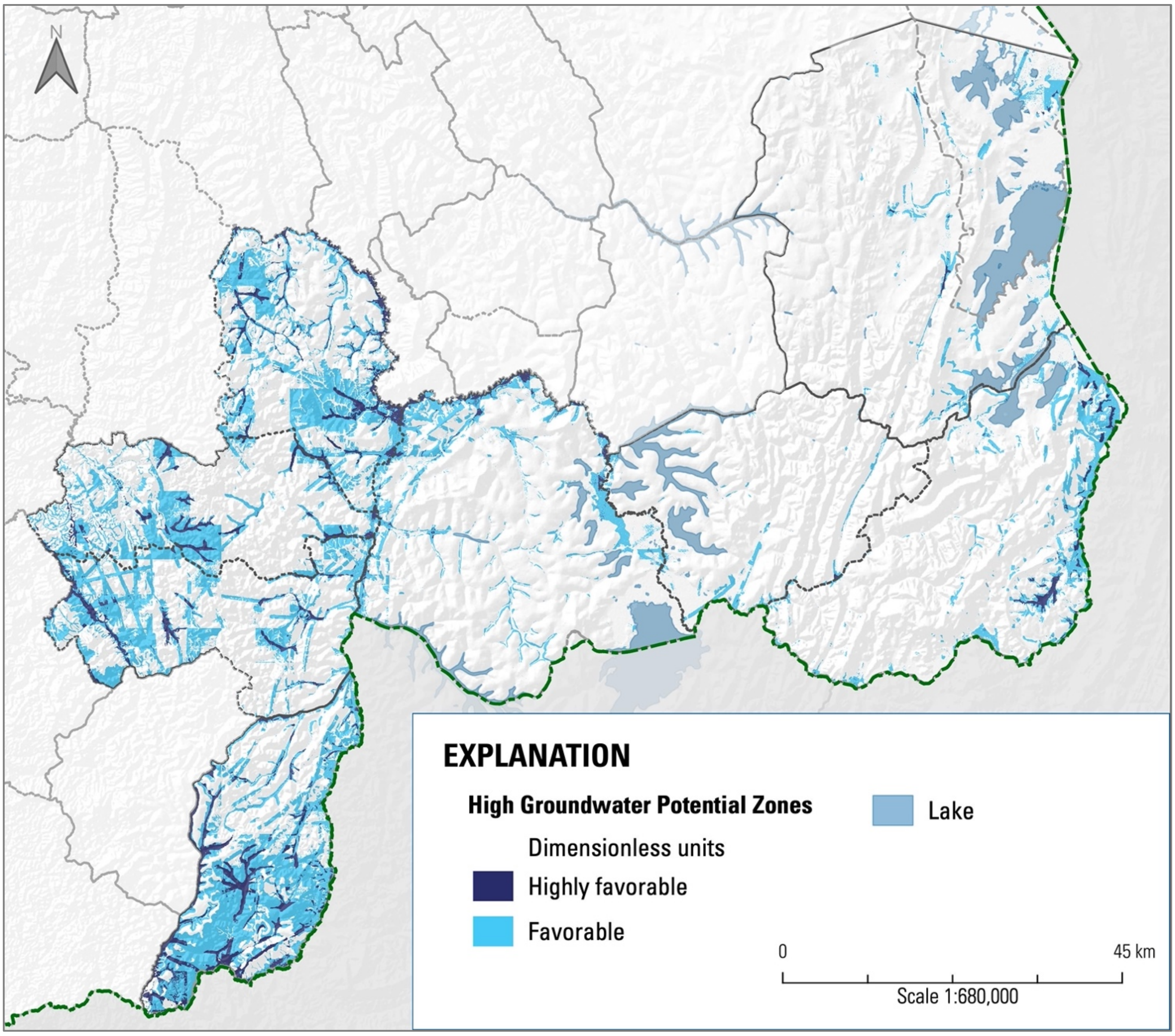


Figure 25. High Groundwater Potential Zones Map



Results and Discussion

Groundwater Potential in Southeastern Rwanda

Region

The results of the GWP model show variation across the study region, with notable differences between the western area (Kamonyi, Ruhango, Nyanza and Gisagara Districts) and the eastern area (Bugesera, Ngoma, Kirehe, Kayonza Districts), as summarized in Figure 26. Overall, the study region has 18% favorable- to very-favorable GWP, with less favorable areas accounting for about 8%. The areas with the highest potential appear to correlate with low-lying drainage network areas, unsurprising for this more arid region.

Southern Province (Amayaga Region)

From a groundwater potential standpoint, the four districts of Kamonyi, Nyanza, Ruhango and Gisagara in the Southern Province have very promising prospects for groundwater development (Figure 27). Altogether these districts have a favorable- to very-favorable GWP (42%). It's also worth noting that less favorable areas in the sub-region are negligible, accounting for only <1%.

Eastern Province

In contrast, the GWP model shows a varied situation in the southern portion of the Eastern Province (Bugesera, Ngoma, Kirehe, Kayonza Districts), see Figure 28. While all four districts here have some favorable and very favorable areas, most of the favorable areas are concentrated in Bugesera and Kirehe districts, each accounting for 11-12% favorable and most favorable GWP. Ngoma District has a significant portion of moderate GWP favorability (81%), while Kayonza appears to have the greatest area that is deemed less favorable GWP (22%), likely due to the prevailing aridity and limited groundwater recharge.

Implications of Groundwater Potential

The groundwater potential map can be used to help guide decision-making and planning related to the development and overall management of groundwater resources. The main applications of the GWP map are discussed further.

Groundwater development

The primary application of the GWP model is regional groundwater exploration. The GWP model can be used to identify optimum areas for siting new groundwater-based supply projects over a large region, and where to focus detailed site investigations to locate, design and install new boreholes. Groundwater exploration can be a costly endeavor, particularly at large regional scale where decisions about where to put a new borehole need to be made effectively. Figure 30 shows an example of application of the GWP model for identifying areas across a region that merit additional field investigation and where new supply boreholes could potentially be installed.

Groundwater management

The GWP model can be applied to help identify where to plan groundwater use, implement monitoring projects and groundwater protection zoning.

Aquifer science

The GWP model can also be used to identify where to conduct additional research on aquifers of strategic importance or with significant knowledge gaps.

Figure 26. Regional groundwater potential trends

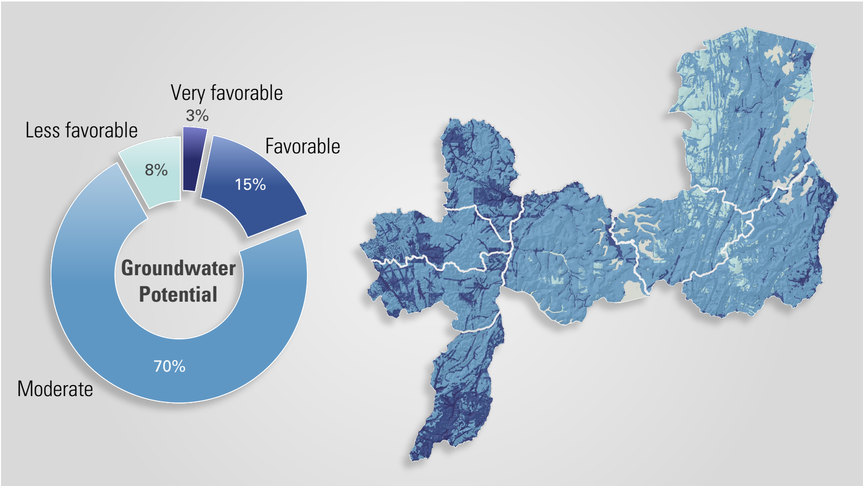


Figure 27. GWP in Kamonyi, Ruhango, Nyanza and Gisagara Districts in the Southern Province

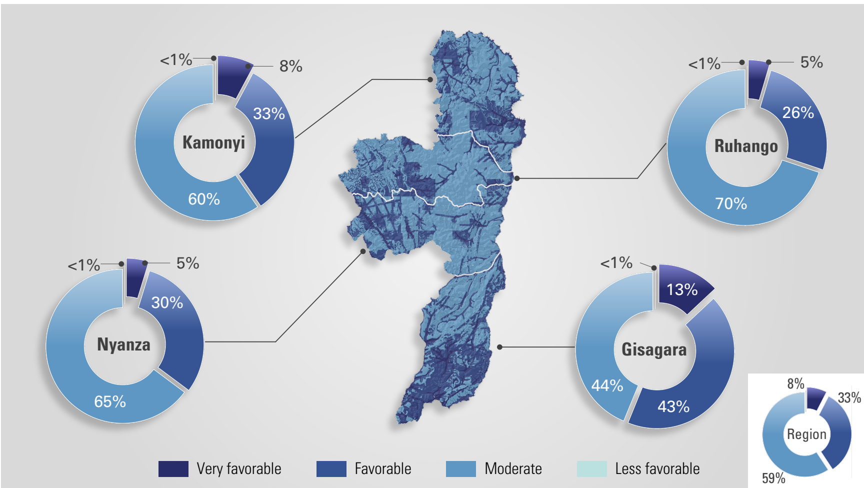


Figure 28. GWP in Bugesera, Ngoma, Kirehe and Kayonza Districts in the Eastern Province

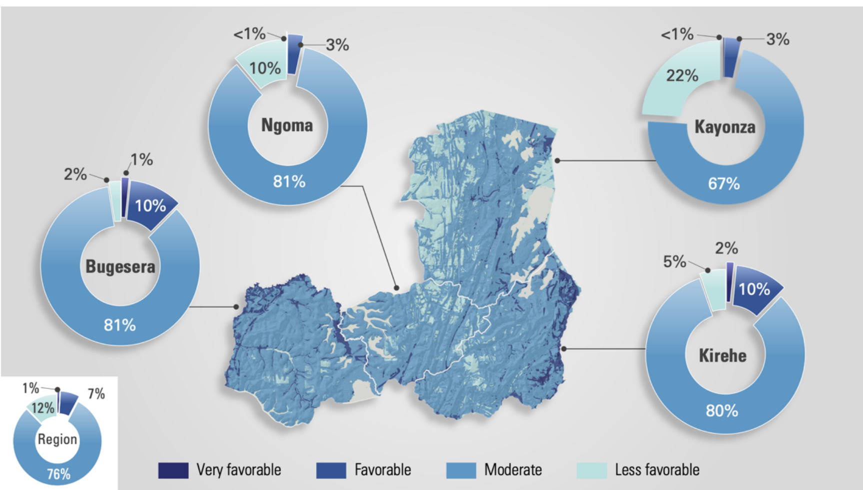
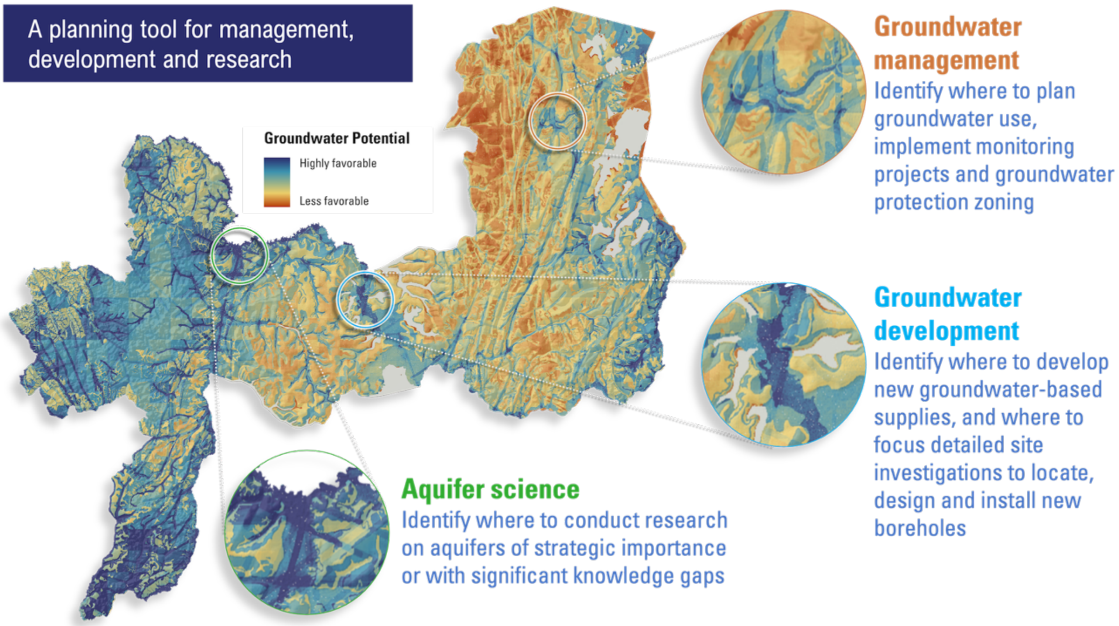


Figure 29. Applications of the Groundwater Potential Map



Summary

Reliable information describing the development potential of groundwater in the southeastern region of Rwanda is needed to resolve a variety of water resource issues including evaluation of target areas for groundwater development, prospecting for borehole sites, planning water supply systems, and monitoring. This report presents the method for estimating groundwater potential through multicriteria analysis and modeling, and presents maps of groundwater potential for the southeastern part of Rwanda to answer these needs.

The method of analysis used to determine groundwater potential in southeastern Rwanda relied on two types of readily available information: (1) raw satellite and processed data from remote sensing, and (2) ancillary data from official maps. Expert judgement also guided the development of key derived thematic layers and drove analysis, drawing from over 30 years of real-world successful application of the methods for groundwater exploration in similar hydrogeological settings.

Twelve thematic parameters related to the favorable conditions that make groundwater 'available' for development were developed, which form the building blocks of the groundwater potential model. Two component models—hydrogeologic favorability and recharge favorability – were combined for use in the indexation of the groundwater potential model.

The Groundwater Potential Map aims to make groundwater exploration in southeastern Rwanda as efficient as possible. The map is a first-level approximation of conditions favorable for a water supply system to be built and operated. It tells the hydrogeologist where to go to focus field exploration that will enable a new well or borehole to be sited. In the fractured bedrock setting of southeastern Rwanda, areas with favorable groundwater potential are those where constructing a productive, sustainable water supply well is most likely to succeed and carries lower risk. By contrast, areas with less favorable groundwater potential are those where conditions for installing a new well are less than optimal and pursuing development carries higher risk.

The results of the GWP model show variation across the study region, with notable differences between the western area (Kamonyi, Ruhango, Nyanza and Gisagara Districts) and the eastern area (Bugesera, Ngoma, Kirehe, Kayonza Districts). Overall, the study region has 18% favorable- to very-favorable GWP, with less favorable areas accounting for about 8%. The areas with the highest potential appear to correlate with low-lying drainage network areas, unsurprising for this more arid region.

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Appendix A. Site Selection for Detailed Study and Drilling

Introduction

The Groundwater Potential (GWP) model and map developed under this project provides reliable information on GWP for the purpose of guiding regional exploration towards the drilling of groundwater-based water supply boreholes and wells. Applying the GWP map to determine areas where groundwater can be developed is a primary use of the map, and the next iterative step in the exploration of borehole sites across large regions.

Making decisions on where to focus resources for field investigation and drilling boreholes must take into account a variety of information ranging from field conditions, estimated water availability, supply needs, project goals and local priorities. To help process these criteria and guide the process towards determining the areas to target for new boreholes, the consultant began a study to develop a method of selecting sites for detailed studies and drilling.

Purpose and Scope

The purpose of this annex report is to present a method for selecting target areas in the study region with the use of the GWP map. The project assignment called for the development of a regional groundwater potential map along with detailed field investigations and identification of potential sites for drilling new boreholes in five target areas (TA). The method of analysis used to determine the location of TAs relied on the use of the regional GWP map and expert analysis of favorable conditions. Ranking and evaluating the most suitable TAs for this project relied on an overlay analysis of GWP and socio-economic parameters, while a collaborative process with stakeholders helped decide on a final selection of TAs for the project.

Background

Definition of a Target Area

A Target Area (TA) is a smaller, more focused area within a larger exploration region which has been identified for additional detailed study and potentially developing groundwater supply systems. For this project, TAs of approximately 10 km^2 are being identified and prioritized to conduct field investigation and the siting of 10 new boreholes.

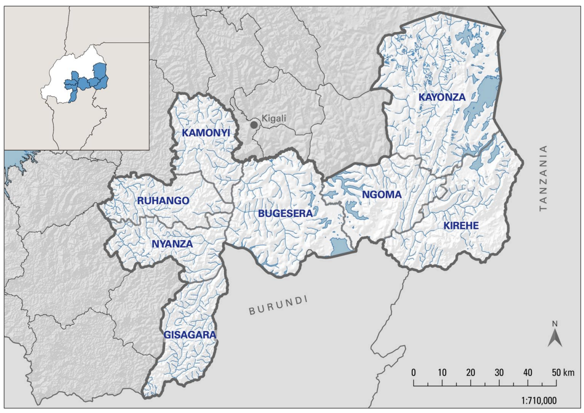
Need for Target Areas in Regional Borehole Siting

In regional exploration for new borehole sites, the GWP map provides the regional basis to identify more focused areas within which to direct next-level investigations and planning of water supply projects. Exploration experts use the GWP map and other information to identify TAs across a large region. TAs enable resources and investment to be focused where the conditions for groundwater development are best and risk for project failure are most mitigated. Without identifying TAs, efforts to study and investigate prospects for installing new boreholes, and certainly drilling, would carry significant risk of failure and unsatisfactory results.

Description of Study Area

The study area is recalled here as the eight districts in southeastern Rwanda (Kamonyi, Ruhango, Nyanza, Bugesera, Ngoma, Kirehe and Kayonza), and is described in the main report above. For the purpose of site selection, the task was to identify five (5) Target Areas within this study area.

Figure 30. Study region where Target Areas are to identified and selected



Study Methods

Approach

A 5-stage exploration process has been developed to guide the identification of potential drilling sites over a region starting from the GWP model. This process has been applied to fit the specific objectives of the present project, which are to identify 10 sites for new boreholes to be drilled across five (5) different areas within the study region. However, this approach could be adapted to other projects with similar objectives.

The flow chart of the staged sequence for selecting sites for detailed studies and drilling is presented in Figure 31. Candidate Target Areas were first derived from the GWPM and exclusion of undesirable areas. A ranking of the candidate Target Areas was then developed based on a numerical spatial analysis and a measure of exploration prospects. A set of socio-economic criteria overlays were then used to evaluate and rank the top tier candidate Target Areas, providing a list of 24 TAs from which to make a final selection for this specific project.

This project plans for a set of 5 TAs to be evaluated by the expert consultant, where field investigation and geophysical surveying will be conducted, and a final 10 potential sites for drilling new boreholes / wells can be targeted.

Identifying Target Areas with Good Groundwater Potential

The first stage of regional exploration is to identify the candidate Target Areas that may be considered for further field investigation and potential siting of boreholes. This stage begins with the setting up of the GWP model, followed by the creation of an Exclusion Overlay, and using an expert decision-process to outline polygonal areas.

Setting the base GWP model

The process of identifying Target Areas across the study region begins with setting up the GWP model as the base layer (left image in Figure 33). Using a histogram analysis, the GWP model is recast to isolate the top two categories of GWP – "highly favorable" and "favorable" (right image in Figure 32).

Figure 31. Procedures used to select sites for detailed studies and drilling

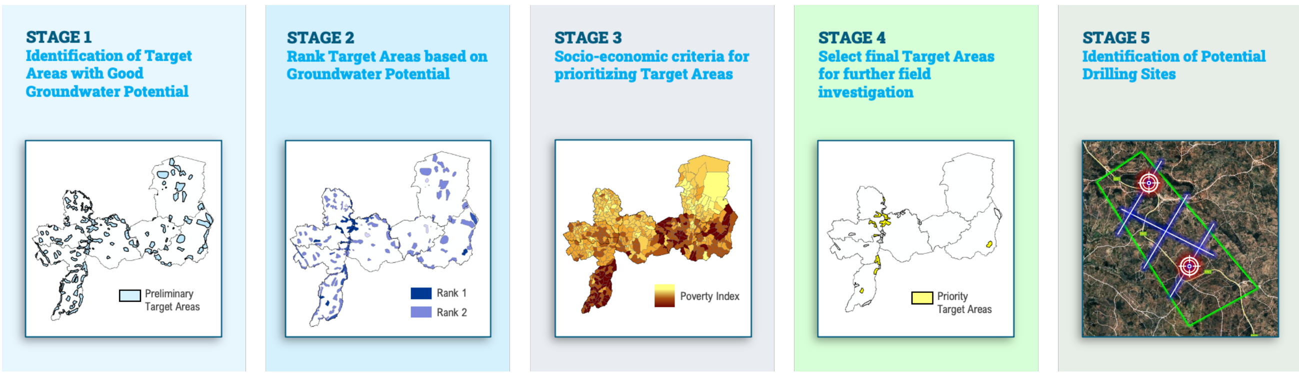
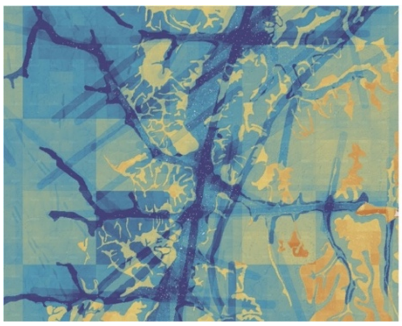
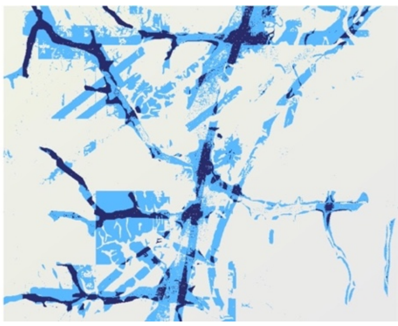


Figure 32. Setting the base GWP model (left) and GWP high-favorability model (right)





Preparation of the Exclusion Overlay layer

A preliminary step in regional exploration is to filter out, or exclude, areas that are not conducive to developing a new well or borehole. These exclusion areas are the areas that are most preferrable to avoid for further investigation or drilling, and include such areas where a drilling rig cannot pass due to an obstacle or steep slope, and areas where it is not possible to place a new borehole.

A composite Exclusion Overlay (Figure 33) is created from combining two raster image masks—(1) slope derived from SRTM DEM [30-m], and (2) unfavorable land derived from water bodies, flooded vegetation and built-up classes of a Land Cover map based on Dynamic World V1, based on Sentinel-2 L1C [10-m].

The Exclusion Overlay can be considered as a first-level reality-proofing of the GWP model for exploration purposes.

Identification of Target Area polygons across the study region

Using expert judgement and analysis, polygonal areas are carefully drawn to maximize GWP and minimize undesirable areas (Figure 34). Other tools such as lineament map, TWI and topography map are used as reference layers. The new TA polygons may include minor amounts of excluded area and/or lower GWPM value areas. Such TAs are candidates for more detailed investigation to confirm their favorability for groundwater resource extraction, and determine specific sites for exploratory test well drilling.

Figure 33. Exclusion Overlay derived from slope and unfavorable land masks

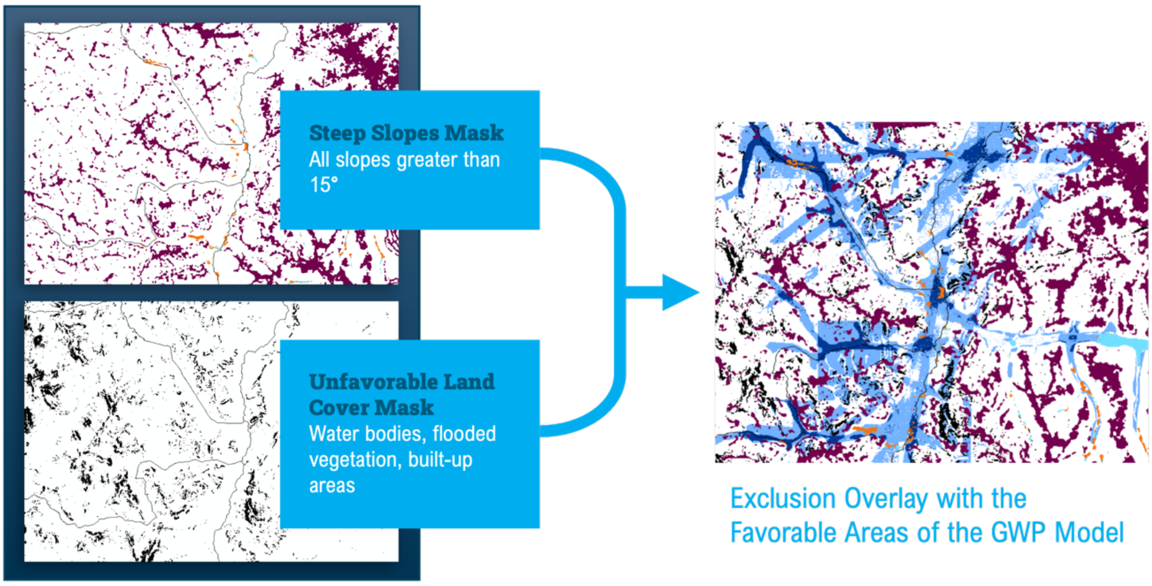
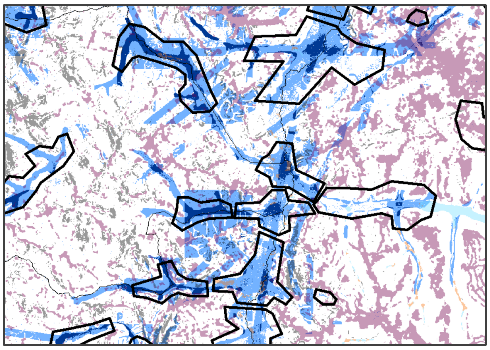


Figure 34. New TAs identified with Exclusion Overlay and Favorable Areas of the GWP model



Target Areas Identified

Following this process, a total of 126 individual Target Areas have been identified as candidates across the study region, having favorable groundwater potential and minimal undesirable conditions for drilling a new borehole (Figure 35). In an effort to build on Sloots (2019), some 23 TAs identified under that project were included in the set of identified TAs. Six (6) of Sloots (2019) TAs were merged with new TAs identified. It should be noted that the project objectives in Sloots (2019) and the current projects were different and therefore the target areas did have much coincidence.

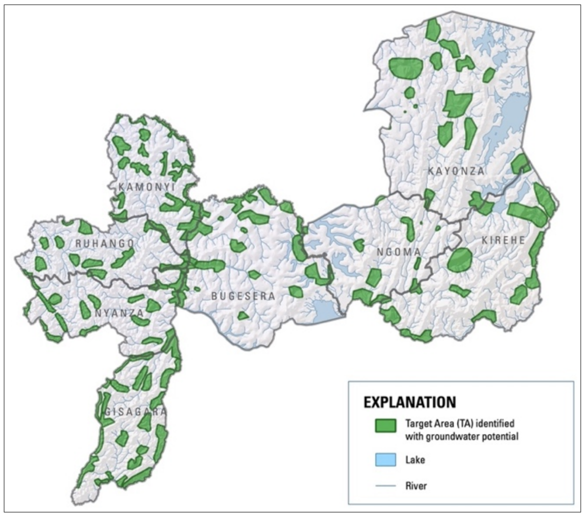
The identified TAs have a mean extent area of 9.9 km², and range from 0.14 to 43.3 km² in extent.

This initial set of 126 Target Areas is a significant milestone for exploration in southeastern Rwanda, showing the first-level analysis of where groundwater development efforts can be pursued across the region with higher probability of success and lower risk. The map of 126 Target Areas can be used as the starting point for stakeholders to plan future investigations and drilling projects in Bugesera, Ngoma, Kirehe, Kayonza, Kamonyi, Ruhango, Nyanza, Gisagara Districts.

Ranking Target Areas based on Groundwater Potential

The set of candidate Target Areas is ranked in order of preference for groundwater potential. This stage of the process is an important step in understanding which areas have the best, most favorable conditions for groundwater development and which have potentially more available water. The ranking is achieved using a combination of numerical-spatial parameters and a measure of exploration prospectiveness.

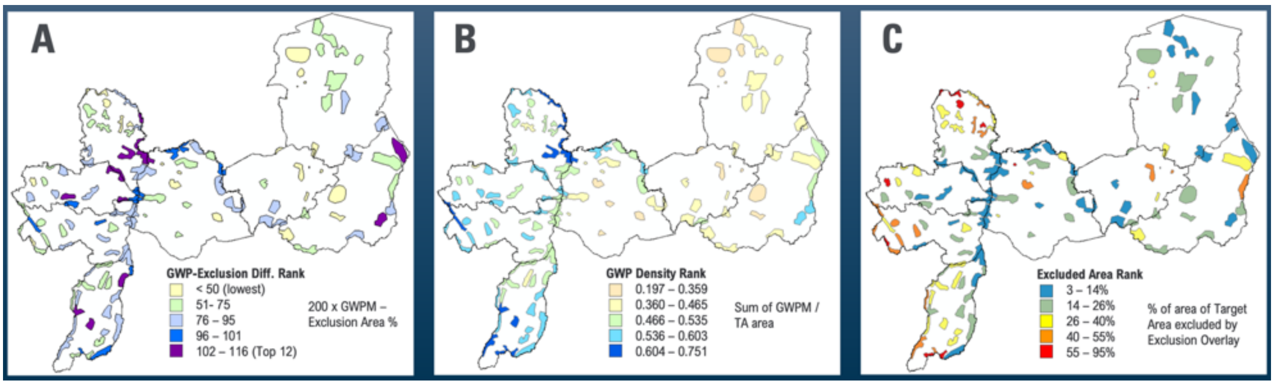
Figure 35. Target Areas (TA) identified with groundwater potential



Numerical-spatial analysis

Using the GWP model values, the total area (km²) of each TA, and the area precluded by exclusion overlay (km²), the parameters of (1) GWP-exclusion differential, (2) GWP density and (3) excluded area were calculated. Figure 36 shows the results for each ranking of numerical-spatial analysis.

Figure 36. Ranking of TAs by (A) GWP-Exclusion Differential, (B) GWP density, and (C) Excluded area



Exploration prospectiveness

The 'exploration prospectiveness' was calculated for each TA, giving an additional measure of the potential opportunity for groundwater development inside the target areas. Experts conducted a desk study consisting of analysis of hydrogeology, geology, faults, lineaments and hot spots of each singular Target Area to identify a total of 224 Potential Test Well Areas (PTWA), defined as 500-m radius areas where key hydrogeologic and land use conditions favor the continued exploration efforts (Figure 37, right). For rating exploration prospectiveness of each TA, the quantity of Potential Test Well Areas (PTWAs) present in each TA was used to rank TAs based on exploration prospects.

Combined ranking of Target Areas based on GWP

A final ranking of GWP was calculated considering the values for GWP, the TA area (km²), GWP-Exclusion Differential and exploration prospectiveness, using the mathematical formula:

$$GWP\ SCORE = GWP\ exclusion\ differential + Exploration\ prospectiveness$$

Re-formulated as:

$$GWP\ SCORE = ((GWPM \times 200) - (Area\ \%\ Excluded)) + (Qty\ PTWA \times 4)$$

The resulting rank of 126 TAs based on GWP was split into four tiers corresponding to varying categories of GWP score (Figure 38). The best ranked TAs are Tier 1 (ranked 1 – 10), and Tier 2 (ranked 11-24). The scored values for the top 24 TAs is provided in Table 14.

The goal of the project being to pre-select 10 Target Areas, ranking the TAs by GWP allowed for the large number of TAs to be distilled to the top two tiers (top 1-24 TAs) so that further analysis can focus on the more favorable TAs (Figure 39).

Figure 37. Identification of (1) favorable structure (1), and Potential Test Well Areas in Target Areas (2-4)

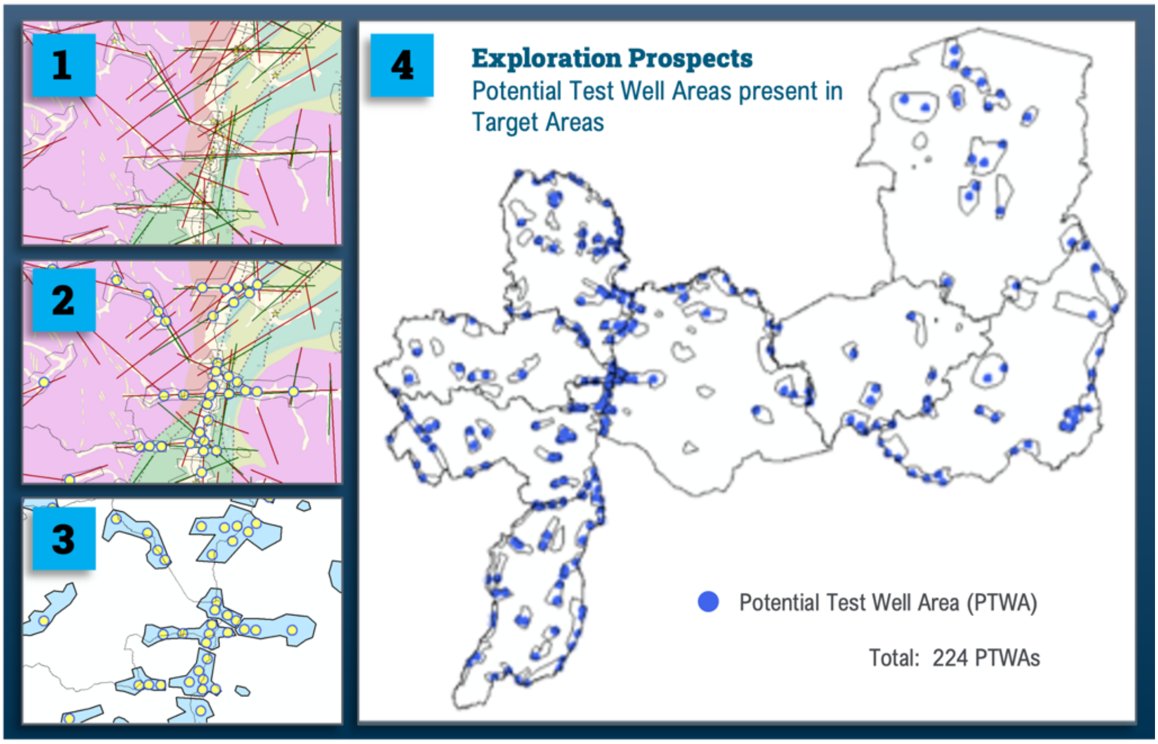


Figure 38. Target Areas ranked by GWP

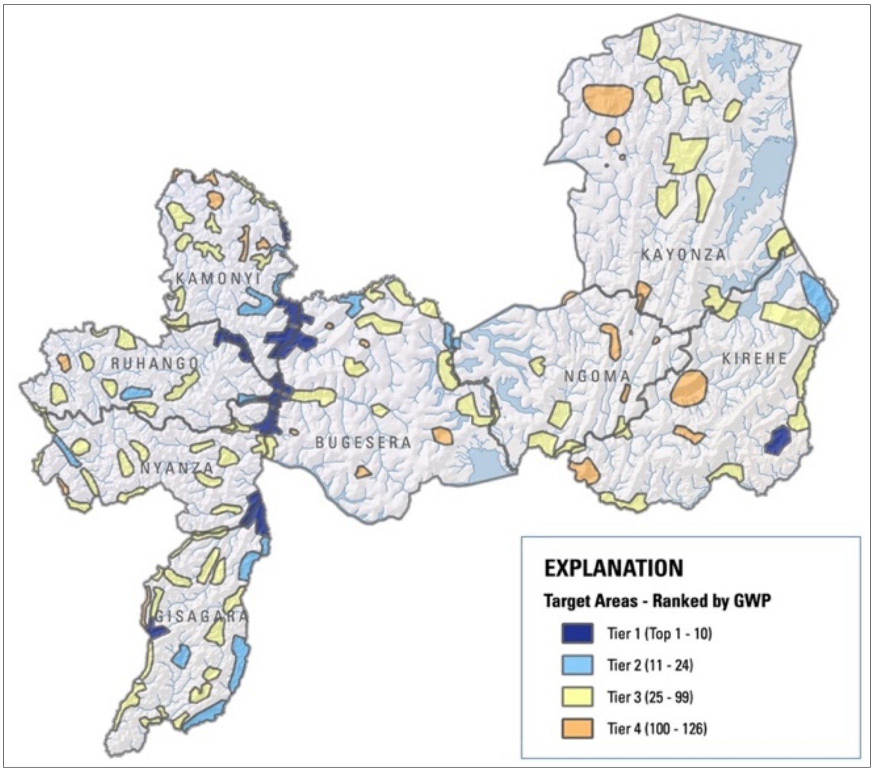
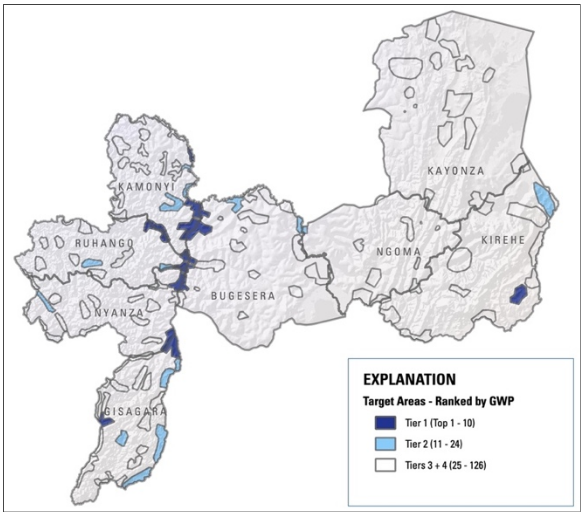


Table 14. GWP ranking scores of the top 24 Target Areas

Name	AREA(m2)	GWP	ExSlope	ExWater	ExFldVeg	ExBuilt	Qty PTWAs	RankGWP-Excl+PTWAs
HN6	16,955,816	0.623	4.05	2.37	0.79	2.43	7	143
HN49	16,254,016	0.571	1.86	0.00	1.89	4.82	4	122
HN33	30,658,925	0.508	1.65	0.41	0.27	3.95	7	123
HN16	14,646,594	0.555	0.00	0.00	0.00	6.56	5	125
HN43	3,833,947	0.751	4.18	5.77	0.00	23.90	2	124
HN48	15,598,194	0.620	13.87	0.00	0.00	7.28	3	115
HN1	8,542,962	0.570	3.06	1.25	1.18	3.29	5	125
HN24	22,383,407	0.496	1.29	0.02	0.08	6.14	7	120
HN0	8,515,637	0.588	1.00	1.46	5.76	1.13	4	124
HN34	7,683,028	0.655	5.29	0.04	0.28	15.09	2	118
HN52	9,108,203	0.594	3.18	0.00	0.00	7.87	2	116
HN35	8,525,282	0.693	25.41	0.00	0.00	3.25	2	117
HN2	13,426,327	0.535	0.76	1.31	5.76	5.40	6	118
HN38	15,123,222	0.545	2.61	1.87	4.43	1.32	3	111
HN39	11,238,556	0.526	2.01	0.18	0.00	1.30	2	110
HN7WE4	11,416,265	0.570	0.76	3.36	0.21	8.89	3	113
HN5	7,603,002	0.664	28.70	0.20	0.39	3.14	3	112
HN50	5,734,437	0.545	1.03	0.05	0.09	5.10	2	111
HN32	20,128,602	0.566	21.77	0.13	0.11	0.79	4	106
HN18	3,530,394	0.640	8.19	4.13	0.03	21.21	3	107
HN105	26,690,329	0.535	1.95	0.44	2.57	0.26	2	110
HN8	8,450,445	0.544	2.62	5.42	0.47	0.02	2	108
HN80	4,215,573	0.559	6.09	0.23	0.00	8.54	2	105
HN47	5,223,590	0.615	12.17	6.01	0.69	2.31	1	106

Figure 39. Top 24 TAs ranked by GWP



Socio-economic criteria for prioritizing Target Areas

In order to balance concerns for water availability and water demand and guide the selection of most suitable TAs, the top 24 TAs were scored according to both GWP and socio-economic criteria. Based on a review of easily accessible spatial datasets, a set of four socio-economic parameters were selected for this exercise: (1) Population, (2) Poverty, (3) Infrastructure, (4) Priority areas for development given by the Rwanda Water and Sanitation Corporation (WASAC). Data sources are provided in Table 15.

Table 15. Socio-economic overlay data sources

Theme	Parameter	Data source
Population	Proximity to people and settlements	High resolution settlement layer (2020)
Infrastructure	Proximity to existing water supply networks	Water supply pipelines derived from JICA (2020) and WASAC (2022)
Poverty	Local livelihoods	Poverty Index by Sector, Rwanda National Institute of Statistics (2014)
High demand areas	Areas that need new water supply developed	WASAC defined priority sectors (2022)

The method applied was a spatial overlay analysis approach in GIS to compute the geometric intersection of the Target Area and the Socio-economic overlays. First, the extent of the TAs was enlarged by 1-km because any substantial new water supplies may be easily distributed within a 1-km distance at reasonable cost. Then, for each of the top 24 TAs, the following process was followed: (1) a trial for each socio-economic parameter was executed to compute numerical values, (2) then values were normalized, and then (3) a sum of all four trials was computed to give a total score for each TA. The trial run for each socio-economic parameter is summarized below.

Target Areas and Population

Population was calculated using numerical spatial analysis of high-resolution settlement data (2020) in relation to the enlarged TA. Figure 40 provides a graphical overview of this trial.

Target Areas and Infrastructure

The underserved population within TAs were mapped and calculated. This represents the estimated population within the buffered TA area that is not located within 250m of an existing water pipeline. High resolution settlement data were used to estimate population values. The infrastructure overlay was derived from the pipeline network vector layers combined from JICA and WASAC, and buffered by 250 m. Values for underserved population were computed from the sum of population overlay area inside the TA that does not intersect with the infrastructure overlay. Figure 41 gives a graphical overview of the trial.

Target Areas and Poverty Index

Values of Poverty Index within the Target Areas were calculated using the Poverty Index by Sector overlay (Rwanda National Institute of Statistics (2014)). The Poverty Index map gives class values for each sector. A weighted mean of PI values was computed for each TA, resulting in the layer in Figure 42.

Target Areas and High Demand

High demand areas (Figure 43) were analyzed using a vector overlay of areas identified by WASAC where additional water supply is needed or planned. The dataset comprised of 17 sectors and one whole district (Kirehe). The areas intersecting Target Areas were computed. It is noted that 15 of the top 24 TAs (Tier 1 and 2) occur within or proximal to many of the WASAC priority areas. All but two of the Top 10 (Tier 1) from hydrogeologic considerations occur where additional water supply is needed.

Socioeconomic Ranking

Socio-Economic Weighting of the Top 24 Target Areas Numeric values were calculated for the TAs based on population, population located further than 250m from an existing pipeline, Poverty Index, and proximity to WASAC Priority Areas (Table 16). The values were then normalized and summed to provide a final socio-economic score for each of the Tier 1 and 2 TAs. The higher the value, the better.

Figure 40. Target Areas and Population Distribution

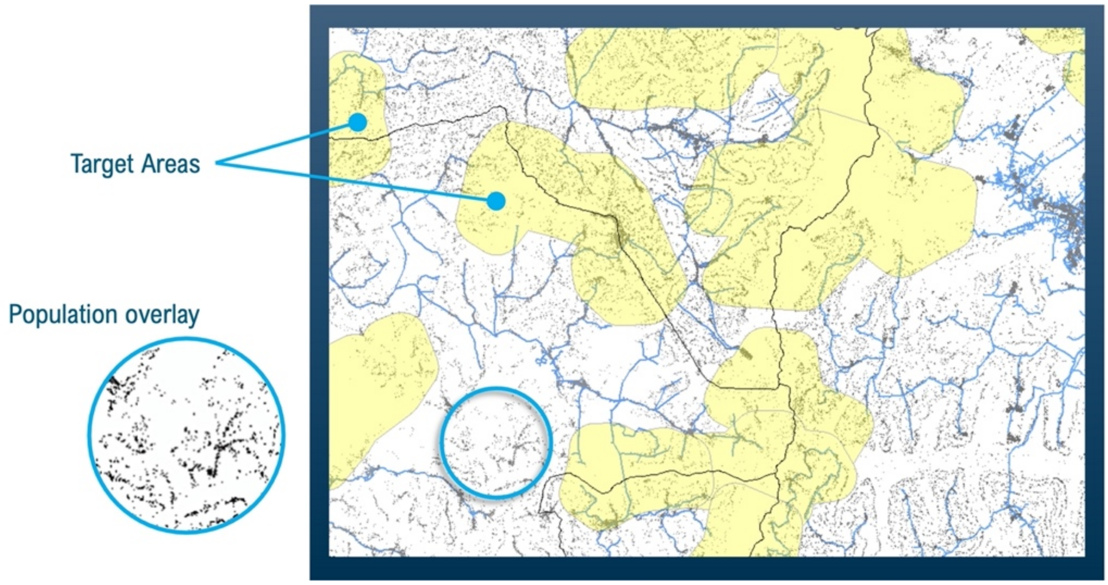


Figure 41. Target Areas and Infrastructure overlay analysis

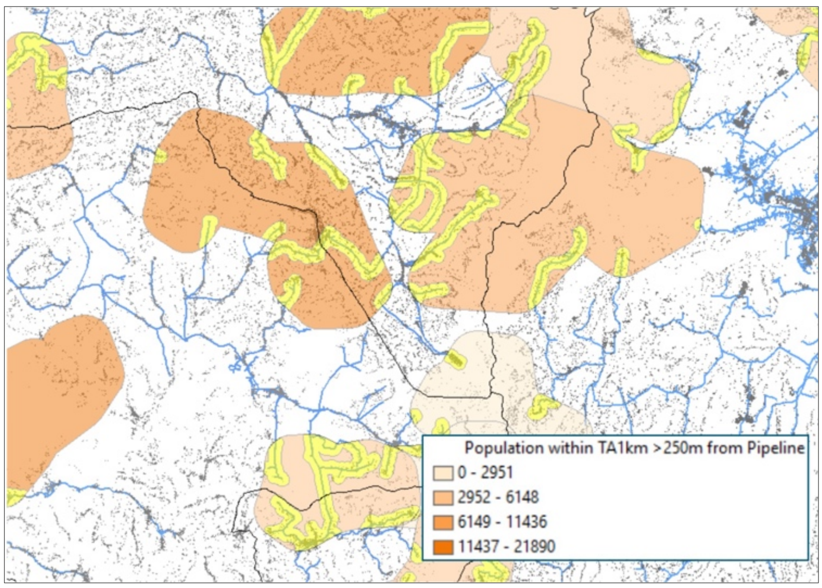


Figure 42. Target Areas and Poverty Index by Sector

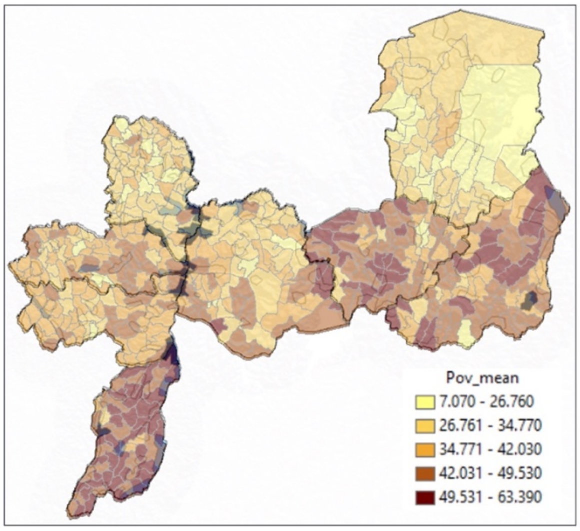


Figure 43. Target Areas and High Demand Areas (Source: WASAC)

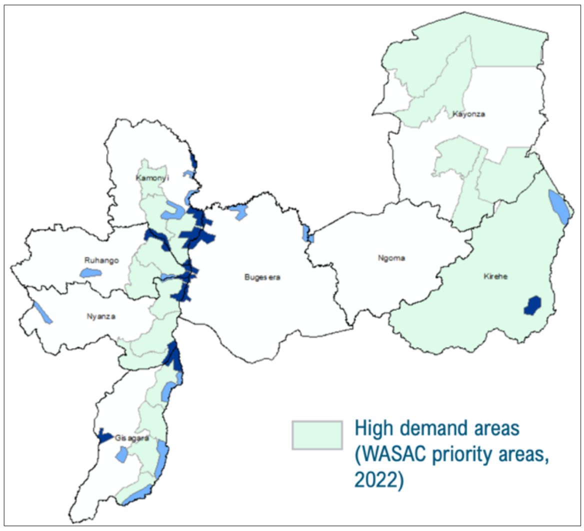


Table 16. Socio-economic ranking scores of top 24 Target Areas

Name	Population	Population > 250m from Infrastructure	Poverty Index Weighted Mean	WASAC Priority Areas	SE Rank, Normalized (0-4)
HN6	9,863	3,333	34.0	8	1.87
HN49	31,396	21,890	37.0	8	3.46
HN33	19,641	9,964	37.0	5	2.24
HN16	15,931	2,309	39.0	10	2.31
HN43	8,209	11,436	28.0	0	1.28
HN48	21,036	15,548	39.0	8	2.88
HN1	6,870	1,201	44.0	8	1.86
HN24	16,917	5,080	40.0	10	2.49
HN0	6,089	1,221	41.0	8	1.78
HN34	19,337	2,415	43.0	0	1.49
HN52	18,989	7,170	42.0	0	1.68
HN35	8,563	5,506	56.0	2	1.72
HN2	9,073	4,398	47.0	8	2.13
HN38	13,533	5,354	35.0	10	2.30
HN39	9,872	6,027	45.0	10	2.39
HN7WE4	9,821	4,951	29.0	0	1.06
HN5	11,650	3,291	35.0	0	1.15
HN50	10,098	3,418	42.0	10	2.23
HN32	10,393	6,668	44.0	10	2.42
HN18	15,589	5,316	29.0	0	1.26
HN105	427	427	40.0	10	1.75
HN8	3,155	2,542	33.0	0	0.81
HN80	2,844	2,504	35.0	10	1.83
HN47	4,566	3,181	21.0	0	0.67

Combined GWP and Socioeconomic ranking

The top 24 Target Areas (Figure 44) were weighted and ranked by a combination of scores from GWP and socio-economic parameters (Table 17). Values for socio-economic ranking were normalized by a factor of 10 before mathematically added with the GWP values to arrive to the final score.

Figure 44. Top 24 Target Areas ranked by GWP and socio-economic parameters

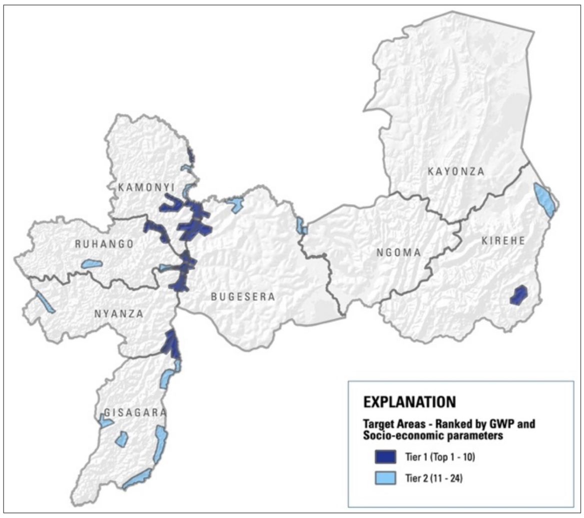


Table 17. Combined GWP and socioeconomic ranking of top TAs

Name	RankGWP-Excl+PTWAs	SE Rank, Normalized (0-4)	GWP Rank + 10*SE Rank
HN6	143	1.87	161.63
HN49	122	3.46	156.49
HN33	123	2.24	145.30
HN16	125	2.31	147.97
HN43	124	1.28	136.75
HN48	115	2.88	143.65
HN1	125	1.86	143.46
HN24	120	2.49	144.73
HN0	124	1.78	141.69
HN34	118	1.49	132.81
HN52	116	1.68	132.69
HN35	117	1.72	134.07
HN2	118	2.13	139.15
HN38	111	2.30	133.90
HN39	110	2.39	133.79
HN7WE4	113	1.06	123.48
HN5	112	1.15	123.35
HN50	111	2.23	133.15
HN32	106	2.42	130.21
HN18	107	1.26	119.48
HN105	110	1.75	127.35
HN8	108	0.81	115.96
HN80	105	1.83	123.19
HN47	106	0.67	112.59

Selection of final Target Areas for further investigation

Stakeholder consultation

The method to select identify, rank and analyze Target Areas within the project study region was presented and approved by a multi-stakeholder panel during a UNICEF Validation Workshop held on 6-7 September 2022 in Kigali. The panel was led by project beneficiary and lead coordinator, Rwanda Water Resources Board (RWB), with Rwanda Water and Sanitation Corporation (WASAC) also participating. The panel reached a consensus that the approach to select Target Areas in the region is a reasonable all-round approach because it reflects best both water availability (supply) and socioeconomic needs (demand) across the study region. Furthermore, the panel approved the resulting sample of 10 Target Areas proposed for further investigation and drilling in this project (Figure 45, left) and recommended that WASAC review and provide the final list of 10 Target Areas.

In a follow up meeting with WASAC representatives on 7 September, WASAC confirmed the preferences and priorities for water development and made a slight amendment to the list of 10 Target Areas slightly, swapping out TA HE 43 with HE 34. The final list and map of Target Areas approved is provided in Figure 45, right.

Selection of final 5 Target Areas for further investigation and drilling

An expert team of representatives of consultant, RWB and WASAC undertook field reconnaissance from 8-16 September 2022 to review conditions and suitability of the ten (10) approved Target Areas and make a final selection of the five (5) most optimal Target Areas for additional field investigation and siting under this project. The resulting final list of 5 Target Areas is provided in Figure 46.

Identification of Potential Drilling Sites.

Under the scope of the project, 10 potential sites for drilling new water supply boreholes and wells will be identified across the 5 Target Areas. The consultant shall conduct a field campaign to perform field reconnaissance, desk study, geophysical surveying and analysis in these Target Areas. The resulting borehole sites for this project will be determined, along with recommendations for test drilling, pump testing, drilling and construction methods, and supervision that should be followed to ensure success of the new borehole systems.

Figure 45. Target Areas recommended by stakeholders (left), and selected and approved by WASAC (right)

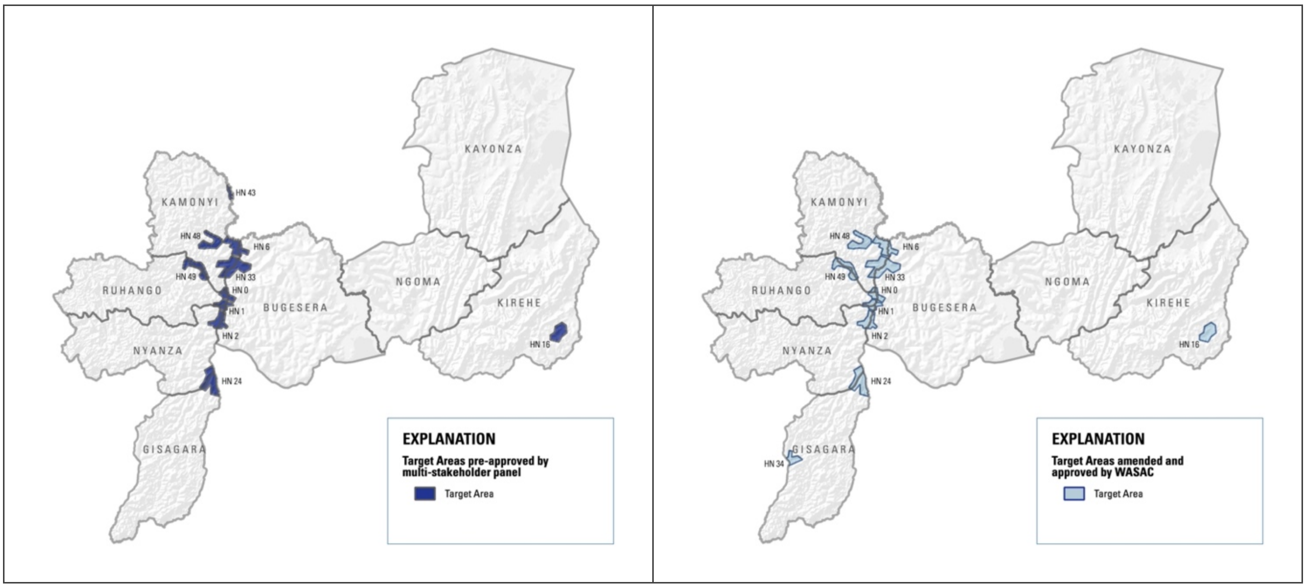
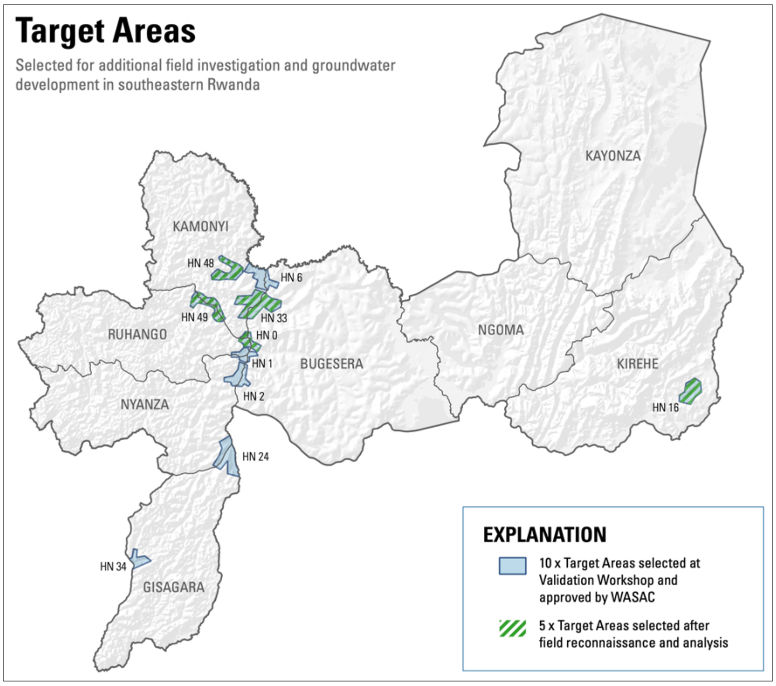


Figure 46. Target Areas (5) selected for additional investigation



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