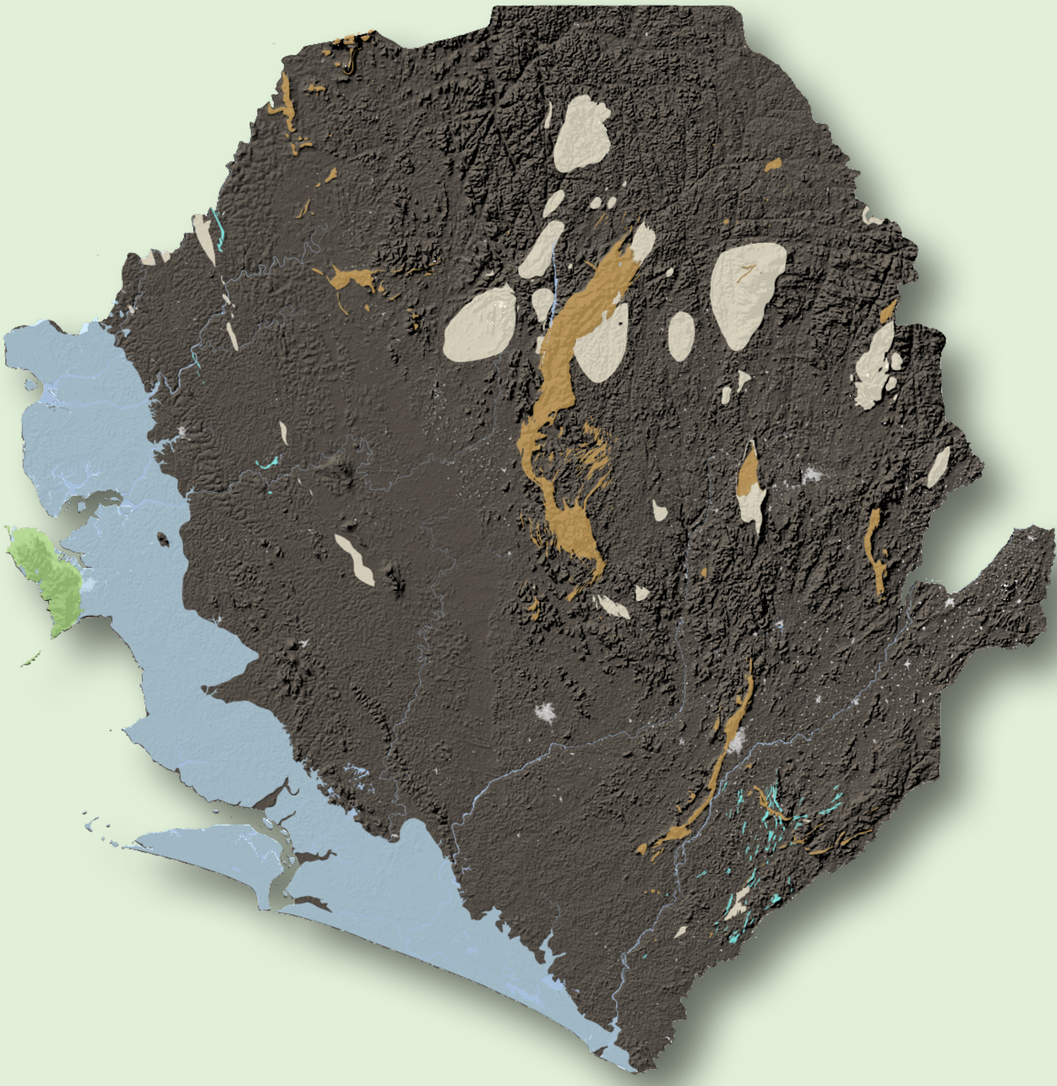
Ministry of Water Resources of Sierra Leone

Sierra Leone Water Company

# Hydrogeology of Sierra Leone



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HydroNova

In association with Edal Drilling Company

# Hydrogeology of Sierra Leone

By Alessio Fileccia, Pietro Teatini, Casey Walther and Paolo Mastrocola

Prepared by Hydro Nova for the Sierra Leone Water Company on behalf of the Ministry of Water Resources of Sierra Leone

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For more information on the Ministry of Water Resources –the national source for policies and data related to water resources – visit *http://mwr.gov.sl* or contact the Ministry at 127 Kuku Drive, Off Jomo Kenyatta Road, Brookfields, Freetown, Sierra Leone.

To view the *Hydrogeologic Atlas of Sierra Leone* and other publications related to this report and other information products, visit: *http://www.salgrid.org*



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## Acronyms and Abbreviations

| | |
|---|---|
| AEM | Airborne Electromagnetic |
| AIP | Airborne Induced Polarization |
| ALOS | Advanced Land Observing Satellite |
| DB | Database |
| GIS | Geographic Information System |
| GoSL | Government of Sierra Leone |
| GVWC | Guma Valley Water Company |
| MWR | Ministry of Water Resources |
| SALGRID | Salone Groundwater Resources Database |
| SALWACO | Sierra Leone Water Company |
| SAR | Synthetic Aperture Radar |
| SRTM | Shuttle Radar Topography Mission |
| VTEM | Versatile Time Domain Electromagnetics |

## Acknowledgements

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# Hydrogeology of Sierra Leone

By Alessio Fileccia, Pietro Teatini, Casey Walther and Paolo Mastrocola

## Introduction

As surface water supplies in Sierra Leone become subjected to increasing pressure from pollution and growing demand, a goal of the government is to develop groundwater as a major national resource, particularly as a strategy to support urbanizing areas and rural communities off the grid. Yet Sierra Leone's aquifers and information on their location and sustainable yield are virtually unknown. Presently, significant numbers of boreholes and shallow hand-dug wells are being constructed across the country without access to in-depth information about regional or national hydrogeology, leading to a host of issues such as poor construction practices, unsuccessful siting, and water quality deterioration. National agencies and local water supply entities, in particular the Ministry of Water Resources (MoWR), the Sierra Leone Water Company (SALWACO), the Guma Valley Water Company (GVWC) and District Councils, are in need of reliable, easy-to-access information that might help them to properly manage the water resources of Sierra Leone. Consequently, the Government of Sierra Leone, through SALWACO and under the auspices of the MoWR, requested Hydro Nova to prepare a digital groundwater map for the whole country that would provide baseline hydrogeologic information. This report includes the main elements of the hydrogeology of Sierra Leone and describes the mapping products, while also providing guidance on sustainable groundwater use.

The flagship product of this study is the *Hydrogeologic Atlas of Sierra Leone*, a series of hydrogeologic maps complemented with other related thematic maps and textual notes, published in official digital and hardcopy formats. The maps were prepared for Sierra Leone by using a geographic information system (GIS) format. The hydrogeologic map of Sierra Leone is shown at a scale of 1:650,000.

The principle objective of the Atlas is to present spatially explicit information regarding the hydrogeologic and hydrologic characteristics of the country in relation to specific geologic settings. The maps and this report provide baseline information useful for a multitude of purposes, including groundwater investigation, development and management. Furthermore, it serves as a necessary first step towards adequately sited and constructed boreholes.

### Previous Work

Prior to the present study, no comprehensive hydrogeological mapping or investigation had been undertaken at the national scale. Similarly, related parametric and thematic maps, such as piezometric or water vulnerability were not yet available. Of considerable value to this study is the Geologic Map of Sierra Leone prepared in 2004 by Keyser and Mansaray at 1:250,000 scale, a successor of the 1948 version (1:1,000,000) surveyed by the Survey and Lands Department, Freetown. The Department of Geology of the University of Sierra Leone, Fourah Bay College has an ongoing geologic mapping programme that generates updates on geology at the district level, though some districts remain unstudied. The active mining sector in Sierra Leone has generated a significant amount of proprietary geologic and geophysical data useful to hydrogeology. Hydro Nova took advantage of data provided by the Nimini Mining Company to conduct a pilot study on the application of airborne electromagnetic data for groundwater characterization in Kono District, discussed later.

Two studies on vegetation and land systems date back to 1951 and 1970, both at 1:1,000,000 scale. In 1974, the University of Illinois prepared a well detailed study on pedology for selected areas in Sierra Leone. The Vegetation and Land Use Map at 1:500,000 scale (FAO, 1976) and at Land Systems of Sierra Leone at 1:500,000 scale (FAO, 1980 and 2015) were used in this study as base data for several thematic hydrogeologic maps.

The first map prepared with some description of hydrogeology in Sierra Leone was a regional study published in 1988 (United Nations, 1988). Following the decade long Civil War (1991-2002), the next significant research was released in 2009 by the British Geological Survey, and updated in 2015 following the Ebola crisis, which highlighted groundwater use patterns with some hydrogeologic parameters and water point data (Lapworth, et al., 2015).

This present study conducted analysis on 28,850 water data points collected from the government's 2012 national survey of water points (Ministry of Energy and Water Resources, 2012). The survey included basic parameters of boreholes and hand-dug wells in the country, though basic hydrogeologic parameters such as static water levels were not measured in the survey. The Salone Water Security Project (www.salonewatersecurity.com) continues to update the water point data, the latest update occurring in 2016.

In recent years, several international agencies have published reports on groundwater abstraction methods in an attempt to promote good practices in shallow hand-dug drilling methods and raise new awareness on the advantages of managed borehole data. The 2012 feasibility study for manual drilling (UNICEF, 2012) has valuable information on lithology and water-table values along a central area, though no interpolation was made.

In addition to the abovementioned ancillary data, professional borehole drilling companies in Sierra Leone generate a significant amount of hydrogeologic data from site investigations, geophysical surveys, water quality analysis and borehole drilling reports. The Ministry of Water Resources is presently establishing a system to collate this data. Reports from some companies, including the Edal Drilling Company, were made available for this study, covering mainly Freetown, Kambia, Kenema, Koinadugu, Putjehun and Port Loko.

## General observations about the state of hydrogeologic log data

A summary of the ancillary hydrogeologic data collected is seen in Figure 1. The following observations are made regarding the state of hydrogeologic log data in Sierra Leone:

- Hydrogeologic data in Sierra Leone remains scattered across different government agencies and entities
- Many drilling companies in Sierra Leone lack proper skills in hydrogeologic logging and supervision, leading to a market that is dominated by a handful of skilled companies and the application of the same well completion standard (e.g. slotted PVC casing, gravel pack with river gravel, backfilled with cuttings), and a lack of variety of methods.
- Boreholes and hand-dug wells are frequently located by unexperienced people and often sited in the less promising areas. Very often, the sites selected are in badly filtered areas and in close proximity to pollution centers (villages or latrines).
- The water point database (WASH) shows that 37% of the 28,850 water points were nonfunctional at the time of the survey (early 2012), and that 51% of water points are seasonal and fail to deliver water year-round.
- Water level measurements can usually be taken in hand dug wells only, though not in existing boreholes which have usually been capped for sanitary reasons.
- Stratigraphic logs are often incomplete, and sometime hand-written. Water-well details lack a standard field format without listing all basic hydrogeologic parameters (lithology, well design, pump type, position, water level and date of reading, location map, well head sketch etc.).
- GPS coordinates of groundwater points when present, are logged in inconsistent grid systems, and typically are not accompanied with a map to facilitate finding the point.

- Pump and step drawdown tests are not performed following standard procedures; instead they generally show drawdown and recovery readings but are normally not processed.
- In many cases units are different for the same test or not specified.
- Results of many ground-based geophysical surveys, such as vertical electrical sounding (VES) type, are not presented for all measurements. In many cases, plotted graph data are missing and calibration near existing boreholes is not carried out.
- The monitoring net for river flows, groundwater and rain precipitation is still at an early stage and very few conclusions can be drawn especially regarding relations between surface and groundwater.

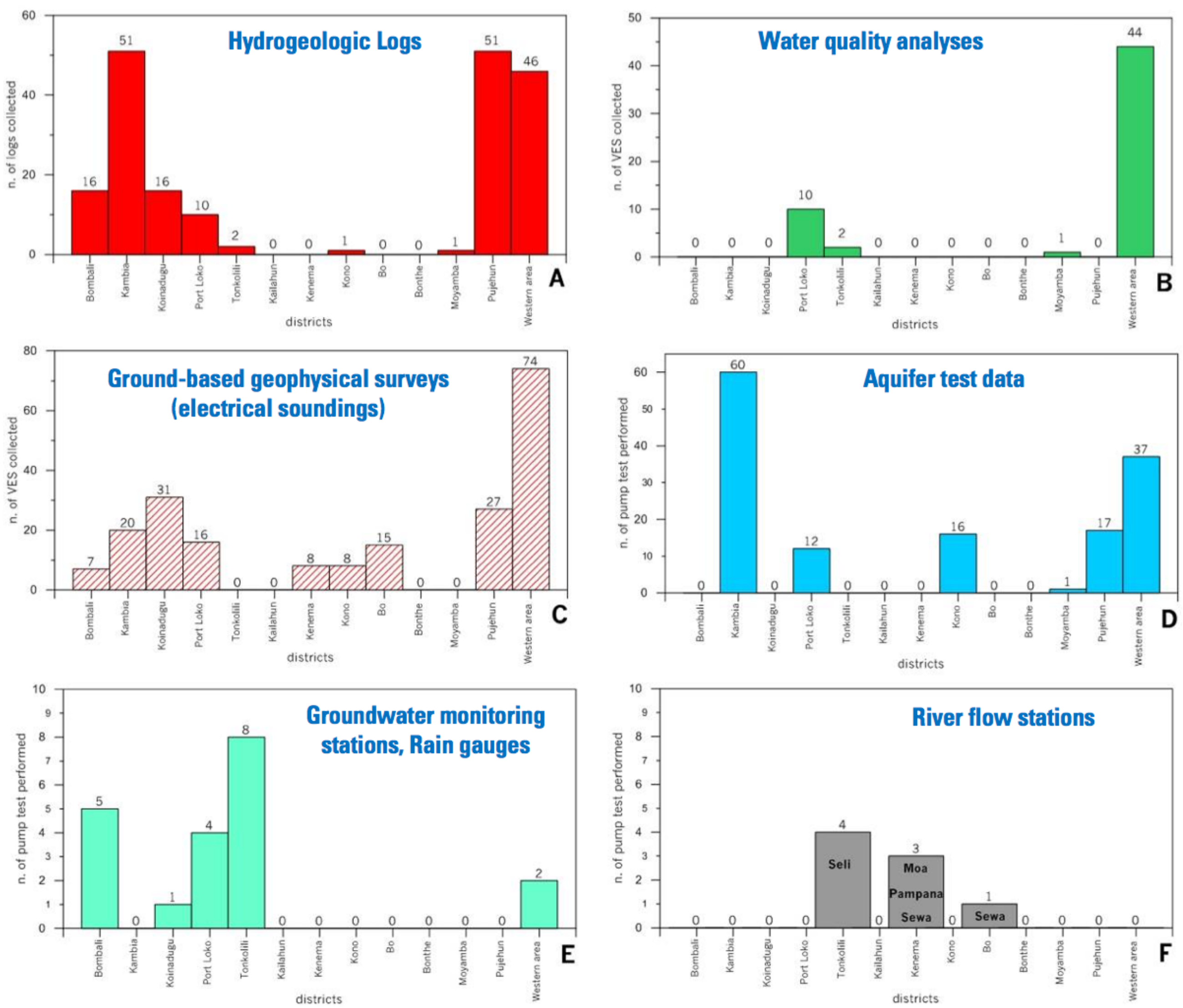



**Figure 1**. Composition of groundwater point data collected, by type and District.
Explanation: (A) Hydrogeologic logs (Sources: Baba, Edal, Geoprospects, GIGC, Guinee Forage, Team Wingin); (B) Water quality analyses (Source: National Water Quality Laboratory, Freetown); (C) Electrical soundings (VES); (D) Aquifer tests (pump tests, step drawdown tests, specific capacity tests); (E) Groundwater monitoring stations and rain gauges; (F) River flow stations

## Methodology Used to Prepare the Hydrogeologic Atlas

To demarcate groundwater characteristics at the national scale, a range of general, parameter and specialized maps were prepared following an iterative sequence. The approach integrates existing ancillary data with advanced remote-sensing and modern mapping and investigation methods applied in the GIS environments (ArcGIS and QGIS). The hydrogeologic maps of Sierra Leone were developed according to IAH standards and guidelines. Table 1 summarizes the overall methodology used to prepare the maps of the Hydrogeologic Atlas.

**Table 1. Mapping methodological framework**

| Remote-sensing derived data | Conventional methods | Hydrogeologic Atlas of Sierra Leone |
|---|---|---|
| • Aerial 1-m elevation data<br>• SRTM 30-m DEM | | Relief Map |
| | • Climate data<br>• River basin analysis | Hydrologic Map |
| | • Geologic Map (2004)<br>• Field reconnaissance | Geologic Map |
| • Landsat 8 imagery<br>• SRTM 30-m DEM<br>• Aerial imagery of Land systems | • Lithology type assignment<br>• Geomorphology analysis from RS<br>• Groundtruthing | Lithologic Map |
| | • Borehole logging<br>• National borehole inventory (2016) | Inventory of Groundwater Points Map |
| | • Hydro-lithology type assignment<br>• Water level readings<br>• Piezometric map | Hydrogeologic Map |
| | • Stochastic averaging of well data<br>• Cross-section analysis<br>• Uncertainty (standard deviation) | Water-Table Elevation Map |
| • Landsat 8 imagery<br>• Aerial imagery of Land systems | • Soil permeability computation and classification | Surface Permeability Map |
| | • Lithology map<br>• Surface permeability map<br>• Aquifer productivity classification | Aquifer Productivity Map |
| • Vegetation map<br>• Aerial imagery of Land systems | • Precipitation data and map<br>• Surface permeability map<br>• Depth-to-groundwater & Water-table elevation analysis | Groundwater Recharge & Discharge Map |
| | • Precipitation & vulnerability maps<br>• Hydrogeologic map<br>• Depth-to-groundwater map | Groundwater Vulnerability Map |
| • Aerial imagery of Land systems | • Classification of drilling suitability<br>• Analysis of suitable drilling methods | Drilling Physical Suitability Map |
| • SRTM, 30-m DEM<br>• Landsat 8 analysis<br>• Synthetic aperture radar<br>• Land Cover | • Precipitation and hydrology data<br>• Drilling Physical Suitability map<br>• Soil moisture analysis<br>• Slope, geomorphology & geologic analysis | Groundwater Exploration Suitability Map |
| | • Spatial variability of hydrogeologic parameters (specific capacity, transmissivity, isobaths, TDS, etc) | Hydrogeology of Freetown Map |

One of the main starting points for the process was the Geologic Map (Keyser and Mansaray, 2004), which was revealed to be an unreplaceable tool for developing the maps for lithology, hydrogeology and aquifer productivity.

Remote sensing data from a range of sources, including Landsat, SAR, SRTM, LIDAR and aerial imagery, were processed on ENVI software and interpreted to generate characteristics and trends valuable for hydrogeologic mapping. In some cases, special data handling algorithms were used to process and produce derived products, such as topography, slope, drainage, geomorphology. For some products, special digital image processing techniques were applied to produce fully developed maps such as the groundwater exploration suitability and the drilling physical suitability maps. In other cases, geospatial information was interpreted to provide additional information for conventional maps, such as the lineaments map which was interpreted from SRTM and Landsat imagery as a key feature for the process to map lithology.

## Generalized Characteristics of Sierra Leone

Sierra Leone lies along the southwestern coastline of West Africa, between the latitudes 7°N and 10°N and between longitudes 10°W and 13.5°W (Figure 2). The total land area of the territory is 71,740 square kilometers ($km^2$). In 2016, the total population of Sierra Leone was 6.1 million with approximately one-sixth of the population living at or near the primary urban center – Freetown.

The economy is based primarily on agriculture and mining, with nearly half of working-age population engaging in subsistence agriculture. Over 56% of land is devoted to agricultural practices, and expanding due to overharvesting of timber and slash-and-burn agriculture. Sierra Leone has experienced substantial economic growth in recent years, mainly from mining, although effects of the civil war and recent Ebola crisis continue to hamper economic diversification.


**Figure 2**. Location of Sierra Leone

## Physiography and Vegetation

Geographically, Sierra Leone can be characterized as a coastal, tropical landscape with a limited range of uniform landforms and climate characteristics. The principle physiographic feature of Sierra Leone is the western Freetown peninsula, which hosts the nation's capital city, with moderate elevations set against large areas of low coastal plains. A predominant physiographic feature characterizing the eastern third of country is highlands and rugged terrain, a primary driver of the country's hydrological cycle. Loma Mansa (Bintimani) is the nation's highest point, at 1,948 m.


**Figure 3**. Generalized topographic relief of Sierra Leone

## Land cover

Land units and vegetation of Sierra Leone were mapped using GLOBCOVER imagery from the European Space Agency (Figure 4). An increase in rainfall from north to south clearly influences vegetation types and patterns. The coastal fringe of the country is largely occupied by mangroves and coastal tree savanna, which are adapted to the coastal environment. Forest covers 37.5 % of the territory. Mixed tree savanna and woodlands are restricted to the drier northern part of the country.

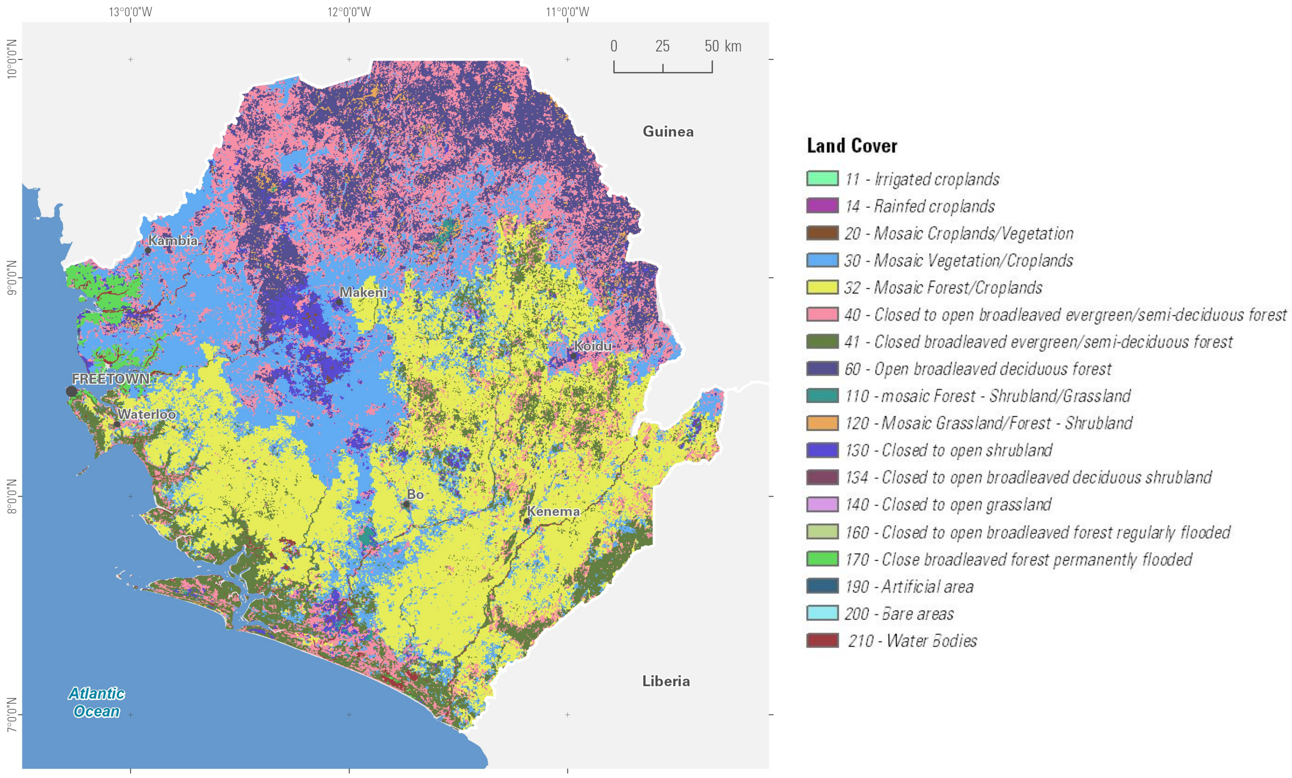



**Figure 4**. Land cover of Sierra Leone
Explanation: Map has been processed from raw satellite GLOBCOVER imagery from ESA, 2009. Classification codes are based on Bontemps, et al (2009).

## Climate

In general, variation in climate is minimal across the country. Rainfall increases by a slight margin from the north to the south. Average air temperatures in Sierra Leone fluctuate from 27°C in March to 25°C in August (CRU, 2017). Data shows that average temperatures have increased 0.2°C since 1901, possibly linked to global warming.

Rainfall has been modeled from 1941 to 1960 (Gregory, 1965) data from meteorological stations (Figure 5). Precipitation is greatest in the Freetown Peninsula, due to the influence of relief, at 5,200 mm/yr on the seaboard banks. In general, the highlands on the peninsula forms a hydrologic divide that separates the western and eastern banks into different rainfall patterns, although the difference is negligible compared to other parts of the country. The southeast receives also receives a significant amount of rain, with about 4,200 – 3,200 mm/yr. Along the coast, rainfall varies from 3,000 – 4,000 mm/yr. The northern region receives the least amount of rainfall, < 2,400 mm/yr.

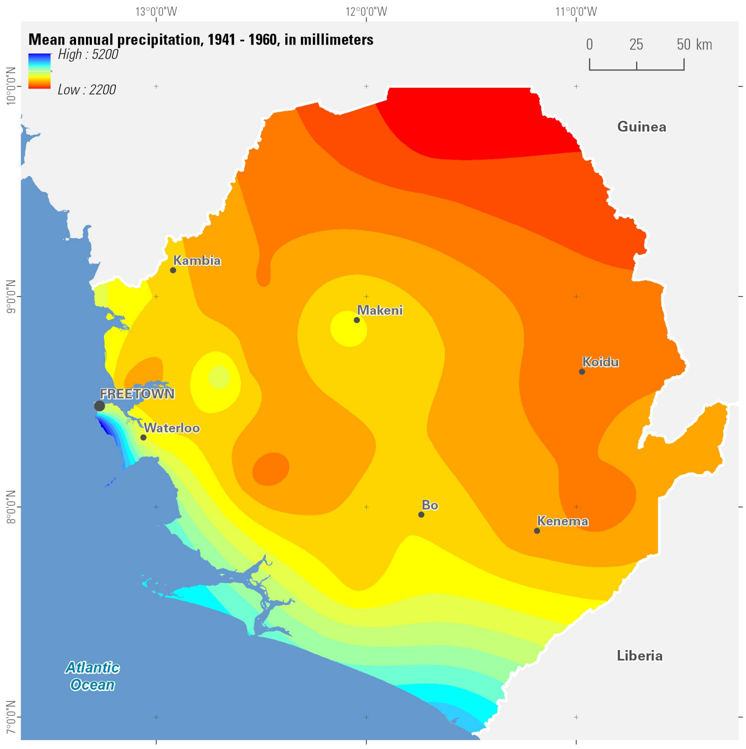



**Figure 5**. Distribution of mean annual precipitation of Sierra Leone

Explanation: The precipitation map and associated graphs were produced by interpolating rainfall statistics of 38 meteorological stations for the period of 1941 to 1960 (Gregory, 1965), provided by the Ministry of Water Resources.


**Figure 6**. Contours of mean annual precipitation and meteorological stations

Explanation: Contours were interpolated rainfall statistics of 38 meteorological stations for the period of 1941 to 1960 (Gregory, 1965), provided by the Ministry of Water Resources.

## Limitations of current climate data

To gain a measure of the certainty of the rainfall data influence on hydrological analysis downstream, the correlation of rainfall data of the 38 meteorological stations located upstream from most major townships in Sierra Leone was analyzed (Figure 7 and Figure 8). At a national scale, the analysis found that the rise of rainfall measurements has a correlation to both to elevation and the proximity to the ocean. For the Freetown area, rainfall increases with elevation generally.

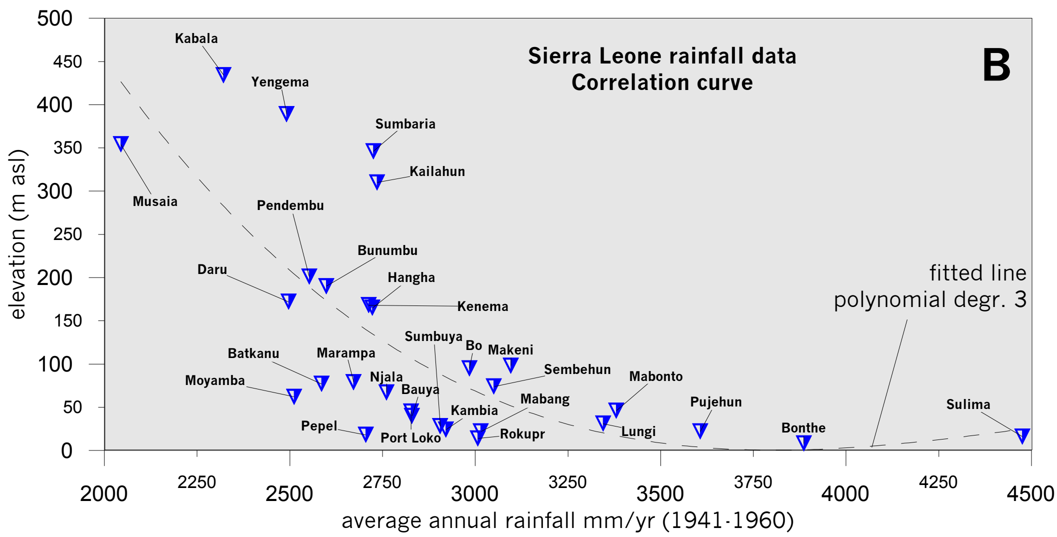



**Figure 7**. Correlation of climate data to locations nationwide.
Explanation: Produced by interpolating rainfall statistics of 38 meteorological stations for the period of 1941 to 1960 (Gregory, 1965). B: The rise of rainfall is due both to altitude and vicinity to the ocean.

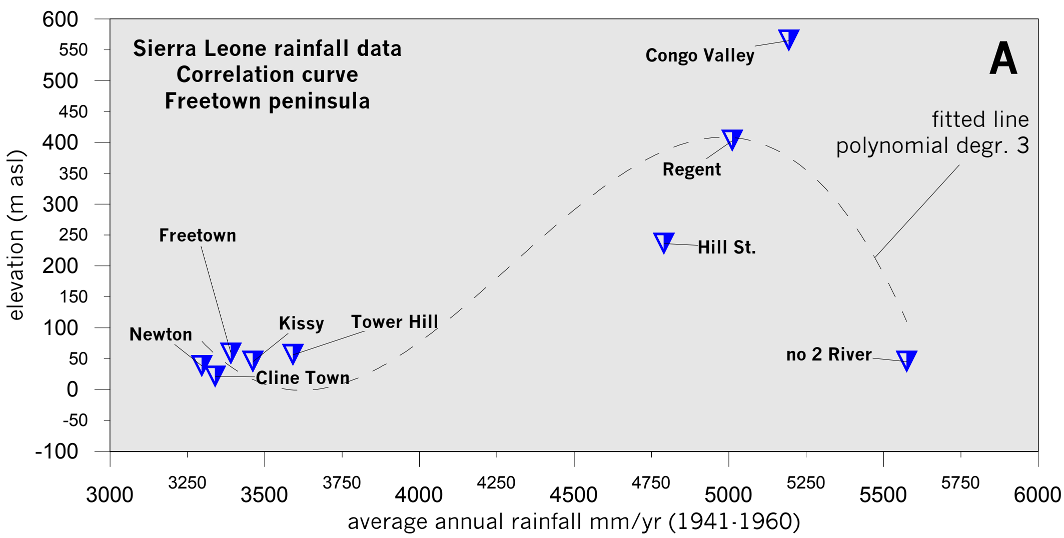



**Figure 8**. Correlation of climate data to Freetown area.
Explanation: Produced by interpolating rainfall statistics of 38 meteorological stations for the period of 1941 to 1960 (Gregory, 1965). (A): Rainfall increases with elevation (m asl).

## Hydrology

Sierra Leone is considered to have an abundant supply of surface water compared with other similar nations in the region. All five perennial rivers (Little Scarcies, Rokel, Jong, Sewa and Moa) flow northeast to southwest, draining most of the country's land surface. The Moa is the longest river (424 km), with its headwaters beginning in the highlands of Guinea. The largest basin is the Sewa (19,022 $km^2$). Four of Sierra Leone's primary basins are shared with its neighbors – the Great Scarcies, Little Scarcies, Moa (Guinea) and Mano (Liberia). Table 2 summarizes the extent of each basin unit.


**Figure 9**. Hydrologic units of Sierra Leone (2017)

Explanation: Rivers and catchment layers are taken from open source database and further elaborated through geospatial analysis of the terrain elevation.

**Table 2. River basins of Sierra Leone, by area ($km^2$)**

| Watercourse Basin | [a]Length (km) | [b](1) Basin area inside Sierra Leone ($km^2$) | (2) Basin area inside and outside of Sierra Leone ($km^2$) |
|---|---|---|---|
| B-01: Great Scarcies | 129 | 2,979 | 8,303 |
| B-02: Little Scarcies | 161 | 13,383 | 18,955 |
| B-03: Moa | 266 | 9,583 | 19,835 |
| B-04: Mano | 424 | 1,959 | 7,776 |
| B-05: Loko | - | 1,565 | 1,565 |
| B-06: Rokel | 290 | 8,236 | 8,236 |
| B-06a: Rokel Estuary | - | 579 | 579 |
| B-07: Gbangbaia | - | 3,121 | 3,121 |
| B-08: Jong | 97 | 8,288 | 8,288 |
| B-09: Sewa | 209 | 19,022 | 19,022 |
| B-10: Western WRA | - | 223 | 223 |
| B-11: Ribbi/Thauka WRA | 56 | 3,670 | 3,670 |
| B-12: Sherbro WRA | - | 612 | 612 |
| **Total** | | **73,220** | **100,185** |

Explanation: Geographic extent of basin areas are given in terms of both (1) the area of the basin that is located within the political territory of Sierra Leone and (2) the total area of the basin without regard to political boundaries, the latter of which is considered a transboundary basin shared by Sierra Leone and a neighboring country. Rivers and catchment layers are taken from open source database and further elaborated through geospatial analysis of the terrain elevation. Sources: a- PEMSU, 1983; b- Salone Water Security Project (2014), Ministry of Water Resources (2015)

## Demand for water

FAO estimated national water withdrawal is 0.3799 $km^3$/yr, a figure that has not been updated since 2000 (FAO Aquastat, 2000). Irrigation is the primary water user, with a withdrawal of 0.3536 $km^3$, followed by the municipal sector with 0.196 $km^3$ and industry with .067 $km^3$. Rural populations depend on surface water for 80% of its water supply. Groundwater is used for a limited number of rural wells and recent installations for large cities, and is expected to intensify.

## Renewable water resources

FAO (Aquastat) estimates Sierra Leone's total renewable water resources as 160 $km^3$ /year (out of 182.6$km^3$ /year which is estimated as rain. This estimate of the nation's water resources – at 88% of mean annual rainfall - is certainly a gross overestimate, as it fails to account adequately for evapotranspiration (Carter et al, 2015). A more realistic estimate is that given by Schuol et al (2008), of 59.3-98.4 $km^3$ /yr, between 32% and 54% of mean annual rainfall. Mansaray A. et al, obtained a similar figure (48%) after a long monitoring of the unconfined aquifer and application of the WTF method. A new groundwater balance calculation is discussed in sections on hydrogeology below.

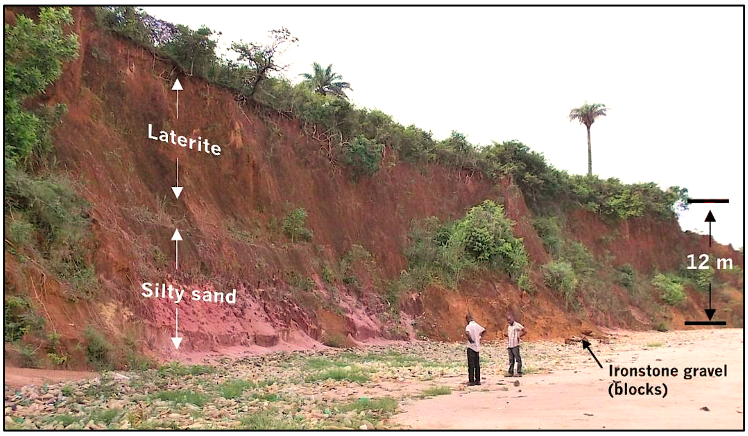
## Geomorphology

About two-thirds of Sierra Leone comprise a series of highly dissected plains and plateaux out of which rise several mountain ranges and massifs. The plains and plateaux are aged erosion surfaces with generally accordant summits, while similar features are also present at higher elevations on the hills and mountains. These surfaces are usually mantled by a deep colluvial drift composed of pisolitic ironstone gravel although, locally (e.g. in the Sula Mountains), where indurated ironstone sheet is prevalent.

Much of the landscape is outlined by numerous, narrow, dendritic stream valleys which have been filled with alluvial and colluvial material to form seasonally flooded swamps. Recent modifications of the hydrographic base level have given rise to a coastal region of swamps and beach ridges, backed by coastal terraces. Differences in geology, elevation, relief and a degree of erosion have conferred a varied landscape. The main morphological provinces are the coastal plains, interior plains, plateaus, and highlands (UN, 1988).

### Coastal terraces

Coastal terraces are the most extensive of the morphological provinces, covering over half of Sierra Leone. Formed on loose sediments (Bullom) and lying at elevations between 2 and 40 m, the relatively unconsolidated nature of the sediments has led to an extremely intricate pattern of dissection by minor streams, especially along the seaward margin of the terraces. Included in this sub-province are higher lying terraces surrounding the Freetown peninsula, estuarine swamps, alluvial plains and beach ridges. In the Freetown area lies a mountain range reaching elevations of about 700 m with level terrace surfaces, capped extensively by laterite sheets. The terraces are intersected by deeply incised streams, with high erosion energy, flowing swiftly from the mountains.




Photography by Alessio Fileccia, 9 November 2016

**Figure 10**. View of the coastal terrace observed during field reconnaissance.
Explanation: Long coastal cliff observed at Konakride community (Lungi), stop PL 31. The laterite cover is 5-7 m thick and overlies the recent loose fine deposit of the Bullom group. Several blocks of cemented ironstone gravel have fallen from the top to the foot of the cliff (see geologic sample in Figure 15).

#### *Estuarine swamps*

At the foot of the coastal terraces lie estuarine swamps, resulting from the deposition of silt and clay along major river channels. These swamps are subject to tidal flooding.

### *Alluvial plains*

Deposition of alluvium occurred in a freshwater environment along the Little Scarcies and Sewa rivers, creating extensive grassland plains. These lie around 15 m asl causing flooding in the area during the rainy season.

Photography by Alessio Fileccia, 2016

**Figure 11**. View of swamps in the coastal terrace province observed during field reconnaissance.
Explanation: Swamp area east of Waterloo, seasonally flooded by a network of rivers.

### *Beach ridges*

Beach ridges of varying age fringe the coastal plains along their seaward side. These are most extensive in the Turner's Peninsula area where they attain widths of up to 20 km. Adjacent to the coast the ridges are elongated and have caused the deflection of major rivers. Most notable of these is the Sewa River (Figure 12), which has joined in their lower reaches to flow parallel to the coast for some 50 km before reaching the sea near Sherbro Island. Further inland, beach ridges become more dissected and do not exhibit such a striking parallel trend. Between Sherbro and the Guinea border, the beach ridges are discontinuous and narrow and attain widths of only a few kilometers.

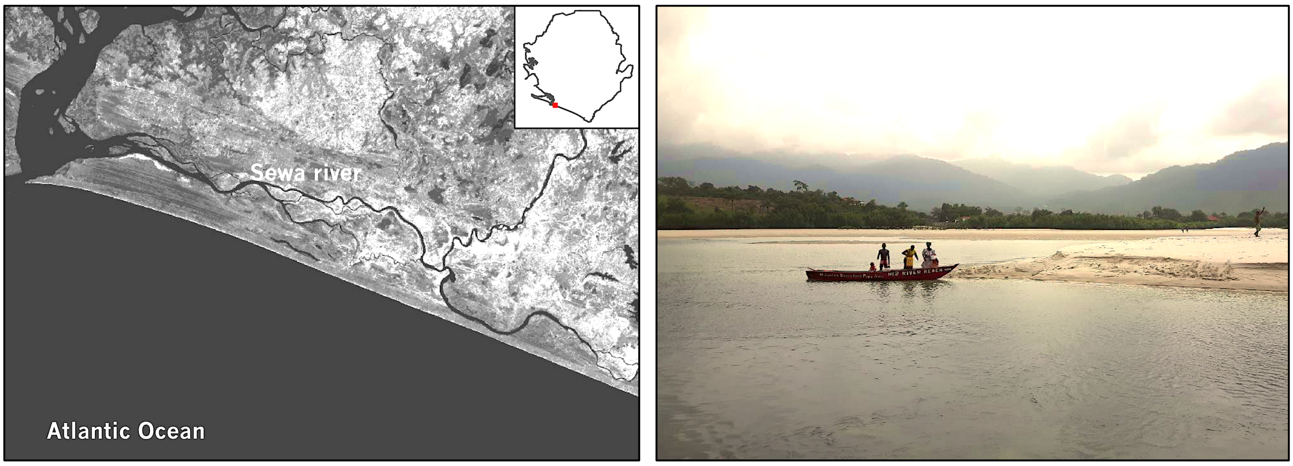



**Figure 12**. Left: Satellite view of beach ridges in the estuary near mouth of the Sewa River. Right: Estuary of river along the south coast near Freetown.
Explanation: (Left) Landsat 8 image showing strong marine currents trend towards the northwest, created elongated beach ridges accumulating the sandy sediments of the river. (Right) Estuary located east of Sussex. The mountain range observed reaches an average elevation of 700 m. (Photography: Alessio Fileccia, 2017.)

## Interior plains

The interior plains are the most extensive morphologic province in Sierra Leone, covering 31,418 $km^2$ (approximately 43% of the country). The plains rise gently from west where they merge almost imperceptibly with the coastal terraces and lie at about 40m elevation to east where they lie at elevations of up to 200 m. They are separated from the plateaus province by a distinct escarpment. Despite an overall low relief, the interior plains are characterized by significant variations in morphology, a result from differences in the rock types on which they have formed. They comprise two main sub regions: (1) an extensive area of low relief dissected *undulating plains*, stretching from the Guinea border in the north to the Liberia border in the south and attaining a maximum width of 100 km in the center of the country, and (2) an area of seasonally flooded swamps and associated terraces of negligible relief, known locally as the *Bolilands*, associated with shale and siltstone (Rokel River Group sediments).

### *Undulating plains*

In the west, hard metamorphic rocks, granulites and schists have given rise to undulating plains with predominantly gentle slopes that are mantled by a thick layer of densely packed pisolitic ironstone gravel. Low, isolated hills occur locally. In the northwest, the plains are bordered by a flat-topped low plateau with distinctive E-W trending incised valleys. Undulating plains have developed on resistant sediments of the Rokel River Group in the central part of the province. The plains are characterized by subdued slopes, extensive terraces and swamps that broaden into featureless depressions (bolis). Parts of the plains also occur integrated with the Bolilands sub-province, being cut back to such an extent that they form subdued isolated remnants. In the east, undulating plains have formed on a complex of granitic rooks. Slopes are generally very gentle. As the density of narrow swamps increases, isolated hills are scattered throughout the area. Foot slope terraces are also prevalent. In the north at the foot of the fringing escarpment, the proportion of gentle slopes increases and low, predominantly rocky, hills become more frequent. Further west, a zone of granitic rocks occurs between the granulites and the consolidated sediments of the Rokel River formation.

### *Bolilands*

The Bolilands sub-province attain a maximum width of 50 km west of Magburaka. They are an intricate association of depressions and low terraces along the Rokel and Mabole Rivers and their tributaries. Flooding is widespread during the rainy season, resulting both from the poor drainage of the low-lying terrain and overflow from rivers and streams.

## Plateaus

Located in the northeast and southeast and lying at elevations between 300 and 700 m is the plateaus province, which covers 15 $km^2$ (approximately 22% of the country). Although formed almost exclusively on granitic rocks, the landscape has a variety of features due to difference in dissection and relief, and can roughly be characterized by undulating high-lying plains and rolling plains and hills.

### *Undulating high-lying plains*

The eastern part of the plateaus is composed mainly of undulating plains, similar in morphology to the interior. Scattered across these plains are high-elevation flat areas and low isolated hills.

Photography by Alessio Fileccia, 2016

**Figure 13**. View of the plateaus province, undulating high-lying plains observed during field reconnaissance. Explanation: Example of a low granite hill in the background near Kamabai, Bombali District, stop BOM 121.

### *Rolling plains and hills*

The western and southern parts of the plateaus province is comprised of dissected hills of low- to moderate-relief with broad foot slopes, broken in places by undulating plains. Narrow alluvial plans occur adjacent to the principle rivers (e.g. the Mongo). In the southern part of the province, the hills are covered by a thick layer of colluvial ironstone gravel. Towards the north, the weathering granite is at a shallower depth, and rock outcrops become a common feature.

## Highlands

The high relief landscape of Sierra Leone covers 14,723 km$^2$ (approximately 20% of the country), and is characterized into two sub-provinces: (1) hills developed on predominantly basic and ultrabasic rocks and (2) hills developed on acid rocks.

### *Hills on-basic and ultrabasic rocks*

These rocks are generally resistant to erosion and have given rise to highly dissected hill ridges of moderate to high relief. In addition, the relatively high proportion of iron and aluminum in the rocks facilitates laterite formation, either in the form of surface crusts or as densely packed ironstone gravel, giving rise to thick lateritic soils. Gravelly hill ridges, at elevations between 470 m and 890 m, are a common feature of both the Freetown Peninsula and the escarpment bordering the Plateaux on its western and southern sides. The Sula Mountains rise out of the Plateaux to elevations of 900 m and are covered by a laterite crust. Along the northwestern border with Guinea, the Sayonia Scarp forms a prominent, laterite-capped ridge rising to 800 m. Occurring on the interior plains in the southwest are remnant ridges and isolated hills, with broad laterite covered foot slopes.

### *Hills on acid rocks*

Hills formed on granitic material have eroded to give a higher proportion of gentle slopes and rock outcrops than those developed on the more basic rocks. Laterite soils have a reduced thickness and are less abundant. Granitic hills rise to 1000 m along the margins of the plateaus and exhibit a variety of features, ranging from rather massive, faulted hills to rocky hill complexes. In the escarpment area, these hills have been strongly dissected by rivers flowing from the plateaus on to the interior plains through deep, often fault-controlled, gorges. This dissection has given rise to the occurrence of granitic hill outliers along the eastern and northern edges of the interior plains. The hills formed on the younger granite exhibit some of the most spectacular scenery in Sierra Leone, culminating at the dolerite capped peak of Bintumani (1,945 m ) in the Loma Mountains.

## Geology

A generalized description of the geology of Sierra Leone is presented below. Information was obtained from studies conducted by Keyser (2004) and others. Sierra Leone occupies the central portion of an Archean craton that was disrupted by the opening of the Atlantic Ocean. The eastern cratonic fragment extends from the Western Sahara and Anti-Atlas Mountains eastward to the Hoggar and southward to Mauritania, Senegal, Guinea, Sierra Leone, Liberia, Ivory Coast, and Ghana. The western portion of the craton forms the Guyana Shield, which extends from northeastern South America. The geology divided into two major tectono-stratigraphic units. The eastern unit is part of the stable Precambrian West African Craton and consists of high-grade metamorphic rocks and granitic gneisses. The western unit contains elements of an orogenic belt named the '*Rokelides*' or '*Rokel River Group*' that was deformed during the Pan-African tectonothermal event, about 550 Ma ago. A minor, 20–40 km wide coastal strip is made up of Pleistocene to Recent marine sediments.

Based on the preceding description, most of Sierra Leone is underlain by a series of ancient, folded, crystalline rocks of varying lithology, of Precambrian age. These rocks are over 2.1 billion years old and are overlain uncomformably by the Rokel River and Sayonia Scarp Groups of late Precambrian to late Ordovician age, and the much younger Bullom Group sediments of Tertiary to Recent age (Figure 14). Prior to the deposition of the Bullom Group, a period of intensive igneous activity occurred in the Mesozoic period which gave rise to the Freetown gabbro complex and associated minor sills and dykes.

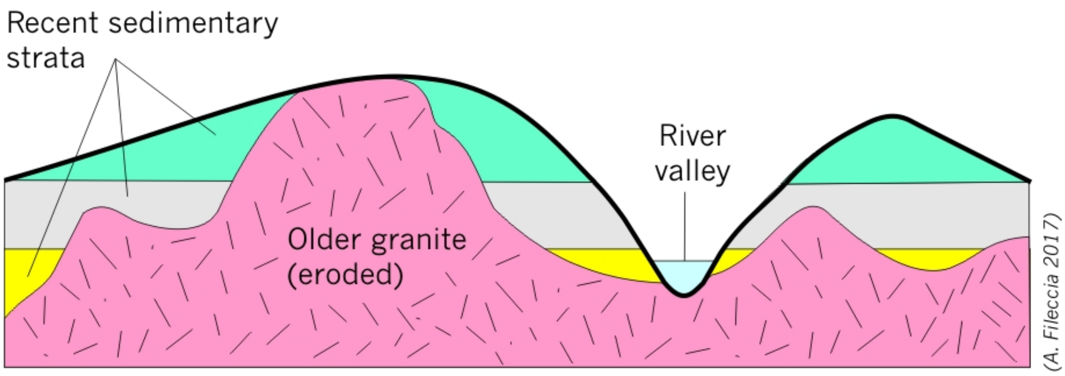



**Figure 14**. Generalized model geologic cross-section of Sierra Leone
Explanation: Not to scale, the cross section illustrates unconformity, where the horizontal beds are lying out of conformity on the eroded surface of the older rock. The older granite intrusion (pink) was exposed to the atmosphere and eroded during an extended period, after which a new environment (e.g. marine) led to the deposition of sedimentary strata (yellow, grey, green). As the rock grains settled underwater, they slowly covered the basin. Following a subsequent marine regression, a new erosion cycle took place bringing the area to the current morphology.

The simplified geologic map (MOWR, 2015) divides Sierra Leone into four units: the Precambrian basement complex, the Sayonia Scarp and Rokel Group, the Ultra-basic igneous intrusives, and the Bullom Group (Table 3), discussed below according to age sequence.

**Table 3. Main geologic units of Sierra Leone**

| Geologic Unit | Age (Increasing from top) | Description |
|---|---|---|
| Bullom Group: | Cenozoic (Tertiary and Quaternary to recent) | Poorly consolidated (unconsolidated) marine and estuarine sedimentary rocks – e.g. sands, gravels and kaolinitic clays with some lignite |
| Ultrabasic igneous intrusives | Mesozoic (Jurassic and Triassic) | Freetown Peninsula Complex and other intrusives |
| Sayonia Scarp and Rokel River Group | Lower Paleozoic (Cambrian and Proterozoic) | Variegated shales, siltstone, mustone interbedded with volcanic and quartzite bands |
| Precambrian basement complex | Noearchean and Archean | Marampa Group: metasediments and volcanics<br>Kasila Group: granulites, basement granites, gneisses and migmatites, volcanic greenstone, amphibolite and gneiss |

Source: Strategy for Water Security Planning, Vol. 3, Ministry of Water Resources (2015)

### *Precambrian basement complex*

The crystalline basement consists of granitic rocks occupying about 75% of the country. The oldest formations date back to the Archean (>3 billion years ago) and can be divided into two major units: (1) the north–south trending Liberian granite/green-stone complex and (2) the northwest–southeast trending Kasila Group. The granite/greenstone complex comprises a series of iron and magnesium-rich rocks (Sula Group) over a quartz-rich basement of granitic composition. The grade of metamorphism in the basement tends to increase towards the edges of the Sula Group giving rise to local occurrences of granulite (Mano-Moa formation). The so-called Younger granite was intruded after the most intense period of deformation at about 2.7 ma ago and occurs around the margins of the Sula Group. The Kasila Group consists of a series of high grade basic granulites, gneiss and migmatite which developed into a zone of extreme sheer deformation to form the southwest margin of the Archean basement complex (Figure 15). Early in the development of the Kasila Group, part of it was thrusted eastwards on to the basement complex, giving rise to low grade schists, banded iron formations and lavas (Marampa Group).

### *Rokel River and Sayonia Scarp Groups*

A significant period separates the deformation of the Precambrian basement complex and the development of the Rokel River trench very late in the Precambrian period. In this trough, a series of unfossiliferous sandy and clayey sediments (Rokel River Group) were deposited to form a belt of rocks 30 km wide and 225 km long, extending south-southeast from the Guinea border. Periodic volcanic activity occurred during this period, creating basic and intermediate lavas and ashes (Kasewe Hills Formation). The Sayonia Scarp Group overlies uncomformably the Rokel River Group and comprises an unfossiliferous sequence of horizontally bedded sandstones and shales, generally considered to be late Ordovician in age.

### *Ultrabasic igneous intrusions*

In the early Mesozoic, the continental land mass known as Gondwanaland broke apart, giving rise to two periods of igneous activity. The earliest of these (200 Ma) was associated with the initial stages of rifting and resulted in the intrusion of the Freetown layered gabbro complex. The rock mass is made of an apparently funnel-shaped body of which the greater part lies out to sea. The complex consists of a 6 km-thick series of cumulate rocks of gabbroic composition, containing layers of dunite, troctolite, olivine-gabbro, gabbro, leucogabbro and anorthosite. The complex is intruded into the gneisses of the Kasila Group and overlain by the Eocene sediments of the Bullom Group. Simultaneously, a series of dolerite sills and coast-parallel dykes were intruded – the sills cap Bintumani and the Sayonia Scarp – while the dykes are very numerous in a zone trending east-southeast through Bo. The second period of igneous activity was the intrusion of Kimberlite dykes and pipes about 90 Ma ago. These are found mainly in the eastern part of the country, particularly at Tongo and Yengema, where they are the source of Sierra Leone's alluvial diamond deposits (Figure 15).

### *Bullom Group*

Also associated with the continental dislocation was the deposition of Tertiary Bullom Group deposits, which occupy a belt up to 45 km wide, at height of up to 40 m, bordering the Sierra Leone coastline. Outcrops are rare and generally poor except for 25 m high sea-cliffs near Lungi (Figure 10). These deposits rest uncomformably on the Kasila Group and the Freetown gabbro and comprise nearly horizontal beds of marine, estuarine and fluvial gravels, sands and clays. Locally, laterites occur within the relatively unconsolidated sediments and form resistant outcrops, such as along the Bullom shore north of Freetown (Figure 15). The alluvial deposits of river valleys and floodplains all over the country belong to this unit.

### *River and stream sediments*

Quaternary sands and gravels of equivalent age to the youngest Bullom deposits occur in the river and stream valleys throughout Sierra Leone. These have subsequently been covered by recent deposits of alluvium and colluvium in valleys and along coastal estuaries. The alluvial deposits tend to be silty or clayey, while the colluvial deposits are mostly sandy. They both give rise to distinctive, relatively fertile, soils which have an important influence on the present and potential land use of the country (Figure 15).

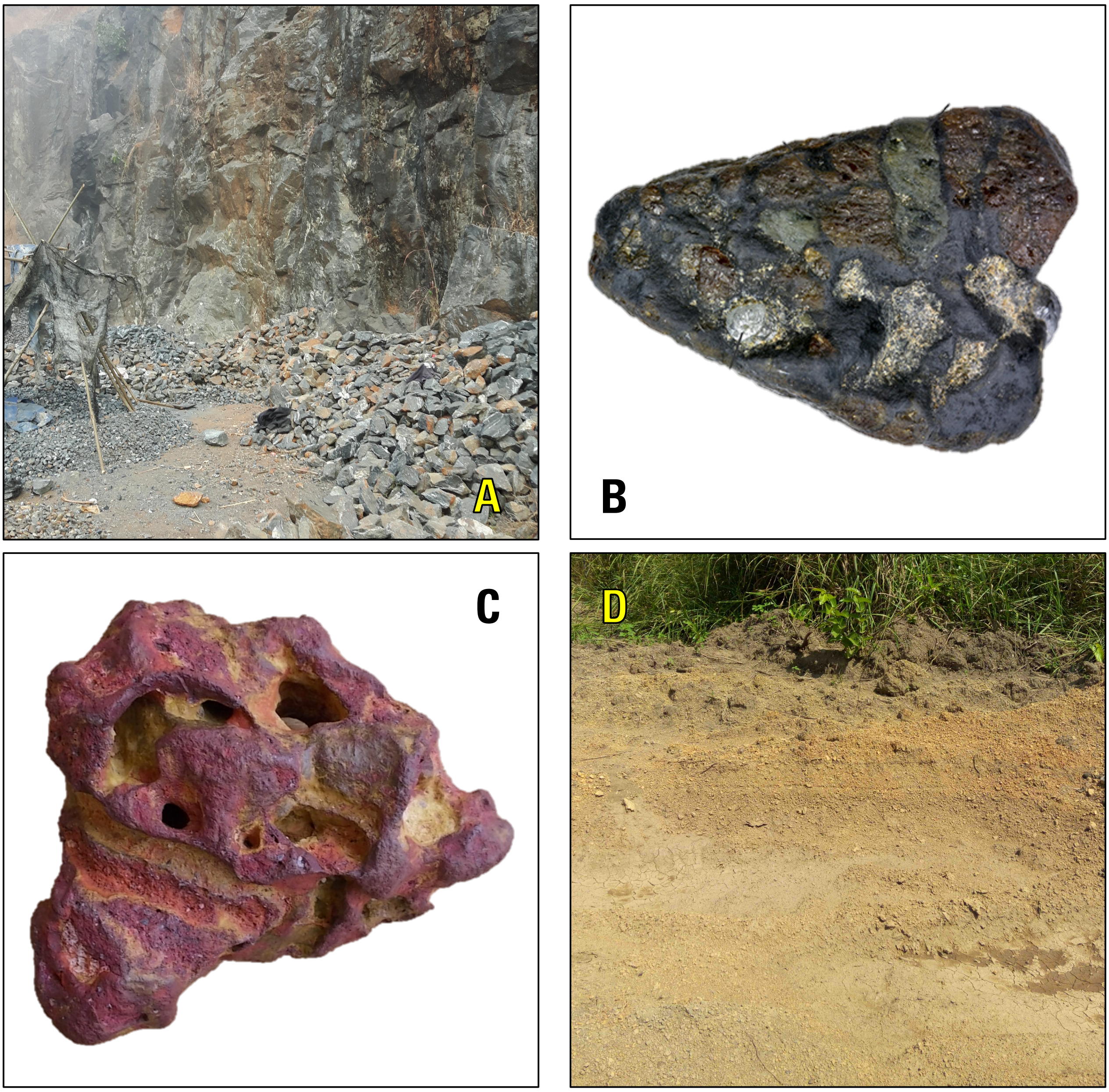



**Figure 15**. Samples of observed geologic units.
Explanation: (A) rock face in the migmatitic gneiss of the Kasila Group, at an abandoned quarry site east of Freetown (Ropath community, Ocra Hill, PL 201 stop); (B) A sample of kimberlite with some of its more common minerals (pyrope, pyroxenes, ilmenite, phlogopite, diamonds), (C) Sample of laterite (cemented ironstone gravel) taken at the foot of the long sea cliff north of Lungi, PL 31 stop; (D) lateritic soil along road cut, 2 km east of Medina town (Kambia). (Photography: Alessio Fileccia, 2016-2017.)

## The Geologic Map of Sierra Leone (2017)

The Geology of Sierra Leone map (Figure 16) was modified from the 2004 edition (Keyser and Mansaray, 2004) which originally comprised of four sheets at 1:250,000 scale and was based on existing reports from 1961 to 1981. Improvements to the base map include minor modifications, digitization, georeferencing and minor format changes to improve appearance and visual differentiation among similar formations. Different formation colors do not reflect the original ones and formation acronyms are overlaid to facilitate the Group distinction. The present map was also modified to serve in the production of the Lithology of Sierra Leone (2017) map. Field validation of the base map observed minor localized anomalies pertaining to the effusive deposits on the metasediments of the Rokel formations. Unfortunately, the usual accompanying notes and geologic cross-sections from the original were not made available for this study.

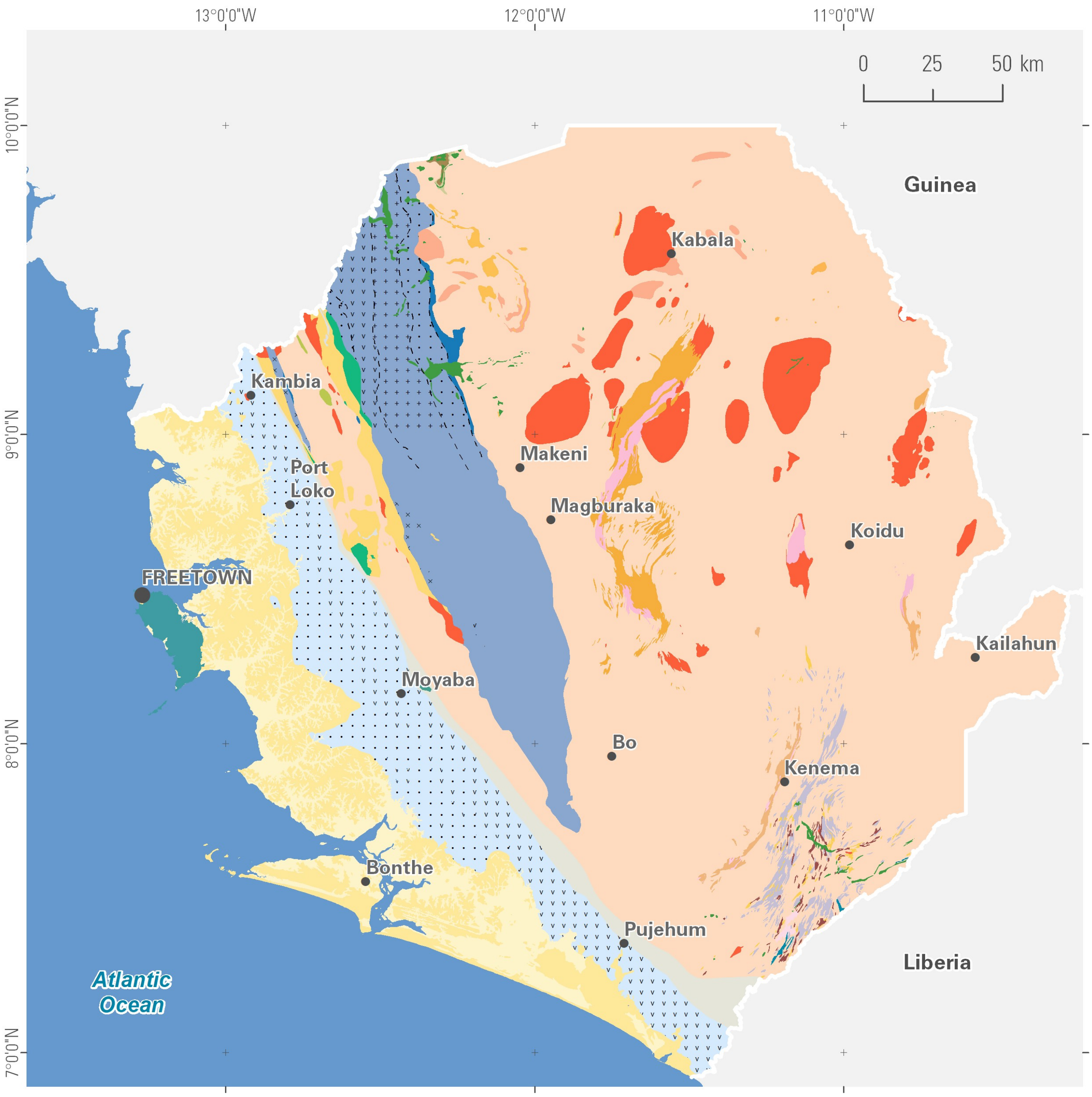



**Figure 16**. Generalized geology of Sierra Leone (2017)

Explanation: The map depicts the distribution of geologic materials and geologic structures across Sierra Leone that are visible at the Earth's surface. Formations, hard rocks and unconsolidated sediments are distinguished according to their mineral composition, age and environment. Each color represents a different geologic unit. Each unit is assigned a set of letter symbols, usually a combination of an initial capital letter followed by smaller letters. The capital letter represents the age of the geologic unit. The small letters indicate either the name of the unit or the type of rock. A total of 28 geologic formations have been mapped, ranging from Archean (3.5 billion years ago) to Quaternary (2 million years ago). The base of this map is modified from Keyser and Mansaray (2004). The base was comprised of four plates at 1:250,000 scale, and was based on a compilation of historical works dating 1961 - 1981.

**Geological Formation**

*Jd - Dolerite*
*Jf - Freetown complex*
*LAn - Anorthosite metagabbro*
*LG - Leonean granite*
*LG Mylonite zone*
*LM - Migmatites / hybrid rocks*
*Lam - Pre-Liberian amphibolite*
*Lb - Bagbe alkalic complex*
*Lba*
*Lbi*
*Lf*
*Lg - Liberian granite*
*Lk*
*Lkm - Magbele*
*Lkt - Tapr*
*Lme*
*Lmg - Mano Moa*
*Lmg - Mano Moa, banded ironstone*
*Lmm - Matoto*
*Lmr - Rokotolon*
*Lmr - Rokotolon, Banded Iron Formantio*
*Ls*
*Lsa*
*Lse*
*Lt*
*Om - Moria*
*Ow - Waterfall*
*PLl - Loko Hills*
*PLg - Migmatitic gneiss and granitoid*
*PLa - Pre Leonean amphibolite*
*Prtm - Tabe-Makani*
*Q - Bullom (alluvium, beach sand etc)*
*Tb - Bullom (sand, clay, clayey sand, lignite)*
*EB - Basic intrusive*
*Er - Rockel River*
*Erk - Kasewe*
*Erm - Mabole*
*Ert - Taia*
*Erte - Teye*

**Table 4. Geologic column of Sierra Leone (2017)**

Explanation: The table shows different lithological units with assigned symbol, geologic group, formation name and approximate age.

| | Lithology | acronym /symbol: Sedimentay / volcanic rocks | | acronym /symbol: Intrusive rocks | Group | Formation | Age | Ma before present |
|---|---|---|---|---|---|---|---|---|
| 1 | alluvium, beach sand etc. | Q | | | Bullom | | Tertiary / Quaternary | |
| 2 | sand, clay, clayey sand, lignite | Tb | | | | | | 65 |
| 3 | Kimberlite dykes | | | K | | Kimberlite dykes | Cretaceous | 142 |
| 4 | dolerite | | | Jd | | dolerite dykes | Triassic / Jurassic | |
| 5 | dunite, gabbro, troctolite, olivine gabbro, leucogabbro, anorthosite | | | Jf | | Freetown complex | | 206 |
| 6 | laminated argillite with rhytmites | Ow | | | Sayonia Scarp | Waterfall | Ordovician | |
| 7 | shale, arkosic ss, cngl. | Om | | | | Moria | | 495 |
| 8 | basic intrusive | | | €B | | Basic intrusive | Upper Cambrian | |
| 9 | variegated shale, laminated siltstone, orthoquartzite, subarkose, arkose | €rm | €r | | Rokel river €r | Mabole €rm | Cambrian | |
| 10 | grey mudstone and shale, occasional beds of grey clayey siltstone, fine grained ss, laminated silty shale | €rt | | | | Taia €rt | | |
| 11 | andesitic lava, spilitic basalt, dacite, dacitic tuff | €rk | | | | Kasewe Hills | | |
| 12 | purple and grey shale with intebedded quartzwacke bands | €rte | | | | Teye | | 545 |
| 13 | grey shale interbedded with quartzite, arkose, subarkose, cngl. | Prtm | | | | Tabe-Makani | | |
| 14 | pelitic and psammitic metasediment, haematite, quartzite and specularite schist; banded iron formations | Lmr | | | Marampa | Rokotolon | Archean | 2500 |
| 15 | massive and banded meta andesite, ultrabasic lava, pillow lava | Lmm | | | | Matoto | | |
| 16 | nepheline syenite, syenite, alkali granite | | | Lb | | Bagbe alkalic complex | | |
| 17 | biotite granite, porphyroblastic granite, granitoid | | | Lg | | Liberian granite | | |
| 18 | quartz-feldspatic gneiss, coarse amphibolite, garnetiferous gneiss lava | Lkm | | | Kasila | Magbele Lkm | | |
| 19 | hypersthene gneiss with feldspatic bands, olivine-bearing metagabbro | Lkt | | | | Tapr Lkt | | |
| 20 | Various lithology: pelitic metasediments, basic lavas, gneiss, garnet/ ultrabasic schists, quartzite, banded ironstone, amphibolite, hornblende schist…. | Green stone belts | (Lt, Lk, Lbi, Lme)<br>(Ls, Lg, Lf, Lba, Lse, Lsa) | | Kambui supergroup | Sula mountains, Kangari hills, Kambui hills, Nimini hills, Gori hills, Serekolia, Sankarama | | |
| 21 | anorthosite metagabbro | | | LAn | | | | 2900 |
| 22 | amphibolite, coronite | Lam | | | | Pre-Liberian amphibolite | | |
| 23 | granulite, quartzite, banded iron formation | Lmg | | LM | | Mano Moa (Lmg) | | |
| 24 | | | | | | Migmatites / hybrid rocks (LM) | | |
| 25 | porphyrblastic banded gneiss, pyroxen-augen gneiss, migmatitic gneiss, granitoid, mylonite | | | LG | | Leonean granite | | |
| 26 | amphibolite | Pla | | | | Pre Leonean amphibolite | | 3500 |
| 27 | ambhibolite, quartzite, banded ironstone | PLI | | | Loko Hills | | | |
| 28 | migmatitic gneiss and granitoid | | | PLg | Loko Hills | Migmatitic gneiss and granitoid | | |

# Hydrogeology

As Sierra Leone has an abundance of surface water, ground water has so far received little attention. Existing data and research have been analyzed to extract hydrogeologic characteristics at the national scale. Similarly, research in the wider African region provided additional insights. A national study in 1980 used geophysical soundings, identifying five geological units whose resistivity can be considered as reference for many areas of the country (UNDP/FAO, 1080).

**Table 5. Geological units identified through geophysical soundings (UNDP/FAO, 1980)**

| Layer type | Resistivity (Ω x m) |
|---|---|
| Lateritic crust | 1200 – 1700 |
| Clay and sand (regolith) | 20 - 30 |
| Hard clay | 80 – 400 |
| Clay | 20 – 30 |
| Basement rock | >900 |

The electrical soundings from that study provided new information about the Bullom lithologies, the Bolilands and the fracturation of the granite formations. The Bullom series consists mainly of clay, but it also contains a sand aquifer 30 – 40 m thick in its eastern part, while the Precambrian basement rock is 250 m deep at Waterloo. Two soundings in the Bolilands penetrated thick clay strata in the first 30 - 40 m. Similarly, the electrical soundings made in granite areas seem to indicate that the fractured and altered rock may be 30 - 40 m thick along the main faults.

Despite a limited knowledge base in hydrogeology, it was possible to give a general but still valid description of the aquifers. In some places the lateritic crust is thick and forms a groundwater aquifer which could perhaps be used, but only to supply small villages. The alluvial deposits are usually very permeable. In the biggest valleys, they can be sufficiently large to provide an adequate water supply for small towns or small irrigated areas. However, it remains to be established whether in groundwater systems in Sierra Leone can compete economically with surface water in meeting the requirements for irrigation, where permanent surface water is abundant.

The Bullom series of the Pleistocene age, especially the sand and clay strata, constitutes the country's main aquifer. Problems of sea-water invasion may arise near the coast and along the estuaries. The Rokel series, which includes argillaceous sandstones and schists and covers a large area of the Bolilands, could host water but volumes have so far been uncertain. The metamorphic schists of Marampa may contain small aquifers in the fracture zones. The altered and fractured zones of the granite basement rock are water-bearing.

A survey conducted on 12 towns using groundwater for their domestic water supply indicated that the average daily discharge is quite variable between 4 and 62.5 $m^3$/h (1 – 17 l/s). For all the water points, except for two surface springs, the yields declined steadily in dry season or the well became dry.

## Hydrogeological units

Recalling the main geologic units presented in the previous section (Table 4), Adekile (2013) provided a simplified hydrogeological classification with four categories corresponding to four geological units. Lapworth (2015) provided preliminary concepts of hydrogeology in humid tropics, lateral pathways and water quality related issues in Sierra Leone. One main distinction is between the relatively low permeabilities of the old, hard rocks of the Precambrian Basement Complex, Saionya Scarp/Rokel River Group and Ultrabasic intrusives on the one hand, and the higher permeability and storage of the Bullom Group sands on the other hand.

The most important of these units is the Basement complex, extending to over 75% of the country, which can be vertically subdivided into an upper weathered zone overlying poorly fractured bedrock. The upper zone is widespread and is a primary source of groundwater for hand-dug wells across the country.

A general classification divides Sierra Leone into four hydrogeological units: (1) Unconsolidated sedimentary deposits, (2) Consolidated metamorphic, (3) Igneous rocks and (4) Basement complex. Each unit is described below.

### *Unconsolidated sedimentary deposits*

The hydrogeologic unit can be subdivided into alluvial (valley fill) and coastal deposits of the Bullom Group formation. Alluvial sediments are sands, gravels and clays that overlying the basement rocks, usually up to 15 m thick. They have primary porosity and can have elevated permeability. Groundwater storage and flow is entirely intergranular. There is limited data on borehole yields from this sub-unit, but it is likely that yields are between 0.3 and 5 liters/second (l/s). Coastal sediments of the Bullom Group are unconsolidated sands and clays (inland alluvial & coastal), usually 10 - 20 m thick, and can form a moderately productive aquifer with potential borehole yields up to 3 l/s. Groundwater flow in coastal sediments is intergranular and storage capacity can be high. Below this, are interbedded sands and clays which are typically 30 - 80 m thick. Boreholes in this unit can often abstract up to 6 l/s (Lapworth et al. 2015).

### *Consolidated metamorphic of Sayonia Scarp and Rokel River formations*

There is a near-surface weathered (regolith) layer that is often dominated by clay. Below this are ancient consolidated meta-sedimentary rocks, with very limited intergranular porosity. Groundwater storage and flow occurs within fractures in the rock (secondary porosity), which are often along old bedding plains, although there is limited information on potential borehole yields in the formation.

### *Igneous rocks*

The igneous rocks belong to various formations and consist of fractured gabbros (secondary porosity). Groundwater is likely to flow through the igneous rocks largely in fractures, although thin weathered zones may also contribute. Similarly, there is limited information on borehole yields in this formation.

### *Basement Complex, Leonean and Liberian Granites*

There is typically a layer of highly weathered rock – the regolith – showing primary porosity, overlying the unweathered bedrock, which has often transformed to a thick tropical soil. This is generally up to 20 m thick, although up to 37 m thick has been seen. The upper section of this weathered zone often has relatively little clay - the clay minerals have often been leached out, leaving metal oxides.

These metal oxides are often in the form of indurated or gravelly layers, which can be highly permeable, and can allow rapid horizontal groundwater flow (primary porosity). Near the lower extension of the weathered zone, the weathered rock is often dominated by clays, and therefore has much lower permeability. Yields from shallow boreholes abstracting from this zone are observed in the range 0.3 to 1.5 l/s. This shallow aquifer tends to dry up rapidly when the rains stop and groundwater drains rapidly away through the permeable material. It is vulnerable to contamination, because of limited attenuation potential in the subsurface and rapid horizontal and vertical groundwater flow pathways for seasonal rainfall recharge.

At the base of the weathered zone, the underlying crystalline bedrock is often extensively fractured and not clay rich, and can store and transmit groundwater through fractures. There can also be deeper fracture zones associated with faults. The average thickness of the fractured aquifer zone is 35 m, but it can be as thick as 60 m. Borehole yields in this formation are typically between 0.3 and 1.5 l/s. Groundwater pathways are usually longer than in the shallow weathered aquifer, and groundwater flow can be rapid over distances of tens of meters. This deeper, fractured aquifer zone is typically a more sustainable groundwater source than the upper weathered zone. It also has more potential for the natural attenuation of contaminants, because of the overlying clay zone and the longer pathways (Lapworth et al. 2015).

Further information on this topic can be found on the Salone Water Security website, which is a focal point for Sierra Leone's national policies, strategies, legislation and regulation on water resources, water management and water security. It is also a repository for hydrological (rainfall, surface water and groundwater) data.

## Overview of aquifer properties

There are very few published records of aquifer properties for Sierra Leone and no national scale research on the distribution of specific parameters (e. g. hydraulic conductivity, transmissivity or water-table levels). Existing reports from local contractors normally record field data without processing. Well yield in liters/second (L/s) is the most common registered parameter.

When also pseudostabilized drawdown is available, Specific Capacity (SC) can be calculated as an indication of transmissivity. Other properties such as storage or specific yield values, are usually derived from estimates of effective porosity based on an assessment of rock composition, even though this approximation could only be acceptable for porous formations and not for fractured rock aquifers. Authors (MacDonald, Chilton, Foster, Wright) have recorded measurements of well yield, hydraulic conductivity, porosity and transmissivity values (the product of aquifer thickness and hydraulic conductivity) in the weathered Basement Complex in other parts of Africa as follows:

*Weathered basement*

- Well yield: 0.1 to 0.3 L/s
- Hydraulic conductivity 0.01 to 5 m/d
- Specific yield 0.05
- Transmissivity 0.2 to 10 $m^2$/day

Values can fall below and above these ranges. Well yield values reported in the weathered basement of Sierra Leone are between 0.3 and 1.5 L/s (Table 6). For sedimentary formations, such as the unconsolidated coastal sediment of the Bullom Group, well yields are significantly higher and values of up to 6 L/s have been reported (no source). No well yield data has been identified to date for the consolidated sediments of the Rokel River Group.

Other values are listed on Salone Water Security web site:

- Yields from 231 boreholes of between 0.4 to 12 L/s, mean of 3.6 L/s (Thomas, 2016)
- An unusual high transmissivity value of 188 $m^2$/d from weathered basement in southern Sierra Leone (Akiwumi 1987).
- In central Sierra Leone, an average hydraulic conductivity (permeability) value of 0.09 m/d (Awikumi 1987)
- Akiwumi (1987) also reports a transmissivity value of 196.3 $m^2$/day for "valley fill" material within the basement complex in the southwest of Sierra Leone and permeability ranges between 0.01 and 0.1 m/d collected during Bumbuna dam construction in the upper 50 m of bedrock

**Table 6. Main hydrogeological units and aquifer parameters from various sources in Sierra Leone**

| Hydrogeological units | [A]Aquifer type | % of land area | Sub-units | [2,3]Well depth (m) | [2]Well yields (l/s) |
|---|---|---|---|---|---|
| Precambrian basement complex | D | 78% | Valley fill deposits | Up to 15 | Nd |
| | | | Weathered zone (laterized clay rich) | Max 37 m | 0.3-1.5 |
| | | | Fractured crystalline bedrock | 35 m average 60 m max | 0.3-1.5 |
| Sayonia Scarp/Rokel River | M | 9% | Weathered layer | Nd | Nd |
| | | | fractured sediments | Nd | Nd |
| Bullom Group | C | 12% | Unconsolidated sands and clays (inland alluvial & coastal) | 10-20 | Up to 3 |
| | | | Interbedded sands and clays | 30-80 | Up to 6 |
| Ultrabasic igneous | D | 1% | Fractured gabbros | Nd | Nd |
| | | | Weathered and fractured dolerite | Nd | Nd |

Source: (1) BGR, (2) Adekile (2013), (3) Akiwumi (1987)

A recent investigation (A. S. Mansaray and others, 2015) reports a value for Specific Yield of 0.18 and a recharge potential of 1,170 mm. These parameters were derived from the application of the Water Table Fluctuation Method (WTF) from a monitoring well during a period of nine months in Moyamba District.

In the Atlas of African Groundwater Resources (BGS, 2012) estimates of groundwater storage (the product of effective porosity and aquifer thickness) across similar geological areas, has shown values for Sierra Leone below 1,000 mm/yr and aquifer productivity of 0.5 – 1 l/s.

## Average Hydrogeologic Parameters

To study trends in national hydrogeologic parameters and provide a sound basis for mapping, this study constructed and collated a database of official and third-party data from existing boreholes, hand-dug wells, geophysical surveys (VES), piezometers and new in-situ tests taken by the Consultant. An overall dataset of over 29,000 records was reviewed, and a final sample of 1,033 boreholes and hand dug wells were found to contain sufficient and reliable information for hydrogeologic analysis. The higher percentages are in Bombali, Port Loko, Pujehun and Bo. Simple pump tests or yield records were available for only 98 of them as illustrated in figure 17.

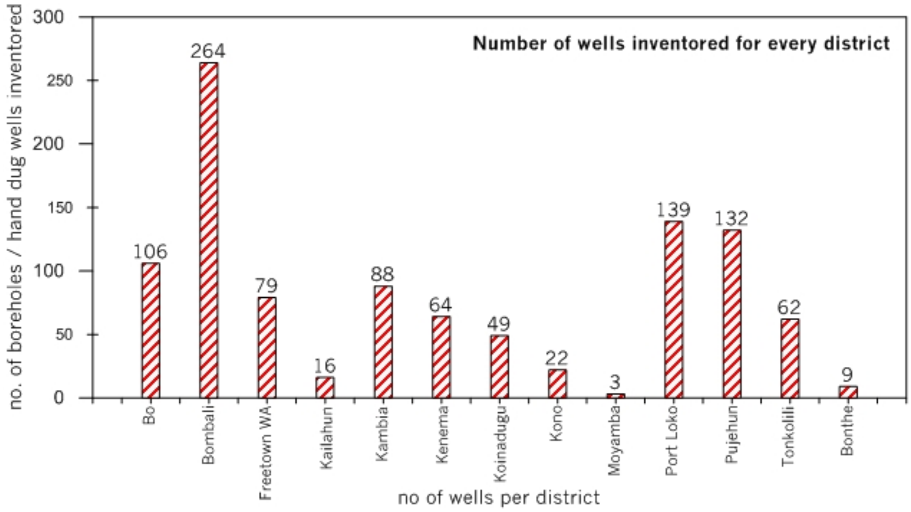



**Figure 17**. Sample number of boreholes and hand-dug wells used in analysis and mapping, by District.
Explanation: A total of 1,033 points. Only those with hydrogeological details have been processed.

Analysis of the sample shows that the average depth of the wells is 41 m, with a range of 5 to 132 m and a mean water level depth located at around 10 m below ground surface (table 7). The basement is 37 m deep, on average. Pump tests were available for a smaller percentage of this inventory.

**Table 7. Hydrogeologic parameters in Sierra Leone, extracted from 1,033 boreholes and hand-dug wells**

| Parameter | Meters (m) |
|---|---|
| **Rest water level (RWL),** below ground surface | |
| Average RWL | 9.20 |
| Minimum RWL | 0.62 |
| Maximum RWL | 42 |
| **Well depth,** below ground surface | |
| Average well depth | 41 |
| Minimum well depth | 5 |
| Maximum well depth | 132 |
| **Depth of fractured rock,** below surface | |
| Average depth of fractured rock | 12 |
| **Basement depth,** below ground surface | |
| Average basement depth | 37 |
| Minimum basement depth | 10 |
| Maximum basement depth | 80 |
| **Thickness of the surface aquifer** | |
| Average thickness | 28 |

## Specific Capacity, Drawdown and Discharge

Direct measurements of transmissivity and porosity are scarce in Sierra Leone. As an alternative, this study used proxies, like yield and specific capacity (SC). Borehole yield (termed aquifer productivity) provide a much larger dataset with which to characterize spatial variations in aquifer productivity. Porosity values, but also other hydrogeological parameters, as transmissivity and permeability, is scale-dependent and values obtained in the laboratory can be highly different from those obtained with boreholes or even larger field tests.

To define the aquifer potential, tests such as pump tests involving artificial stresses over large areas are generally preferred over those performed in the laboratory. This concept is better illustrated in figure 18, which shows the change in porosity as the volume increases in the rock formation.

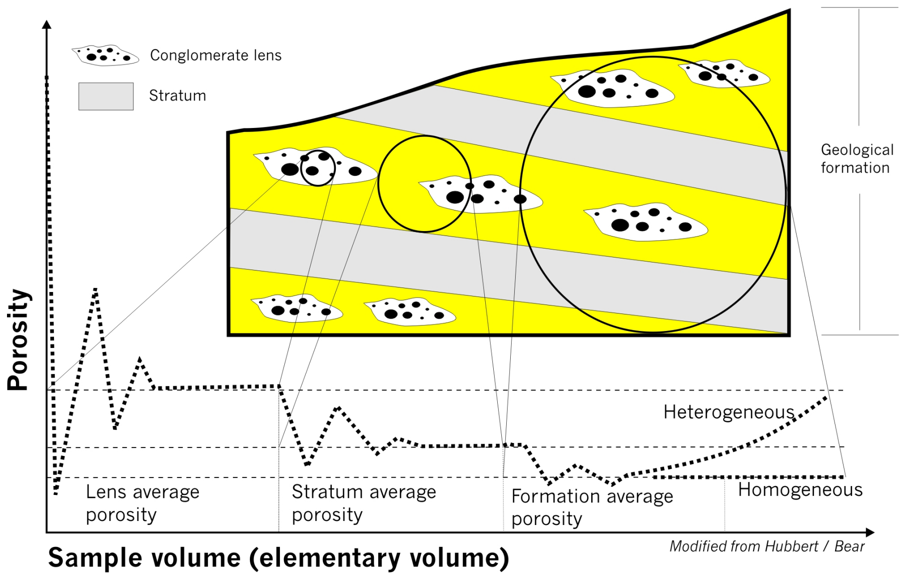



**Figure 18**. Variation of porosity value with aquifer volume.
Explanation: Porosity, like other hydrogeologic parameters, is considered scale-dependent, that is, the larger the investigated volume, the lower the parameter value. (Modified from Hubbert/Bear).

From the hydrogeologic inventory, the specific capacity (SC) was calculated at national scale, drawing from raw data from a selection of 100 boreholes that had sufficient relevant information. Results of calculations are given in Table 8 and fig. 19-20. Field tests in Western, Kambia and Pujehun Districts are more abundant. Yields are as low as 1-1.5 l/s. The population distributions is normal with a median smaller than the mean, so a reasonable figure for specific capacity should be around 7 $m^3$ /d/m. Additional analysis on SC in areas of interest (AOI), such as Freetown, are provided in subsequent sections in this report.

**Table 8. Average values for specific capacity (SC), drawdown and discharge in various Districts**

| District | Avg. T (sqm/d) | Avg. SC (cum/d/m) | No. of wells | Avg. DD (m) | Avg Q (l/s) |
|---|---|---|---|---|---|
| Bonthe | 2.78 | 100.3 | 9 | 7 | 1.32 |
| Kambia | 2.553 | 25.3 | 20 | 11 | 1.2 |
| Pujehun | 3.3 | 74.4 | 17 | 5.2 | 1.46 |
| Bombali | - | 6.7 | 1 | 19.2 | 1.5 |
| Kono | - | 230 | 1 | 0.76 | 2 |
| Moyamba | - | 7 | 1 | 25.63 | 2 |
| Port Loko | - | 19.95 | 6 | 21 | 1.7 |
| Tonkolili | - | 152 | 2 | 4 | 2.2 |
| Western Area | - | 11.6 | 41 | 27.7 | 1 |

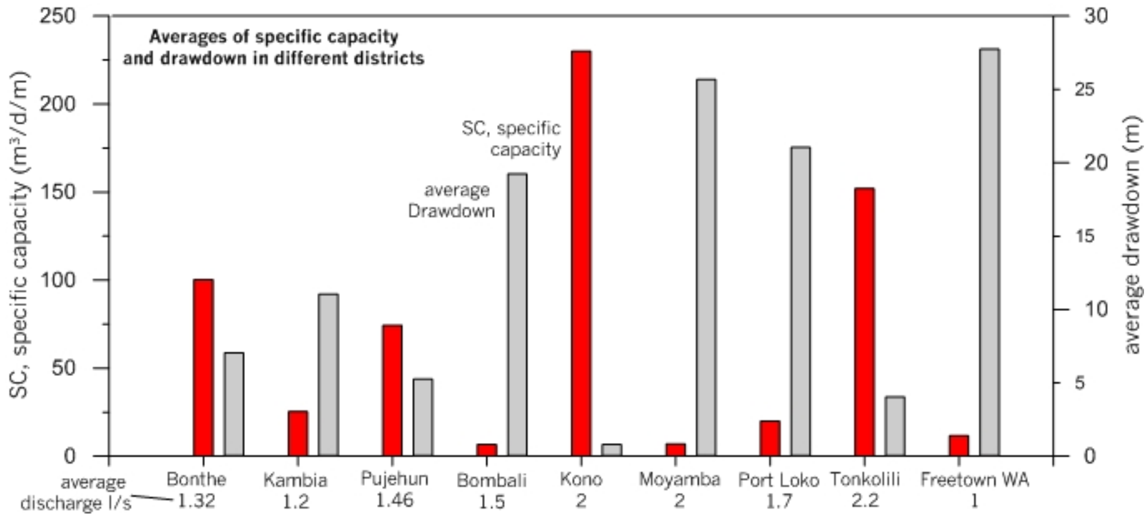



**Figure 19**. Average values for specific capacity (SC), drawdown and discharge in various Districts.

The following figures (Fig. 20-21) show more generally the distribution of SC for all pump tests. SC is consistently low with a median value of 7 ($m^3$/d/m).

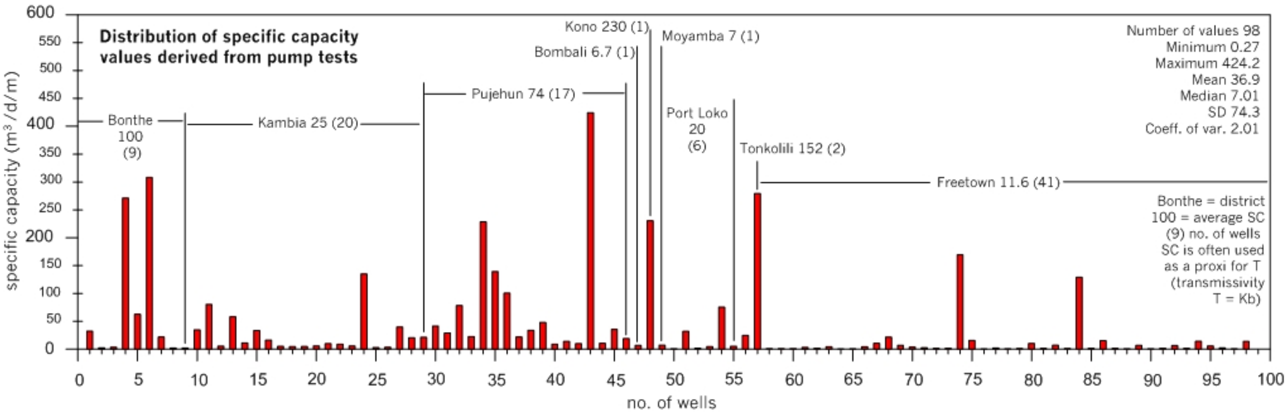



**Figure 20**. Distribution of specific capacity (SC) in Sierra Leone, with statistical analysis

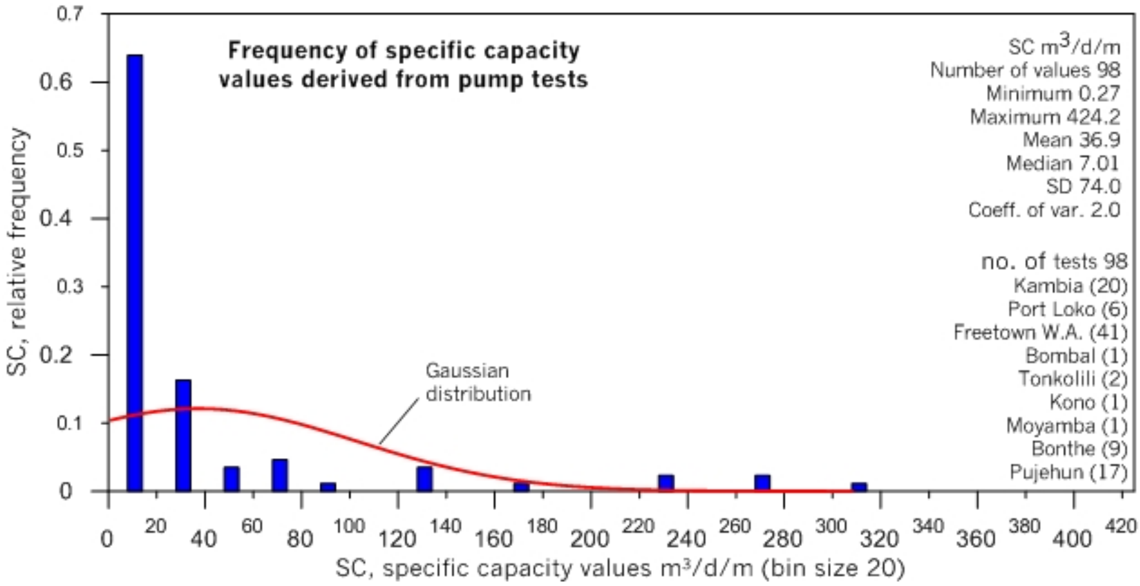



**Figure 21**. Frequency of specific capacity (SC) in Sierra Leone, with statistical analysis

Various authors have used regression methods to develop equations relating specific capacity and transmissivity. Huntley (1992) devised a predictive equation for estimating transmissivity from specific capacity data in fractured aquifer. This method was applied to all values derived from the processing of data, and results are illustrated on Figure 22. Among the data recovered, 46 pump tests were available and interpreted using the Jacob “straight line” method (MOWR), while the remaining 42 boreholes were processed to calculate SC and the derived T. T values have a very low degree of precision, most likely due to very short pumping periods and/or high well losses. This trend is clear from the two scattered plots.

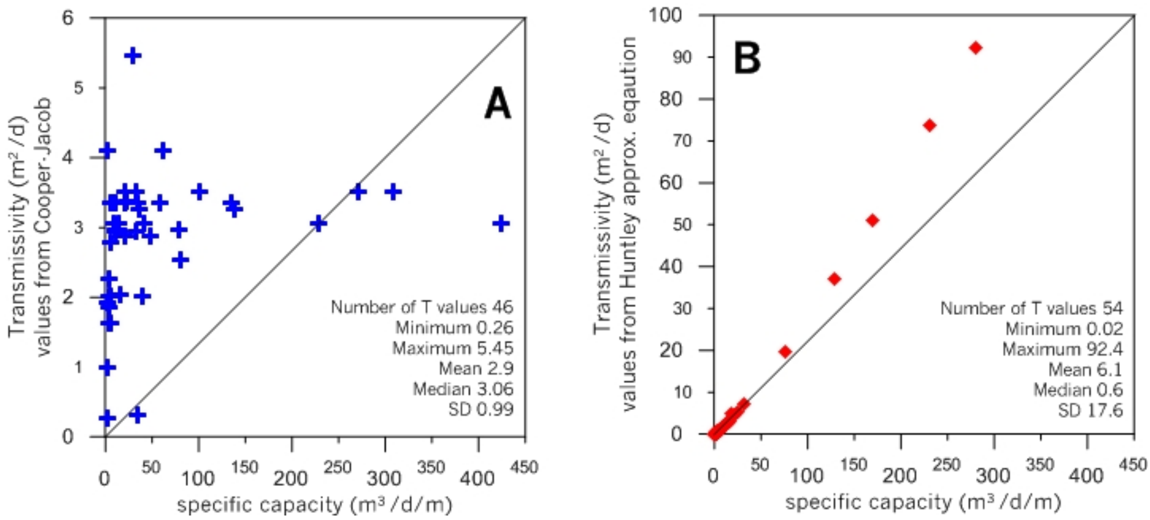



**Figure 22**. Scatter plot of transmissivity (T) and specific capacity (SC)
Explanation: (A): T calculated from Cooper-Jacob straight line method on 46 tests (MOWR), T and SC are obtained independently; (B): T calculated with Huntley approx. formula using SC values, for the remaining 42 sites.

In figure 22 (A), only T and SC values obtained in the field are compared (46 pump tests), showing a poor correlation. In fig. 22 (B), T, obtained with an approximation formula, and SC measurements are compared. In (B), the correlation decreases with larger values of SC, a possible confirmation of poor test quality and the introduction of some unknown errors.

### *Conclusions about hydrogeological parameters*

As a conclusion, aquifer properties of the unconfined fractured aquifer can be considered rather low, in accordance with the more general measurements obtained by other authors on the crystalline basement in Africa. Transmissivities either in the porous or in the fractured formations vary from 3 to 6 $m^2$/d, while considering the average aquifer thickness of 28 m, hydraulic conductivity ranges from 0.1 to 0.2 m/d.

## Water Wells and Water-table Fluctuations

Hand-dug wells in Sierra Leone range in depth from less than 10 m to over 20 m. Boreholes in fractured rock and sediments are drilled to depths of 46 – 100 m. Borehole depths recorded from 359 locations varied from 9 - 63 m with a mean of 33.6 m. A map with position and values of static water levels in a limited part of the basement complex of central Sierra Leone is included in the MWR / UNICEF manual drilling document (Adekile 2013). Most wells recorded groundwater level within 10 m of ground surface, and exceeded 20 m in some locations.

Seasonal variations are rarely recorded. Akiwumi (1994) recorded seasonal groundwater level fluctuations from 18 boreholes in weathered basement in the Bumbuna area of between 1.3 m and 8.1 m (mean of 3.6 m). In Thomas's spreadsheet, groundwater levels were recorded on a single occasion in 359 boreholes at between 1 and 21.7 m depth with a mean of 8.1 m. The dates of measurement are unrecorded, though are divided into wet and dry season levels. Only two records (both in Kambia District) have groundwater levels in the wet and dry season indicating ranges of 3.75 and 16.76 meters, respectively.

The detailed WASH survey on existing wells in Sierra Leone (2012) includes 28,845 groundwater points. The number of in-use groundwater points is 18,908. Only 7,696 are seasonal and get dry several months of the year. At the time of this study, 11,212 water wells were functioning all year round (39% of the total). The large number of damaged points indicates serious shortfalls in ensuring the sustainability of constructed water points, and the high rate of seasonality points to a systematic problem in selecting well-locations properly and drilling deep enough.

Regarding groundwater level response to rainfall, hydrographs from monitoring stations started to record on a systematic way only recently and in a few points (Tonkolili, Bombali, Koinadugu). This study deployed the use of in-hole well logging instruments into hand dug wells to record water table changes in the weathered aquifers. All hydrographs show a strong recharge-discharge relationship with distinctive increments of water level soon after start of rainfall. In Bombali the recession period usually starts mid-August with an initial rate of 1.5 m per month reducing to 1m per month from the end of October through to the year end. Data from 2013 suggest that the decline will continue at around 1m per month and will be nearly fully discharged by mid-March. The seasonality of the aquifers was also noted from Mansaray (2015). In the monitored well of Mokonde Community (Moyamba district), a strong relationship between recharge and peak daily events was ascertained, also due to upstream recharge. Furthermore, following the rainy season, base flow was detectable throughout the year at decreasing rate.

In summary, the key points regarding water-table fluctuations in Sierra Leone are:

- Water tables respond rapidly to the first rains in May;
- Water tables rise to a peak around mid- to end August, coinciding with the peak of the rains;
- Water tables recede rapidly after the peak rainfall month, despite the subsequent months having significant rainfall;
- Water tables continue to recede through the dry season, reaching their lowest levels in April.

## The Conceptual Model

All groundwater studies rely on a conceptual representation of the groundwater flow system. The aim of the conceptual model for Sierra Leone, as for any, is to simplify the field environment and organize data in a way that aids analysis. Key features of conceptual models include:

- Relationship and extent of hydrogeologic units, ie. hydrostratigraphy and hydrofacies;
- Aquifer material properties such as porosity, hydraulic conductivity, transmissivity, storativity (storage coefficient) and isotropy;
- Potentiometric surfaces, sometimes represented by groundwater contour maps;
- Water budgets, ie. inflows and outflows such as surface infiltration, lateral boundary flux, leakage through confining units, withdrawals and injections;
- Boundary locations, ie. depth to bedrock, impermeable layer boundaries, etc.;
- Boundary conditions, ie. fluxes, head, natural water bodies;
- System stresses, ie. withdrawals wells, infiltration trenches etc.;
- Dynamic relations varying through time;
- Water chemistry, according to objectives such as drinking, irrigation, pumping, etc.

### *Model assumptions*

The baseline hydrogeologic conceptual model for Sierra Leone is based on a set of main assumptions, listed below (a.-k.). These assumptions help establish the conceptual boundaries to the model, being derived from the data gathered during this study, and can be further refined as new data and information become available in the future. The model is also based on simplifications applied over a large region, so some directions may not be valid on a local scale, and consequently more than one conceptual model can be formulated (see figures 18 and 19).

a. The environment under study is characterized by large extensions of fractured rocks of an average thickness of 25 m, over a hard basement.

b. Along the Atlantic coast, an elongated area of loose sediments, 40-50 km large and 20-30 m thick is present.

c. The entire region is covered by an extended layer of highly weathered rock (laterite) of variable thickness (approximately 2-30 m).

d. The hard rock basement has an undulating morphology with an average depth of 37 m below ground.

e. Rainfall precipitation ranges between 2,400 and 5,000 mm/yr, with high infiltration rates.

f. Vegetation cover is also common with large swamp areas, forests, savannas, coastal woodlands, grassland and mangroves; the vegetation is responsible for high evapotranspiration rates. Moreover, the vegetable cover reduces evaporation during the dry season allowing the flow of water, especially along the small water courses in the dense forest, thus contributing to the extension of the recharge period during the dry season.

g. Transmissivity is generally low for the fractured and porous formations and weathered surface layer (T = 3 – 20 $m^2$/d), and yields from boreholes is considered between 1 and 2 l/s but may differ slightly locally.

h. The permeability (hydraulic conductivity) of the surface layer is also generally low (K = 0.1 – 0.2 m/d). With exception of the more elevated areas upcountry, K values can be a bit higher in the Freetown Peninsula and the sandy sediments along the coast from Bonthe to the Liberian border.

i. A strong recharge–discharge relationship has been noted, with a rapid response of groundwater to rainfall and long recession periods following the end of the rainy season (2-3 months).

j. The study of some water level variations in some selected wells seems to support the concept of general aquifer heterogeneity with a response close to a double porosity medium.

k. From the water-table readings, we note a close relation between groundwater and surface streams and also between surface relief and the water-table; the path of groundwater flows follows closely the river courses.

### *Hydrogeologic schemes*

The abovementioned assumptions allow the following hydrogeological schemes to be formulated:

1. Shallow, unconfined aquifers are prevalent throughout the country. These aquifers are partly confined near the coast in some areas.

2. The aquifer bed consists of a hard rock basement (intrusive, extrusive or metamorphic).

3. The top extent of the aquifer traces at a reduced gradient along the gentle undulating morphology of the ground surface.

4. Compact crystalline basement outcrops along many of the big rivers, thus indicating also the presence of the aquifer bed, the local base level and the general low aquifer thicknesses; clues are evident that many of both main and minor rivers have a strict relationship with the lateral porous and fractured aquifers.

5. There is a general correlation between main groundwater flow lines and river courses. The main aquifer boundaries are considered as nearly coincident with the surface watersheds.

6. Due to the aforementioned schemes, and also due to the lack of large alluvial deposits, several small unconfined aquifers are present (fragmented aquifer); their extensions and number can vary during the year following the wet and dry periods and are influenced by the rough basement morphology; in dry season, for example, the water-table may drop, and can fragment entire aquifers into smaller ones. (Figure 24)

7. The surface layer and the fractured rock are characterized by high heterogeneity and anisotropy with permeability (K) dependent of direction. Due to the variations in permeability between the weathered and the fractured formations the aquifer response to seasonal variations is like that of a medium with double porosity (fig. 23(c)).

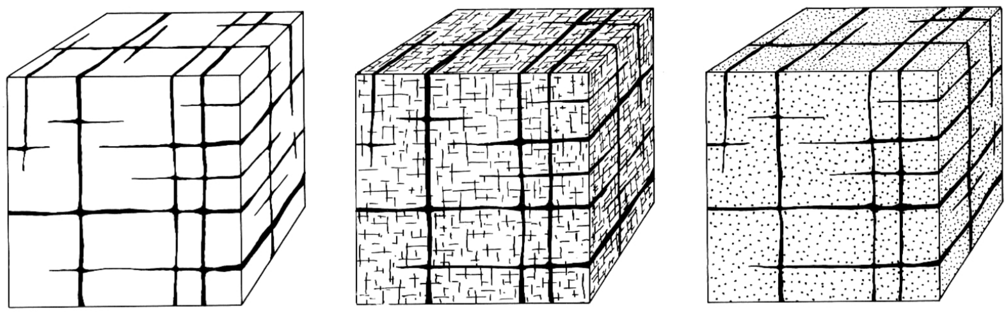



**Figure 23**. Conceptual diagrams of three types of secondary porosity.
Explanation: The porosity of a rock is its property of containing pores or voids. If we divide the total unit volume V, of an unconsolidated material into the volume of its solid portion Vs, and the volume of its voids Vv, we can define the porosity as n = Vv/V. Porosity is usually expressed as a decimal fraction or as a percentage. With consolidated and hard rocks, a distinction is usually made between primary porosity, which is present when the rock is formed, and secondary porosity, which develops later as a result of solution or fracturing. The diagrams above show that fractures can be oriented in three main directions, which cut the rock into blocks. In theory, the primary porosity of a dense solid rock may be zero and the rock matrix will be impermeable. Such a rock can be regarded as a single-porosity system (A). In some rocks, notably crystalline rocks, the main fractures are accompanied by a dense system of microfissures, which considerably increase the porosity of the rock matrix (B). In contrast, the primary porosity of granular geological formations (e.g. sandstone) can be quite significant (C). When such a formation is fractured, it can be regarded as a double-porosity system because the two types of porosities coexist: the primary or matrix porosity and the secondary or fracture porosity. Source: Kruseman et al, 1990.

8. The weathered basement form the most widespread and important aquifer across Sierra Leone. The weathered zone is derived from the underlying parent rock formations, under intense rainfall and large seasonal groundwater table variations. The resulting thick tropical soils form an important part of both the unsaturated zone and shallow aquifers (Akiwumi, 1987; UN, 1988).

   At depth, below the weathered zone, open fractures can be found associated with fault zones. The flow of groundwater follows therefore, two paths in different medium: a slower one in the weathered upper layer with low porosity and permeability, and a faster pathway in the lower fractured rock with higher permeability. (Figure 24).

   Maini and Hocking (1977), for example, give the equivalence between the hydraulic conductivity of a fractured rock and that of a porous (granular) aquifer. From their tests, it follows that the flow through, say, a 100-m thick cross-section of a porous medium with a hydraulic conductivity of $10^{-12}$ m/d could, in a fractured medium with an impermeable rock matrix, also come from one single fracture only 0.2 mm wide. In weathered crystalline basement, most sustainable groundwater sources tend to exploit groundwater in fractures at the base of the weathered zone. This can be in fractures 15 – 40 m depth, depending on the thickness of the weathered zone.

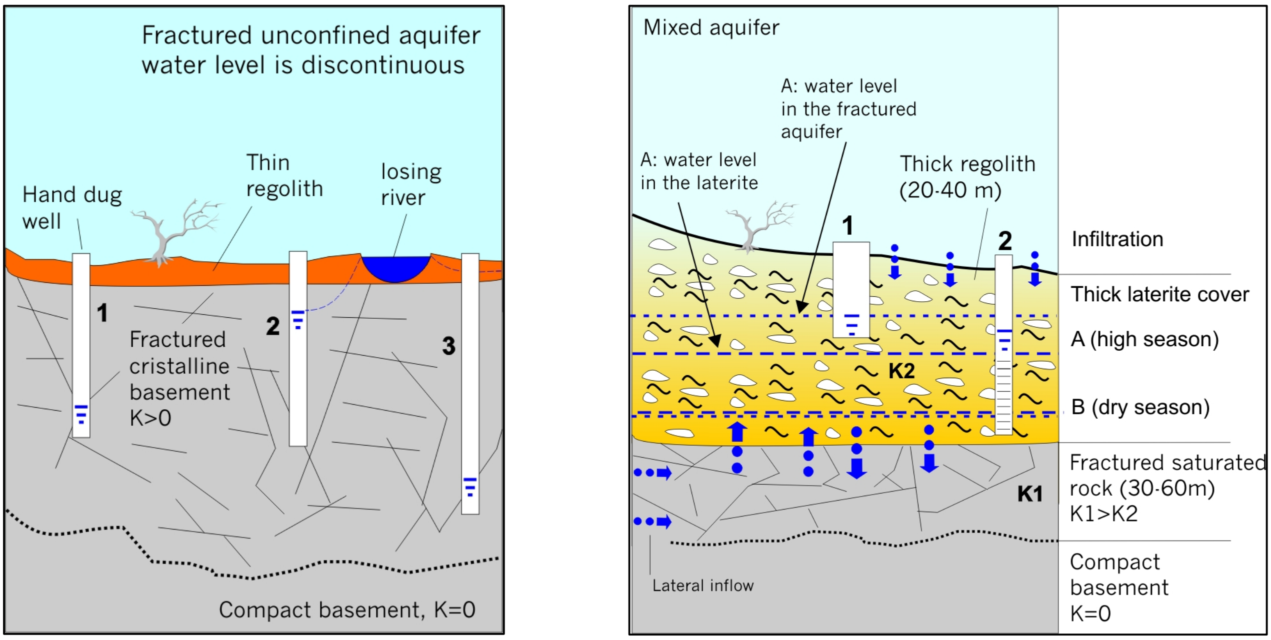



**Figure 24**. Schematic diagrams of two typical aquifer types in Sierra Leone.
Explanation: (Left) Groundwater flow in a fractured aquifer with thin regolith cover. Recharge can derive from rain (water wells 1-3) and river infiltration (fractures connect river and hand dug well no. 2). The different situations can lead to long or short water availability during the year. (Right) In a mixed aquifer where thick regolith is present, water can flow in two medium with different hydraulic conductivities. The two aquifers are both unconfined but their communication is through the low permeability of the upper weathered layer. During the wet season, water is supplied at different rate depending on local hydrogeological conditions, either from rainfall or nearby river or both. At the beginning of the recharge two separate water levels may exist (A), but after a few weeks the levels compensate each other, reaching a minimum distance to the ground surface. During the recession period the fractured aquifer loses water at a higher rate, especially if connected with a river, while the weathered upper layer dewaters at lower rate. At the end of the dry season (B), usually in April, the two piezometric levels are in equilibrium but at lower elevation.  The figure shows a typical situation of Sierra Leone aquifers where hand dug well no. 1 is sustainable for a limited period of the year, while borehole no. 2 supplies water all year round.

9. In the unconsolidated deposits of the Bullom Group, the aquifer discharges naturally, not far from the Atlantic Ocean. Here, the highest discharge rates have been noted (up to 6-7 l/s) during the recession period. The structure is simplified on Figure 25 at a position near Lungi where groundwater leaves the silty sand formation at the base of a cliff with height of 15 m.

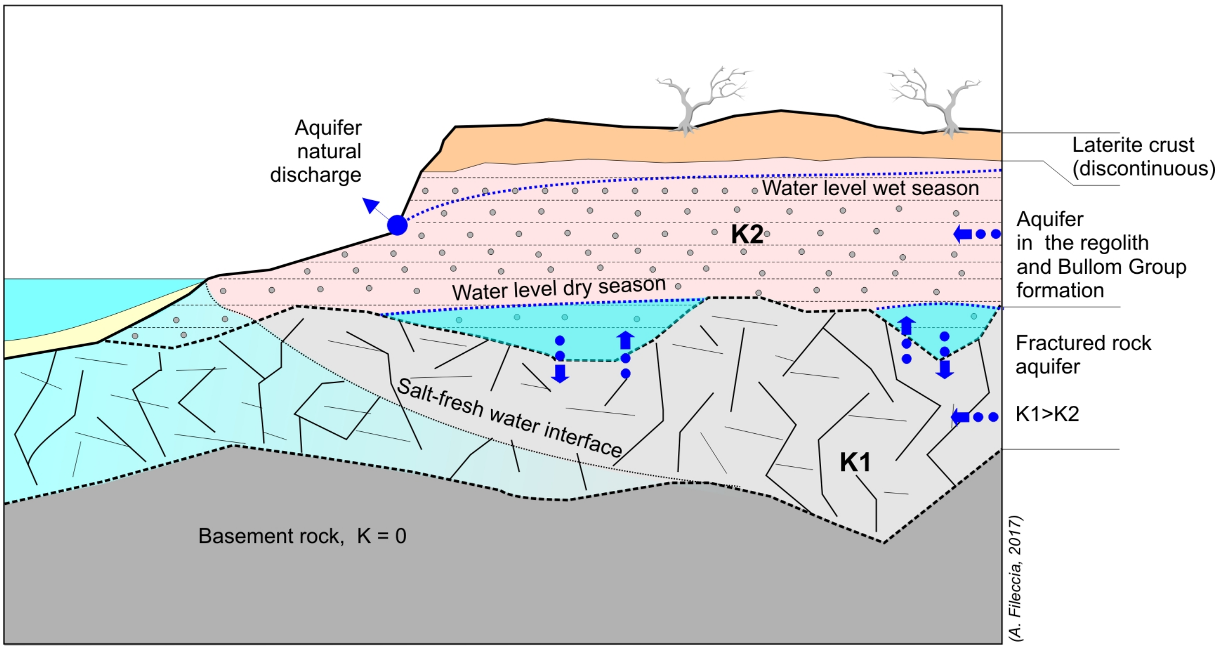



**Figure 25**. Simplified aquifer structure in the coastal zone of Sierra Leone
Explanation: Example given is the Bullom Group formation near Lungi. Natural discharge at the base of the cliff vary following different regimes. During the dry season, several separated aquifers can be present due to the undulating morphology of the basement.

10. As a general description, the groundwater recharge is rapid during the rainy season, occurring within hours in some circumstances and through the surface soil, often responding to individual rainfall events. This suggests the widespread existence of sub-vertical preferential flow pathways in the unsaturated zone. The high rate of discharge from the aquifer indicated by seasonal base flow to the rivers, the drying up of many shallow wells and the relatively rapid decline of groundwater levels after rain, can be explained by the existence of preferential flow paths and zones of higher permeability below the weathered upper layer.

### *The conceptual model*

The hydrogeologic system of Sierra Leone can be conceptualized as two zones:

Zone 1: A shallow (regolith) groundwater zone, accessed by dug wells, with K values likely to be less than 0.1 m/d, and which is vulnerable mainly to sources of contamination from the surface.

Zone 2: A deeper fractured groundwater system with longer flow paths and higher K values, which is accessed by boreholes and supplied either from the overlying porous aquifer or lateral sources (e.g. discharging rivers)

### Assessment:

Using the simple water balance equation (discussed below), we estimate that the water storage in the unconfined aquifer is 580 $m^3/s$ and less than one-third of which (193 $m^3/s$) may be considered as a sustainable resource. This value is apparently high and decisions about developing the aquifer will need to consider the fact that: (a) the water volumes are unevenly distributed over the region, and (b) aquifers have a general low transmissivity.

## Annual renewable groundwater resources

For a sustainable development of water resources, it is imperative to make a quantitative estimation of the available volumes. To this aim, one of the preliminary tasks is a realistic assessment of components of the hydrological cycle and then plan their use avoiding overdrawing or lowering the groundwater table. The precise assessment of recharge and discharge is rather difficult, as no a unique technique is currently available for their direct measurements. Hence, many of the methods employed for groundwater resource estimation are indirect. Several attempts have been made to calculate some figures on the available groundwater resources for Sierra Leone. FAO (Aquastat) estimates Sierra Leone's total renewable water resources as 160 $km^3$ /year out of 182.6 $km^3$ /year which is estimated as rain. This estimate is certainly a gross overestimate, as it fails to account adequately for evapotranspiration (Carter et al, 2015). Schuol et al (2008) estimated it to be 59.3 - 98.4 $km^3$ / year, or 32 - 54% of mean annual rainfall.

To quantify groundwater resources, it is essential to understand the behavior and characteristics of the water-bearing rock formations. Moreover, one main step is the reconstruction of aquifer geometry or the disaggregation of large catchments or regions into smaller groundwater systems. For each of the preliminary delimited aquifer basin, recharge and discharge fluxes are then mapped. Starting with the delineation of potential recharge areas and potential discharge areas according to their geological and geomorphic character, attention is then paid in assigning fluxes to each unit to estimate recharge and discharge volumes for the entire groundwater catchment.

### *Water budget equation*

The water-budget equation is simple, universal, and adaptable because it relies on few assumptions on mechanisms of water movement and storage. Calculations are normally made for a single year and refer to a singular groundwater basin, considering the influxes ("inputs") and withdrawals ("outputs") of the system being studied, with lateral aquifers and artificial abstraction. A basic water budget for a small watershed can be expressed as:

$$P = ET + R + I$$

Where: *'P'* is precipitation, *'ET'* is evapotranspiration (the sum of evaporation from soils, surface-water bodies, and plants), *'R'* is the surface runoff (measured at gauging stations), and *'I'* is the effective infiltration (water percolating through the soil and the unsaturated part and reaching the aquifer below), often measured indirectly.

### *Calculation*

Data for precipitation (P) puts the estimate at 2.5 – 3 m/yr (2,500 – 3,000 mm/yr). Determining surface runoff (R) is difficult because few gauging stations are operating presently in Sierra Leone and their positions are well upstream and far from estuaries. If we extend the available annual river flows to the entire country, the total runoff estimate is 1.01 m/yr. There are no field data at all on 'ET', but considering other researches in similar African countries (Sharma, 1985), 'ET' could approach 50-60% of the value for rainfall (P), or 1.25 - 1.5 m/yr. Using the equation with the above values, the result for effective infiltration (I) is 0.24 m/yr. Artificial abstraction (borehole pumping) is not yet a significant factor for withdrawals presently. From the WASH 2009 census, we can account for 15,000 operating boreholes in Sierra Leone with an average production of 1 l/s, making another $6.5x10^{-6}$ m.

A major caveat to the above procedure is that some components of the water-balance equation are less precise (i.e. runoff, ET, amount of base flow to coastal wetlands or aquifers during low flow periods, outflows or inflows from lateral transboundary aquifers, temporal and spatial variation in groundwater storage, upward seepage), thus lending this approach high degree of uncertainty overall. Still, we can insert the calculated values into the simple water balance evaluation (Table 9).

**Table 9. Components of the water balance and approximated values**

| Flow term | Inflows (m) | Outflows (m) |
|---|---|---|
| Rainfall | 2.5 | |
| Evapotraspiration | | 1.25 |
| Upward seepage | | ? |
| Horizontal outflow | | ? |
| Horizontal inflow | ? | |
| Surface runoff | | 1.01 |
| Effective infiltration | ? | |
| Artificial abstraction | | $6.5x10^{-6}$ |
| Base flow along coastal aquifers | | ? |
| Total | 2.5 | 2.26 |

Explanation: Volume units are given in meters, as in the amount of water in a square meter ($m^2$) applied to any area of calculation in a given year. For example, rainfall volumes of 2.5 m applied to the surface area of Sierra Leone (71,740 $km^2$) would be calculated as 179.350 $km^3$/yr.

Studies have shown that evapotranspiration rates vary from 30 to 90 percent of the rates from nearby open water. The evaporation component can be reasonably estimated; but the transpiration component depends on knowledge of how much water the plants release through transpiration. Transpiration rates have been estimated to be from 0.53 to 5.40 times evaporation alone. Water balance studies in the central African tropics (Sharma, 1985) estimate that more than 80% of the annual rainfall could return to the atmosphere by evapotranspiration.

Reliable data for a correct water balance evaluation are scarce in Sierra Leone and the table above is presented more as an exercise using figures with a very limited groundtruthing. The area considered is the entire territory of Sierra Leone. Regarding the annual flow from the main rivers, measurements are available for a limited number of water courses and years (Rokel, Pampana, Sewa, Moa). Furthermore the gauging stations are located upstream, far from estuaries and do not measure the total flow discharged to the sea.

> For a total basin area of 30,417 $km^2$, the measured average flow is 24,642 x $10^6$ $m^3$ /yr (1970 -1976). Extrapolating the runoff volume for all the country (73,220 $km^2$), we assume a total runoff of 74,000 x $10^6$ $m^3$ /yr (74 $km^3$).

Solving the balance equation, without considering the unknowns ('?'), we get an effective infiltration of 0.24 m. If we consider that after one hydrologic year the water table reaches the same level of the preceding year, approximating the seasonal range in water level to 5 m and specific yield to 0.05, we then obtain a storage volume of 18.3 $km^3$, or 0.25 m.

### *Recommendation on improving the calculation*

To improve the very simple model described we suggest to:

1. Maintain and continue updating the hydrogeological DB on a regular basis
2. Expand the monitoring network for surface and groundwater resources
3. Assess various groundwater contour maps for different seasons during the year at a national and local level to gather reliable information on the recharge and discharge
4. Improve the hydrogeological parameter certainty by scheduled aquifer/permeability tests

# Contents of the Hydrogeologic Atlas

The set of groundwater maps of Sierra Leone provide general information on the extent and geometry of regional aquifer systems. The maps are intended to serve as a base for future management of groundwater and present information to non-specialists. The aim of the effort is to serve as a starting point for more detailed local and regional groundwater investigations serve as a new foundation for the national groundwater database. The maps display the main lithologies, the general aquifer types, their productivity, the average groundwater flow directions and water-table depth below surface, the surface permeability, the approximate extension of recharge and discharge areas, the distribution of hand-dug wells and boreholes with valid water level readings and their characteristics. Due to the scarce and heterogeneous nature of data available and the scale of the final output, the maps relied on advanced interpolation modeling techniques and expert judgment. An extensive field campaign was not foreseen in the scope of the study, though groundtruthing was performed on a limited number of spots. For a limited area (Freetown district) with a greater number of boreholes and tests some parameter maps were prepared, contouring the Aquifer Specific Capacity and Depth of Basement.

Notes are given on each map that explain the main hydrogeologic concepts behind them along with observations of the main trends. Explanatory notes assist users to read the full grasp of the information presented, providing detailed information that could not be accommodated on the map itself for reasons of readability.

## Description of Aquifer Systems

### The Hydrogeologic Map of Sierra Leone (2017)

The Hydrogeology of Sierra Leone map (Figure 26) is a useful tool for hydrogeologists, groundwater specialists, and water-resources managers and planner in developing and protecting water resources in Sierra Leone. In addition, this map can serve as a catalyst in promoting future research within areas where current hydrogeologic information is limited or insufficient. The Hydrogeology of Sierra Leone map was developed by reviewing available hydrologic and hydrogeologic data, analysis of remote sensing data, and field (in situ) measurements of spot locations. The map shows the main hydrogeologic units and water-table elevation contours, for two particular timeframes – December 2016 and April 2017 – and are representative of the general flow conditions for a large area of the country. Piezometric contours for the two remaining basins of Moa and Mano rivers were not mapped due to a lack of sufficient data.

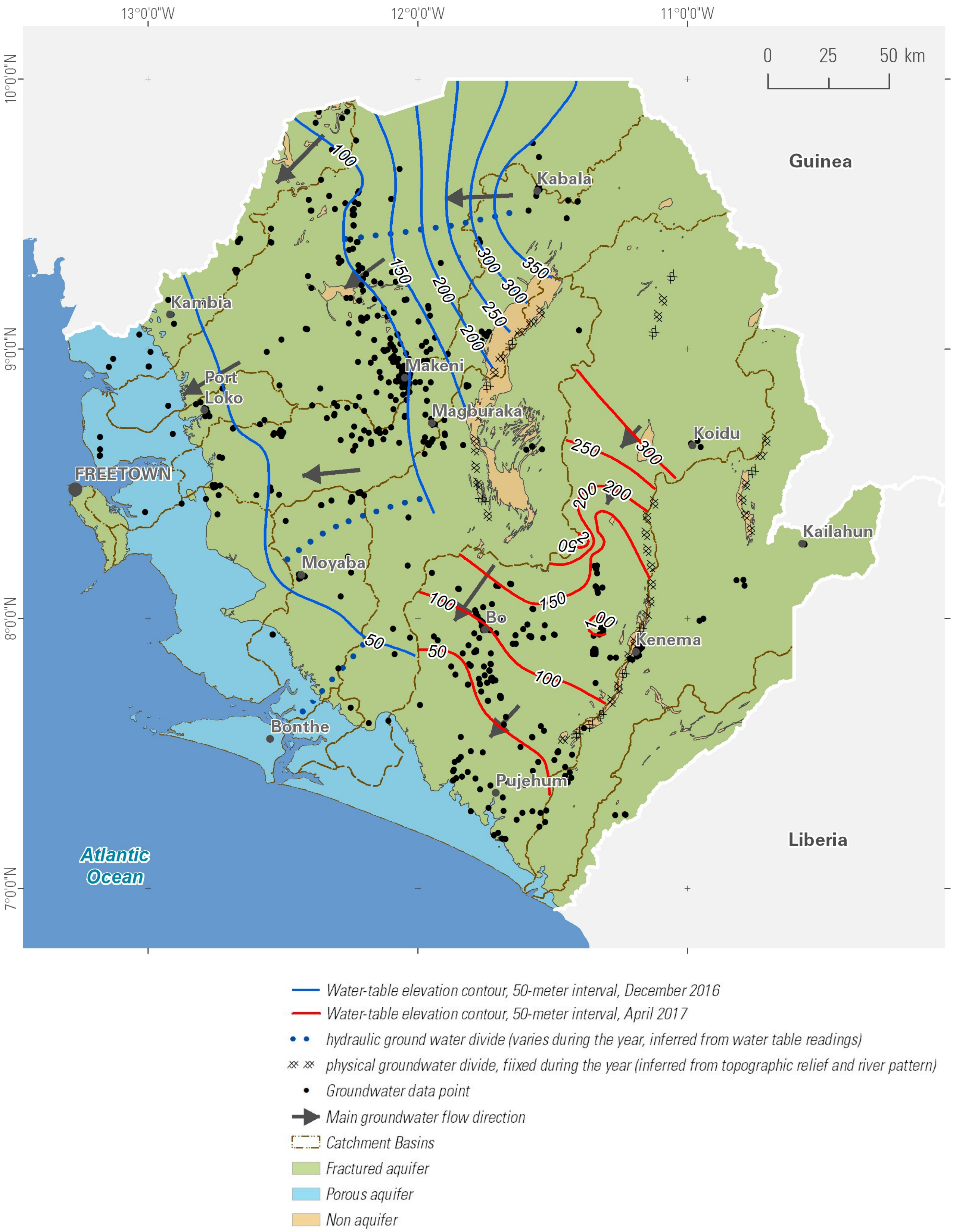



**Figure 26**. Groundwater provinces of Sierra Leone

Explanation: The Hydrogeology of Sierra Leone map (Hydrogeologic Map of Sierra Leone) depicts the distribution of the three main hydrogeologic units at a national scale. Observed water-table elevations are given in two areas (red and blue contours), see also Figure 26. Water-table elevation measurements were taken in-situ in boreholes and hand-dug wells at different periods (December 2016 and April 2017).

## Main hydrogeologic units

The main hydrogeological units of Sierra Leone have been derived from an interpretation of the Lithological Map (2017) where rocks were ranked according to their lithologies. Three categories reflect the range of division that limited data would allow. The hydrogeological units are: (1) Porous aquifers, (2) Fractured aquifer, (3) Non- or impermeable aquifers. They are described below.

### *Porous aquifers*

Unconsolidated sands and silty sands, inland and coastal, 12% approximate of land area. Only those deposits belonging to the Bullom Group along the coast were mapped. Loose sandy soils along river banks in the interior of the country have not been mapped due to their limited extension related to map scale. It must also be underlined that a great percentage of Sierra Leone surface is covered by a laterite layer hosting a surficial aquifer hydraulically connected to the underlying fractured aquifer below. Considering the tests performed in Bonthe, Pujehun, Moyamba, Port Loko and Freetown, SC is in the order of 7 to 100 $m^3$/d/m with mean value of 43 $m^3$/d/m. Q average is 1.6 l/s and well depths is 36 m.

### *Fractured aquifers*

The fractured aquifers of Sierra Leone are normally at the base of the weathered zone, with a thickness of 25 m approx. They occupy the rest of the country and are made of hard or weathered rock formations of different lithologies and fracturation, namely:

- Acid crystalline rocks of the basement, on the interior highlands
- Hard, stratified and metamorphosed sediments, along an elongated area running NW-SE and almost entirely made by Rokel River formation
- Highly fractured ultrabasic igneous rocks, outcropping at the Freetown peninsula
- Basic extrusive rocks of the Kasewa hills formation
- Metamorphic highly fractured rocks of the Banded Iron Formation in the Marampa group. Due to the high degree of secondary porosity this formation hosts some limited but anyway important local aquifers.

### *Impermeable unit (non-aquifers)*

Impermeable aquifers are situated primarily in the central and southeast part of the country. The formation is made from the various lithologies of the greenstone belt, with low grade metamorphism: schists, gneisses, pelitc metasediments, amphibolites. The unit is also classified as a fixed physical groundwater divide that separates watersheds and hydrogeological basins (e.g. Sewa and Pampana basins). Dolerite and kimberlite dykes belong to this unit, but due to their linear structure the mapping of this unit is largely indicative, and where they are more numerous they have been delimited by a dotted line.

## The flow regime

Also shown on the Hydrogeologic Map are the groundwater contours (also termed Piezometric map or Equipotential lines map), which are overlain on the main colored units. The curvilinear lines are a graphic representation of the hydraulic gradient, or piezometric surface, above sea level. The water-table is considered the surface representing the top of the saturated zone, below which pores in the rock matrix are filled with water.

Because Sierra Leone's sub-surface environment is characterized predominantly by unconfined aquifers, the head at the water table correlates to its elevation (m) relative to sea level (asl). The contours, or equipotential lines, represent lines of equal head in the groundwater body. Changes in the spacing of the equipotential lines represent a change in the hydraulic gradient, that in turn is related to permeability or aquifer bottom morphology fluctuations.

The flow direction of groundwater is also shown (arrows). In general, groundwater flow diverges away from recharge areas and converge as they near an area of concentrated discharge. Considering that water is always subjected to slow movements, due to changes in recharge and discharge, water points must be measured during a short period of time (hours or a few days), depending on the extent of the region being represented. The map illustrates the situation in December 2016 on the western side, and April 2017 along the Sewa Basin.

## Lithology

Lithology represents an intermediate step between geology and hydrogeology, aiming to synthesize the pure geological classification into a new classification that considers mainly the material of which different formations are made. The key steps to mapping lithology included:

- The conversion of geological formations of different lithology, environment and age into lithological units
- The identification and selection of the linear structures as faults, fractures or dykes necessary to better describe the groundwater flow systems
- The characterization of boundary conditions as controlled by geology and structure

In practice this procedure only presents partial information leaving out the age but allowing to separate porous and fractured formations.

### Lithology units

The original geologic formations have been standardized into 9 lithological units. The subdivision attempts to consider the rock material itself, disregarding any reference to the age formation. For example, it can thus be possible that an extrusion lava that originally was in the Geologic Map as belonging to two different formations is here considered as one lithological unit. This procedure is only based on personal judgement and some field validation, so it is expected that future refinement is in order.

#### *Recent sedimentary unconsolidated deposits*

These sediments belong to the Bullom Group and occupy the low-lying coastal plain of Sierra Leone, extending up to 45-50 km inland and are found at heights of up to 40 m above present sea level. Outcrops are rare and generally poor except for 25 m high sea-cliffs near Lungi. The Bullom Group consists of a laterally variable sequence of poorly consolidated, near horizontal, often iron-stained gravels, sands and clays with occasional laterites and lenticular seams of lignite. The clays are generally kaolinitic, red, purple and white in color with plant remains. In a borehole drilled to a depth of c. 120 m (100 m below present sea level), E of the Freetown Peninsula, a sparse fish and mollusk fauna obtained from borehole sludge indicated an age not older than Eocene and possibly as young as Miocene for near basal sediments. The sands, sometimes graded, but rarely cross-bedded, are generally poorly sorted, with a clay matrix; partially disintegrated feldspars occur. Quartz grains are very angular and under the scanning electron microscope show no evidence of marine or prolonged fluvial activity. Interbedded with the sands are occasional grit beds, stringers of rounded quartz pebbles, and horizons of kaolin clay clasts. Intra-formational laterites occur within the sands and often form puddingstone horizons. Rare, thinly bedded calcareous clays and grits have also been recorded.

#### *Intrusive acid rocks, with thin ferrallitic (lateritic) cover*

The greater part of Sierra Leone is occupied by an ancient granitic shield containing gneissic relics of still older formations. They date from the early Archean and include coarsely crystalline granites, quartz granulites, and hematitic granulites. Upon them, apparently uncomformably, lie metamorphosed sediments. In northern Sierra Leone, a complex history of granite formation, migmatization, deformation along east-west axes, and pegmatite formation can be found. This thermotectonic episode is defined as the Leonean and it is assumed that it preceded the deposition of the Kambui Group.

### *Highly fractured intrusive basic rocks, with thick ferrallitic (lateritic) cover*

The Freetown peninsula and the Banana Islands are part of an apparently funnel-shaped body of gabbroic rocks of which the greater part lies out to sea (Freetown basic complex). The complex consists of a 6 km thick series of cumulate rocks of gabbroic composition, containing layers of dunite, troctolite, olivine-gabbro, gabbro, leucogabbro and anorthosite. The complex is intruded into the gneisses of the Kasila Group. Sedimentation structures such as cross-bedding are common in the gabbro layers and some 6,000 m of thickness is exposed.

### *Less fractured intrusive basic rocks*

This group partly belongs to Kasila geologic formation as listed in the official Geologic Map. This distinctive group of mafic gneisses, migmatite, mylonite and granulites lies along the south-western part of the West African craton in Sierra Leone and passes south-eastward into Liberia.

### *Effusive mainly basic rocks*

These rocks belong to Kasewe Hills Formation and small episodic lavas of the Rokel river formation have not been considered. Outcrops occur in lenses up to 2 km thick within the Mabole and Taia Formations, and are composed of volcanic tuffs and lavas. Andesites are dominant, but spilites, basalts and tuffs of dacitic composition also occur. Pillowed spilites show that some eruptions were sub-aqueous, while air-borne pyroclastics are also present, both interbedded with lavas, and further from the volcanic centers, interbedded with Taia Formation pro-delta deposits.

### *Hard metamorphosed sedimentary rocks*

This class encompasses some sedimentary material of marine origin that was subject to low grade of metamorphic process. The rocks belong to three different formations: Rokel River Group, Sayonia Scarp, Marampa. The Rokel River Group occupies a belt 30 km wide, trending SSE for some 225 km into southern Sierra Leone and was folded and slightly metamorphosed ca. 500 Ma ago, the time of the Pan-African thermotectonic event. The group has been divided into six formations: the Tabe, Makani, Teye, Mabole, Taia and Kasewe Hills. The materials have formed in marine environment with conglomerates, sandstones, siltstones, shale and the typical layered structure of sedimentation has been maintained due to the low grade of metamorphism. Sayonia Scarp and Marampa Group were also included in this class being formed by similar rocks (conglomerates, sandstones, shales, schist, under littoral conditions)

### *Weathered deposits of banded iron formations*

This class was introduced due to the presence of large groundwater inflow in abandoned open pit mines, suggesting different permeability properties. The deposits belong to the Marampa Group and are made of low grade metamorphic schist.

### *Various lithologies of the greenstone belt*

Four belts of weakly metamorphosed volcano-sedimentary material, of about 2,700 Ma, are enclosed by older granulites, gneisses and migmatites in the eastern part. The belts are linear and tightly folded along N-S to NE-SW axis which is also the regional grain of the structures in the older basement complex. Lithologies are variable and consisting with pelitic metasediments, basic lavas, gneiss, garnet/ ultrabasic schists, quartzite, banded ironstone, amphibolite, hornblende schist.

### *Dolerite and kimberlite dykes*

Dolerite dykes and sills are widespread in Sierra Leone. Dolerites are most common close to the coast, intruding Precambrian rocks and those of the Rokel River Group as parallel dyke swarms traceable into Liberia. Further inland, the dykes become thinner and occur with more variety of trends, paralleling major NE, ESE faults. The dykes show a variation in mineralogy, but the general opinion is that they are contemporary. Dolerite sills form resistant caps of 2 major mountains in Sierra Leone, Bintumani (1,948 m) and Sayonia Scarp (1,000 m). Sills occur at progressively lower levels when traced westwards, forming similar tabular structures up to 120 m thick in the Rokel River Group at a height of 150 m The progressive decrease in sill elevation with respect to sea level towards the coast may be evidence for a post-Triassic continental margin subsidence associated with the opening of the Atlantic Ocean and the formation of new continental.

## Lineation

The distribution of lineaments (faults, dykes and fractures), are useful for analysis of groundwater flow, recharge and discharge. The mapping of lineaments entailed the interpretation of satellite image to reveal the main trends, frequency and average length of these structures. Geological structures and morphology have a good degree of correlation, particularly for the younger intrusions and linear elements.

The first are characterized by high morphological relief as better illustrated in the figure below**,** where the formation boundary of the hard rocks of the Kasila Group is nearly coincident with higher elevations.

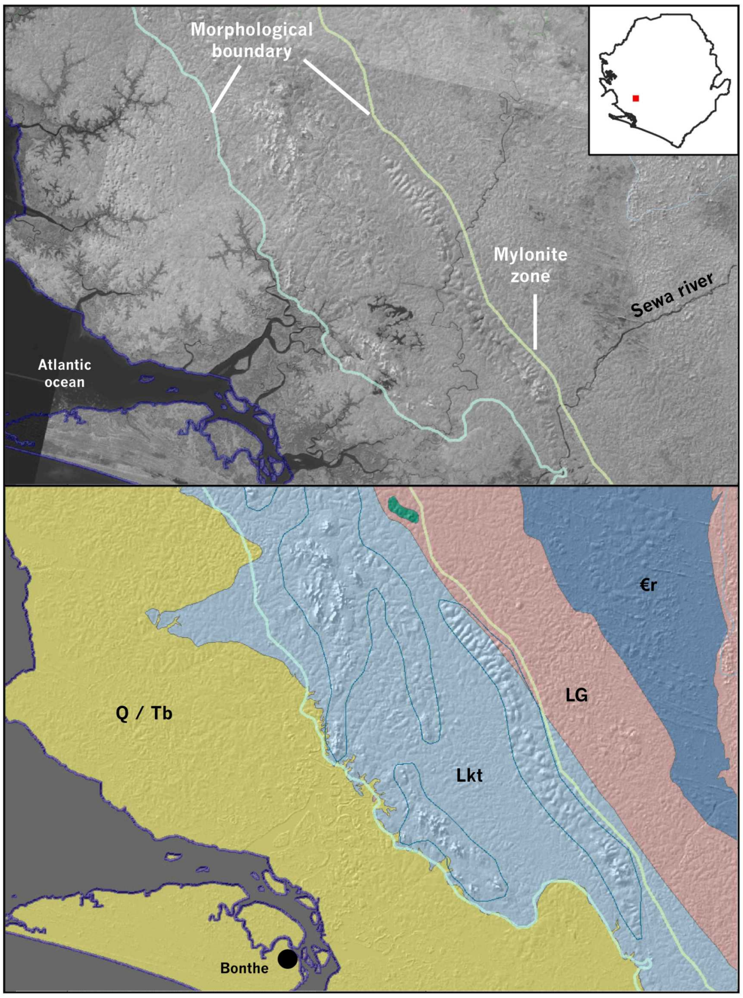



**Figure 27**. Satellite imagery interpretation of lineation morphology.

Explanation: Above, Landsat image showing good correlation between a morphological boundary and the hard rock of Kasila Group formation. The figure below is an inset from the digitized Geologic Map with different formations. Q/Tb recent sediments; Lkt gneiss, metagabbro (Kasila Group); LG gneiss, migmatite (Leonean granite); €r fine grained metamorphosed rocks of the Rokel river formation.

Similar description can be applied on a country scale (Figure 28), to the sector at higher elevation, between:

- Freetown complex and the coastal plains (where the laterite soil is probably thinner than elsewhere)
- Kasila Group and recent sedimentary sediments
- Rokel river formations and older crystalline rocks, with emphasis in the northern part

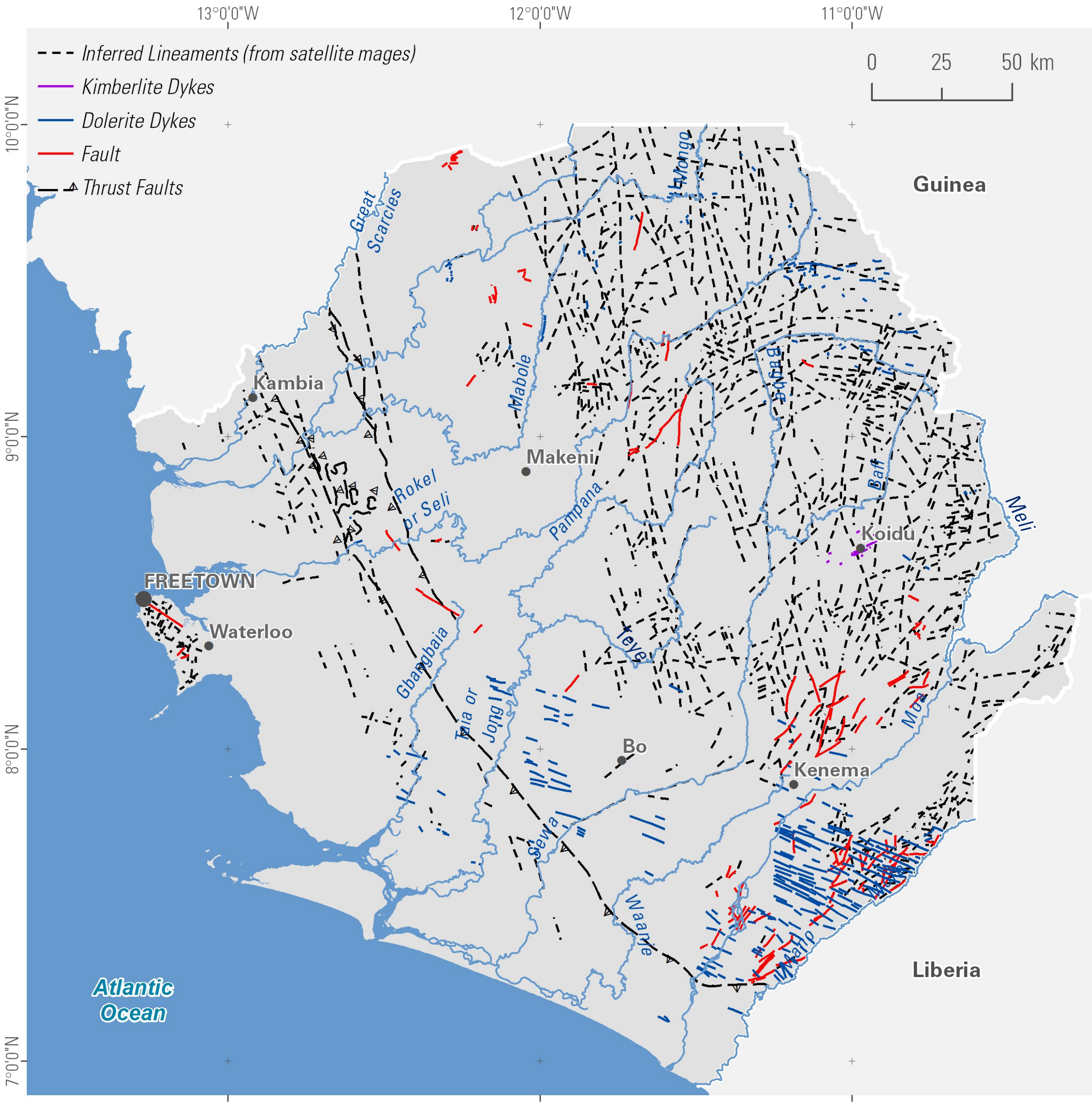



**Figure 28**. Lineaments of Sierra Leone

Explanation: Lineament trends identified through remote sensing analysis. Type of lineaments are given.

The high number of linear trends and their concentration is also clearly visible from the drainage pattern at a national and local scale (Figure 29).

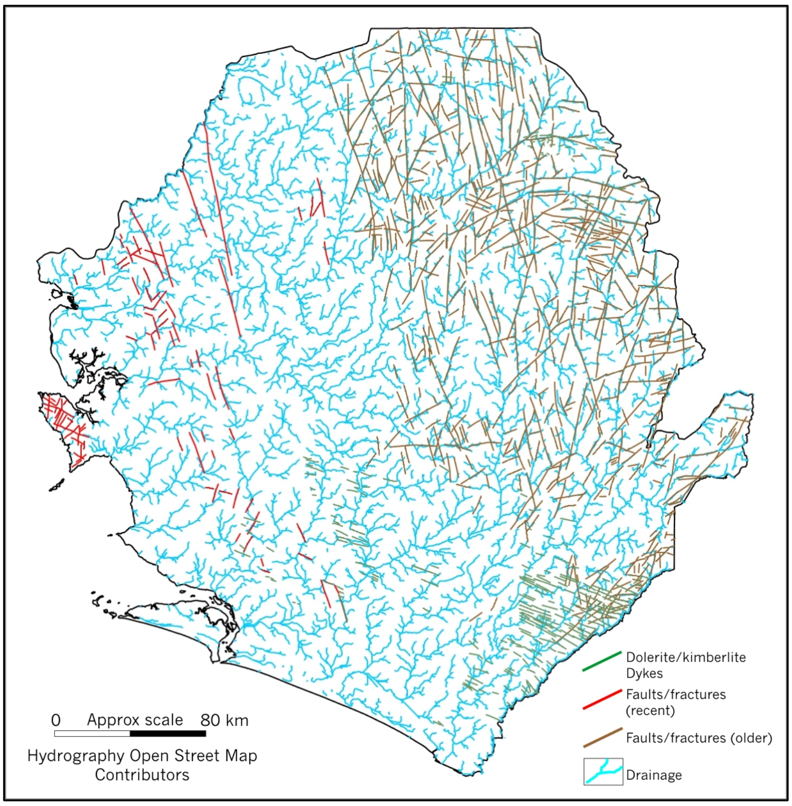



**Figure 29**. Drainage and lineament patterns.

Explanation: Faults and fractures in brown color are mainly Precambrian in age while red lineation is more recent (Mesozoic). The latter are related to the opening of the Atlantic Ocean and the similar transform systems in Guinea and Liberia. Dykes have dated to a recent magmatic activity.

Where topography is flatter and the soil thickness increases, like between Makeni and Port Loko in the interior plains, the bedrock structure is less dominant and the drainage changes to dendritic.  Most of the lineaments are concentrated in the eastern part of the country in the older Precambrian rocks, with main trend NW-SE and frequency of 13% (Figure 30).

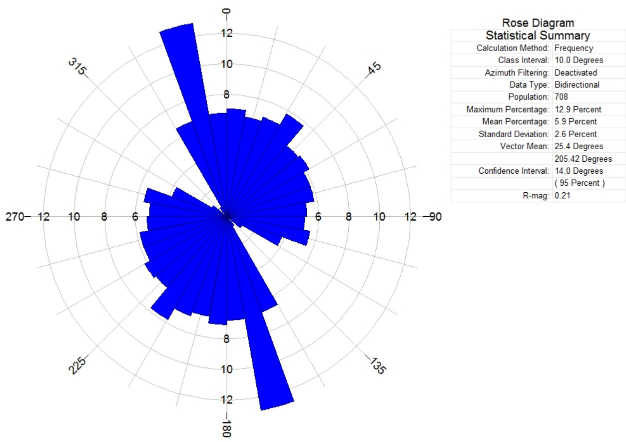



**Figure 30**. Rose diagram of lineation trends

Explanation:  Polar graph obtained through satellite image analysis of 708 lineations. Main trend is N165°E and belongs to older tectonic events (Precambrian) with a frequency of 13%. Younger dykes have a N120°E trend.

The most recent tectonic elements are located in the Freetown peninsula and along a large elongated area stretching NW-SE on the Kasila Group and west of the Mylonite zone. This complex structural evolution is related to the role of transform and extensional faults during the Tertiary and the formation of the Atlantic Ocean and is bounded by the Guinea transform system to the north and the Monrovia transform system to the south.

## Lithology Map of Sierra Leone (2017)

Lithology (Figure 31) has been mapped as an intermediate step between the geologic and hydrogeologic point of view, depicting the distribution of geologic units classified as mainly type of rock composition and texture. The Geology of Sierra Leone (2017) map used as a starting point; the 28 geologic units were interpreted as nine lithological units. Information on formation age and environment were excluded, facilitating the differentiation of porous and fractured formations. For example, a formation such as an extrusion lava would belong to two classification units on the Geology of Sierra Leone map is here considered as one lithological unit. Lineation (lines) was added (to the fully published version) to show formation contacts and folding, following a detailed analysis by remote sensing and field groundtruthing. Geological structures and morphology generally show a good degree of correlation, particularly for the younger intrusions and linear elements. The Lithology of Sierra Leone map can yield valuable insights into the formation and productivity of soils, agricultural suitability, the movement of water and other important properties that influence hydrogeology.

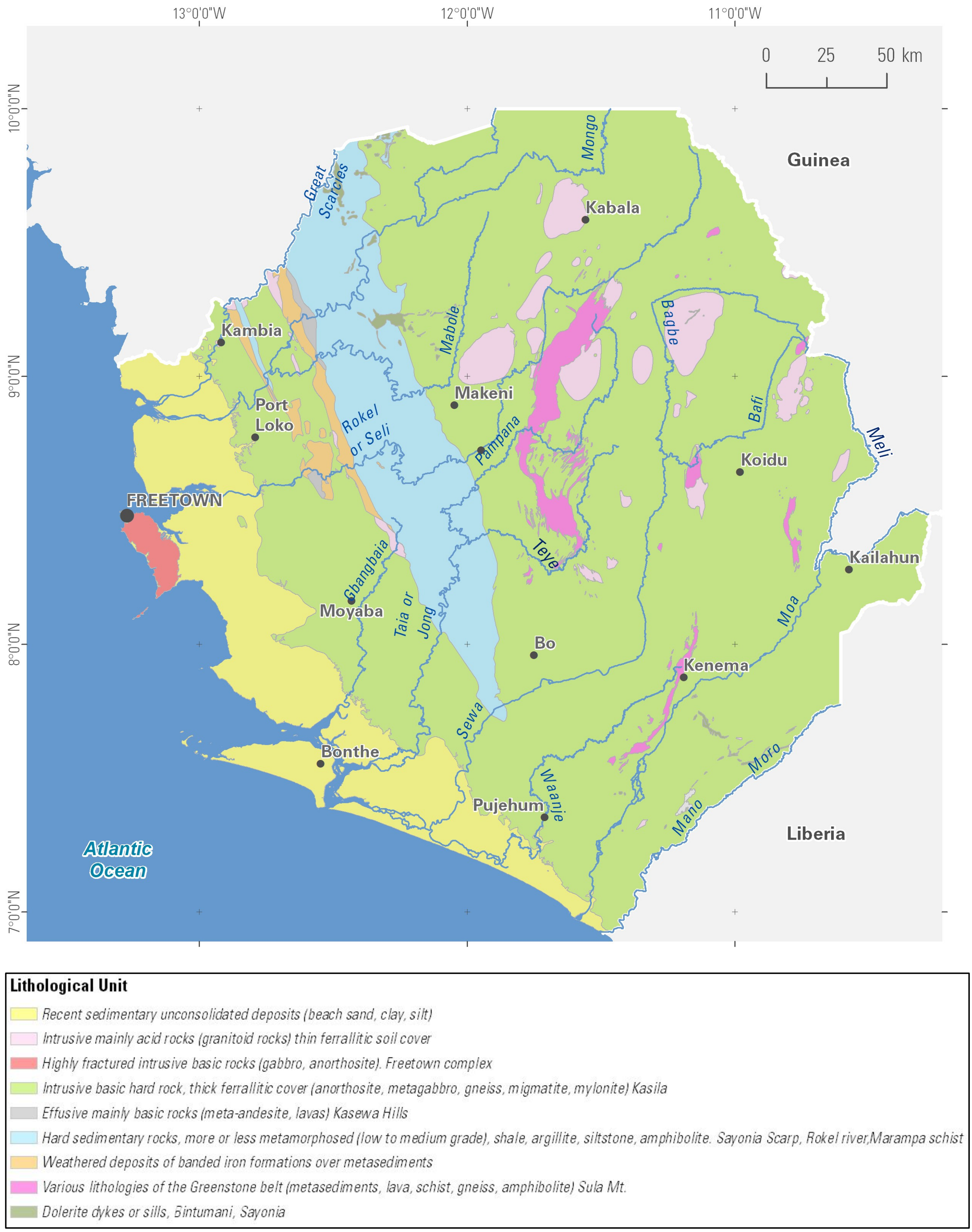



**Figure 31**. Lithology of Sierra Leone (2017)

Explanation: This map used the Geology of Sierra Leone (2017) map as a starting point; the 28 geologic units were interpreted as nine lithological units.

## Surface Permeability

### Surface Permeability of Sierra Leone map (2017)

The Surface Permeability of Sierra Leone map (Figure 32) classifies the surface soils based on a qualitative definition of their permeability, considering soil constituents, marsh or swamp areas, water basins, rock outcrops. The map was prepared as an indirect inference through detailed analysis of existing data (e.g. Land System and Vegetation Maps, UNDP/FAO (1976)) and interpretation of remote sensing intelligence, including Landsat 8 imagery. It needs a more detailed groundtruthing with field tests on the permeability of the surface soil to validate some estimates. It does not consider rainfall precipitation and other factors as regolith thickness, joint or fracture distribution. It must not be examined alone but in conjunction with other map of the set to better understand where connections of surface and ground water is more rapid.

The following permeability units are provided:

- Marsh, swamp areas along the coast and inland of low permeability;
- Coarse grained soils and outcrops in high relief zones of high permeability, and
- Areas of intermediate properties with low relief and fine textured soils.

Swamps and marshlands are prominent features with less permeable or impermeable surface zones as in elongated strips on the coastline and central part of the country. Moreover, the permeable zones are located where soil cover is thin and overlays fractured rocks, such as the mountain ranges upcountry. The permeability values in the legend should be considered as an indication, at a national scale, based on the few pumping tests on the weathered surface aquifers.

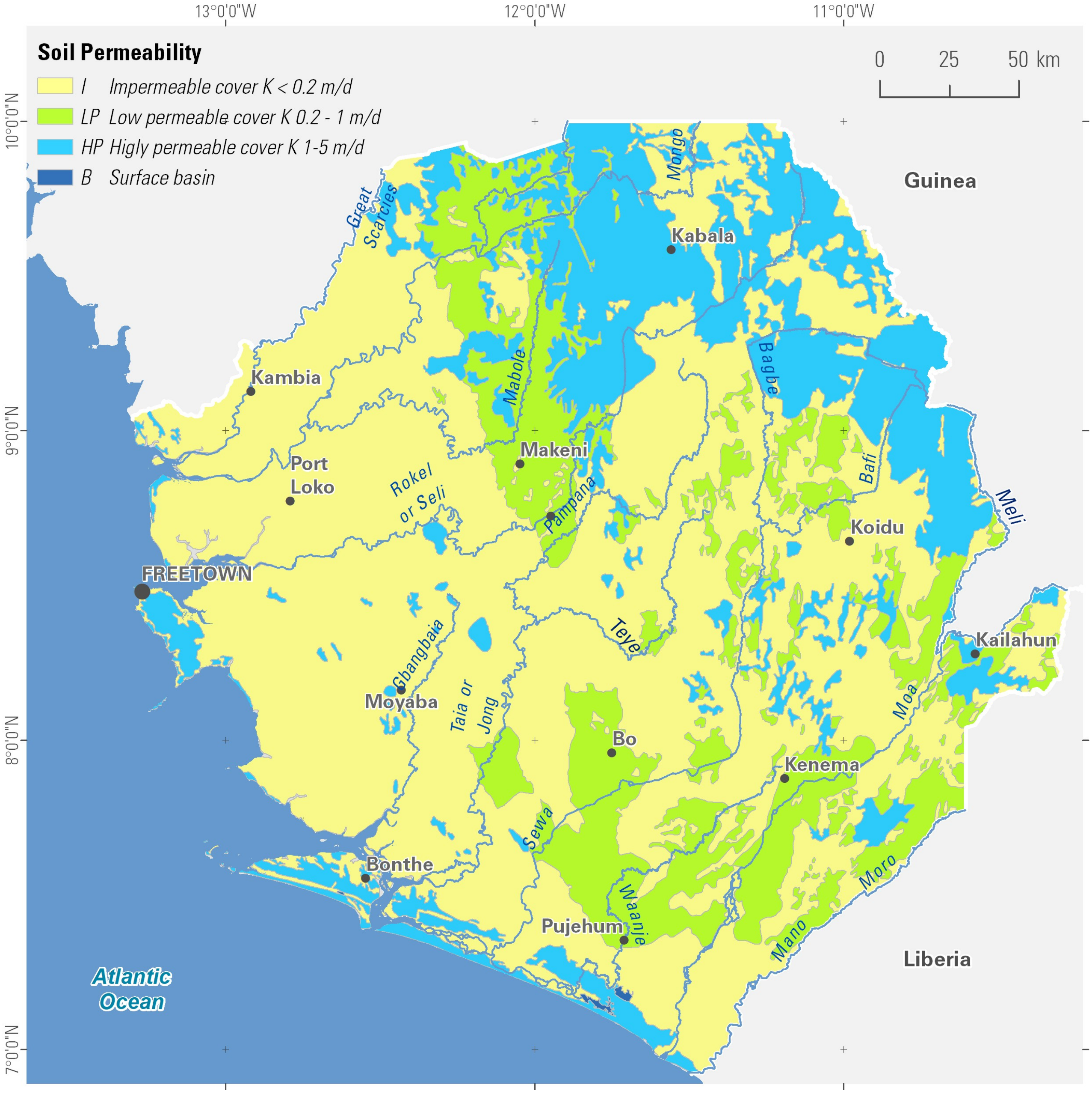



**Figure 32**. Surface permeability of Sierra Leone (2017).

In the high relief fractured rock aquifers of the uplands, for instance, permeability is greatest where the rock either outcrops or is covered by thin soils of high permeability. These areas most often correspond with the upper slopes and hill crests of catchment headwaters. Lowlands or gently undulating terrains with marshes and swamps, are indices of a low permeable cover, preventing water percolation to the aquifer bellows.

The Surface Permeability of Sierra Leone is a useful tool for hydrogeologists and water managers to better classify aquifer vulnerable areas, and for regional planning in general. Permeability estimates (*K*) are for general guidance only. Calculated *K* values do not consider rainfall precipitation and other factors as regolith thickness, joint or fracture distribution. Projects requiring precise measurements of permeability should validate soil permeability with in situ investigation.

## Configuration of the Water Table

Three conventions were applied to define the position of the water table in Sierra Leone: (1) conventional groundwater contour, or piezometric mapping, (2) estimated depth-to-groundwater mapping, and (3) water-table elevation averaging. Overall these renderings tell us that the water table in Sierra Leone is generally shallow overall, around ten meters on a country scale. Over a large central area between Makeni and Magburaka, groundwater is closer to surface in a broad wetland with typical drainage originating from a point southwest of Makeni. The three methods agree that groundwater table deepens in a northeast–southwest trend going towards the Atlantic Ocean, due to the extension of the impermeable cover (see Surface Permeability Map above).

### Piezometric map (observed)

The piezometric gradient (Figure 33) observed in December 2016 and April 2017 varies from 0.004, upcountry to 0.0008 on a flat elongated area corresponding to the Rokel River formation. Elevation ranges from 400 m asl to 0 near the coastline. A mean groundwater divide, changing with time, runs from Kabala to the west (Little Scarcies). April contour lines depict the draining role of Sewa river, south west of Kodu and favored by the narrowing of the watershed due to the presence of impermeable boundaries on each side. A similar relation was assessed in Freetown, near the Orugu and Koqwena Rivers. Although measurements have been taken in two different seasons the 50-m contour line can be followed in the two main basins. This is less true further north, due to the presence of the physical boundary.

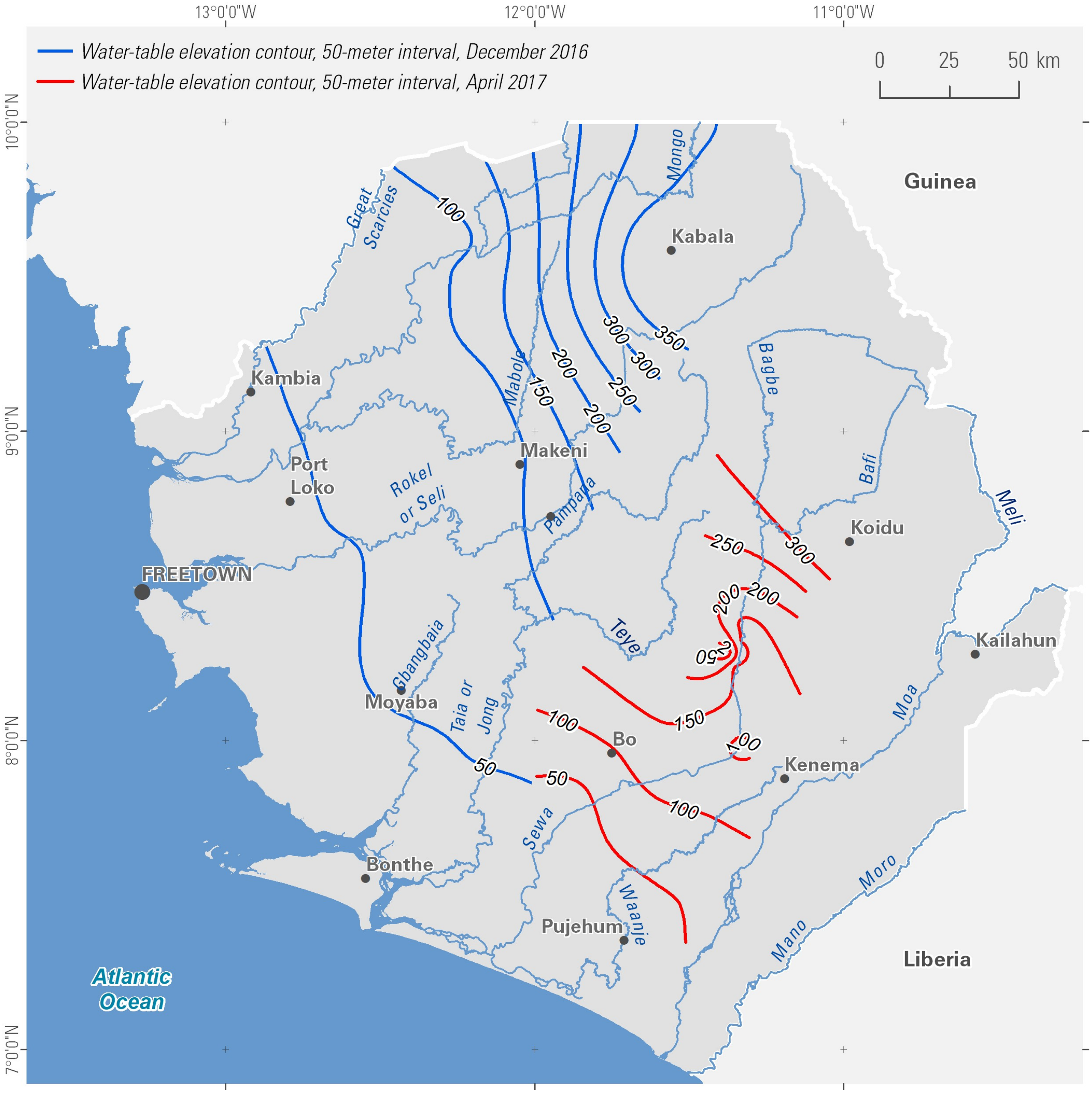



**Figure 33**. Observed piezometric data, December 2016 and April 2017

On a general note and considering also the piezometric map assessed for the whole country with average values obtained over many years, the water table can be regarded as a subdued replica of the topography or land surface. This typical behavior was clearly explained by Toth in 1963, while studying Canadian aquifers, and occurring most likely in relatively low-permeable and/or anisotropic aquifers subjected to unusually high (in view of the low permeability) areal recharge rates or in nearly flat terrain. Moreover, shallow aquifers in flat or gently rolling terrain may exhibit a water table that seems a subdued replica of the terrain surface. In a very general sense, the water table and the topography are often correlated, and the water-table lows occur at surface waters, which, in turn occur in topographically low areas (see Figure 34 and the Depth-to-Groundwater Map in Figure 35).

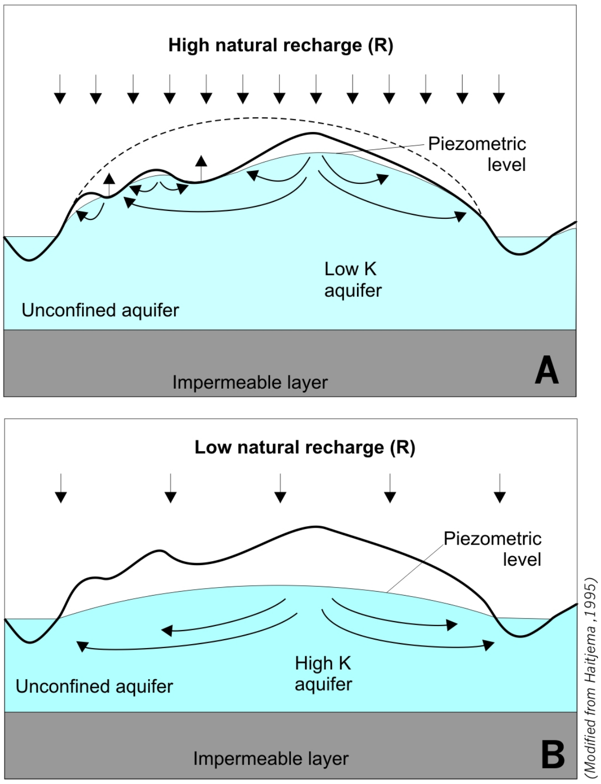



**Figure 34**. Cross-section diagram of aquifers influenced by topography versus recharge

Explanation: (A) Cross section over a regional aquifer shows a water table in response to aquifer recharge for two different cases. In (A), a high recharge rate in combination with a low aquifer hydraulic conductivity would lead to the dashed water table if the aquifer would extend that high, while in (B), a relatively low recharge rate and high aquifer hydraulic conductivity results in a water table that barely touches the terrain surface. In fact, what matters is not the absolute values of the recharge and the conductivity but the dimensionless ratio of R/k. In (A), the water table can be characterized as "topography controlled," while in (B), there is essentially no correlation between the topography and the water table. Different authors have demonstrated that the nature of the water table (topography-controlled or not) depends on the recharge, the aquifer transmissivity, the aquifer geometry and to some degrees the topography itself. (After Haitje, 1995).

In addition to this work, we applied an averaging interpolation method to map water-table elevation, discussed further below.

## Estimated Depth-to-Groundwater

The Estimated Depth-to-Groundwater in Sierra Leone map (Figure 35) depicts an estimate of the distance (m) from the land surface to the surface of the water table, also referred to as the "unsaturated zone thickness". In drilling terms, it is the estimated depth at which the surface of the first aquifer is positioned. In existing boreholes or wells, it is the natural groundwater level that is not influenced by abstraction or artificial recharge, also known as Static Water Level (SWL).

The Estimated Depth-to-Groundwater map generally is representative of the average conditions in the study area; however, the actual depth of the surface of the water table may differ from the estimated position at specific locations, and short-term, seasonal, and long-term variations in the differences can be expected. Site-specific estimates of the depth-to-groundwater in areas of steep land-surface relief, steep water-table gradients, abrupt local change in hydrogeologic properties, or strong stresses to the groundwater system such as focused recharge or pumping, may result in depths-to-groundwater that deviate from the average. Simplifications and inaccuracies must be accepted due to the great distance among the measurement points. The map was constructed during two limited timeframes: December 2016 and April 2017 and derives from the preceding groundwater contour map.

The method of analysis used to determine the water-table configuration relied on water-level readings from shallow boreholes, hand-dug wells and surface-water features that are representative of the water table. The procedure is based on a preliminary research and classification of main water points on the field, followed by the measurement of their position, elevation and depth to water table. Data are then processed to calculate the final water table elevations above the sea and the interpolation of their values.

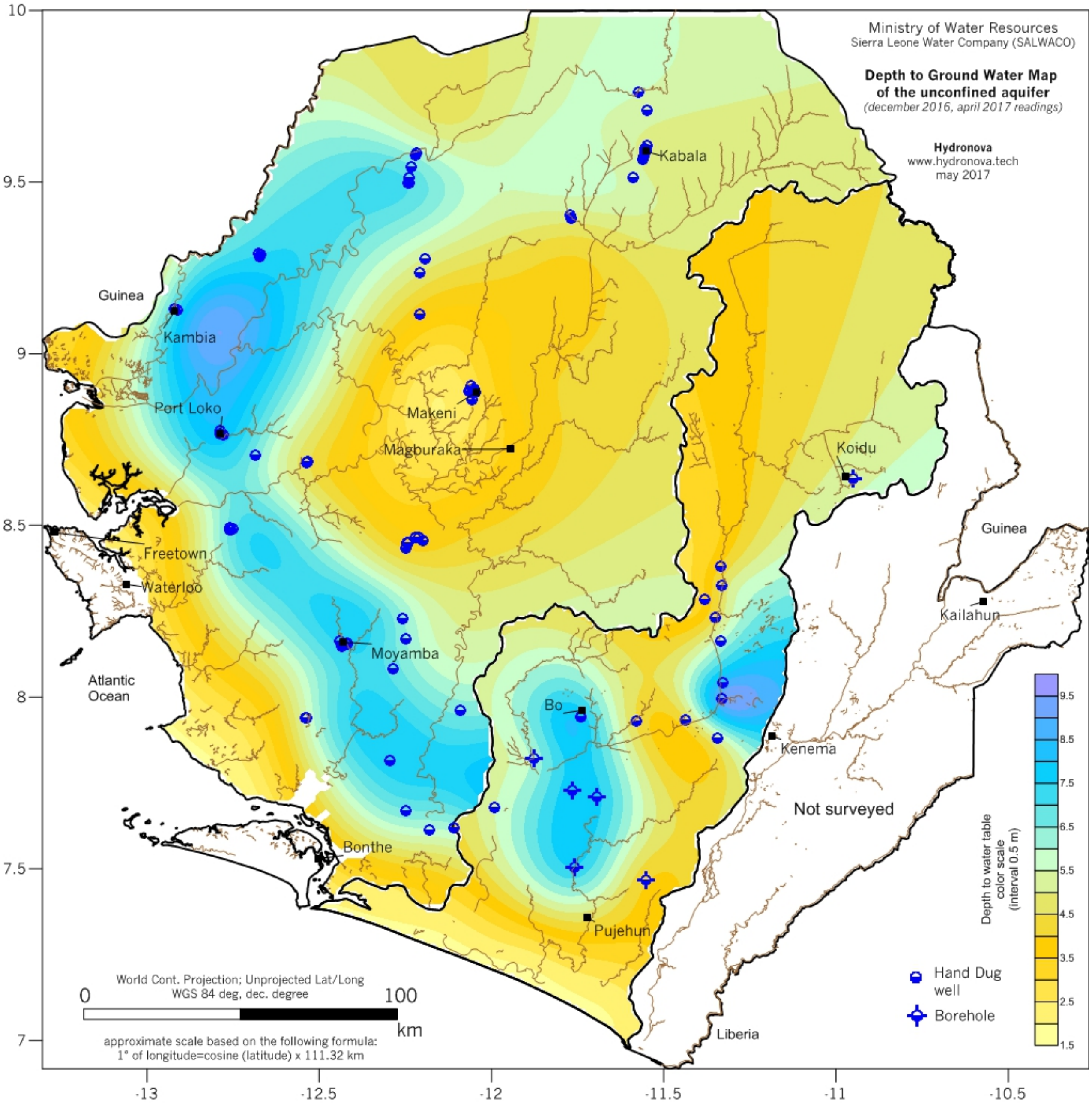



**Figure 35**. Estimated depth-to-groundwater based on observed data, December 2016 and April 2017
Explanation: Depth-to-groundwater levels are modeled according to, and based solely on piezometric data taken in situ from boreholes and hand-dug wells.

## Estimated Water-table Elevation Map (2017)

Building on the approach presented above for piezometric mapping, the study generated the Estimated Water-table Elevation map (Figure 36) to provide a full national scale map. The map was generated by interpolating the available piezometric measurements from approximately 450 hand-dug wells and boreholes (MOWR, 2016). Figure 37 provides the location of the groundwater points used for this exercise. The map is representative of the average condition in the study area because for each site an average value has been used and the records are not simultaneous, possibly covering a large (multi-year) period. Therefore, site-specific estimates of the water-table position in areas of steep land-surface relief, steep water-table gradients, abrupt local change in hydrogeologic properties, or strong stresses to the groundwater system because of recharge or pumping, may result in water-table elevation that significantly deviates from the average value. Permeability may vary significantly in different zones.

The Water-Table Elevation of Sierra Leone map depicts the hydraulic gradient, or piezometric surface, above sea level. The water table is considered the surface representing the top of the saturated zone, below which pores in the rock matrix are filled with water. Because the sub-surface water resources in Sierra Leone are in phreatic aquifers, the piezometric surface represents the elevation (m) relative to sea level (asl) of the water surface. The map can be useful for many applications, including understanding aquifer susceptibility, groundwater flow direction, contributing areas to boreholes, depth to water, or at what level groundwater may affect construction or other land development activities.

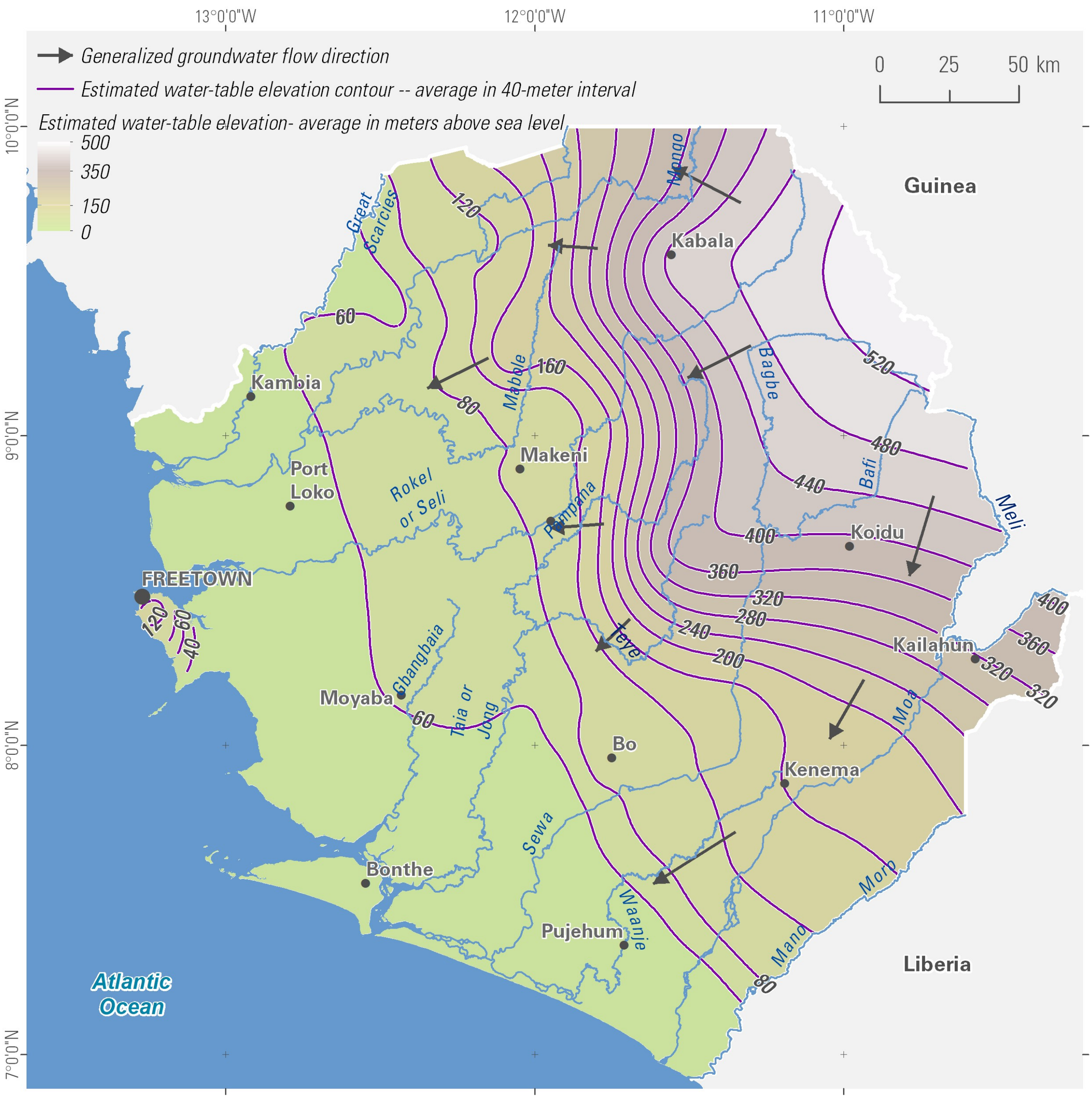



**Figure 36**. Estimated water-table elevation of Sierra Leone, based on averaged observed data
Explanation: The water-table elevation contours are an interpolation of measurements collected from 450 wells and boreholes. Location of the data points and relative uncertainty of this modeling approach are shown in Figure 37.

The contours, or equipotential lines, represent lines of equal head in the groundwater body, with values ranging from more than 400 m asl to the North-East to < 60 m along the coastal zone. Changes in the spacing of the equipotential lines represent a change in the hydraulic gradient. The flow direction of groundwater is perpendicular to the equipotential lines. In general, groundwater flow occurs from North-East to South-West, i.e. from the most elevated zones seaward, and diverges away from recharge areas and converge as they near an area of concentrated discharge.

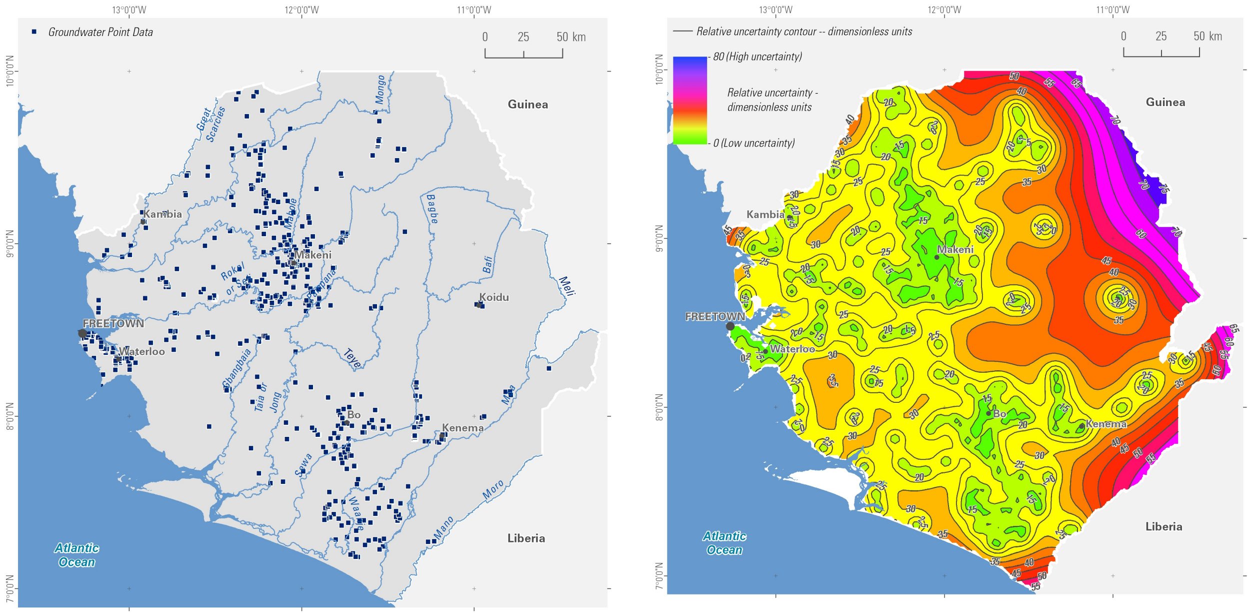



**Figure 37.** (Left) Groundwater observation points used to configure the water table elevation model. (Right) Relative uncertainty of the estimated water-table position in Sierra Leone.

### *Limitations*

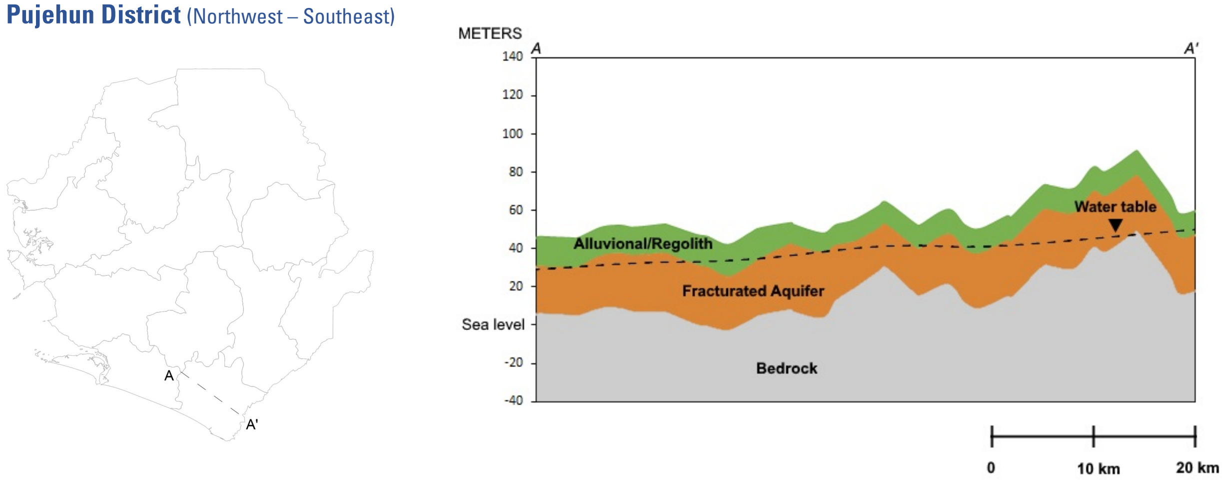
The values reported here represent the average water-table position computed on a 20-meter-square grid through the kriging interpolating technique. Kriging itself provides an evaluation of the accuracy characterizing the interpolation outcome through the standard deviation (stdev) associated to the interpolated values. Figure 37 shows the distribution of standard deviation (stdev) of the water-table elevation model applied to the entire country. Stdev provides a quantification of the uncertainty interval associated to the interpolated values. The result shows greater reliability of the water-table estimates in areas where groundwater data points are more concentrated where stdev is on the order of 5 to 10 m, and significantly decreases with greater proximity from data points.

The water-table elevation data are a useful tool for determining the approximate horizontal direction of groundwater flow at the water table, as well as other applications (generating 2-dimensional cross-sections as seen below), but should be used with caution because of the intrinsic reliability of the available measurements (which are average values acquired at different times) and the lack of information (and thus large uncertainty) in some portions of the county. Users are cautioned to consider the nature of the information presented here before making decisions using it that concern personal or public safety or the conduct of business that involves substantial monetary or operational consequences.

### *Generalized stratigraphic cross-sections*

The same data used to produce the water-table elevation has enabled the simplified stratigraphy of certain areas of Sierra Leone to be modeled. The density and reliability of data were sufficient to generate 2-dimensional cross-sections for Pejehun and Kambia Districts (Figure 38 and Figure 39).

### [1] – Pujehun District (Northwest – Southeast)




### [2] – Pujehun District (Northeast – Southwest)

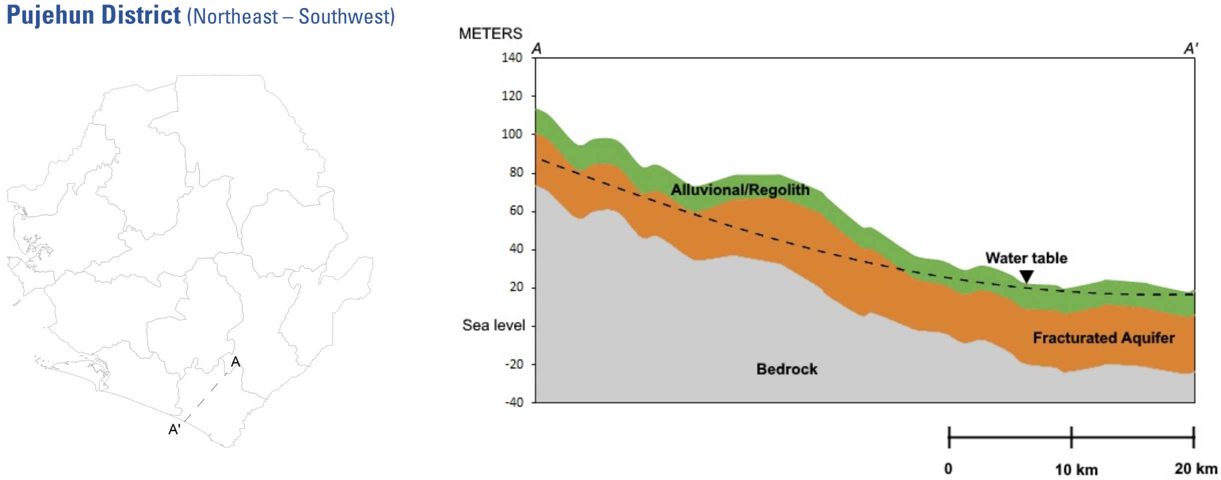



**Figure 38**. Generalized stratigraphic cross-sections of Pujehun District.
Explanation: (1) Northwest to southeast cross-section, (2) Northeast to southwest cross-section.

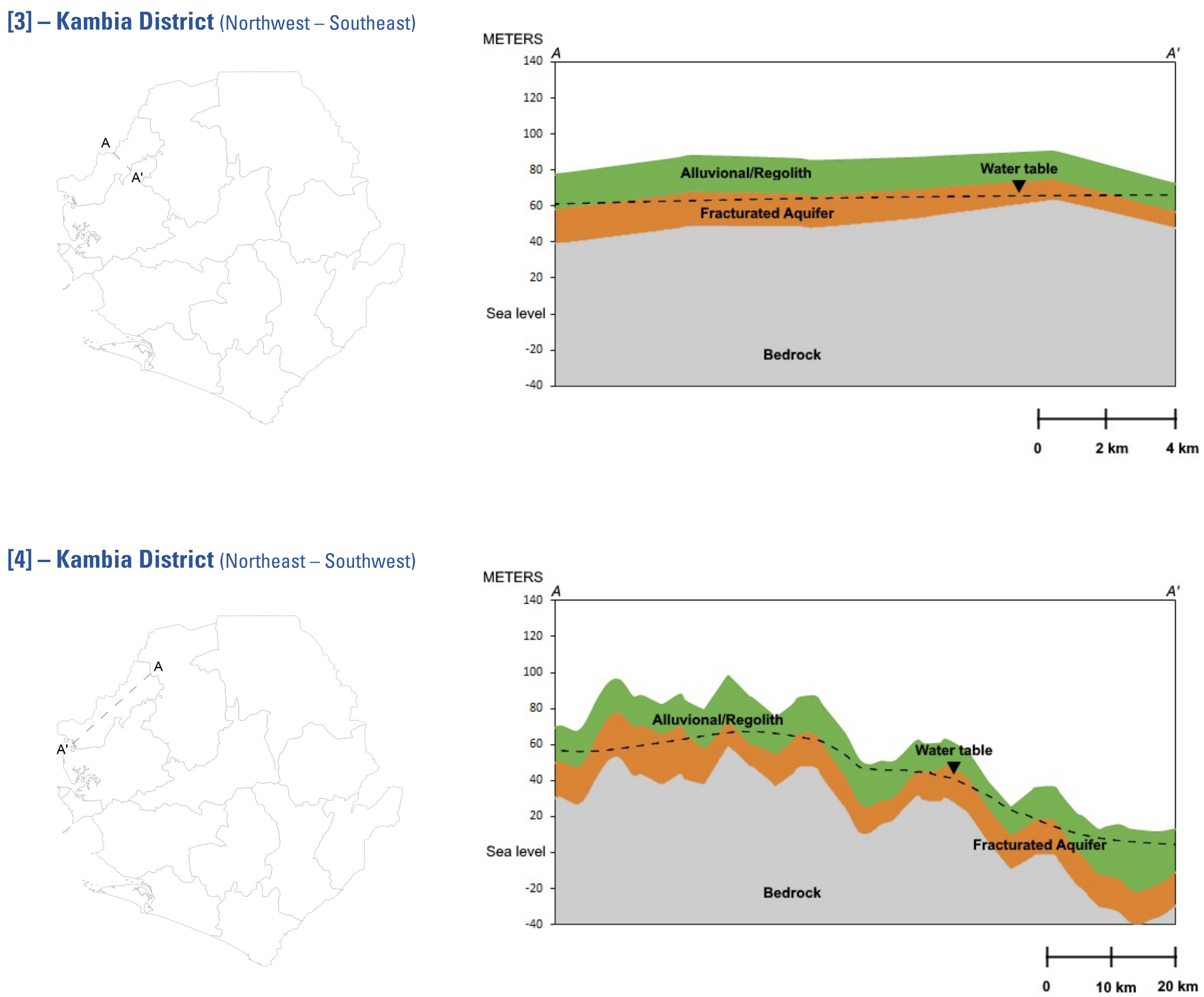



**Figure 39**. Generalized stratigraphic cross-sections of Kambia District.
Explanation: (3) Northwest to southeast cross-section, (4) Northeast to southwest cross-section.

## Groundwater Recharge and Discharge

Groundwater recharge is the downward flow of the water from the surface driven from the hydraulic gradient from the ground surface to the aquifer below and again to surface points at lower piezometric level. The phenomenon usually occurs in the vadose zone below plant roots and is often expressed as a flux to the water table surface. Groundwater is typically recharged naturally by rainfall and to a lesser extent by rivers and lakes. Recharge is controlled by land use, soil type and climate. Groundwater discharge is the loss of water from an aquifer.

### Groundwater Recharge and Discharge of Sierra Leone map (2017)

The Groundwater Recharge and Discharge of Sierra Leone map (Figure 40) depicts the areas where water is added to or lost from the saturated zone at a country scale. The map refers only to the recharge and discharge parameters, but other factors are important to understand the complex relationship between groundwater and surface water, such as regolith thickness and joint or fracture distribution. It is also understood that recharge and discharge vary over time in a land with 'droughts and flooding rains'. Recharge and discharge fluxes are not fixed in time, instead they move up and down with the climate. Colors are those from IAH classification.


**Figure 40**. Groundwater recharge and discharge areas of Sierra Leone
The map has made an extended use of the following properties: surface permeability, fracture distribution, depth of the unconfined aquifer below ground, and rainfall distribution. Classification is based on IAH standards.

In the humid areas of Sierra Leone, recharge is more related to peak rainfall events and drops during dry season, while discharge continues for two to three months after the end of the rainy season. Recharge areas occupy the interior zones with greater elevation and larger outcrops of fractured rocks found northeast of a fictitious line joining Makeni and Kenema towns.

Discharge can occur by leakage to the ocean, rivers or another aquifer. It may also occur from depths through narrow breaks in a low permeability layer (e.g. mound springs). In this map, however, discharge is represented primarily as occurring in the land surface from a shallow water-table. Discharge areas along the flat and swampy area immediately south-west of Makeni-Kenema line and approximately corresponding to the Rokel River formation. Another discharge area is close to the coast, between the two estuaries of Great Scarcies and Mano rivers. No additional information was possible to collect on the larger transit zones between the two preceding areas

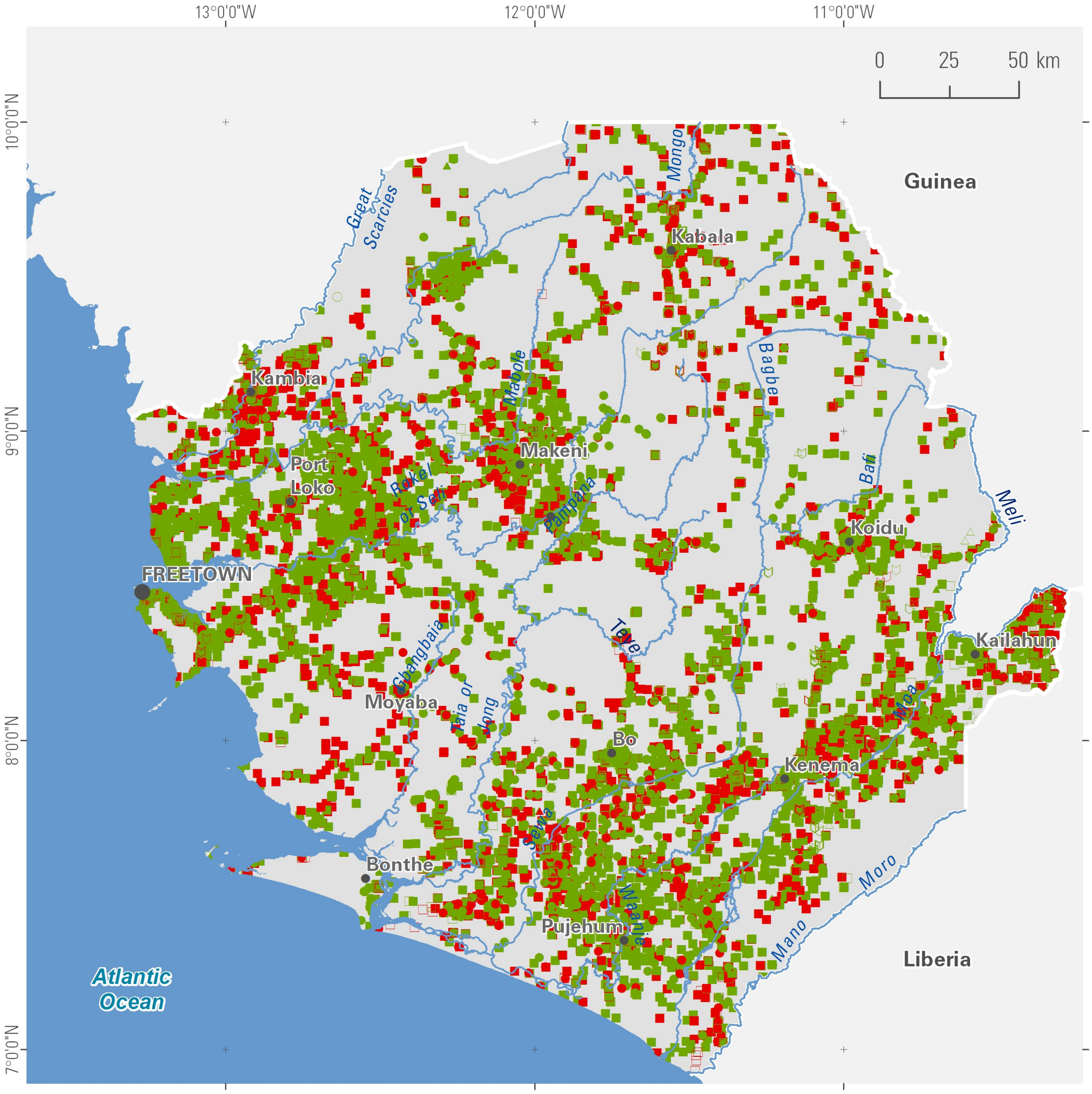
The map is a tool intended mainly for hydrogeologists who are aware of its level of information. It can depict more interesting areas as potential groundwater supply sources and those more vulnerable. This is a preliminary attempt to map recharge and discharge phenomena at the national scale, and due to the fragmented structure of the aquifer and the scale used, it was possible to separate only a few areas and no information on transit areas are inserted.

Characterizing recharge and discharge fluxes assisted in establishing a water balance, as previously discussed. One critical activity in this regard was the mapping of potential recharge and discharge areas according to their geological and geomorphic character. A second task concerned assigning fluxes to each landscape unit to estimate recharge and discharge volumes for the entire groundwater catchment.

## Groundwater Use

### Inventory of Groundwater Points of Sierra Leone (2017)

The Inventory of Groundwater Points in Sierra Leone map (Figure 41) shows the wealth of the nation's known groundwater abstraction points. The map was based on information modified from the water points inventory of 2016 published by the Salone Water Security Project. Out of over 300,000 water points in the 2016 dataset, some 28,000 points related to groundwater were extracted, including boreholes, hand-dug wells and springs.




| Type | Category | Functionality status | Legend |
|---|---|---|---|
| *Spring* | *Protected* | *Yes* | ▲ |
| | | *No* | ▲ |
| | *Unprotected* | *Yes* | △ |
| | | *No* | △ |
| *Borehole* | *Tube Well or Borehole* | *Yes* | ● |
| | | *No* | ● |
| | *Unequipped* | *Yes* | ○ |
| | | *No* | ○ |
| *Hand-dug Well* | *Protected* | *Yes* | ■ |
| | | *No* | ■ |
| | *Unprotected* | *Yes* | □ |
| | | *No* | □ |
| *Sub-surface Dam* | | *Yes* | |
| | | *No* | |

**Figure 41**. Groundwater points of Sierra Leone, extracted from Ministry of Water Resources Inventory, 2016

The inventory was also analyzed at the district level, showing density of wells, boreholes and springs (Figure 42).

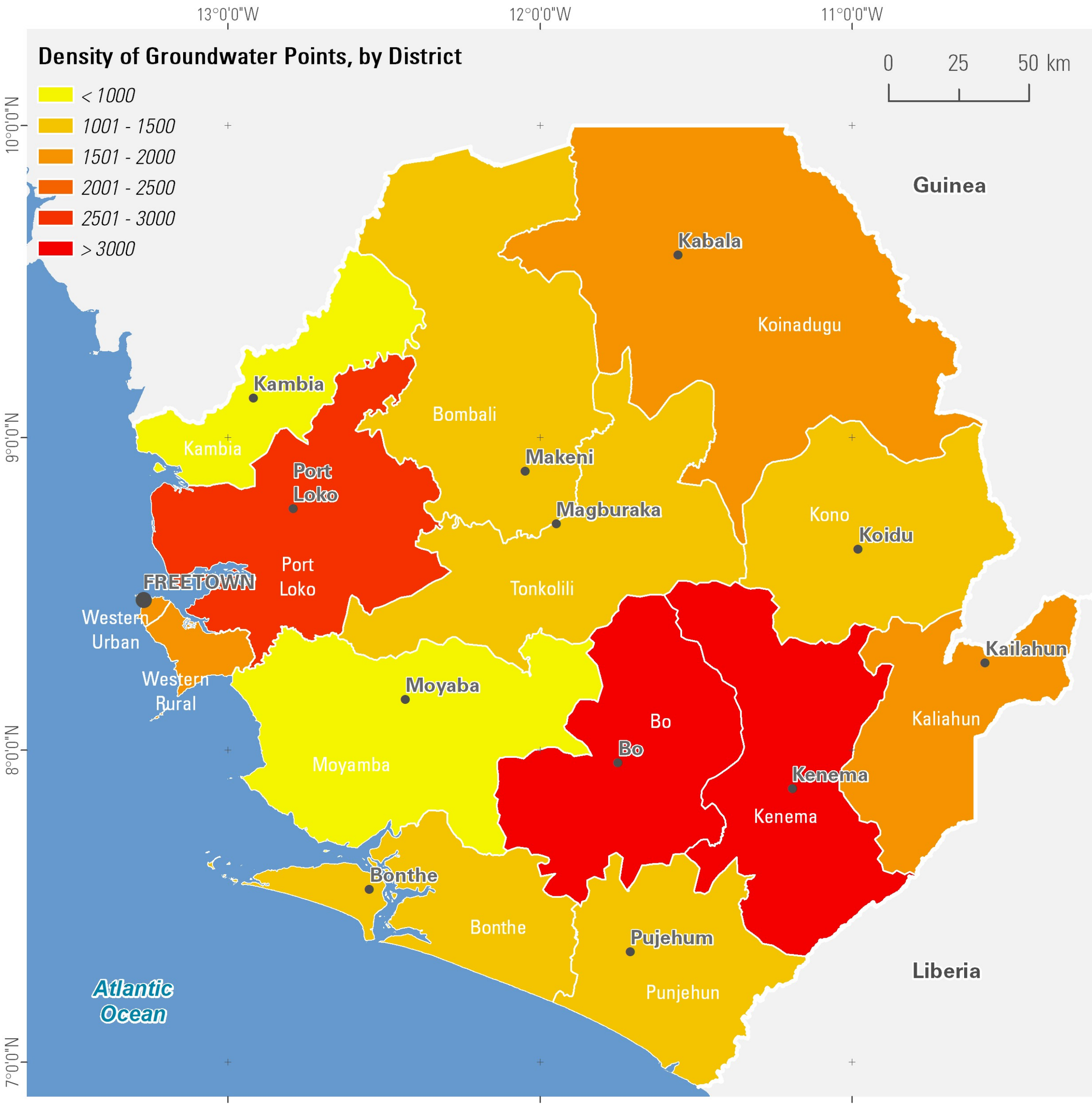



**Figure 42**. Density of groundwater points in Sierra Leone, by district.
Explanation: Extracted from Ministry of Water Resources Inventory, 2016

The primary aim of the Inventory of Groundwater Points in Sierra Leone map is to show at a glance where the main abstraction points are concentrated. It provides decision-makers an idea of which communities are dependent upon groundwater, and the locations where there is a need for further investigation to develop groundwater resources. It also facilitates the siting of new boreholes to minimize interference or competition for the same source aquifer. The map, as with others, should be used in tandem with other maps and data, such as the hydrogeologic maps. This Inventory should be considered incomplete, as sort of a snapshot of the current knowledge base of known boreholes and wells. Therefore, areas with large amounts of abstraction points may not be represented. This map should be updated along with the overall water point inventory. Plans to develop groundwater in any area should be based on a site investigation to assess the functionality of proposed construction.

## Aquifer Productivity

The permeability of the rock types in Sierra Leone can be further refined based on permeability considerations often derived from pure analogy between geology (lithological rock type) and hydrogeology (hydraulic conductivity values) (Struckmeier & Margat, 1995). This provides a measure of aquifer productivity. Recharge is sometimes used in assigning aquifer productivity and small-scale hydrogeological maps, such as the Hydrogeology Map of Africa and the World Hydrogeological Map, often depict aquifer recharge as a measure of aquifer productivity.

### Aquifer classification

Aquifer productivity classes were adopted from Krasny (1993), Struckmeier, Margat (1995):

**Table 10. Aquifer categories according to groundwater potential**

| Aquifer category | Specific capacity (l/s/m) | Transmissivity ($m^2/d$) | Permeability (m/d) | Approx. Yield (l/s) | Groundwater potential |
|---|---|---|---|---|---|
| **A, C** | >1 | > 75 | >3 | > 10 | High: withdrawals of regional importance (supply to towns, irrigation) |
| **B, D** | 0.1 - 1 | 5 – 75 | 0.2 – 3 | 1 - 10 | Moderate: withdrawals for local water supply (small communities, small-scale irrigation) |
| **E** | 0.001 – 0.1 | 0.05 - 5 | 0.002 – 0.2 | 0.01 -1 | Limited: smaller withdrawals for local water supply (hand pump, private consumption) |
| **F** | < 0.001 | < 0.05 | < 0.002 | < 0.01 | Essentially none: sources for local water supply are difficult to ensure |

A color scheme (Figure 43) was applied to the aquifer potential classification above to represent hydrogeological characteristics. Dark blue and dark green colors represent aquifers with high potential. Light blue and light green colors represent aquifers with moderate potential. Formations with limited potential are colored in light brown while strata with essentially no groundwater are in dark brown. For groundwater systems with high or moderate potential the coloring scheme also considers the dominant type of groundwater flow within the rock. Blue colors are used for systems in which flow is mainly intergranular while green colors represent systems formed by hard rock, including karst rock, in which flow occurs in fissures, fractures or dissolution cavities.

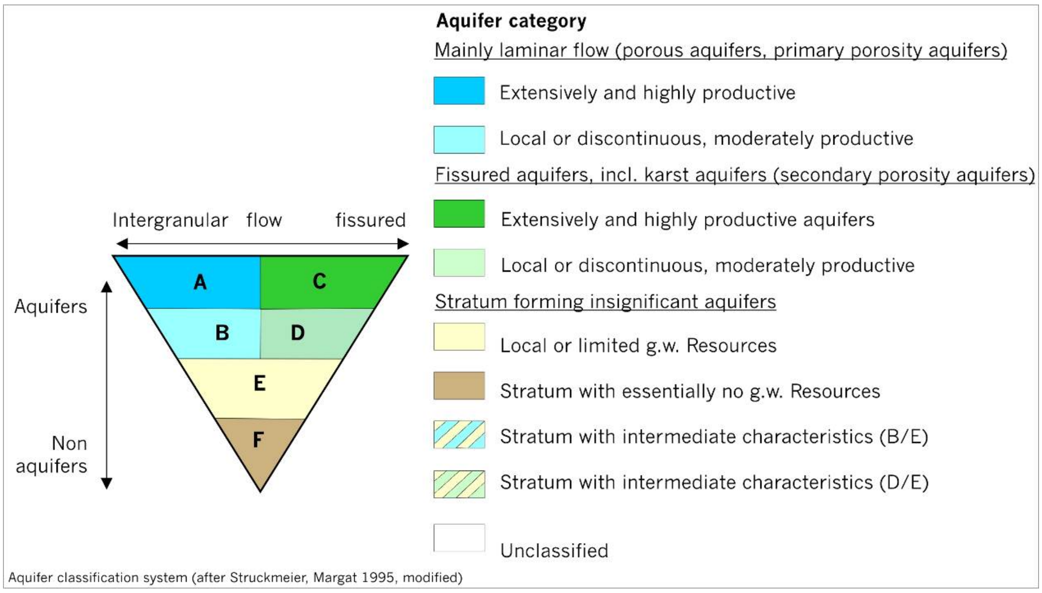



**Figure 43**. Aquifer Classification system (after Struckmeier, Margat 1995)

## Aquifer Productivity of Sierra Leone map (2017)

The Aquifer Productivity of Sierra Leone map (Figure 44) classifies the aquifers of the country according to their potential for water abstraction in the short and long term. The map classifies different aquifers according to their potential for water abstraction in the short and long term. Six categories were recognized from areas of no groundwater resources to those of low-moderate resources.

The Aquifer Productivity of Sierra Leone map is a useful tool for decision-makers to plan water supply projects from the point of view of the aquifer unit. Other uses of this map include site and regional planning, natural resources land management, environmental monitoring and planning. The Aquifer Productivity of Sierra Leone map was prepared following IAH standards (1995): by considering the lithologies in permeability classes of primary and secondary porosity, evaluating the hydrogeological parameters on the basis of field tests and expert knowledge, and evaluating rainfall distribution, recharge and discharge areas and general groundwater flows.

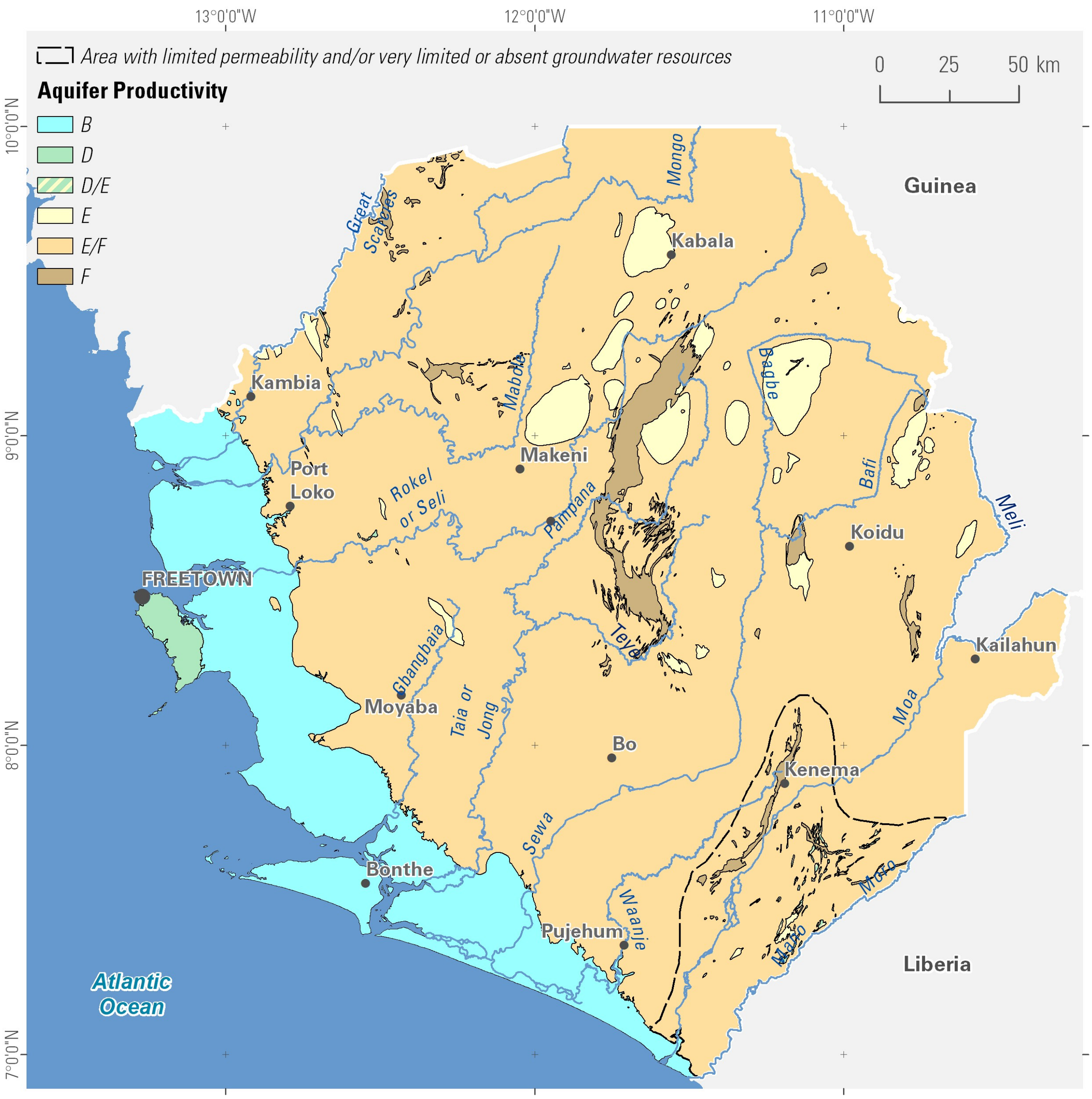



**Figure 44**. Aquifer productivity of Sierra Leone, 2017

The aquifer types can be grouped according to the groundwater productivity. The following process was used to assign productivity:

1. Evaluation of borehole data to characterize hydraulic properties
2. Calculation of recharge distribution
3. Analysis and expert judgement

The main rock types have been grouped into permeable and low permeability formations (according to IAH standards) using the lithology base map and expert judgement. Permeable formations have been further grouped into porous (gravel, alluvium, sand etc.), fissured (basalt, gneiss, granite, etc.).

The general productivity of the aquifers is low due to the values of transmissivity collected so far (5-6 $m^2$ / d). Most productive zones are in the porous formation stretching along the Atlantic coast and Freetown peninsula. Some more fissured areas like the Banded Iron Formation near Marampa have shown to produce large quantities of water but the real supply have still to be ascertained. A further zone with very limited or absent resources in the southeastern part of the country from Kenema to the Liberian boarder, with numerous elongated dolerite dykes has been delimited.

At this stage of the investigations aquifers can therefore be considered for local water supplies of small communities. More promising areas where focus future researches are in Freetown peninsula, along the Atlantic coast and probably in the interior of the country where fracture intensity is higher. Any future exploitation must anyway account for different more efficient, catchment systems other than water wells (e.g. drainage galleries or trenches).

The classification combines information on aquifer productivity (lateral extent) and the type of groundwater flow regime (intergranular or fissured). As stated in the preceding chapters, data availability and their correctness affected the assessing of the classification that was finally adopted.  The productivity map should only be considered as a starting point from which the Country should be able to update the information whenever new field data becomes available.  The various techniques employed in determining aquifer productivity are technical and require hydrogeological professionals.

## Groundwater Vulnerability

Understanding where groundwater is susceptible to contamination is key to proper management of the resource.  The study has analyzed groundwater vulnerability in Sierra Leone according to the overlying strata and mapped the areas to provide guidance for planners and decision-makers.

### Groundwater vulnerability classification

Classifying vulnerability follows IAH (1995) standards and makes use of the surface permeability distribution and depth of water-table below ground. Categories and parameters are provided in Table 11.

**Table 11. Aquifer vulnerability classification**

| Vulnerability category | Unsaturated layer | Thickness of the unsaturated layer | Aquifer type |
|---|---|---|---|
| **Extremely high** | Absent or discontinuous | Very thin | Fractured or karst |
| **High** | Highly permeability (K <1 m/d) | < 2m | |
| **Medium** | Moderately permeable (Kv 0.8 – 0.008 m/d) | 2-20 m (or 2- | Unconsolidated formation |
| **Low** | Low permeability (Kv < 0.008 m/d) | >20 m | |
| **Very low** | Impermeable | Significant thickness | Clay or shale |

Explanation:  Modified from Vrba and Zaporozec (1994)

Using the above parameter definitions for vulnerability, three main zones were established for Sierra Leone, making also use of approximated values for hydraulic conductivity (0.1-0.05 m/d), porosity (0.05) and a large gradient (0.1). Considering that one of the main pollution issues is the presence of bacteria, we considered a resident time for fecal bacteria of 60 days, and a water table depth limit of 10 m while introducing a conservative value.  With these assumptions, it takes approximately 60 days for an organic pollutant to reach the water table, from surface. Horizontal travel time has not been accounted for.

### *Vulnerability units*

Three vulnerability units have been delineated for Sierra Leone (Table 12). Two zones of relative high vulnerability are differentiated.

**Table 12. Aquifer vulnerability units for Sierra Leone**

| Code | Aquifer Vulnerability Unit | Description |
|---|---|---|
| **HV** | High (a) | Thin, highly permeable cover, or rock outcrops |
| **HV** | High (b) | Near-surface water-table (less than 10 m on average) |
| **LV** | Medium to low | Water-table level deeper than 10 m |

## Groundwater Vulnerability of Sierra Leone (2017)

The Groundwater Vulnerability of Sierra Leone (Figure 45) map depicts the land areas where the quality of groundwater is susceptible to contamination, both natural and human. Areas have been assessed and subdivided to provide a range of risk of contamination. Areas with high vulnerability are considered most threatened by contamination and which may warrant detailed site investigations, ongoing monitoring and establishment of protection system.

The Groundwater Vulnerability map is a tool that promotes the sustainable use of groundwater resources by providing a guide in determining which areas across Sierra Leone are more susceptible to groundwater contamination. It should be used as a guide for decision makers in locating and determining the suitability of future developments projects to minimize the impact that such projects will have on the surrounding groundwater resources. The map provides a starting point for understanding the groundwater problems that exist and those that may develop in the future.

The preparation of the map involved the simplification of complex geologic and hydrogeologic situations. It is important for users of this map to consider local conditions when assessing a particular development option. The Aquifer Vulnerability illustrated refers only to the hydrogeologic characteristics of the aquifer (intrinsic permeability), disregarding any pollution center that could be located on the surface. A high-vulnerable aquifer with high permeability can still be exploited if no centers of anthropogenic or natural pollution are present on the surface or in the groundwater protection zone as defined by specific investigations. Similarly, it is not suitable to utilize low-vulnerable aquifers with low permeability to supply water in the long-term for industrial activities producing chemical waste. Furthermore, groundwater protection zones can be established to manage areas with high vulnerability or where the underlying flow system is susceptible to dramatic modification due to new well fields or high-volume water work projects.

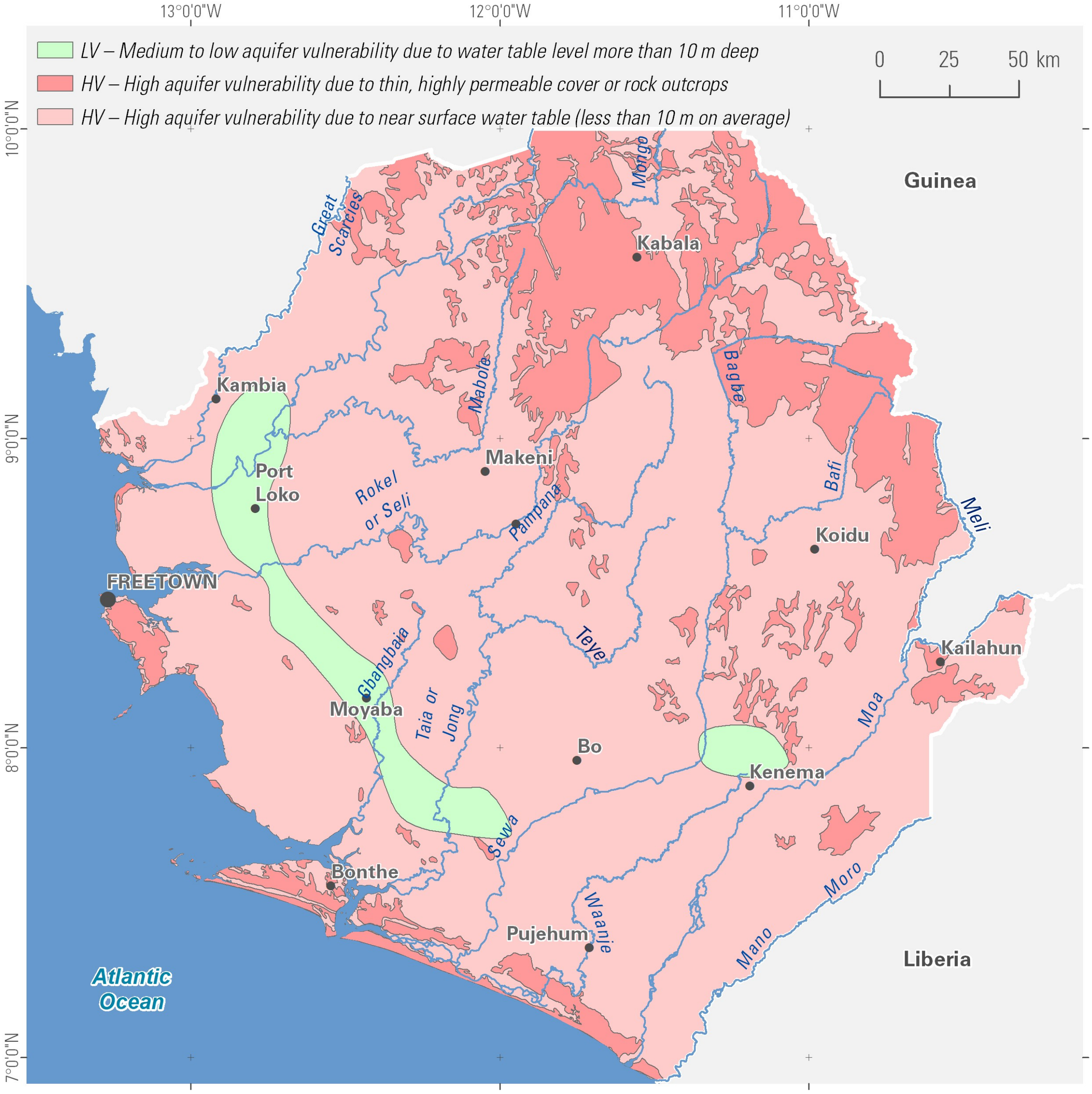



**Figure 45**. Groundwater vulnerability of Sierra Leone, 2017.

## Groundwater quality and data limitations

Presently, data in Sierra Leone are insufficient to support a complete and reliable analysis and mapping of groundwater quality parameters at the national scale. The bulk of official data on groundwater quality exists as laboratory analyses performed as part of drilling completion reports of boreholes and hand-dug wells located in Western, Bombali, Port Loko and Moyamba Districts. Unfortunately, most of the existing water quality analyses did not record a location (GPS), preventing an interpolation or analysis of chemical distribution and variation in space.

Despite the absence of sufficient data, a few general observations can be gleaned from existing literature: Generally speaking, the quality of groundwater resources in Sierra Leone is considered moderately good and potable in many areas of the country. Some borehole investigations (Massally et al, Edal) show that two-thirds of the samples are within international (WHO) limits for turbidity. A small percentage (5-10%) exceeded WHO guidelines for electrical conductivity

(EC), while 12 to 25% had iron (Fe) and manganese (Mn) values in excess of WHO standards. One key area of concern is in Freetown, where bacterial contamination from fecal and non-fecal coliforms were retrieved in 30% of wells tested. Another area of concern are those in the vicinity of mining activities, where values for iron and manganese or other heavy metals were prevalent. Bacteria are a common issue near populated areas where many hand-dug wells are present, facilitating the infiltration of polluted water from surface.

### *Recommendations for improving groundwater quality data for future mapping*

To develop a groundwater quality map at the national scale, it is recommended that a survey of groundwater quality be undertaken at national scale, including the following components:

1. **Sample:** For a standard geographic distribution, the survey should include a sample from a minimum of ten (10) boreholes per District, for a total minimum of 130 points. In addition to the standard national distribution, additional samples should be taken in other "areas of concern", or vulnerable areas, including 6 - 10 points in the Freetown area and 4 points near each mining activity area in the country.

2. **Parameters:** Each sample should test and analyze the minimum basic, physio-chemical and biological parameters (Table 13).

3. **Mapping:** The above data can enable groundwater quality parameters to be modelled and mapped using conventional tools and methods.

4. **Updating the Groundwater Vulnerability Map**: Also, the above measures can enable the Groundwater Vulnerability Map to be updated.

**Table 13. Recommended groundwater quality parameters for further study and mapping**

| Component | Parameter | |
|---|---|---|
| **Basic** | (1) Borehole ID number<br>(2) Location (GPS), lat., long., elev. | |
| **Physio-chemical** | (3) Temperature<br>(4) pH<br>(5) Electrical Conductivity (E.C.)<br>(6) Total Dissolved Solids (T.D.S.)<br>(7) Salinity<br>(8) Chlorine (Cl-)<br>(9) Aluminum (Al)<br>(10) Ammonia ($NH_3$)<br>(11) Bromine (Br)<br>(12) Total hardness (mg/l)<br>(13) Copper (Cr)<br>(14) Fluoride (F)<br>(15) Iron (Fe)<br>(16) Magnesium ($Mg^{2+}$)<br>(17) Manganese ($Mn^{-2}$) | (18) Molybdenum (Mo)<br>(19) Nitrite ($NO_2^-$)<br>(20) Nitrate ($NO_3^-$)<br>(21) Potassium (K)<br>(22) Phosphate<br>(23) Silica ($SiO_2$)<br>(24) Sulphate ($So_4^{-2}$)<br>(25) Sulphide ($H_2S$)<br>(26) Sulphite<br>(27) Chloride (Cl-)<br>(28) Arsenic (As)<br>(29) Chromium (Cr)<br>(30) Bicarbonate<br>(31) Zinc (Z) |
| **Micro-biological** | (32) E. Coli<br>(33) Fecal Coliforms<br>(34) Non Fecal Coliforms<br>(35) Vibro-parahaemolyticus<br>(36) Salmonella | |

## Specialized Tools for Groundwater Development and Planning

Two tools have been developed to assist in groundwater development planning. Both are based on advanced water intelligence technologies built to provide valuable insights in a data scarce environment, and can be used in conjunction with other conventional maps and investigative methods to improve the identification and localization of exploitable aquifers and supports planning for borehole siting, design and construction.

### Drilling Physical Suitability map (2017)

The Drilling Physical Suitability of Sierra Leone map (Figure 46) depicts the distribution of qualitative geologic conditions conducive to drilling boreholes and shallow hand-dug wells. *Drilling physical suitability* (DPS) is a composite of the physical properties of near-surface geology – soil class, shallow geologic formation type, hardness of rock, and morphology – which are important factors for determining the appropriate method of drilling. Areas are classified along a scale of high to very low DPS (Table 14). For each class, physical characteristics for drilling suitability are given and drilling methods are recommended. No single drilling method is best for all geologic conditions, and the methods and equipment capabilities vary as widely as the application requirements can.

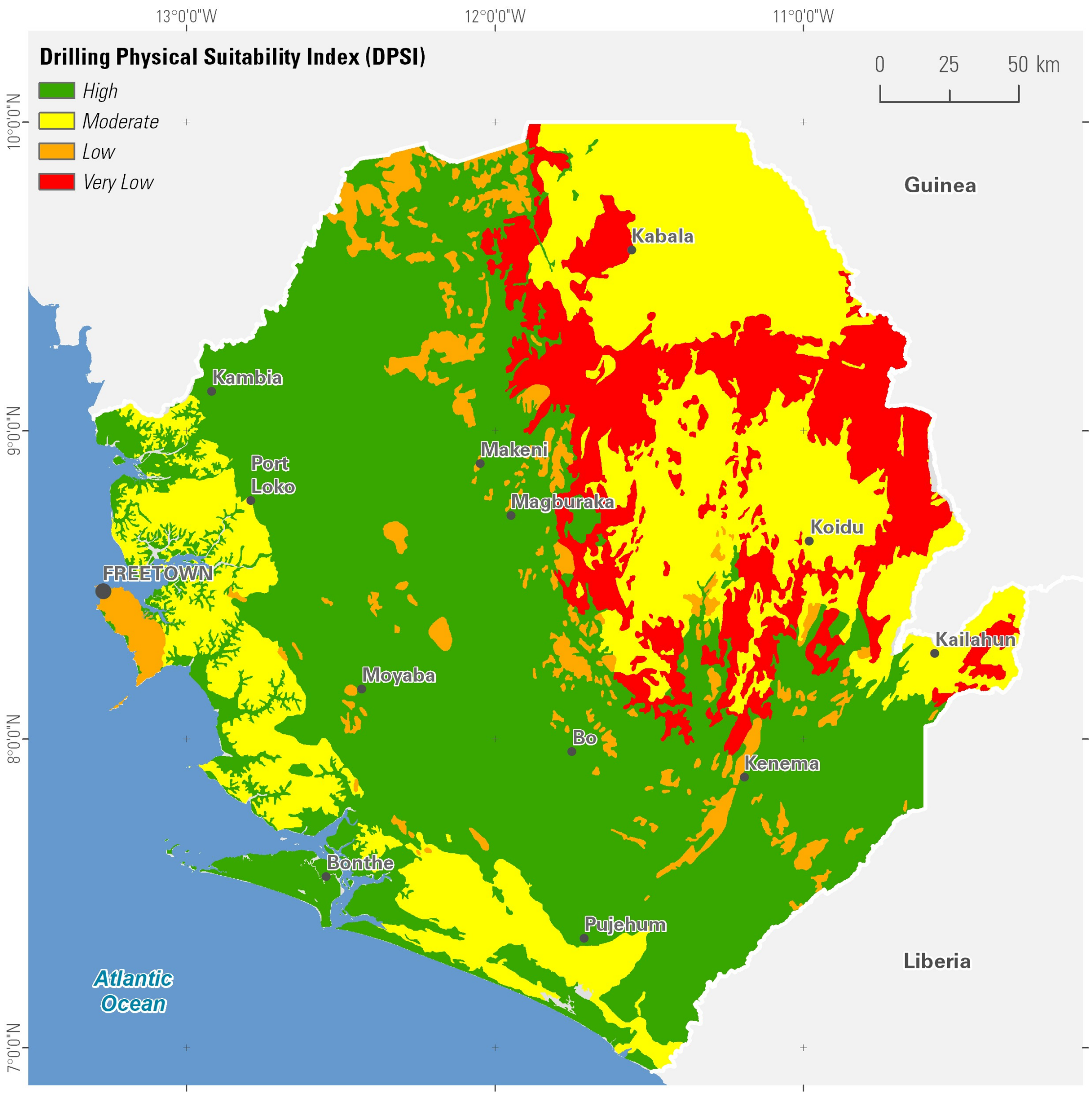



**Figure 46**. Drilling physical suitability of Sierra Leone

Primary source of data for the development of the DPS map was the Land Systems of Sierra Leone Map (1:500,000), UN-FAO (2015), which used aerial photography and field reconnaissance to model interactions between geological formations, superficial soil layers and topography. Boolean operators were then applied in a GIS environment to classify areas according to geologic suitability for drilling in the near-surface geology. Groups of physical suitability conditions were generated to account for the unique soil, physiographic, morphology and geologic conditions in Sierra Leone. For recommended standard drilling methods, the DPS categories were interpreted using the classification of relative performance of different drilling methods in various types of geologic formations from Sterrett (2007).

The DPS map is intended to be a general guide for selecting the best, most effective drilling method for drilling of boreholes and hand-dug wells in the near-surface strata throughout Sierra Leone. This map may also be a useful tool for other physical activities, such as borehole design and construction. The map does not provide information about hydrogeology and does not infer the presence of groundwater. Other relevant factors, such as ease of access for drilling equipment to sites, are not considered. A good knowledge of the range of drilling methods and equipment, as well as their limitations and appropriate application for various geologic conditions, is required to utilize DPS.

**Table 14. Drilling physical suitability classification scheme for near-surface conditions in Sierra Leone**

| DPS Category | Composite physical characteristics | Recommended drilling method(s) and/or type(s)[a] |
|---|---|---|
| High | • Stony and gravelly- to very gravelly ferralitic and plinthic soils overlain on: inland terraces, depressions, floodplains, weathered granitic basement, or colluvial gravel on low- to moderate sloped terrain<br>• Undeveloped- to weakly-developed sand on coastal beach plains<br>• Weakly-developed muds and hydromorphic clays along coastal river estuaries | _Best_: Casing advancement method with direct air rotary drilling, Dual-wall reverse drilling with fluid rotary, Hand-dug drilling (except where soil is thin or outcropping rocks)<br><br>_Satisfactory_: Fluid rotary drilling, cable tool drilling<br><br>_Not recommended_: Air rotary drilling, down-hole hammer air rotary drilling |
| Moderate | • Gravel-free ferralitic soils on terraces<br>• Hydromorphic clays and gravel-free ferralitic soils on coastal floodplains | _Best_: Fluid rotary<br><br>_Satisfactory_: Cable tool drilling, Dual-wall fluid rotary, Hand-dug drilling (except where soil is thin or outcropping rocks)<br><br>_Not recommended_: Air rotary drilling, Down-hole hammer air rotary drilling |
| Low | • Hard rocks, granites<br>• Shallow soils on plateau mountains and lateritic hills and terraces<br>• Stony and gravelly ferralitic soils with shallow soils on moderate-to-high sloped hills formed from predominantly acid rocks<br>• Very gravelly ferralitic soils with shallow soils on moderate to high sloped terrain formed from basic and ultrabasic rocks | _Best_: N/A<br><br>_Satisfactory_: Rotary drilling<br><br>_Not recommended_: Hand-dug drilling, Casing advancing methods |
| Very Low | • High sloped terrain | Unsuitable for most methods |

[a] Interpreted from classification scheme from Sterrett (2007)

Key observations from the map shows two main DPS regions. The northeastern part of the country (Koinadugu, Kono, eastern Tonkolili) is characterized as having very low to moderate DPS, corresponding with the higher elevations, high variability and prevalence of shallow ferralitic soils on sloped terrains. Much of the northeast will benefit from fluid rotary or cable drilling methods, as well as some areas good for hand-dug wells, though some areas are unsuitable for most methods. The southern and western areas have better DPS, with mostly high-to moderate values. Most of Freetown area will benefit primarily from rotary drilling, while fluid rotary, cable tool drilling and hand-dug wells are suitable in the coastal zone.

## Groundwater Exploration Suitability map (2017)

In Sierra Leone, it is becoming more costly and difficult to find new sources of high-quality groundwater. To site and design boreholes effectively in this environment, groundwater investigations must maximize the collection of data and apply the most suitable exploration methods. Generally, the options for drilling feasibility prospection methods available to the hydrogeologist include: exploration drilling, hydrogeologic logging, airborne hydrogeophysics, surface hydrogeophysics, sub-surface geophysics (usually down-hole).

The Groundwater Exploration Suitability of Sierra Leone map (Figure 47) depicts the distribution of qualitative conditions conducive to effective sub-surface investigations. *Groundwater exploration suitability* (GES) is a function of hydrogeologic factors important for determining the feasibility of new boreholes, driven primarily by the potential for shallow groundwater occurrence. Areas with high GES values (green) have a good probability of shallow groundwater occurrence and require surface geophysical surveys and hydrogeologic logging to site and design new boreholes effectively. Areas with moderate-to-low GES values are less likely to have promising shallow groundwater occurrence and require more intensive exploration programs to determine borehole feasibility. Investment in exploration activities is not recommended in areas of low GES (black areas).

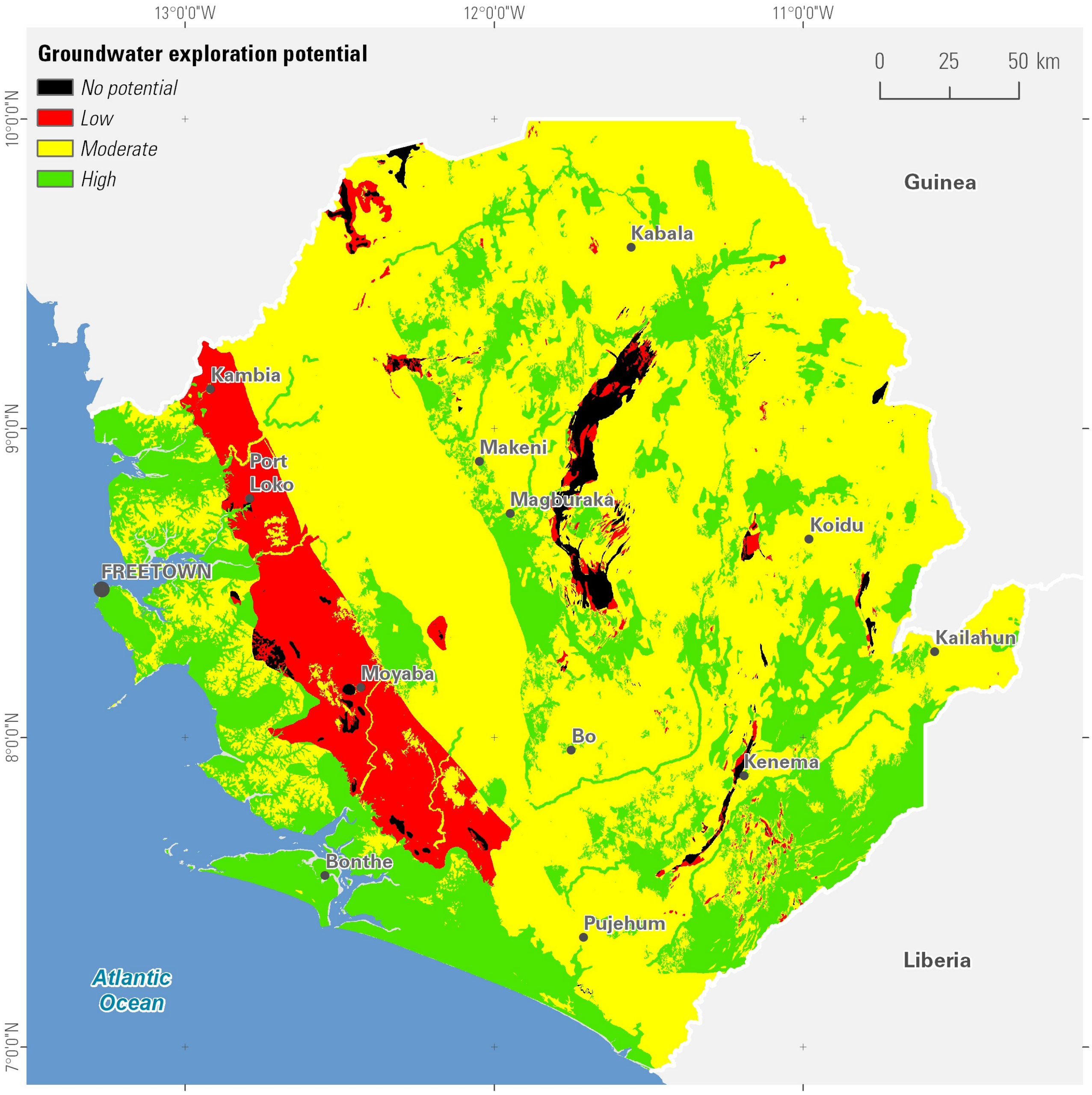



**Figure 47**. Groundwater exploration suitability of Sierra Leone

GES is applicable for early stages of siting and designing wells, and in determining zones that are favorable for conducting detailed, focused groundwater exploration. The ultimate aim of the GES map is to help minimize project costs and increase quality and quantity of water.

GES for Sierra Leone was developed from information derived from multiple remote sensing products. A proprietary algorithm was applied to process and interpret groundwater occurrence and exploration suitability. The main input components of GES are: proximity to main drainage channels, slope, geology (lithology), drilling physical suitability, lineament density, land cover, soil moisture and rainfall patterns. Components were calibrated to local conditions and amalgamated into a single model that predicts shallow groundwater occurrence.

Four classes of GES have been delineated (Table 15), with a scale of high (green), moderate (yellow), moderate-to-low (red) to low (black). The potential to prospect for shallow groundwater occurrence has been interpreted for each GES class, ranging from good potential (70-99%) for high GES to very limited to no potential (0-9%) for low GES. The bare minimum exploration methods for each GES class are also given.

**Table 15. Groundwater exploration suitability (GES) classification scheme**

| GES class | Shallow groundwater occurrence potential | Minimum suggested exploration methods |
|---|---|---|
| High | Good potential (70-99% probability) | Surface geophysical, hydrogeologic logging, water quality testing |
| Moderate | Moderate potential (40-69% probability) | Exploration drilling, hydrogeologic logging, surface geophysical, water quality testing |
| Moderate to low | Low potential (10-39% probability) | Exploration drilling (multiple bore wells), hydrogeologic logging, airborne geophysics, surface and sub-surface geophysics surveying, water quality testing |
| Low | Very limited to no potential (0-9% probability) | Not suitable for detailed groundwater exploration |

*Validity and limitations*

The validity of the GES map was tested against data from 754 existing boreholes with piezometric measurements. The test found that the majority (94%) of existing piezometric boreholes are situated in areas of high and moderate GES and only a negligible proportion (1%) fell in the areas of low GES, supporting the validity of the approach.

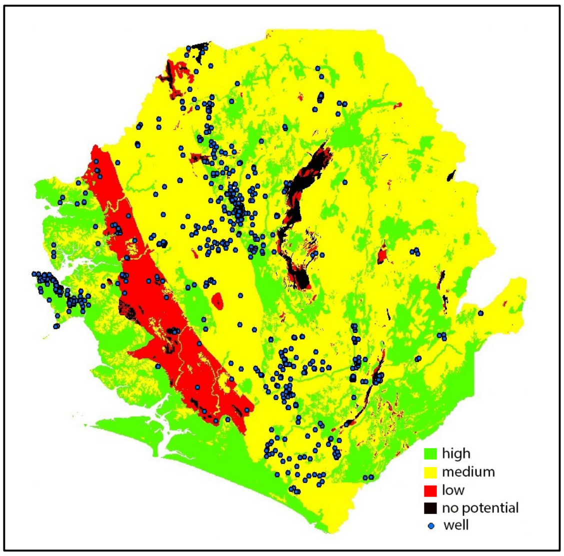



**Figure 48**. Validation of the GES map, with calibration points (existing boreholes with piezometric data).

GES does not consider hydrochemistry or hydraulic parameters; therefore, users of the map should plan for aquifer testing and water quality analysis. Suggested exploration methods are based on technical suitability and do not consider local costs of methods.

# Analysis of Selected Areas

At the additional request of the MOWR, we provide here a brief analysis of hydrogeology of four areas of interest (AOI): (1) Freetown, (2) Makeni, (3) Kabala and (4) Musaia. In addition, we provide additional analysis of hydrogeology for a fifth area, (5) Nimini (Kono District), with the application of an advanced groundwater exploration technique, Airborne Electromagnetic (AEM).

For the four AOI's, the goal was to provide any additional level detail on groundwater potential that can be achieved with the data collected during the national scale and minor fieldwork in those areas. Geoelectrical resistivity surveys were carried in spot locations in the four AOI's with the aim of gathering additional estimates on local aquifers. Due to a lack of existing boreholes with hydrogeological logs with which to calibrate the resistivity soundings, the findings from the geophysical surveys can only be considered indicative at best.

The objective for the Nimini pilot area was to showcase the AEM technology and derive recommendations for applying the technique in other locations in Sierra Leone. The results for all five areas are not comprehensive, but provide a sound basis for future investigations. At the end of this section, we provide a set of specific recommendations for focused investigation for each of the five areas.

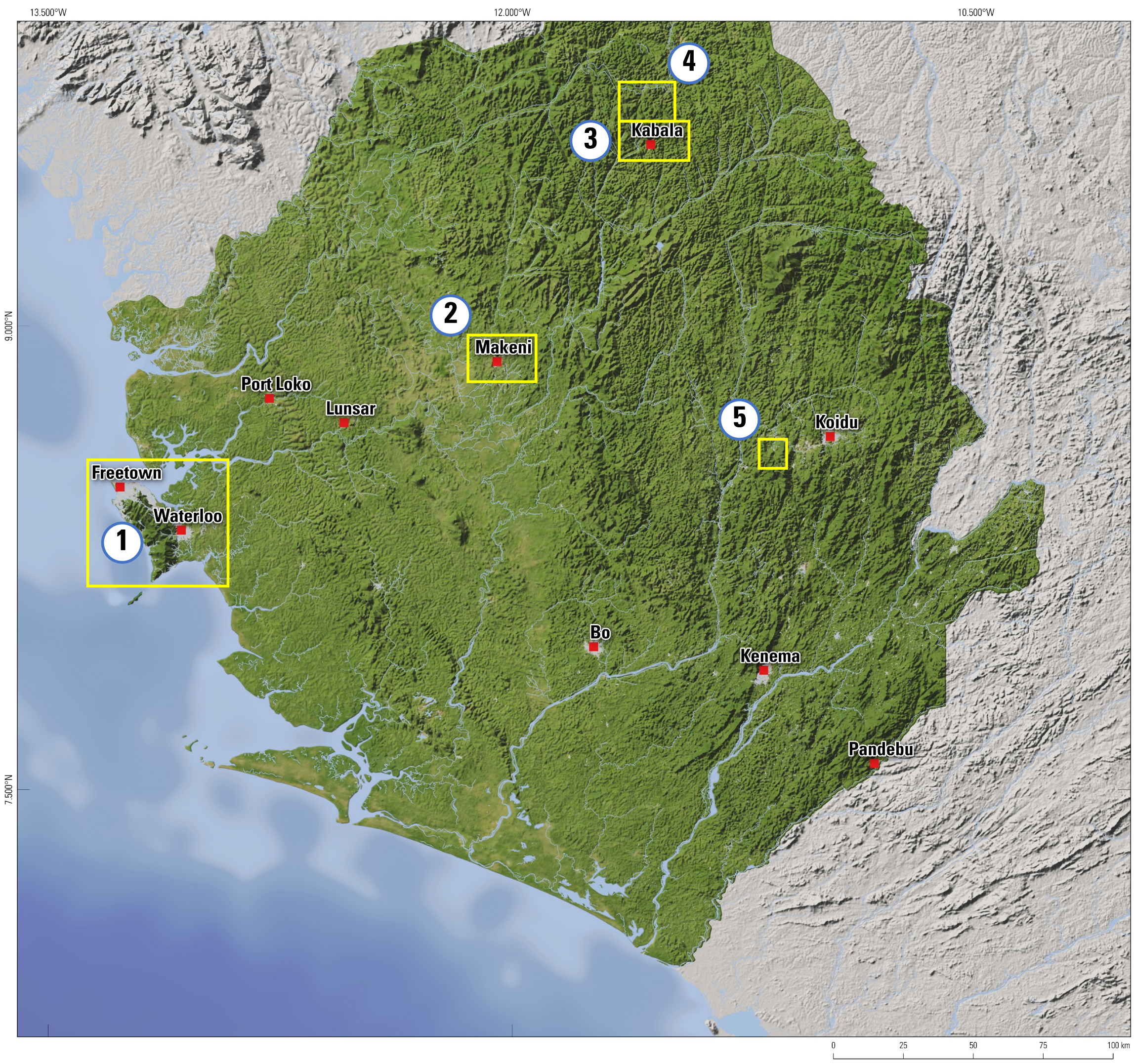



**Figure 49**. Location of areas of additional study
Explanation: (1) Freetown area, (2) Makeni area, (3) Kabala area, (4) Musaia area, (5) Nimini mining area (AEM pilot study)

## Freetown (Western District)

A more detailed analysis of the Freetown area has been conducted, based on existing hydrogeological information and new surface geoelectrical soundings. The following hydrogeologic aspects are analyzed for Freetown, provided in the following sections: (1) basic hydrogeologic parameters, (2) specific capacity, (3) surface-to-groundwater relations, (4) depth-to-basement, (5) geophysical survey results. Recommendations for further investigation in Freetown are found at the end of this chapter.

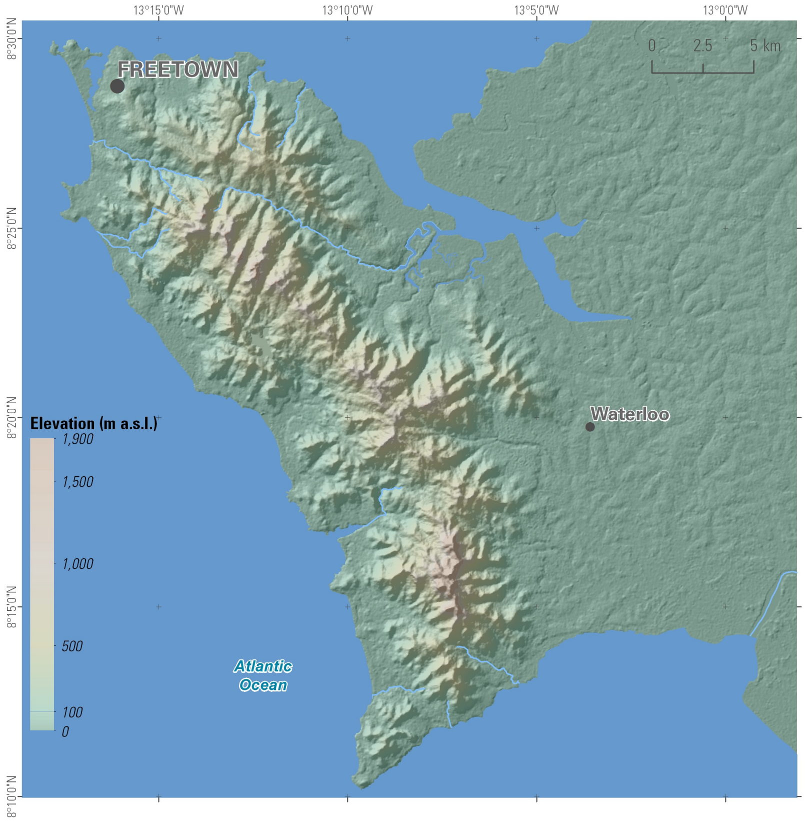



**Figure 50**. Areal extent of the Freetown area.

### Basic Hydrogeologic Parameters of the Freetown Area

This study investigated the Freetown Peninsula, Western District during November-December 2016, by analyzing over 74 borehole drilling reports and conducting field investigation, which entailed visits to existing boreholes, assessing local piezometric maps to highlight surface-to-groundwater relations that could be taken as an example for similar geologic environments in the country. Unfortunately, existing data do not include recordings or estimates of transmissivity, permeability, storage/porosity, influence radius are available. A summary of the main parameters calculated for Freetown Area is given in Table 16.

**Table 16. Basic hydrogeologic parameters for Freetown Area**

| Parameter | Average value | Unit | Note |
|---|---|---|---|
| SWL | 12 | Meters below ground level (m bgl) | Static water level below ground |
| DWL | 38.8 | m bgl | Dynamic water level below ground |
| DD | 27.7 | m bgl | Drawdown in the water well at the end of test |
| Q | 87.7 | cum/d | Pump discharge during the test |
| Q | 1 | l/s | Pump discharge during the test |
| SC | 11.6 (4.5)* | cum/d/m | Specific capacity (Q/DD) |
| Depth | 71 | m bgl | Borehole depth |
| Screen length | 32 | m | Thickness of the screened aquifer |
| Bedrock depth | 34 | m bgl | Depth of hard rock basement |

Explanation: Calculations made from processing of data from 74 drilling reports of boreholes drilled between 2009 and 2015. *Average SC value of 4.5 is used, not considering two outliers. (Source: Edal Drilling Company).

The sample examined is representative of the general situation in the Freetown Area. It must be underscored that slightly better results in terms of total abstraction rate could be obtained with an improved well design (e.g. use of continuous-slot screens, and proper gravel pack). The below section provides more details on Specific Capacity assessment for Freetown.

## Specific Capacity of the Freetown Area

The average value for the specific capacity in the Freetown Area is 11 $m^3$/d/m, while the depth to water is 12 m (bgl) and the bedrock depth at 34 m (bgl). No confined aquifers were encountered during drillings. Two abnormally high SC values of 169 and 129 $m^3$/d/m were recorded. Not considering the two, SC drops down to 4.5 $m^3$/d/m.

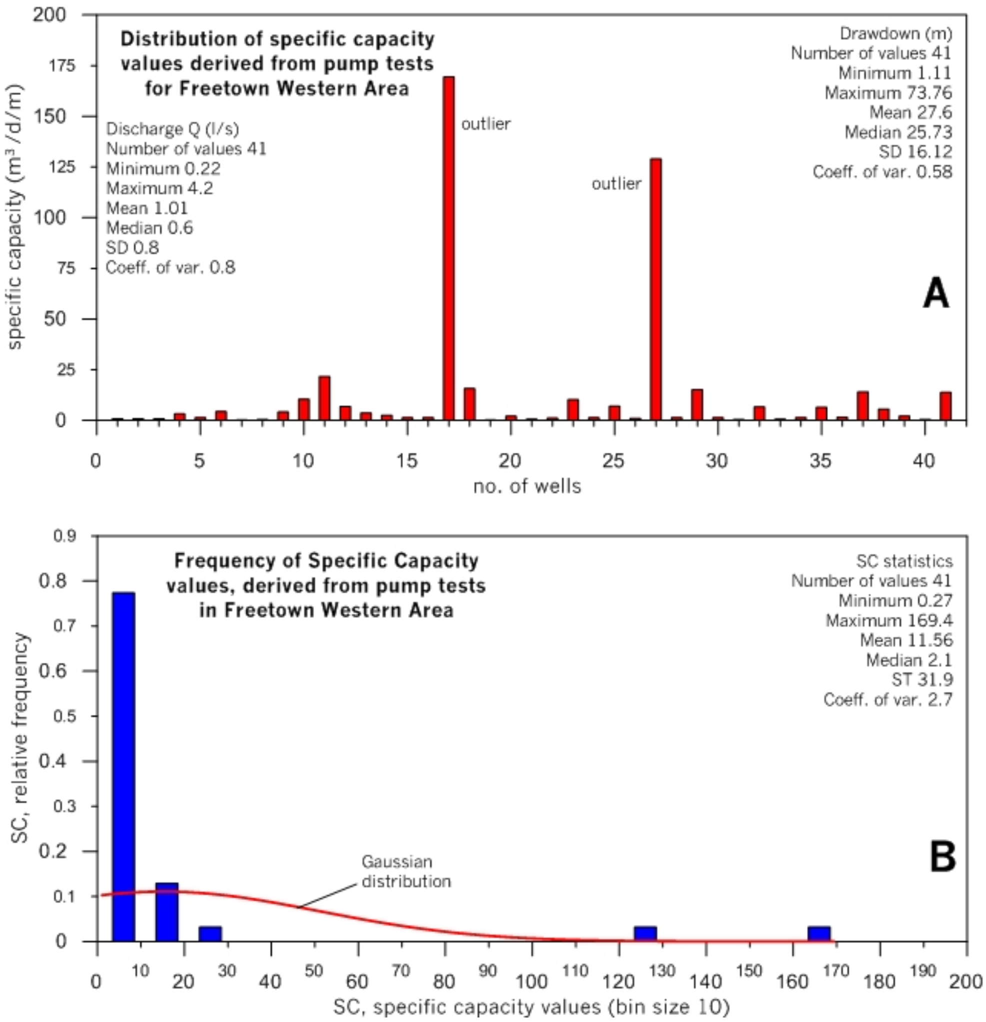



**Figure 51**. Summary of specific capacity (SC) distribution and frequency in the Freetown area.

### *Specific Capacity of Freetown Area Map*

The Specific Capacity of the Freetown Area map (Figure 52) depicts a measure of expected performance of boreholes and local aquifers -- "specific capacity" (SC) -- along the north and north eastern area of Freetown peninsula. SC is short-term sustainable discharge of a well in relation to the drawdown observed during a pump test and is a valuable hydrogeologic parameter for designing production boreholes. Values are given in cubic meters (m3) per day (d) per meter (m), or (m3/d)/m. SC can be a rough approximation of the hydraulic conductivity of an aquifer (or transmissivity, T), a product of aquifer permeability and thickness. Areas of high SC correspond to more potential aquifers. It is important to emphasize that SC can only be used as a rough approximation of T, since it is influenced by several human-controlled factors like pumping time, pumping rate, well construction, and an absence of piezometers, etc. SC was modeled from pump test data obtained from boreholes in the Freetown area and then interpolated using the kriging method. SC was calculated as a ratio between pump discharge and maximum drawdown levels measured during pump tests. Tests entailed pumping the well until the drawdown level was stabilized (or change was negligible). Analysis of pump test reports showed that measurements in some wells were taken before the drawdown levels had stabilized (while still decreasing).
Introduce the Specific Capacity of Freetown Area map.

In the figure below, SC values are shown to be highest in Cline town and Waterloo.

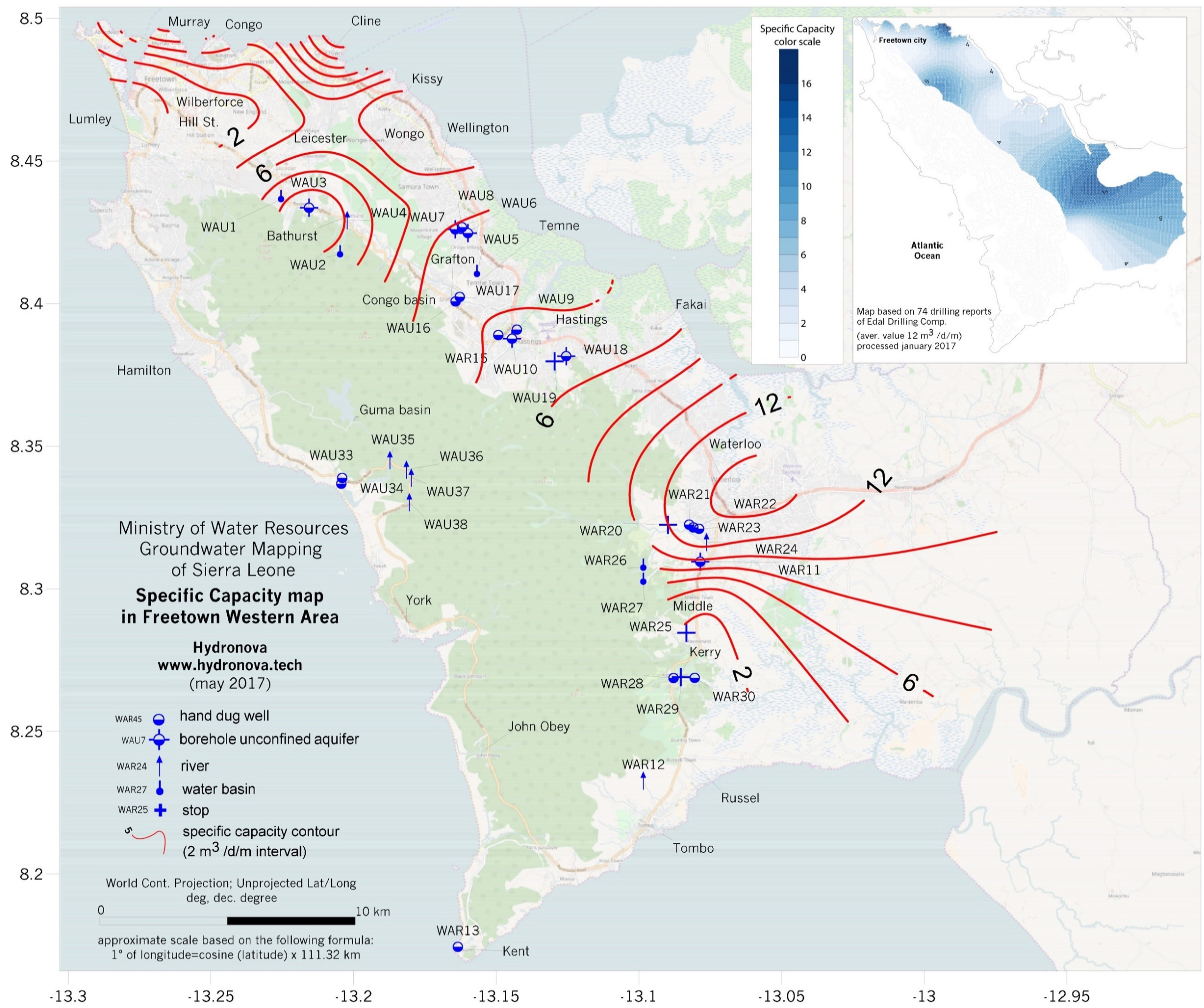



**Figure 52**. Specific capacity of the Freetown area.
Explanation: The map shows the distribution of SC derived from 74 drilling reports. Main values, corresponding to higher aquifer potential, are near Cline town, Wellington and Waterloo.

## Surface-to-groundwater Relations in the Freetown Area

As described in the section on the Hydrogeologic Map, an example of close relation is assessed between surface water and groundwater was assessed in November 2016 along in the Western District. Water table readings along the two banks of Orugu River, near Hastings and during the recession period, clearly show that the water course is draining the unconfined aquifer (Fig. 51). The same situation was found in nearby stream, the Koqwena River at Waterloo.

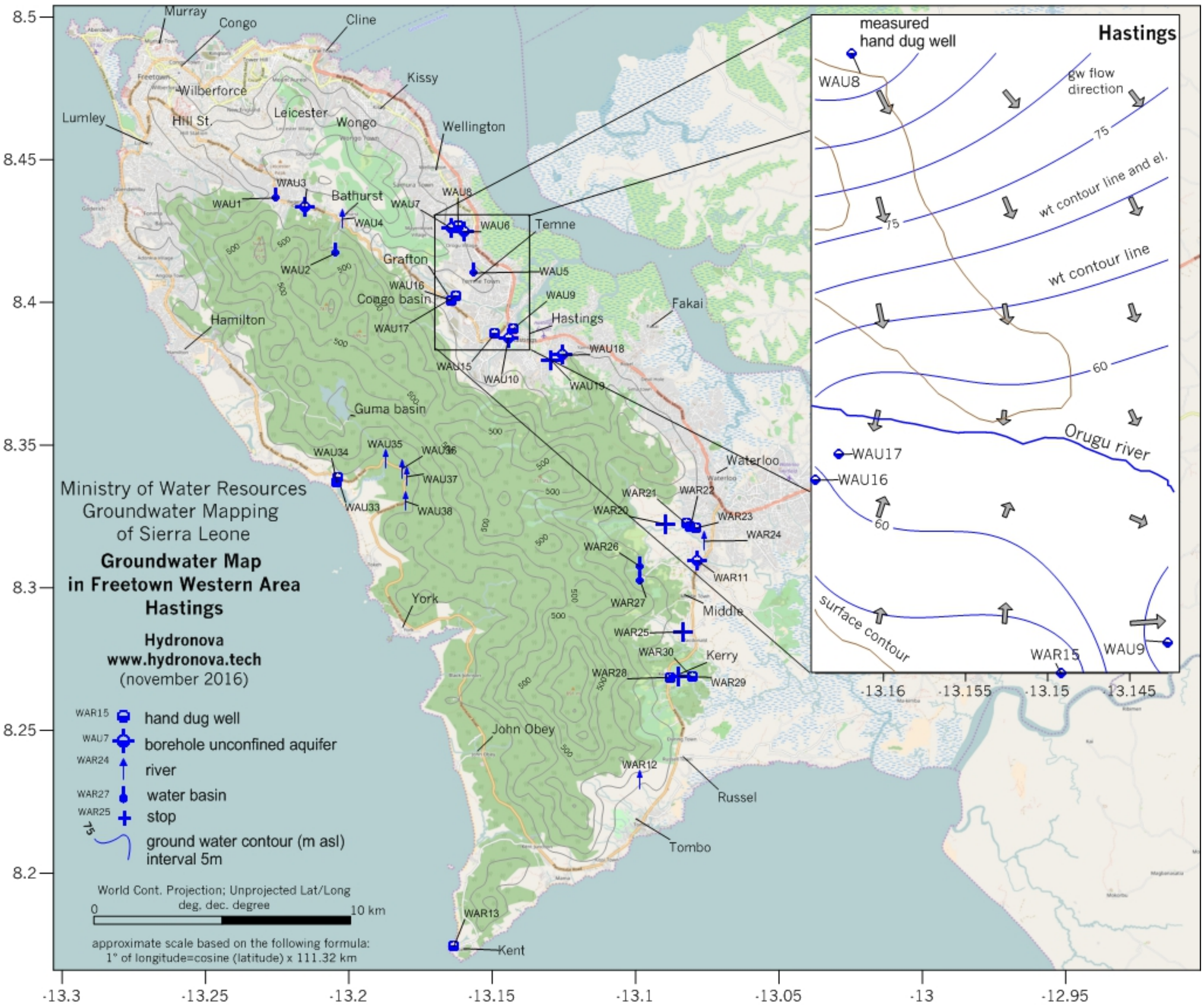



**Figure 53**. Groundwater level contours along the Orugu River, Western District.
Explanation: Contours along the Orugu River show the influence on local drainage. Readings were made during the recession time after the rainy season.

## Depth-to-Basement Surface in the Freetown Area

The Depth-to-Basement Surface in the Freetown Area map depicts an estimate of the distance in meters (m) from the land surface to the surface of the compact gabbroic rock, also referred to as the "basement", along the north-northeastern area of the Freetown Peninsula. In drilling terms, it is the estimated depth (m) at which the surface of the basement is positioned. In existing boreholes or wells, it is the estimated maximum depth (m) achievable with conventional methods. The map can be useful in several applications, including in the planning of the construction design of new boreholes and wells, as well as other development activity (e.g. roads, buildings and sewers). For future hydrogeologic modeling, the map may be used as a baseline to identify the geometry of overlain aquifers, and can help identify areas where more detailed studies and supplemental data are needed to provide for greater resolution. The method of analysis used to estimate the depth-to-basement relied on existing borehole drilling logs and reports. The model considers Freetown's physiographic context. Kriging method was applied to maximize the use of existing data and produce a surface grid model. The results have been scrutinized to ensure that the interpolation is consistent with available hydrogeologic information. The Depth-to-Basement map is representative of the estimated conditions in the study area; however, the actual depth of the surface of the water table may differ from the estimated position at specific locations, and short-term, seasonal, and long-term variations in the differences can be expected. Site-specific estimates of the depth-to-basement in areas of may result in depths-to-basement that deviate from the average. Due to a wide range of drilling procedures used to generate the raw drilling data used, it is difficult to distinguish the contact between hard and fractured rock in depths below the overburden.

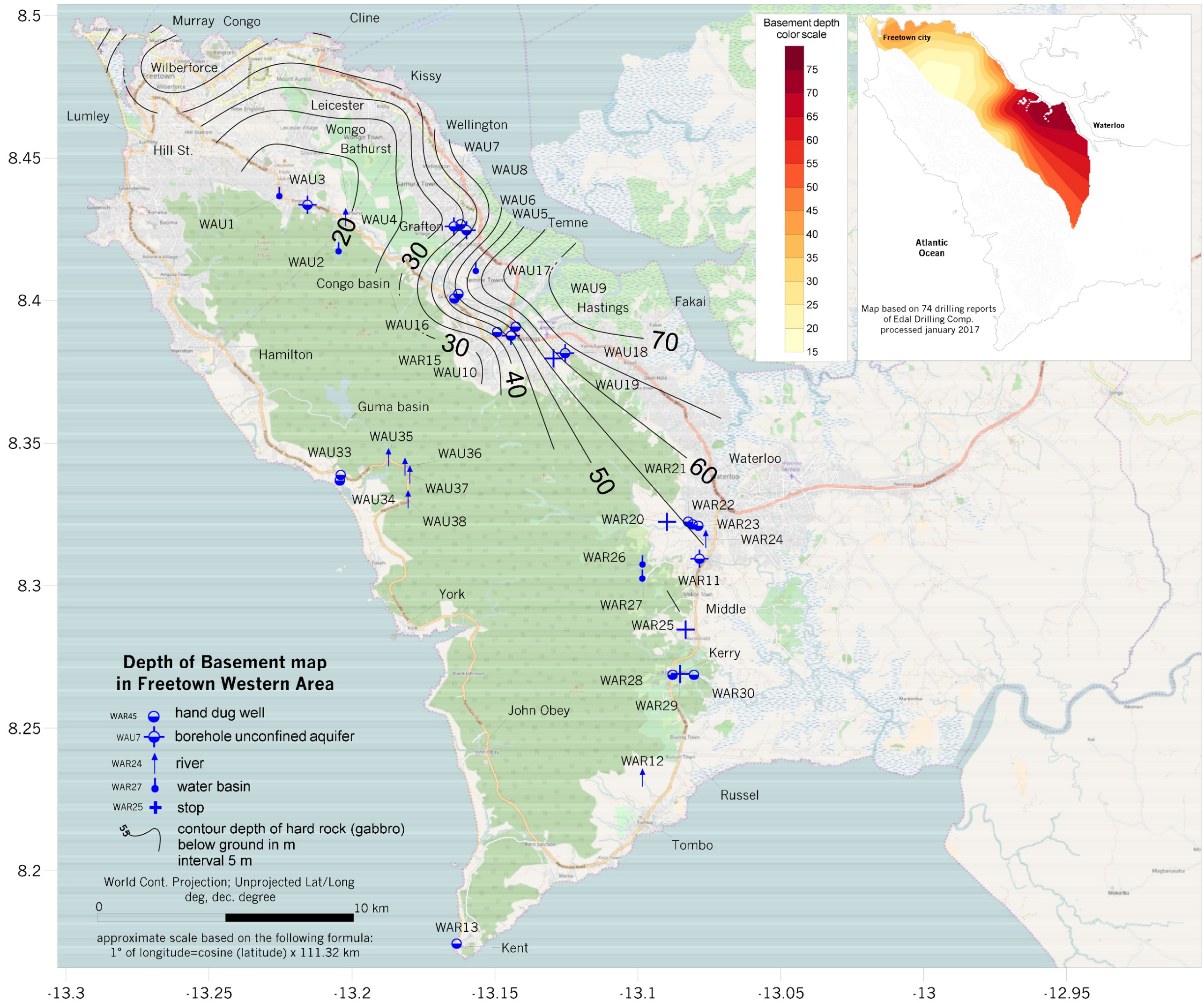



**Figure 54**. Depth-to-basement in the Freetown area.
Explanation: The basement deepens towards east and northeast as deep as 70 m.

The figure above shows the distribution in space of the top of the compact gabbroic rock along the north and northeastern area of Freetown peninsula. Values are derived from lithologic logs and correspond to the depth in meter below ground, of the compact rock. The values derive from a desk examination of local reports and largely depend on the reliability of the driller's log. In many situations, and due to the type of drilling procedure, it is difficult to differentiate the boundary between hard and fractured rock below the overburden. The basement seems to deepen near Murray, Wellington, Grafton, and Hastings, towards the east and northeast, under the Bolilands. East of Fakai the interpolation of data, points out a value greater than 75 m below surface.

## Geophysical Investigation Results in the Freetown Area

### *Location*

A surface geoelectrical resistivity survey were carried out in Freetown area, performed with VES method in April 2017 on three sites: Freetown 1, Freetown 2 and Freetown 3. The focus of the survey was on the eastern part of Western District in Benguma and Newtown townships (see figure below for location). No information on hydrogeologic logs were available from existing boreholes in the area.

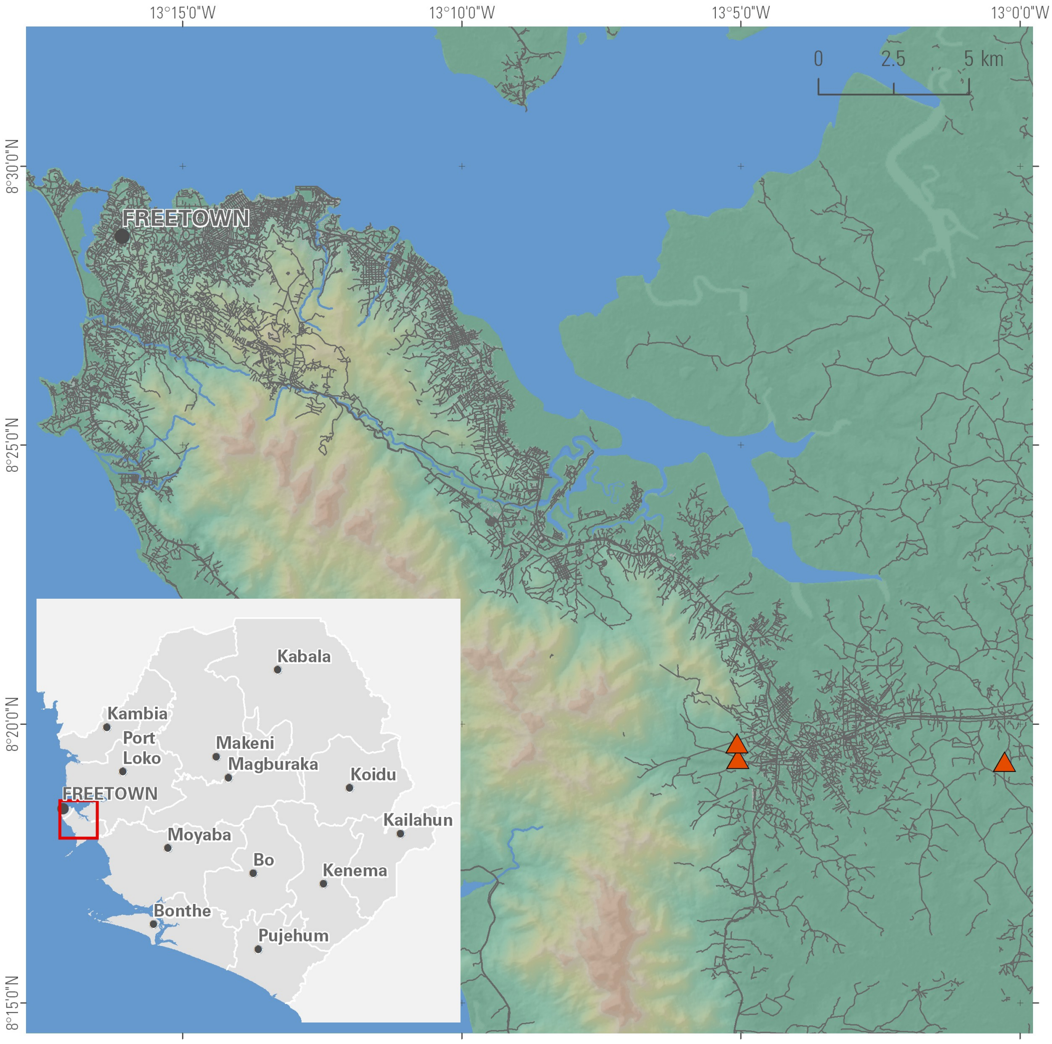



**Figure 55**. Location of surface geophysical survey (VES) completed for the Freetown area.

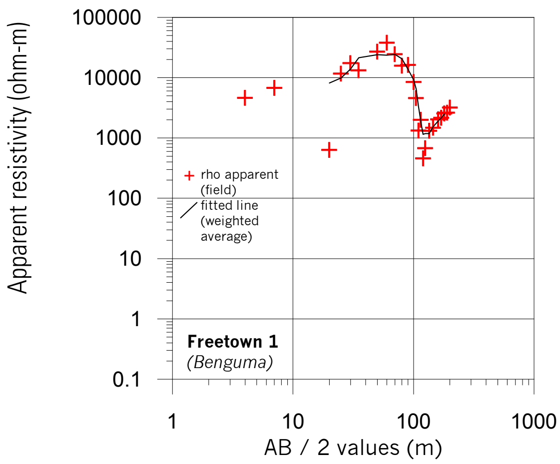
Explanation: Location (GPS, degrees):

| VES point | X | Y | Elev. |
|---|---|---|---|
| Freetown 1 (Benguma) | -13.08430 | 8.32296 | 46 |
| Freetown 2 (Benguma) | -13.08449 | 8.32765 | 56 |
| Freetown 3 (Newton) | -13.00468 | 8.32216 | 38 |

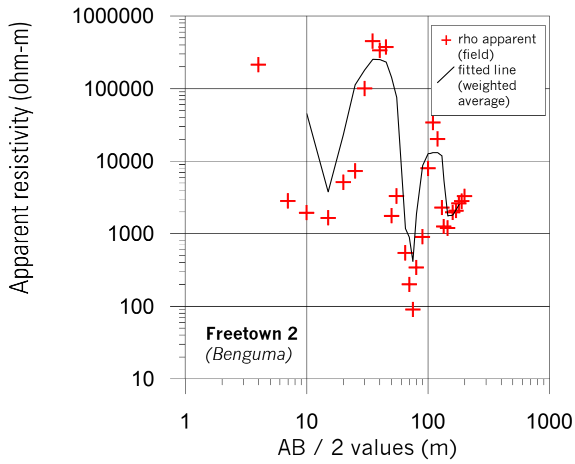
### *Data*

A summary of the resistivity data acquired for Freetown 1, 2 and 3 are given below, with apparent resistivity (ohm-m) curves in Figure 56 and AB/2 (m) readings found in Table 17 and 18.

*Freetown 1 (Benguma)*




*Freetown 2 (Benguma)*




*Freetown 3 (Newton)*

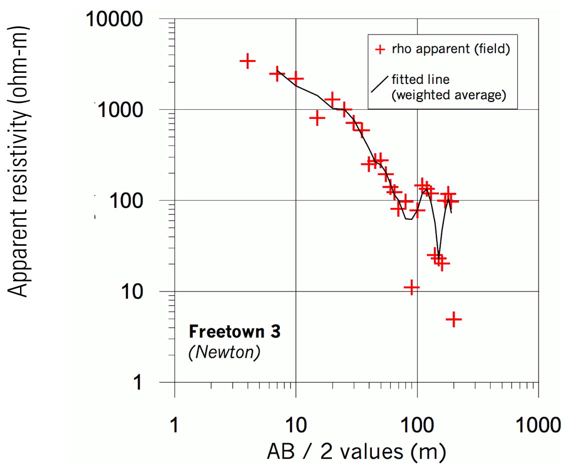



**Figure 56**. Acquired resistivity curves for Freetown 1, Freetown 2 and Freetown 3 with corresponding layered models of rho apparent and fitted line weighted average.

**Table 17. Resistivity readings, VES points Freetown 1 and Freetown 2**

*Freetown 1*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 14,819 | 2.25 | 2.25 |
| rho 2 | 469 | 3.18 | 5.43 |
| rho 3 | 1.1E+5 | 5.12 | 10.6 |
| rho 4 | 681 | 11.9 | 22.5 |
| rho 5 | 10.6 | 24.9 | 47.4 |
| rho 6 | 9,682 | - | - |

*Freetown 2*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 2.9E+8 | 0.562 | 0.562 |
| rho 2 | 863 | 1.64 | 2.2 |
| rho 3 | 64,946 | 4.06 | 6.26 |
| rho 4 | 130 | 8.33 | 14.6 |
| rho 5 | 9,361 | 32.8 | 47.4 |
| rho 6 | 2.6E+5 | - | - |

*Freetown 1*

| AB/2, (m) | Resistivity, (Ω · m) |
|---|---|
| 4 | 4,632.71 |
| 7 | 6,718.17 |
| 10 | - |
| 15 | - |
| 20 | 632.447 |
| 25 | 11,671.7 |
| 30 | 17,338.3 |
| 35 | 13,182.7 |
| 50 | 26,855.2 |
| 60 | 37,911.5 |
| 70 | 24,313 |
| 80 | 15,751 |
| 90 | 16,244.3 |
| 100 | 8,453.24 |
| 105 | 4,544.86 |
| 110 | 1,324.15 |
| 115 | 1,988.92 |
| 120 | 457.09 |
| 125 | 676.338 |
| 135 | 1,308.93 |
| 145 | 1,480.7 |
| 160 | 2,030.93 |
| 170 | 2,153.42 |
| 180 | 2,540.27 |
| 190 | 2,611.29 |
| 200 | 3,169.24 |
| - | - |
| - | - |

*Freetown 2*

| AB/2 (m) | Resistivity, (Ω · m) |
|---|---|
| 4 | 21,3341 |
| 7 | 2,817 |
| 10 | 1,946.58 |
| 15 | 1,654.41 |
| 20 | 5,126.42 |
| 25 | 7,328.31 |
| 30 | 99,945.8 |
| 35 | 44,7429 |
| 40 | 33,6165 |
| 45 | 37,2383 |
| 50 | 1,765.41 |
| 55 | 3,307.56 |
| 60 | - |
| 65 | 545.437 |
| 70 | 199.54 |
| 75 | 90.4862 |
| 80 | 341.656 |
| 90 | 904.059 |
| 100 | 7,939.99 |
| 110 | 34,044.7 |
| 120 | 20,198.7 |
| 130 | 2,284.72 |
| 135 | 1,253.08 |
| 145 | 1,196.6 |
| 160 | 1,958.55 |
| 170 | 2,077.26 |
| 180 | 2,618.81 |
| 190 | 2,791.72 |
| 200 | 3,265.77 |

**Table 18. Resistivity readings, VES point Freetown 3**

*Freetown 3 (Newton)*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 2,589 | 8.86 | 8.86 |
| rho 2 | 231 | 41 | 49.9 |
| rho 3 | 0.0942 | - | - |

| AB/2, (m) | Resistivity, (Ω · m) |
|---|---|
| 4 | 3419.602 |
| 7 | 2465.532 |
| 10 | 2186.495 |
| 15 | 803.5875 |
| 20 | 1284.665 |
| 25 | 999.2519 |
| 30 | 710.5187 |
| 35 | 589.0794 |
| 40 | 250.4915 |
| 45 | 270.4444 |
| 50 | 276.7854 |
| 55 | 194.1002 |
| 60 | 140.2447 |
| 65 | 123.3345 |
| 70 | 80.70918 |
| 80 | 96.84197 |
| 90 | 11.06445 |
| 100 | 77.89646 |
| 110 | 146.3288 |
| 120 | 134.5043 |
| 130 | 119.7504 |
| 140 | 24.9877 |
| 150 | 23.09645 |
| 160 | 20.20509 |
| 170 | 99.18707 |
| 180 | 117.8719 |
| 190 | 97.09327 |
| 200 | 4.892039 |

*Interpretation*

The key results from the geoelectrical survey in the eastern part of Western District is summarized as follows:

- Freetown 1 (Benguma): Detected a hard rock layer, perhaps laterite, at 10 m depth with a conductive layer below. The basement is at this point was detected at 50 m depth.
- Freetown 2 (Benguma): Detected a hard rock layer, perhaps laterite, at 9 m depth with a conductive layer below. The basement at this point was detected at 47 m depth.
- Freetown 3 (Netwon): No basement was detected down to 50 m, indicating it is deeper.

Despite a lack of hydrogeologic log in the vicinity with which to calibrate these three geoelectrical resistivity soundings, it can be inferred that the basement rocks dip generally eastward, where the formation encountered increases in this direction. The depth to the basement is about 50 m in the western point (Benguma) and greater than 50 m in the eastern part of the area (Newton) and cannot be reached from the acquired data in the eastern part. Finally, the contact boundary between the basement complex and formation layer above it cannot be determined without further data.

The end of this chapter gives recommendations on further investigations for Freetown.

## Makeni (Bombali District)

A more detailed analysis of the Makeni area has been conducted, based on existing hydrogeological information and new surface geoelectrical soundings. The following hydrogeologic aspects are analyzed for Makeni, provided in the following sections: (1) basic hydrogeologic parameters drawn from mainly available datasets from official monitoring stations and a field site reconnaissance, and (2) geoelectrical resistivity soundings performed in April 2017 for this study. Recommendations for further investigation in Makeni are found at the end of this chapter.

### Basic Hydrogeologic Parameters of the Makeni Area

Makeni area is located some 10 km at the southern limit of Little Scarcies-Mabole catchment basin. Average elevation is around 100 m (asl). Rocks are part of the crystalline basement (gneisses, migmatites and granites) covered by a weathered material of variable thickness (10-40 m) as indicated by various drilling reports (GIGC-SARLU, Geoprospects Ltd). Most aquifers in the area that are being exploited are unconfined in the porous surface layer of weathered material, where also some sand and gravel layers have been detected. The general flow direction of the water-table in the Makeni area is towards the SW, with some probable flow towards the Mabole River to the north, with an inferred hydraulic gradient of 0.004. The urban area has been investigated with four electrical soundings with AB up to 400 m.

The MOWR maintains a monitoring station (Makeni - Bombali DC - BSD Well, SN03) that records rainfall data (every 24 hrs.), air and water temperature and groundwater level (every 15 min.) in a well drilled in the weathered basement complex. See figure below for the position of the monitoring stations.

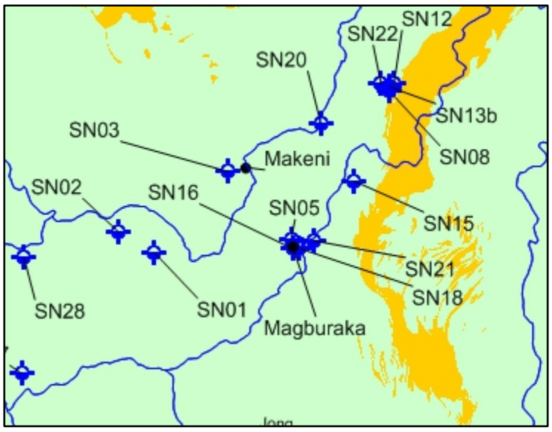



**Figure 57**. Location of measuring stations near the Makeni area.
Explanation: Position of the MOWR monitoring stations in Sierra Leone. Recorded parameters are: rainfall (every 24 hrs.), groundwater level, water and air temperature and barometric pressure every 15 min. In the figure boundaries of the main watersheds and extensions are overlaid on the three main hydrogeological units.

Data was recorded in the Makeni area during a recharge period in August 2013 that allows for a modeling of the depth-to-water and the water-table (Figure 58).

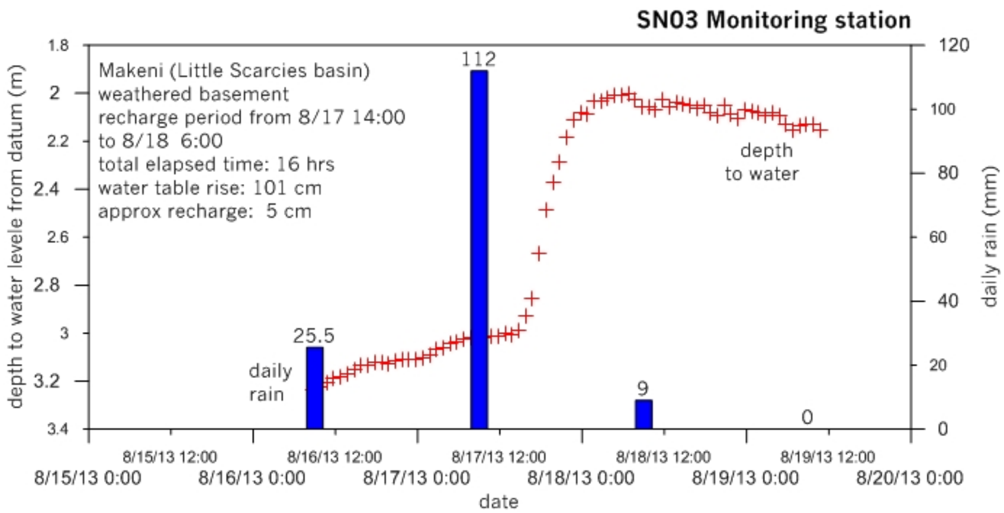



**Figure 58**. Extrapolated data from SN03 station (Makeni)

### *Water table*

Water table is close to the surface (2-3 m) in Makeni, and again, it can be underlined that infiltration is likely to be relatively rapid, occurring within hours. See how close are the two peaks of rainfall and water level rise (less than 24 hrs.). The approximated recharge, considering a specific yield value of 0.05, is 5 cm. No other data are available on the extension of the basin supplying the well.

Another interesting example is near Addax Hospital, 26 km SW of Makeni. The well is located at 200 m from the right bank of the Rokel-Seli Basin (ADDAX Environmental Office - Borehole FS01). The area is intensively cultivated at 70 m elevation. Rock formations are the metasediments of the Rokel River Group. We find that the relative slow rise of the water level in the well and the nearly flat top, may suggest an hydraulic connection with the river (Figure 59).

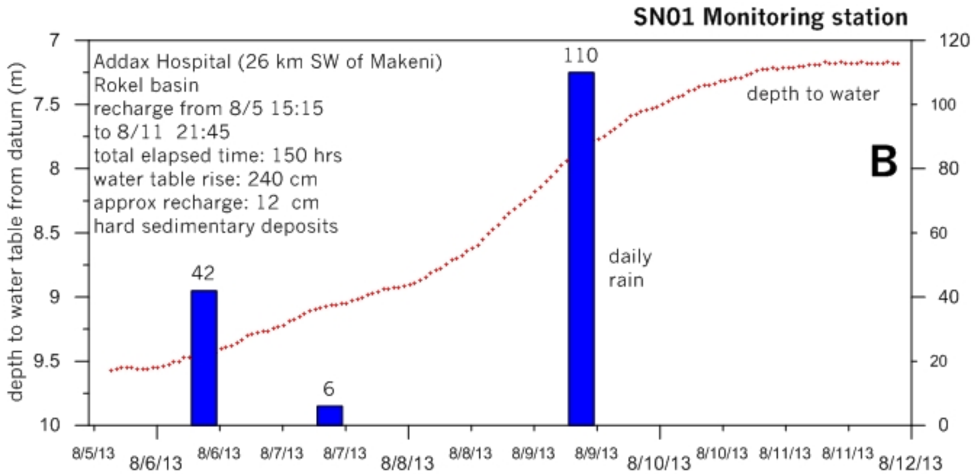



**Figure 59**. Extrapolated data from SN01 station (Makeni).

The approximated recharge, considering a specific yield value of 0.05, is 12 cm. No other data are available on the extension of the basin supplying the well.

## Geophysical Investigation Results in the Makeni Area

### *Location*

A surface geoelectrical resistivity survey were carried out in Makeni area, performed with VES method in April 2017 on four sites: Makeni 1, Makeni 2, Makeni 3 and Makeni 4. The focus of the survey was on the southeastern part of Makeni (see figure 60 below for location). No information on hydrogeologic logs were available from existing boreholes in the area.

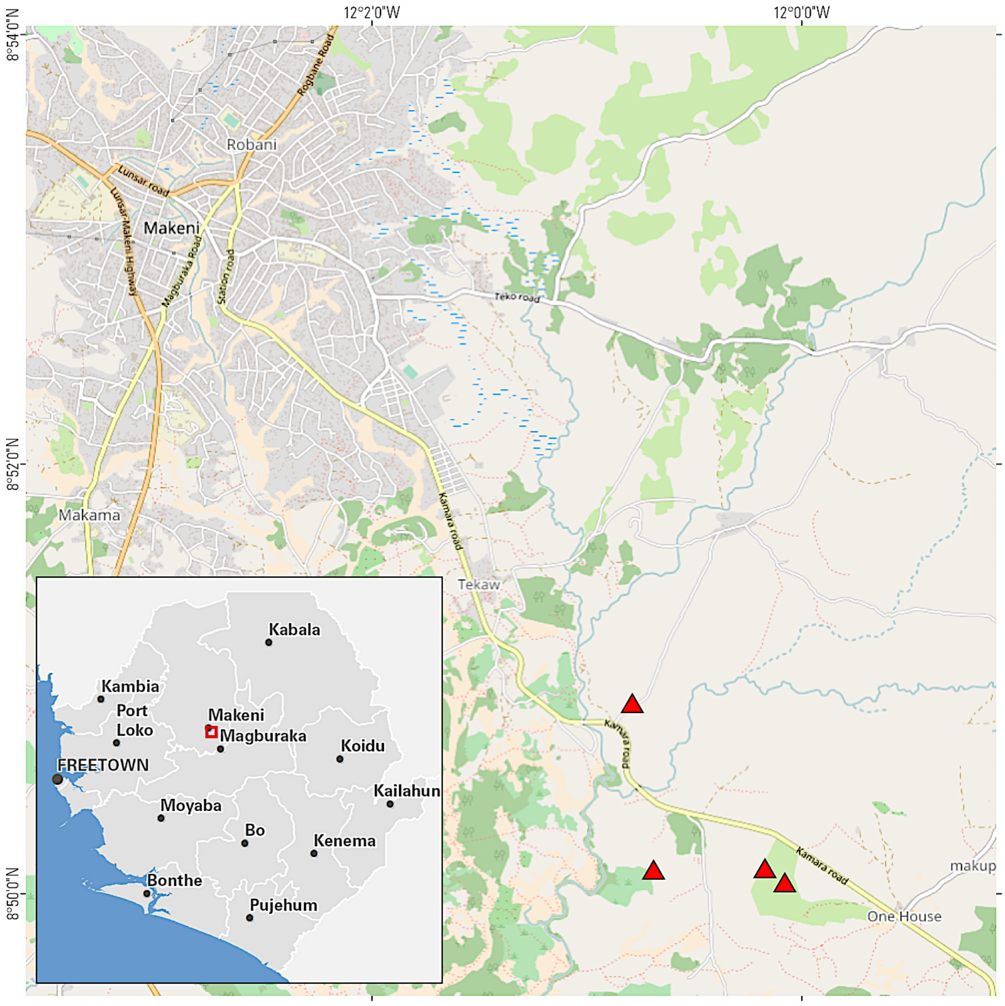



**Figure 60**. Location of the surface geophysical survey (VES) completed for the Makeni area.

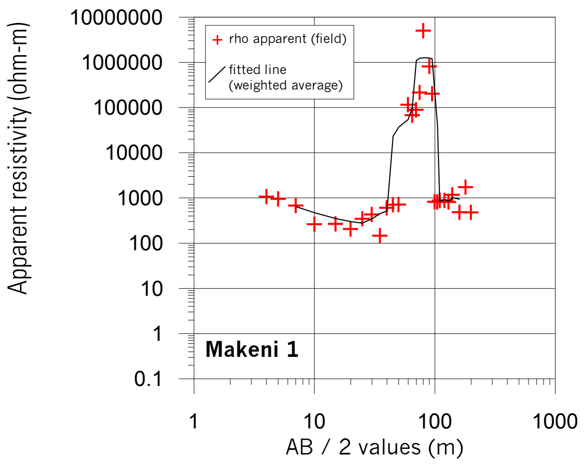
Explanation: Location (GPS, degrees):

| VES point | X | Y | Elev. |
|---|---|---|---|
| Makeni 1 | -12.00278 | 8.83527 | 85 |
| Makeni 2 | -12.00127 | 8.83418 | 77 |
| Makeni 3 | -12.01299 | 8.84816 | 76 |
| Makeni 4 | -12.01137 | 8.83517 | 75 |

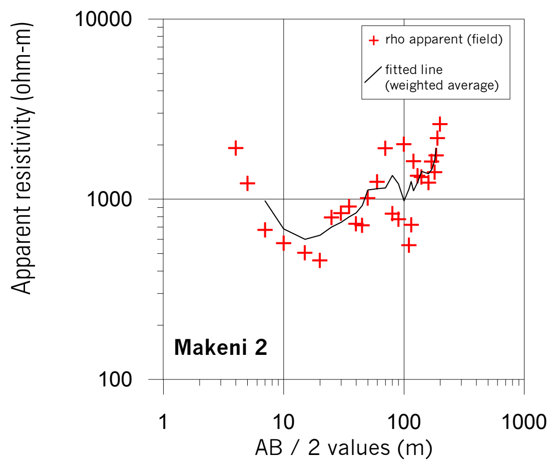
### *Data*

A summary of the resistivity data acquired for Makeni 1, 2, 3 and 4 are given below, with apparent resistivity (ohm-m) curves in Figure 61 and AB/2 (m) readings found in Table 19 and 20.

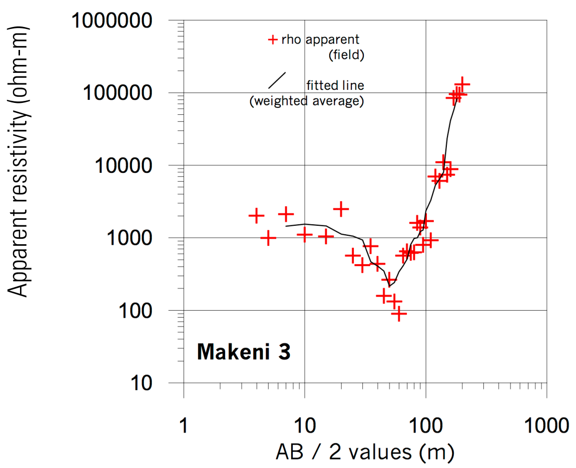
#### *Makeni 1*




#### *Makeni 2*




#### *Makeni 3*




#### *Makeni 4*

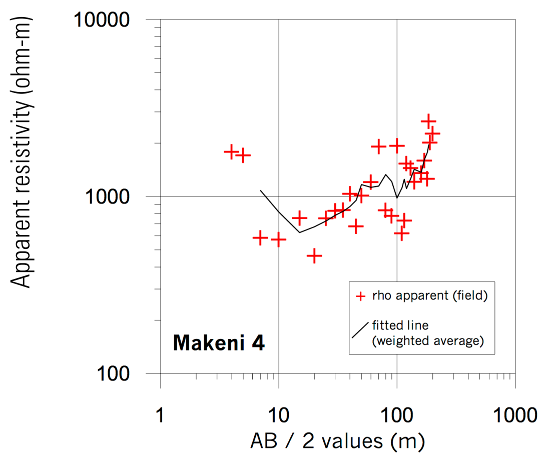



**Figure 61**. Acquired resistivity curves for Makeni 1, Makeni 2, Makeni 3 and Makeni 4 with corresponding layered models of rho apparent and fitted line weighted average.

**Table 19. Resistivity readings, VES points Makeni 1 and Makeni 2**

*Makeni 1*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 2,509 | 1.97 | 1.97 |
| rho 2 | 112 | 2.16 | 4.13 |
| rho 3 | 40,936 | 5.24 | 9.37 |
| rho 4 | 11.9 | - | - |

| AB/2, (m) | Resistivity, (Ω · m) |
|---|---|
| 4 | 1,071.2 |
| 5 | 949.66 |
| 7 | 678.29 |
| 10 | 261.52 |
| 15 | 265.32 |
| 20 | 205.25 |
| 25 | 345.65 |
| 30 | 428.47 |
| 35 | 146.5 |
| 40 | 605.56 |
| 45 | 704.64 |
| 50 | 712.2 |
| 60 | 11,4569 |
| 65 | 67,323 |
| 70 | 88,894 |
| 75 | 214,251 |
| 80 | 5.00E+06 |
| 90 | 807,240 |
| 95 | 199,943 |
| 100 | 827.68 |
| 105 | 816.76 |
| 110 | 875.43 |
| 120 | 884.24 |
| 130 | 814.04 |
| 140 | 1,173.9 |
| 160 | 484.2 |
| 180 | 1740.2 |
| 200 | 477.61 |
| - | |

*Makeni 2*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 5,511 | 1.58 | 1.58 |
| rho 2 | 428 | 9.09 | 10.7 |
| rho 3 | 1,045 | 76.2 | 86.8 |
| rho 4 | 1.7E+5 | - | - |

| AB/2 (m) | Resistivity, (Ω · m) |
|---|---|
| 4 | 1,923.21 |
| 5 | 1,225.34 |
| 7 | 675.281 |
| 10 | 570.977 |
| 15 | 503.869 |
| 20 | 457.11 |
| 25 | 790.125 |
| 30 | 837.037 |
| 35 | 911.834 |
| 40 | 729.467 |
| 45 | 716.116 |
| 50 | 1,014.43 |
| 60 | 1,248.58 |
| 70 | 1,913.06 |
| 80 | 833.266 |
| 90 | 773.143 |
| 100 | 2,017.59 |
| 110 | 556.082 |
| 115 | 720.213 |
| 120 | 1,621.22 |
| 130 | 1,346.62 |
| 140 | 1,327.13 |
| 160 | 1,236.81 |
| 170 | 1,618.3 |
| 180 | 1,409.16 |
| 185 | 1,748.97 |
| 190 | 2,185.59 |
| 200 | 2,611.77 |

**Table 20. Resistivity readings, VES points Makeni 3 and Makeni 4**

*Makeni 3*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 3.1E+5 | 0.574 | 0.574 |
| rho 2 | 1,517 | 9.27 | 9.85 |
| rho 3 | 149 | 5.91 | 15.8 |
| rho 4 | 1.8E+5 | - | - |

| AB/2, (m) | Resistivity, (Ω · m) |
|---|---|
| 4 | 2,006.607 |
| 5 | 989.0289 |
| 7 | 2,101.334 |
| 10 | 1,107.41 |
| 15 | 1,037.172 |
| 20 | 2,479.799 |
| 25 | 563.9387 |
| 30 | 418.9582 |
| 35 | 763.506 |
| 40 | 435.8281 |
| 45 | 157.5986 |
| 50 | 263.5098 |
| 55 | 131.9347 |
| 60 | 89.64352 |
| 65 | 563.9764 |
| 70 | 650.4717 |
| 75 | 618.7792 |
| 80 | 631.0258 |
| 85 | 1,596.031 |
| 90 | 1,378.451 |
| 95 | 795.0959 |
| 100 | 1,696.431 |
| 110 | 922.2248 |
| 120 | 6,973.195 |
| 130 | 6,067.926 |
| 140 | 10,959.35 |
| 150 | 7,396.191 |
| 160 | 8,801.075 |
| 170 | 84,432.15 |
| 180 | 95,083.55 |
| 190 | 94,020.84 |
| 200 | 130,323.8 |

*Makeni 4*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 4,640 | 1.85 | 1.85 |
| rho 2 | 148 | 1.64 | 3.49 |
| rho 3 | 966 | 87.7 | 91.1 |
| rho 4 | 1.6E+5 | - | - |

| AB/2 (m) | Resistivity, (Ω · m) |
|---|---|
| 4 | 1,784.5 |
| 5 | 1,704.7 |
| 7 | 582.21 |
| 10 | 570.98 |
| 15 | 754.15 |
| 20 | 461.58 |
| 25 | 752.42 |
| 30 | 828.24 |
| 35 | 836.43 |
| 40 | 1,030.8 |
| 45 | 677.22 |
| 50 | 1,009.6 |
| 60 | 1,202.9 |
| 70 | 1,906.8 |
| 80 | 832.45 |
| 90 | 774.5 |
| 100 | 1,931.5 |
| 110 | 617.72 |
| 115 | 728.98 |
| 120 | 1534 |
| 130 | 1,442.8 |
| 140 | 1,207.9 |
| 160 | 1,351.4 |
| 170 | 1,589.6 |
| 180 | 1,253.4 |
| 185 | 2,652.7 |
| 190 | 2,008.6 |
| 200 | 2,264.2 |
| - | - |
| - | - |
| - | - |
| - | - |

*Interpretation*

The key results from the geoelectrical survey in the eastern part of Western District is summarized as follows:

- Makeni 1: Detected the basement at a depth of 10 m.
- Makeni 2: Detected the basement at a depth of 87 m.
- Makeni 3: Detected the basement at a depth of 16 m.
- Makeni 4: Detected the basement at a depth of more than 91 m.

Despite a lack of hydrogeologic log in the vicinity with which to calibrate these three geoelectrical resistivity soundings, it can be inferred that the basement rocks in the southeastern part of Makeni area are located at a range of 10 – 91 m deep or slightly greater. Finally, the contact boundary between the basement complex and formation layer above it cannot be determined without further data.

Taking into account the analysis above and the need for additional data in Makeni, the end of this chapter prescribes a set of recommendations on further investigations for Makeni.

## Kabala (Koinadugu District)

A more detailed analysis of the Kabala area has been conducted, based on existing hydrogeological information and new surface geoelectrical soundings. The following hydrogeologic aspects are analyzed for Kabala, provided in the following sections: (1) basic hydrogeologic parameters drawn from mainly available datasets from official monitoring stations and a field reconnaissance, and (2) three geoelectrical resistivity soundings performed in April 2017 for this study. Recommendations for further investigation in Kabala are found at the end of this chapter.

### Basic Hydrogeologic Parameters of the Kabala Area

Kabala area is located some 100 km north east from Makeni in the Rokel river basin at an elevation of 450 m (asl). Rocks are mainly granitic with thin lateritic cover. Drilling reports from Wingin Contractor give an average thickness of the weathered surface layer between 5 and 30 m. Productive boreholes were 50% of the total. An unconfined aquifer is present, with water table at 4 - 5 m below surface.

The monitoring well from MOWR was drilled into the weathered basement (Kabala, Koinadugu DC - WSD Well, SN24) at the crossing of two long lineaments (perhaps fractures) detected from satellite images. This station too suggests the rapid transit of water from the ground surface to the sub-surface. The approximated recharge, considering a specific yield value of 0.05, is 6.6 cm. No other data are available on the extension of the basin supplying the well. The urban area has been investigated with 3 electrical soundings with AB up to 400 m.

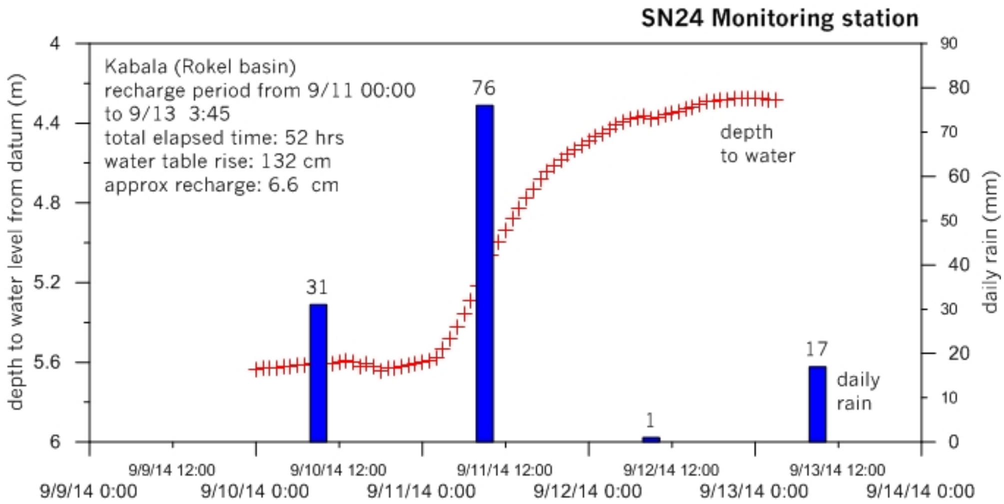



**Figure 62**. Extrapolated data from SN24 station (Kabala).

## Geophysical Investigation Results in the Kabala Area

### *Location*

A surface geoelectrical resistivity survey were carried out in Kabala area, performed with VES method in April 2017 on four sites: Kabala 1, Kabala 2 and Kabala 3. The focus of the survey was on the north-central part of Kabala town (see figure below for location). No information on hydrogeologic logs were available from existing boreholes in the area.

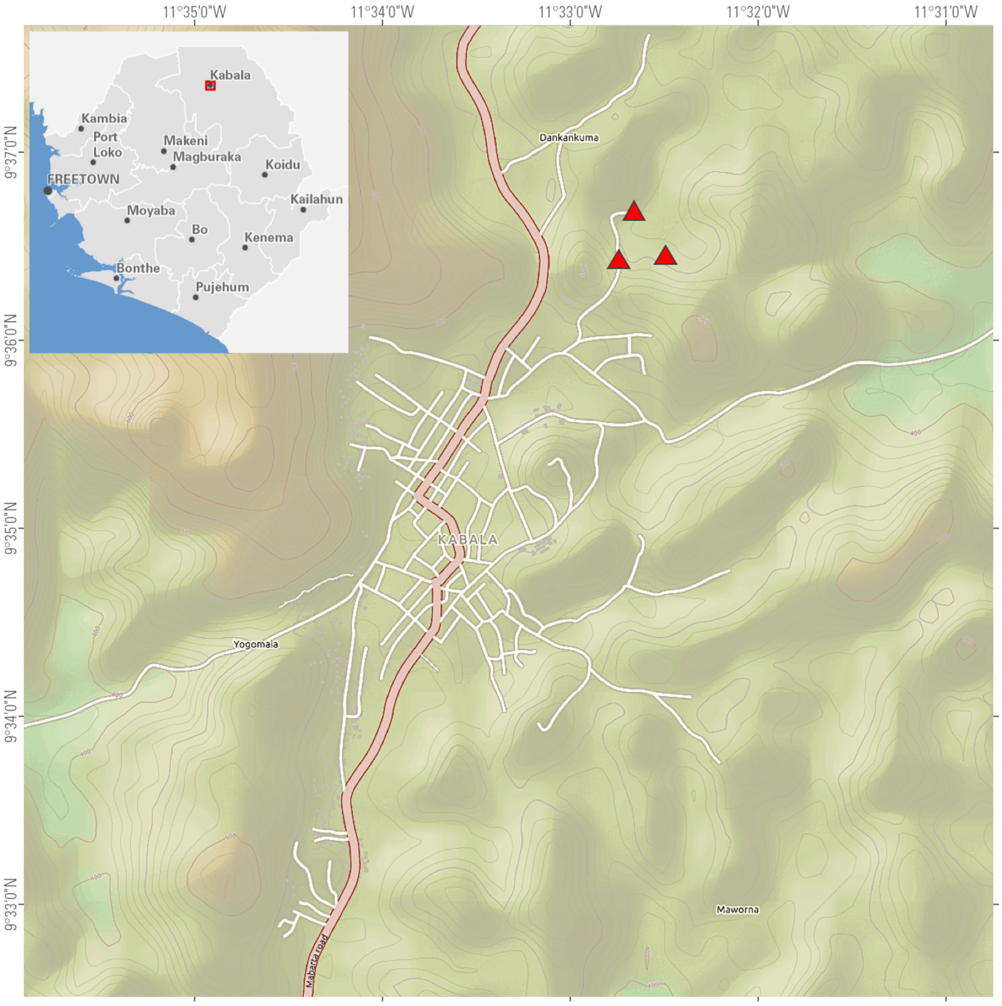



**Figure 63**. Location of the surface geophysical survey (VES) completed for the Kabala area.

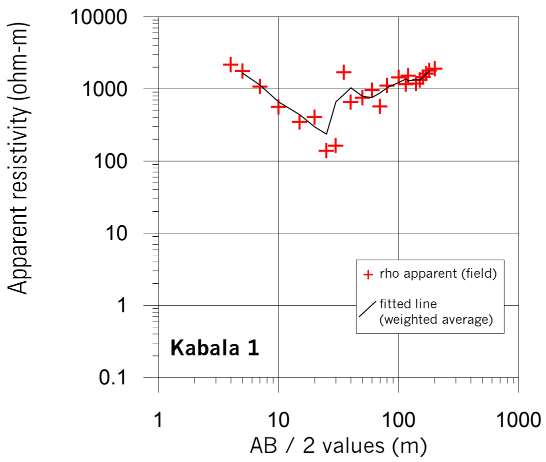
Explanation: Location (GPS, degrees):

| VES point | X | Y | Elev. |
|---|---|---|---|
| Kabala 1 | -11.54285 | 9.60402 | 454 |
| Kabala 2 | -11.54082 | 9.60118 | 449 |
| Kabala 3 | -11.54391 | 9.60102 | 434 |

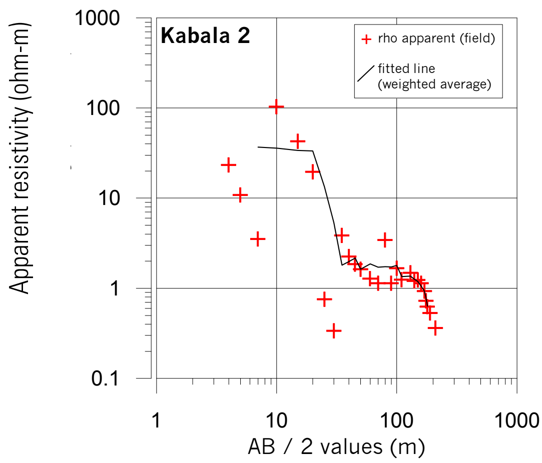
*Data*

A summary of the resistivity data acquired for Kabala 1, 2 and 3 are given below, with apparent resistivity (ohm-m) curves in Figure 64 and AB/2 (m) readings found in Table 21 and 22.

*Kabala 1*




*Kabala 2*




*Kabala 3*

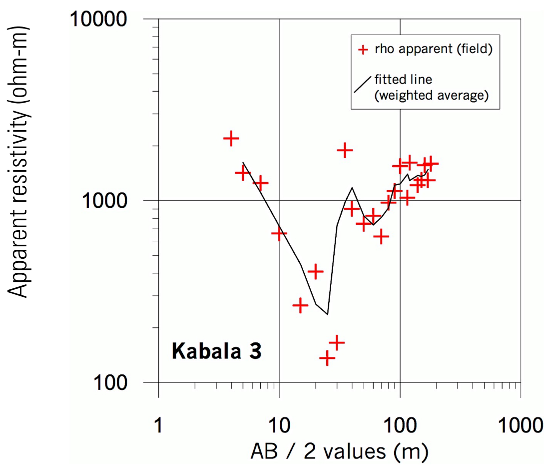



**Figure 64**. Acquired resistivity curves for Kabala 1, Kabala 2 and Kabala 3 with corresponding layered models of rho apparent and fitted line weighted average.

**Table 21. Resistivity readings, VES points Kabala 1 and Kabala 2**

*Kabala 1*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 3,363 | 2.19 | 2.19 |
| rho 2 | 845 | 2.9 | 5.09 |
| rho 3 | 101 | 5.79 | 10.9 |
| rho 4 | 1.9E+5 | - | - |

| AB/2, (m) | Resistivity, (Ω · m) |
|---|---|
| 4 | 2,164.089 |
| 5 | 1,755.233 |
| 7 | 1,076.165 |
| 10 | 562.572 |
| 15 | 347.568 |
| 20 | 402.988 |
| 25 | 138.585 |
| 30 | 163.704 |
| 35 | 1,690.157 |
| 40 | 655.115 |
| 50 | 751.949 |
| 60 | 961.025 |
| 70 | 569.926 |
| 80 | 1,103.65 |
| 100 | 1,438.115 |
| 110 | |
| 115 | 1,157.113 |
| 120 | 1,521.498 |
| 140 | 1,183.875 |
| 150 | 1,322.72 |
| 160 | 1,455.15 |
| 170 | 1,631.776 |
| 180 | 1,788.113 |
| 200 | 1,897.665 |

*Kabala 2*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 2,736 | 3.28 | 3.28 |
| rho 2 | 56.2 | 3.34 | 7.22 |
| rho 3 | 72.8 | 15.1 | 22.3 |
| rho 4 | 92,337 | 21.3 | 43.6 |

| AB/2 (m) | Resistance |
|---|---|
| 4 | 23.292 |
| 5 | 10.809 |
| 7 | 3.5081 |
| 10 | 103.42 |
| 15 | 42.55 |
| 20 | 19.539 |
| 25 | 0.75331 |
| 30 | 0.33755 |
| 35 | 3.8472 |
| 40 | 2.2391 |
| 45 | 1.8539 |
| 50 | 1.6176 |
| 60 | 1.2742 |
| 70 | 1.1378 |
| 80 | 3.4373 |
| 90 | 1.1326 |
| 100 | 1.6688 |
| 110 | 1.2418 |
| 130 | 1.4812 |
| 140 | 1.2034 |
| 150 | 1.2331 |
| 160 | 1.1361 |
| 170 | 0.926 |
| 180 | 0.72637 |
| 180 | 0.62418 |
| 190 | 0.53 |
| 200 | |
| 210 | 0.36193 |

**Table 22. Resistivity readings, VES point Kabala 3**

*Kabala 3*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 3,240 | 0.753 | 0.753 |
| rho 2 | 49.6 | 2.5 | 3.25 |
| rho 3 | 1.14 | - | - |

| AB/2, (m) | Resistivity, (Ω · m) |
|---|---|
| 4 | 2,196.3636 |
| 5 | 1,422.2404 |
| 7 | 1,247.106 |
| 10 | 661.56351 |
| 15 | 264.94931 |
| 20 | 407.49926 |
| 25 | 136.31881 |
| 30 | 165.3179 |
| 35 | 1,890.0638 |
| 40 | 900.10005 |
| 50 | 747.16532 |
| 60 | 826.31458 |
| 70 | 634.11341 |
| 80 | 973.67375 |
| 90 | 1,129.4316 |
| 100 | 1,547.9094 |
| 110 | - |
| 115 | 1,038.9271 |
| 120 | 1,619.8775 |
| 140 | 1,215.2301 |
| 150 | 1,297.8639 |
| 160 | 1,567.3739 |
| 170 | 1,291.5505 |
| 180 | 1,596.8286 |
| 200 | - |

*Interpretation*

The key results from the geoelectrical survey in the north-central part of Kabala is summarized as follows:

- Kabala 1: Detected the basement at a depth of 10 m.
- Kabala 2: Possible detection of the basement at a depth of 21 m, noting significant fitting error.
- Kabala 3: Inconclusive reading.

Despite a lack of hydrogeologic log in the vicinity with which to calibrate these three geoelectrical resistivity soundings, it can be inferred that the basement rocks in the north-central part of Kabala area are located at approximately 10 m deep, with some indication of deeper basement levels nearby. Without further data, the contact boundary between the basement complex in the region and formation layer above it cannot be determined.

The geoelectrical resistivity survey in Kabala provides a first layer of information. Achieving a better, more robust analysis of groundwater potential in Kabala will require additional data and information. With that objective in mind, the end of this chapter prescribes a set of recommendations on further investigations for Kabala which can assist in siting and designing wells in the area.

## Musaia (Koinadugu District)

A more detailed analysis of the Musaia area has been conducted, based on very limited hydrogeological information and new surface geoelectrical soundings. On this very limited basis, the following hydrogeologic aspects are analyzed for Musaia, provided in the following sections: (1) basic hydrogeologic parameters drawn from a general overview of national scale data and field reconnaissance, and (2) three geoelectrical resistivity soundings performed in April 2017 for this study. Recommendations for further investigation in Musaia are found at the end of this chapter.

### Basic Hydrogeologic Parameters of the Musaia Area

No hydrogeologic logs or monitoring stations are available for this site, inhibiting robust analysis of hydrogeological parameters around Musaia. Nonetheless, a few comments can be made about the Musaia area.

Located some 20 km north from Kabala in the Little Scarcies river basin, Musaia sits at an elevation of 350 m (asl) and situated along the left bank of the Mango River. Rock formations are mainly granitic with thin lateritic cover. From the lineament analysis, the river course is clearly fracture controlled and around the urban area some abandoned meanders host an unconfined aquifer with water level at 4 -5 m below ground. The urban area has been investigated with 3 electrical soundings with AB up to 400 m.

## Geophysical Investigation Results in the Musaia Area

### *Location*

A surface geoelectrical resistivity survey were carried out in Musaia area, performed with VES method in April 2017 on four sites: Musaia 1, Musaia 2 and Musaia 3. The focus of the survey was on the central part of Musaia town (see Figure 65 below for location). No information on hydrogeologic logs were available from existing boreholes in the area.

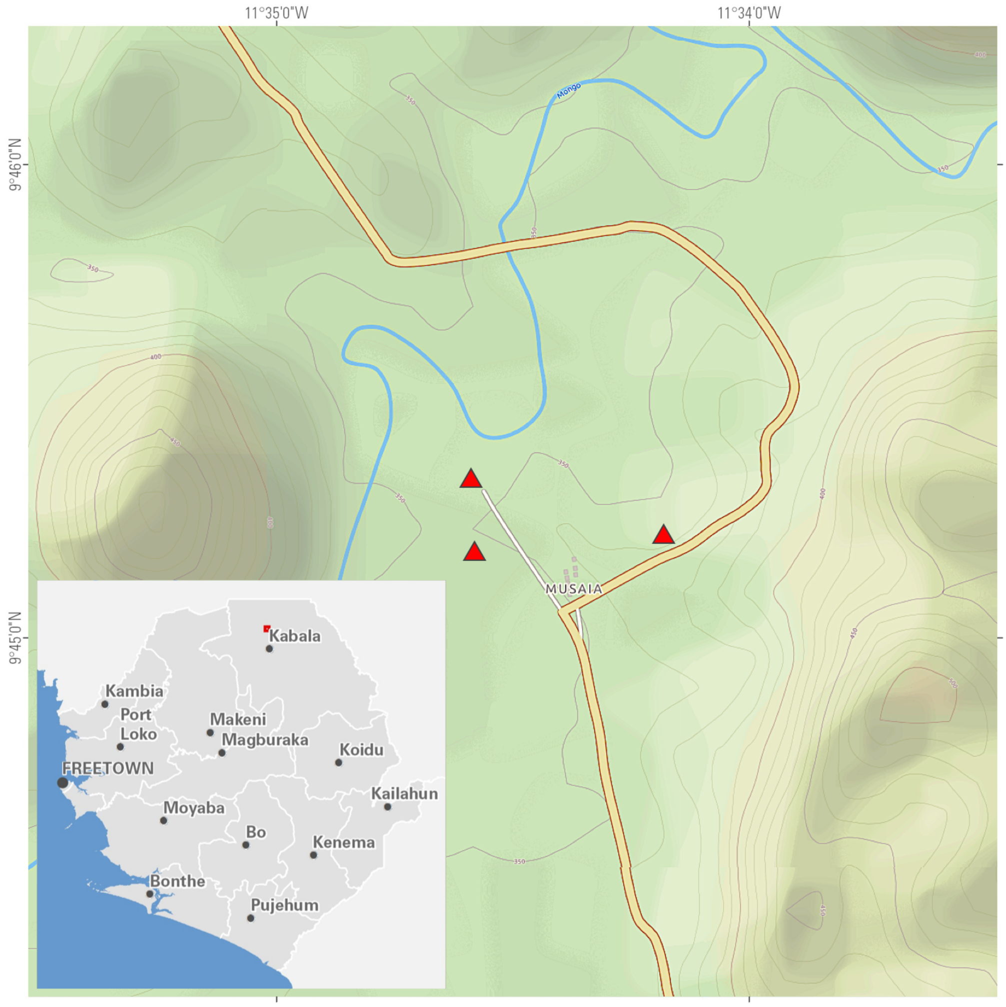



**Figure 65**. Location of the surface geophysical survey (VES) completed for the Musaia area.

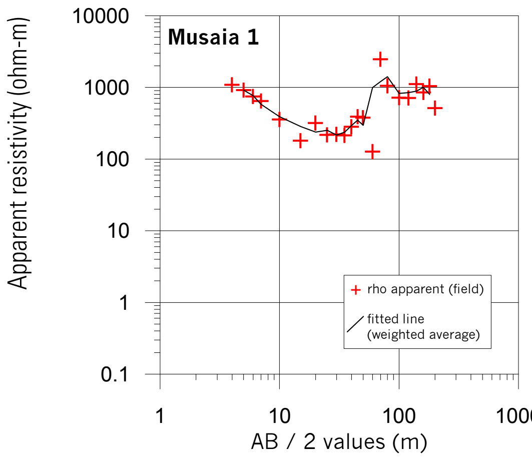
Explanation: Location (GPS, degrees):

| VES point | X | Y | Elev. |
|---|---|---|---|
| Musaia 1 | -11.57418 | 9.76061 | 348 |
| Musaia 2 | -11.57415 | 9.76256 | 355 |
| Musaia 3 | -11.56911 | 9.76095 | 371 |

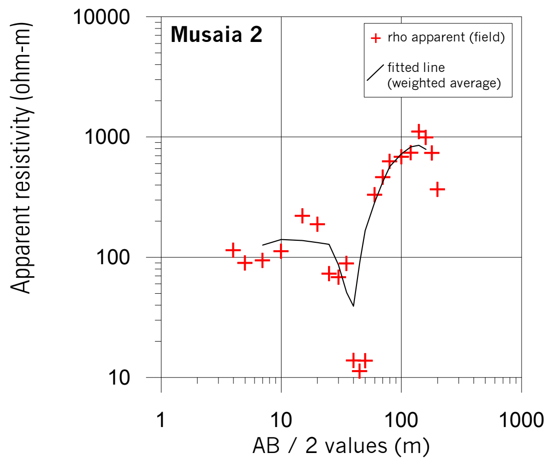
### *Data*

A summary of the resistivity data acquired for Musaia 1, 2 and 3 are given below, with apparent resistivity (ohm-m) curves in Figure 66 and AB/2 (m) readings found in Table 23 and 24.

### *Musaia 1*




### *Musaia 2*




### *Musaia 3*

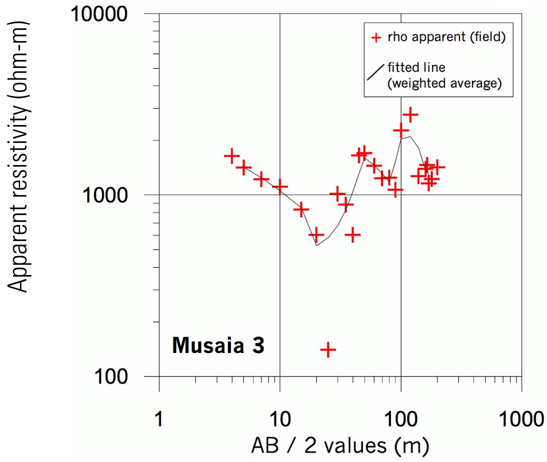



**Figure 66**. Acquired resistivity curves for Musaia 1, Musaia 2 and Musaia 3 with corresponding layered models of rho apparent and fitted line weighted average.

**Table 23. Resistivity readings, VES points Musaia 1 and Musaia 2**

*Musaia 1*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 1,522 | 2.89 | 2.89 |
| rho 2 | 154 | 16.3 | 19.2 |
| rho 3 | 9,918 | 12.7 | 31.9 |
| rho 4 | 12.1 | - | - |

| AB/2, (m) | Resistivity, (Ω · m) |
|---|---|
| 4 | 1,087.172 |
| 5 | 911.342 |
| 6 | 747.849 |
| 7 | 641.609 |
| 10 | 355.04 |
| 15 | 180.023 |
| 20 | 316.502 |
| 25 | 216.555 |
| 30 | 221.081 |
| 35 | 213.456 |
| 40 | 282.388 |
| 45 | 388.163 |
| 50 | 375.739 |
| 60 | 126.466 |
| 70 | 2,469.914 |
| 80 | 1,046.965 |
| 100 | 715.647 |
| 120 | 712.397 |
| 140 | 1,110.293 |
| 160 | 848.355 |
| 180 | 1,042.299 |
| 200 | 511.864 |

*Musaia 2*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 74.4 | 2.66 | 2.66 |
| rho 2 | 366 | 2.59 | 5.25 |
| rho 3 | 222 | 1.8 | 7.05 |
| rho 4 | 22.8 | 7.57 | 14.6 |
| rho 5 | 4.3E+5 | 32.8 | 47.4 |
| rho 6 | 14.6 | - | - |

| AB/2 (m) | Resistivity, (Ω · m) |
|---|---|
| 4 | 114.487 |
| 5 | 89.771 |
| 7 | 93.987 |
| 10 | 111.929 |
| 15 | 221.39 |
| 20 | 188.043 |
| 25 | 73.099 |
| 30 | 68.207 |
| 35 | 88.826 |
| 40 | 13.87 |
| 45 | 11.276 |
| 50 | 13.754 |
| 60 | 330.11 |
| 70 | 463.579 |
| 80 | 627.855 |
| 100 | 684.634 |
| 120 | 739.454 |
| 140 | 1109.98 |
| 160 | 987.158 |
| 180 | 736.088 |
| 200 | 365.956 |
| - | - |

**Table 24. Resistivity readings, VES point Musaia 3**

*Musaia 3*

| rho (Ω · m) | | h (m) | Z (m) |
|---|---|---|---|
| rho 1 | 1,669 | 5.68 | 5.68 |
| rho 2 | 111 | 4.17 | 9.85 |
| rho 3 | 33,695 | 8.54 | 18.4 |
| rho 4 | 33.3 | - | - |

| AB/2, (m) | Resistivity, (Ω · m) |
|---|---|
| 4 | 1,641 |
| 5 | 1,414 |
| 7 | 1,219 |
| 10 | 1,110 |
| 15 | 832 |
| 20 | 601.8 |
| 25 | 140.2 |
| 30 | 1013 |
| 35 | 884.3 |
| 40 | 602 |
| 45 | 1,651 |
| 50 | 1,701 |
| 60 | 1,447 |
| 70 | 1,236 |
| 80 | 1,244 |
| 90 | 1,068 |
| 100 | 2,267 |
| 120 | 2,769 |
| 140 | 1,270 |
| 160 | 1,393 |
| 165 | 1,462 |
| 170 | 1,157 |
| 180 | 1,225 |
| 200 | 1,421 |

*Interpretation*

The key results from the geoelectrical survey in the central part of Musaia is summarized as follows:

- Musaia 1: Detected the basement at a depth of 32 m.
- Musaia 2: Detected the basement at a depth of 47 m.
- Musaia 3: Detected the basement at a depth of 18 m.

Despite a lack of hydrogeologic logs in the vicinity with which to calibrate these three geoelectrical resistivity soundings, it can be inferred that the basement rocks in the central part of Musaia area are located between 18 and 47 m deep, with a possible westward dip from Musaia 3 to Musaia 1 and 2. Without further data, a broader understanding of hydrogeology is limited, and the contact boundary between the basement complex in the region and formation layer above it cannot be determined.

The geoelectrical resistivity survey in Musaia provides a first layer of information. Achieving a better, more robust analysis of groundwater potential in Musaia will require additional data and information. With that objective in mind, the end of this chapter prescribes a set of recommendations on further investigations for Musaia which can assist in siting and designing wells in the area.

## Nimini (Kono District): Application of Airborne Electromagnetic Technology for Groundwater Exploration

A pilot application of airborne electromagnetic (AEM) technology for detailed groundwater exploration in Kono was undertaken to showcase the technique for possible consideration for application in other parts of Sierra Leone. This following is a brief summary of the results of the pilot. AEM data of the type VTEM (Versatile Time Domain Electro-Magnetics) were acquired in 2010 by the Nimini Mining Limited. The survey was initially planned for mineral exploration. The aim was to re-process the data and generate models to derive new insights.

Robust resistivity models were generated for the hydrogeological study of the area. Furthermore, the results showed features that might be of interest for possible future exploration activities. Specifically, the results presented contain: 1) improved conductivity sections/maps/models, 2) conceptual hydro-geological model on selected sections, 3) input to further modelling/mapping.

### Location

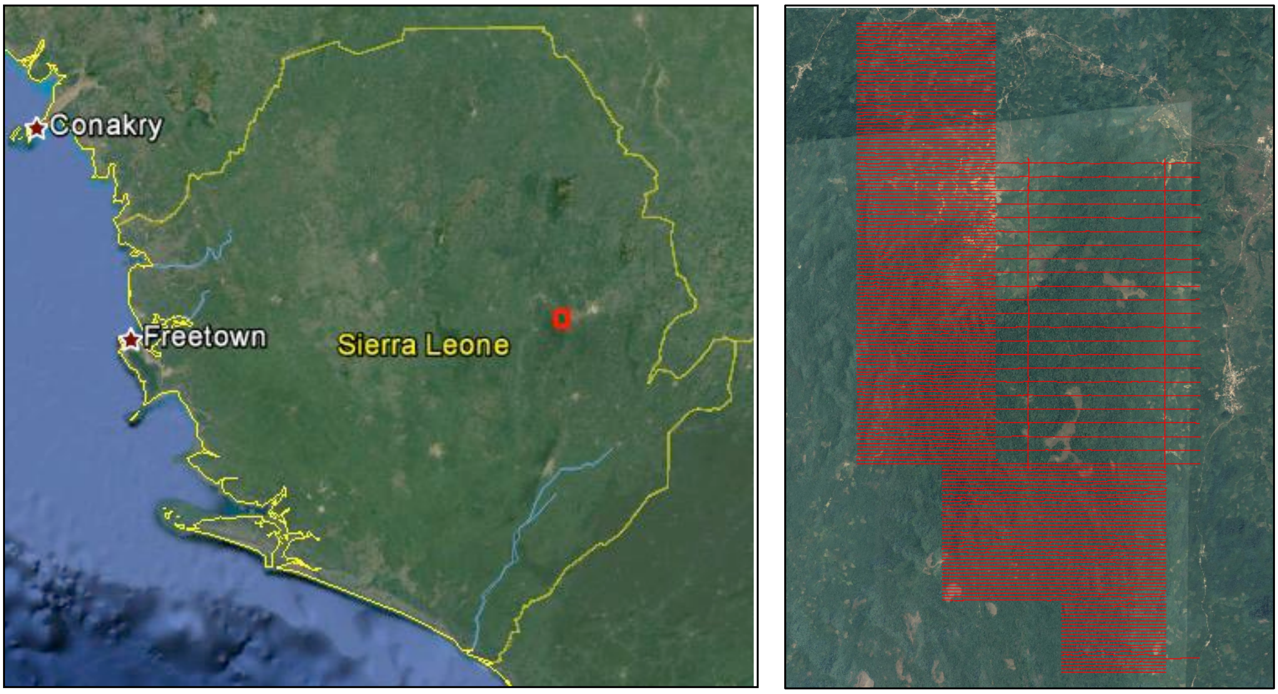



**Figure 67**. Location map and flight pattern of the VTEM

## Method

The AEM method (Figure 68) is based on the response of subsurface structures excited by the eddy currents caused by a primary magnetic field produced by a transmitting (Tx) loop. This response is recorded as a voltage decay curve (the transient) of the secondary magnetic field, by means of a receiving (Rx) coil. Both Tx and Rx are carried by a helicopter or by a fixed-wing aircraft. The inversion of the transients allows to extract a 1D model of resistivity, down to 300-600 m depth. By means of inversion of the data, one can reconstruct a detailed 3D resistivity distribution of the survey area, which, in turn, can be further interpreted and provide the basis for hydrogeological modelling.

The advantages of the AEM method are:

- To cover **large areas** (at basin scale) in short time (about 300 linear km per day)
- To provide **great data density** (about 100 models per $Km^2$)
- To provide **quantitative** results
- Good platform to **integrate** other data (hydrogeology, ground geophysics, etc.)
- **Deterministic** subsurface parameters derived
- Great value for groundwater management

For these reasons AEM has been widely applied to hydrogeological mapping and Groundwater management around the world. Australia, Denmark, US remain some of the countries that, to date, used it most heavily.

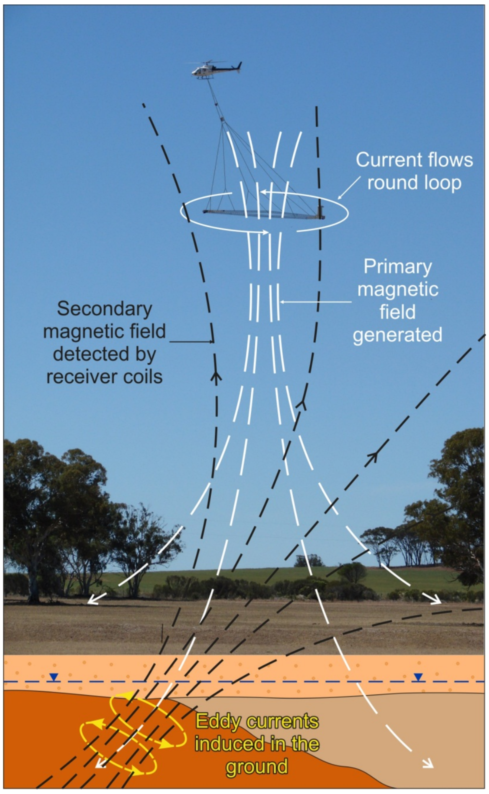



**Figure 68**. AEM data acquisition methodology

## Main pilot study results

The main purpose of the project was to provide information useful for hydrogeological studies. The focus is therefore centered on this application. Other features that could be potentially interesting for general geological mapping and exploration are highlighted. It must be stressed that the following comments are based on simple geological information made available; they must therefore be considered purely preliminary and illustrative.

## Resistivity modeling

The results are presented in a plan view as slices of resistivity at different elevation above sea level, and at different depths below ground in the following images.

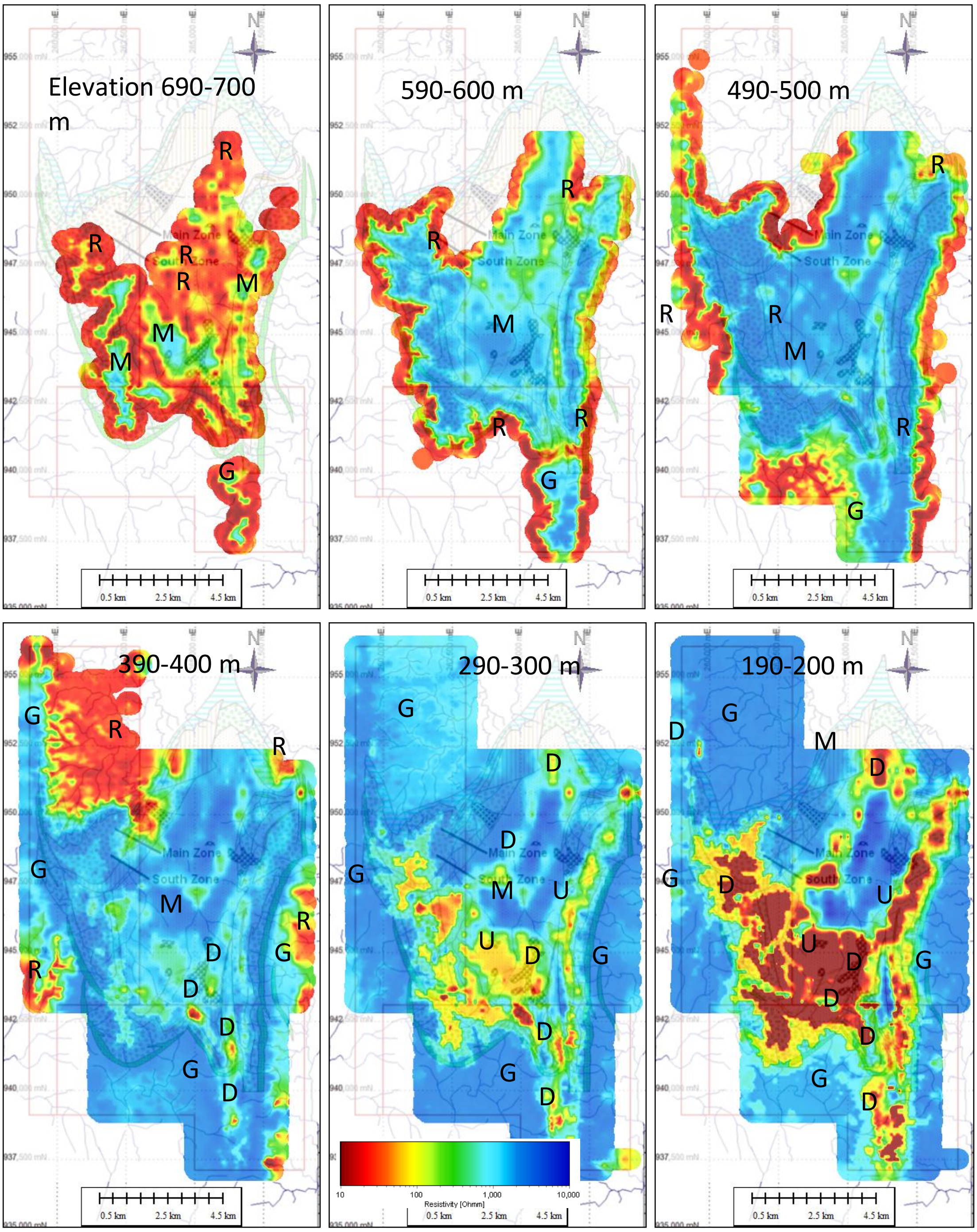



**Figure 69**. Resistivity elevation maps overlaying geology. R = regolith, M = Mafic Volcanics (amphibolite), U = Ultramafic Volcanics (serpentinized- chloritized), G = Granite-Gneiss, D = Dykes

The following main observations are made from the *elevation slices*:

- The conductive regolith at the borders spreads laterally as we go deeper, due to the topographic setting of the Nimini Hill.
- As mentioned above, there is no resistivity contrast between Granite-Gneiss basement and Mafic volcanics. On the contrary, the deep conductive formations below Mafics could be interpreted as Serpentinized Ultarmafics that would follow the surficial contacts between the greenstones belt and the granitic shield. It should be stressed that these slices are not masked considering the DOI, but the last elevation map (at 190-200 m asl) shows reliable occurrence of the conductive Ultramafics within the outline of the greenstones belt.
- The location of the dykes follows some N-S or NNE-SSW trends, in accordance with the local structural pattern and the main mineralization.

The resistivity *depth slices* (Figure 70) provide more information about the behavior of the regolith, which could represent the main local aquifer.

- At 0-10 m depth, the regolith shows nearly everywhere a clear conductive response, except for the NE corner. There are no borehole data to justify this evidence, but one possibility is that shallower regolith layers are coarser in NE.
- Going to depth we follow the remarkable thickening of regolith in the eastern flank, with the conductive zones reaching a depth of 70-80 m. This result is in accordance with the available sparse stratigraphic info.
- At 40-50 m, the conductive Ultramafics are already visible, and this pattern agrees with the syncline structure of the greenstones belt.

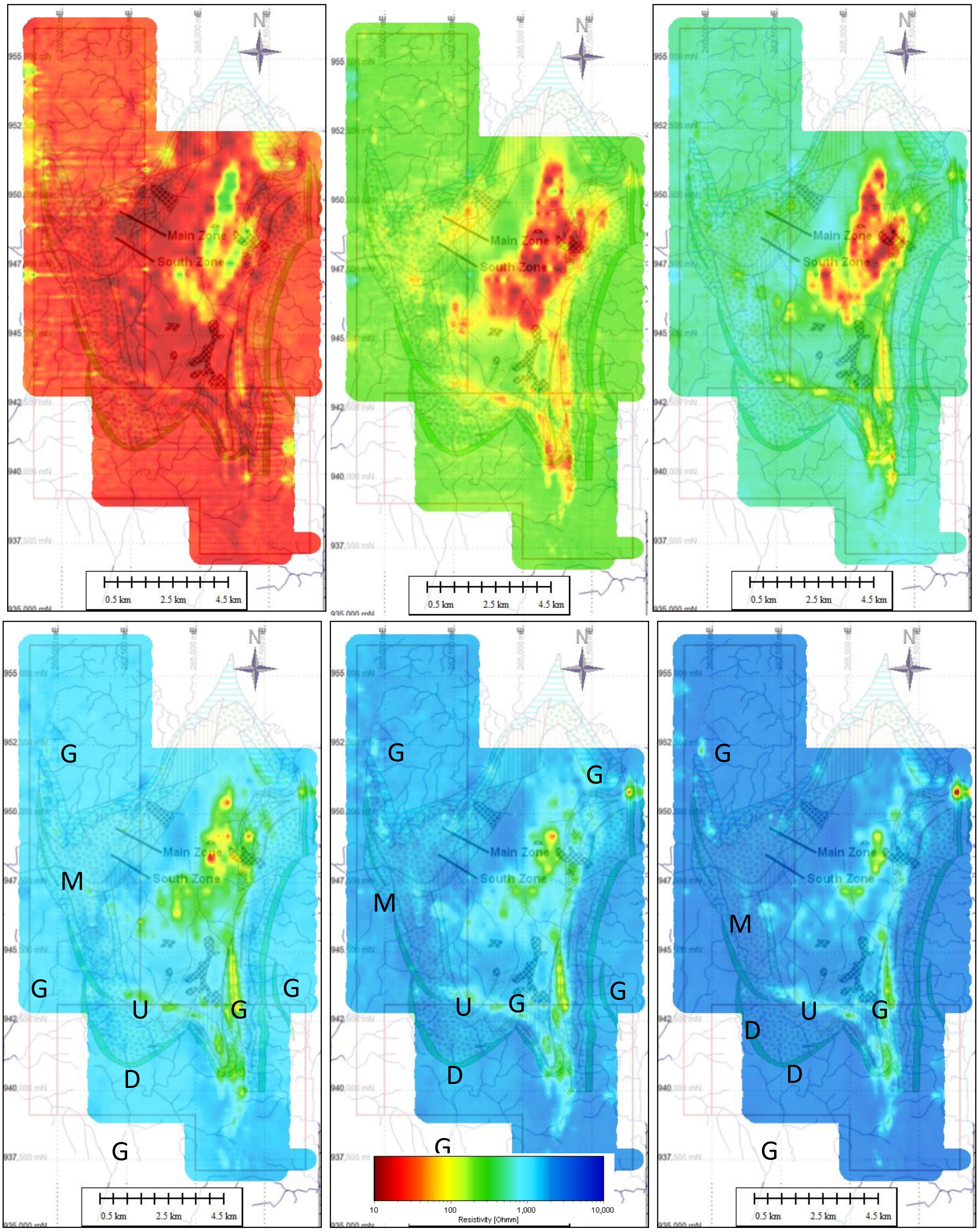



**Figure 70**. Resistivity depth maps overlaying geology. R = regolith, M = Mafic Volcanics (amphibolite), U = Ultramafic Volcanics (serpentinized- chloritized), G = Granite-Gneiss, D = Dykes.

The variability of the resistivity in the area can be fully appreciated producing and inspecting a 3D model (figure below).

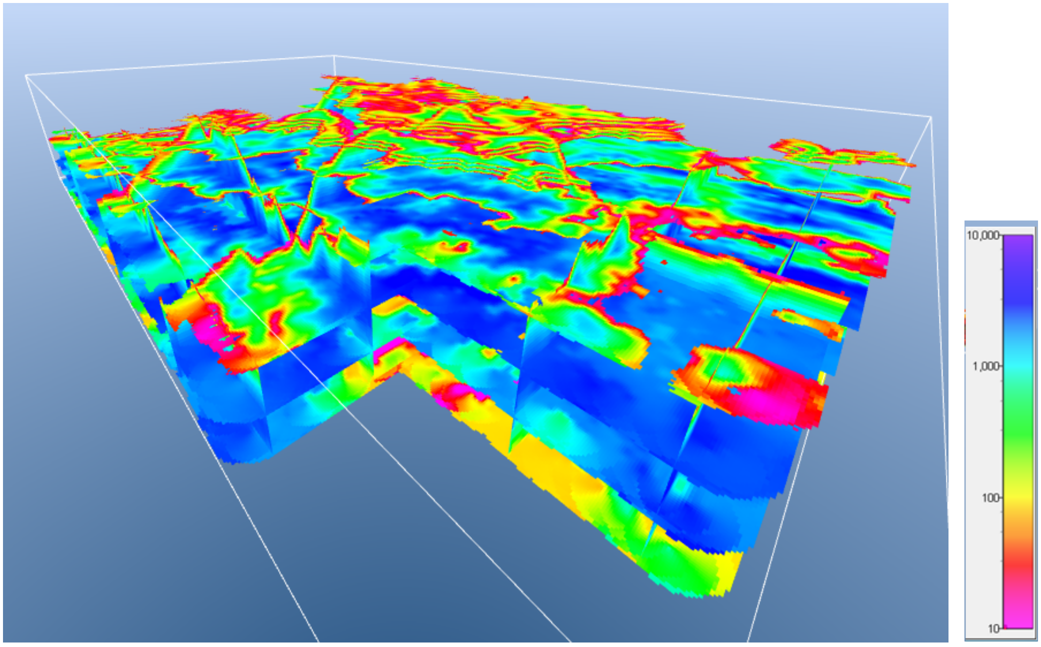



**Figure 71**. 3D view (from SW) of the spatial variability of subsurface resistivity (Ohm m) over the whole area

## Recharge

Focusing on the hydrogeological aspect, the most relevant outcome was the resolution of the regolith cover, thanks to its high conductivity and chargeability. Figure 72 also shows local spatial correlation between thicker conductive overburden, strongly chargeable on the flanks, and Laterite.

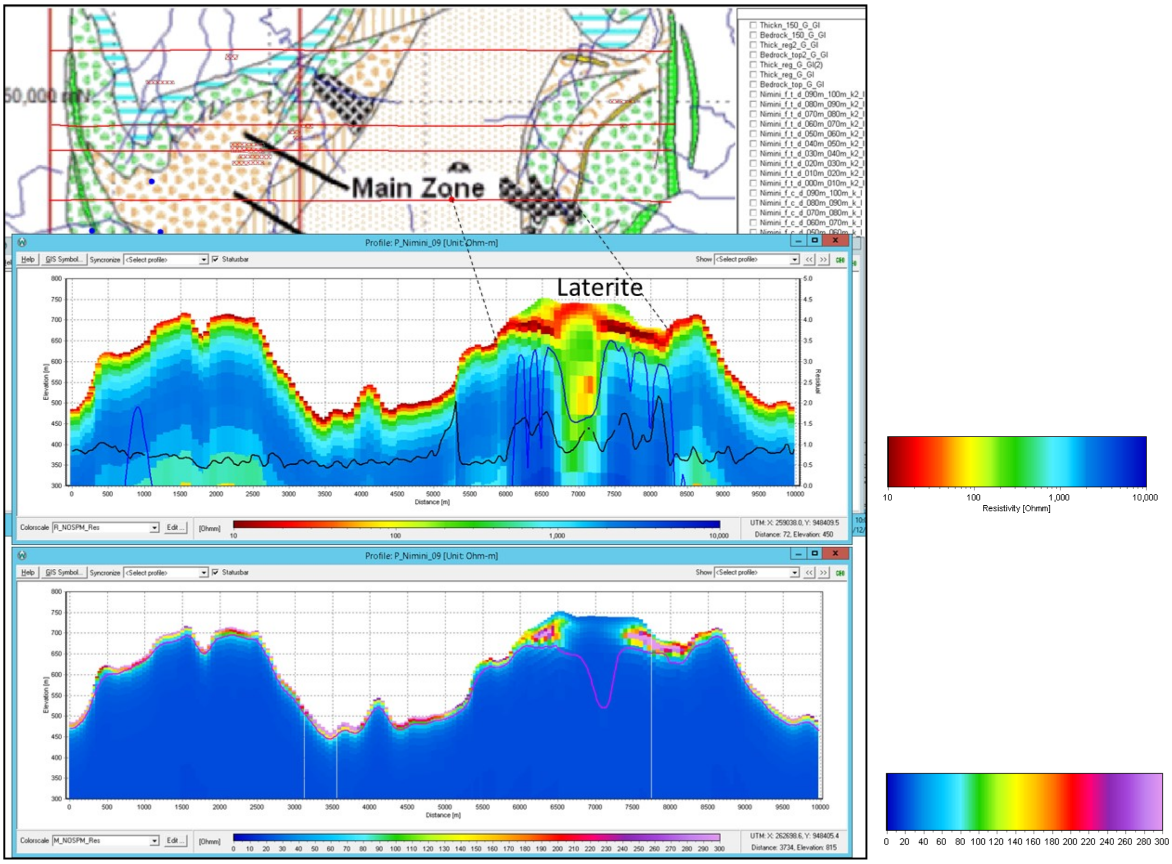



**Figure 72**. Geological map (top), vertical resistivity (middle), vertical chargeability section (bottom, mV/V). The blue line in the middle panel shows the DOI for resistivity. The magenta line in the bottom panel shows the DOI for chargeability

## Bedrock modeling

The elevation of the bedrock (i.e. the bottom of regolith) and the regolith thickness were obtained with automated picking of resistivity vertical gradients. Trial and error tests allowed selecting a fixed the value of 150 ohm-m as limit of the bedrock top. The bedrock elevation map (Figure 73) shows a tight geological control, with the maximum values mostly confined into the greenstones belt. There is also a direct topographic influence, due to the higher elevations in the hills.

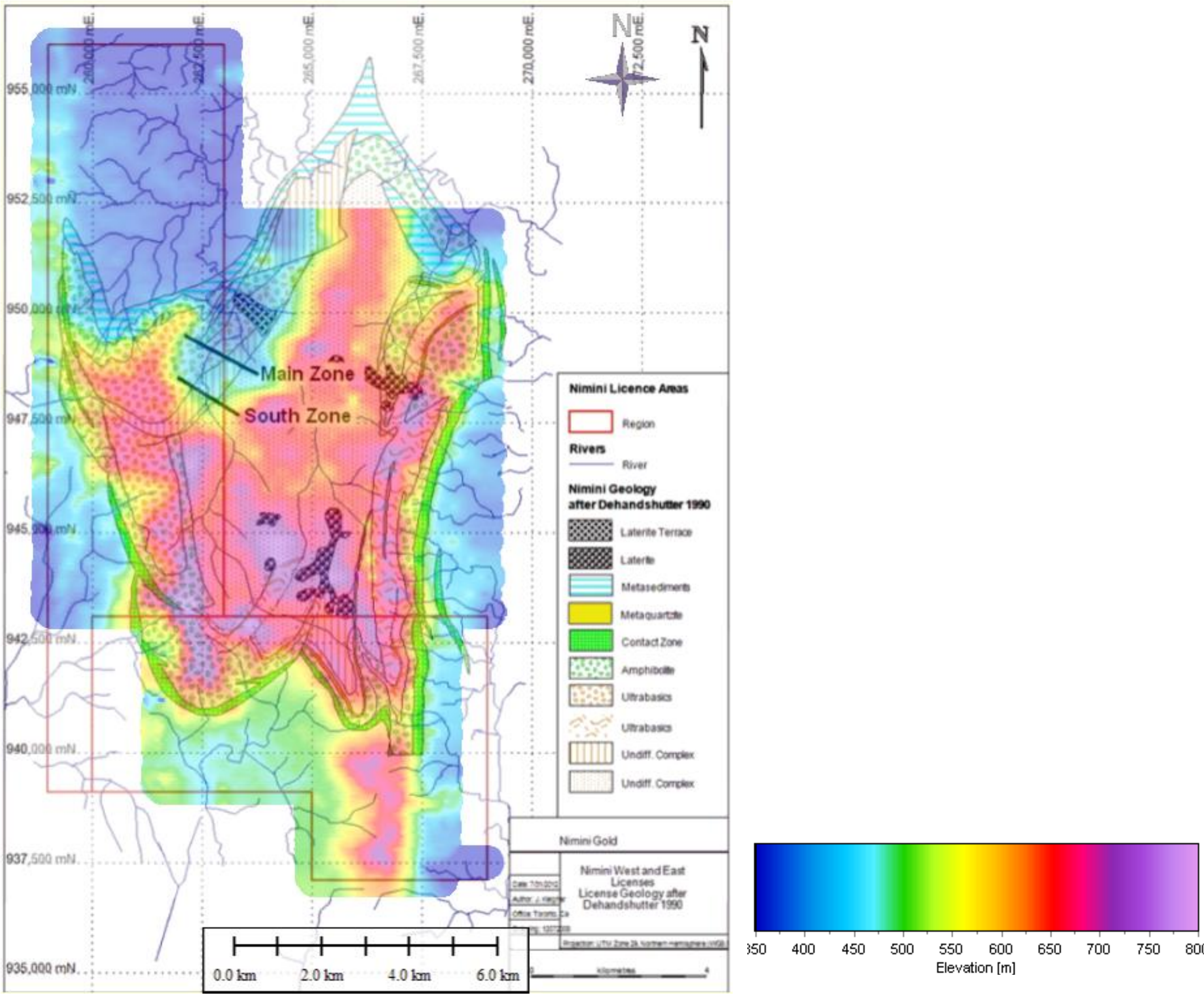



**Figure 73**. Bedrock elevation (m asl) model from AEM data processing

## Regolith modeling

From a hydrogeological point of view, another relevant piece of information is the thickness of the regolith potential aquifer, shown in the following picture. There is a wide thick zone along the eastern flank of the hill, exceeding 50 m, with some digitations Southward. The regolith is more abundant within the greenstone belt, rather than in the granitic-gneiss basement. This information, linked to the elevation of the bedrock and the resistivity of the overburden (Figure 74), can play a crucial role for further hydrogeological modelling. See Figure 75 for the 3D representation of the regolith.

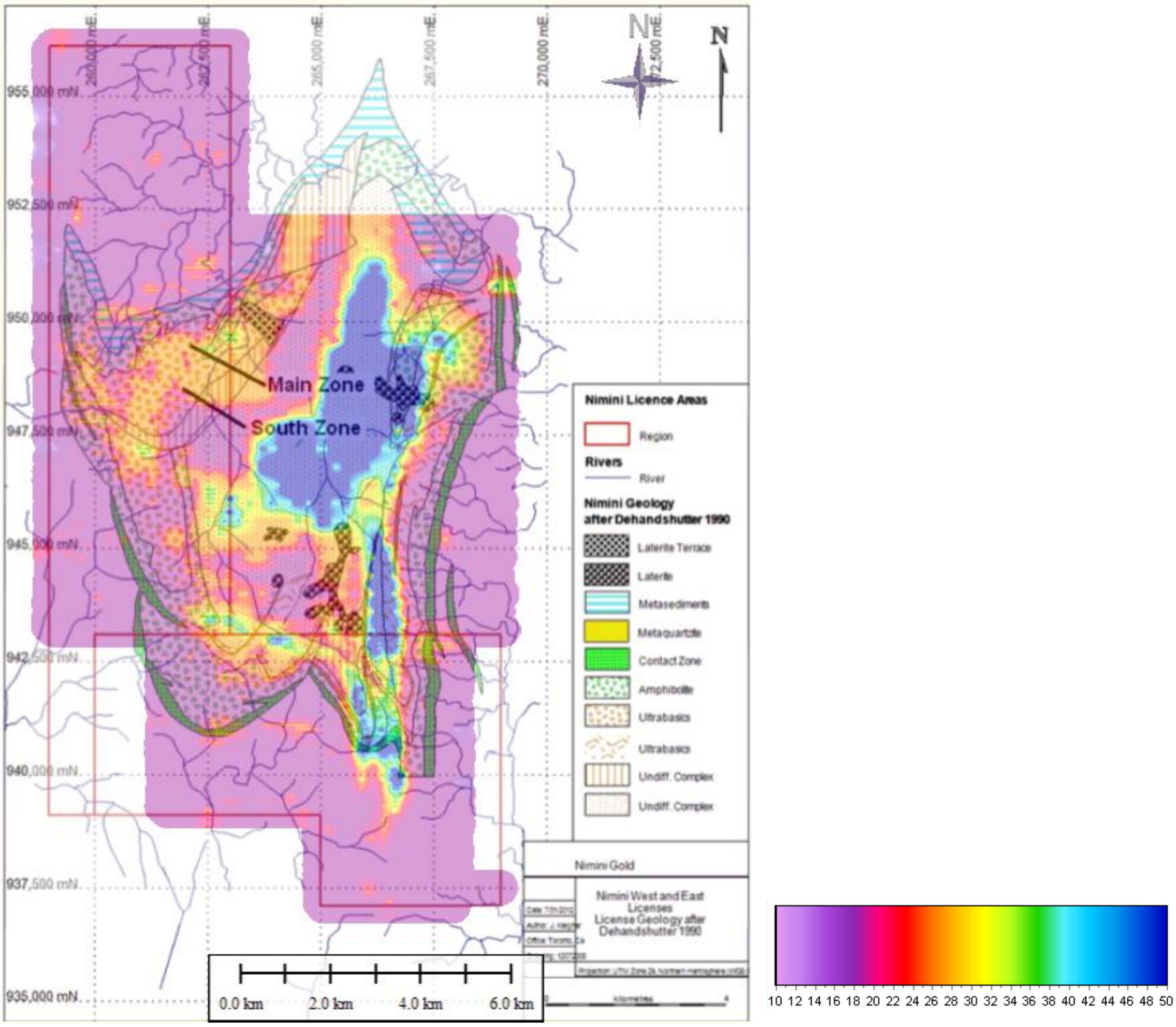



**Figure 74**. Regolith thickness (m) model from AEM data processing

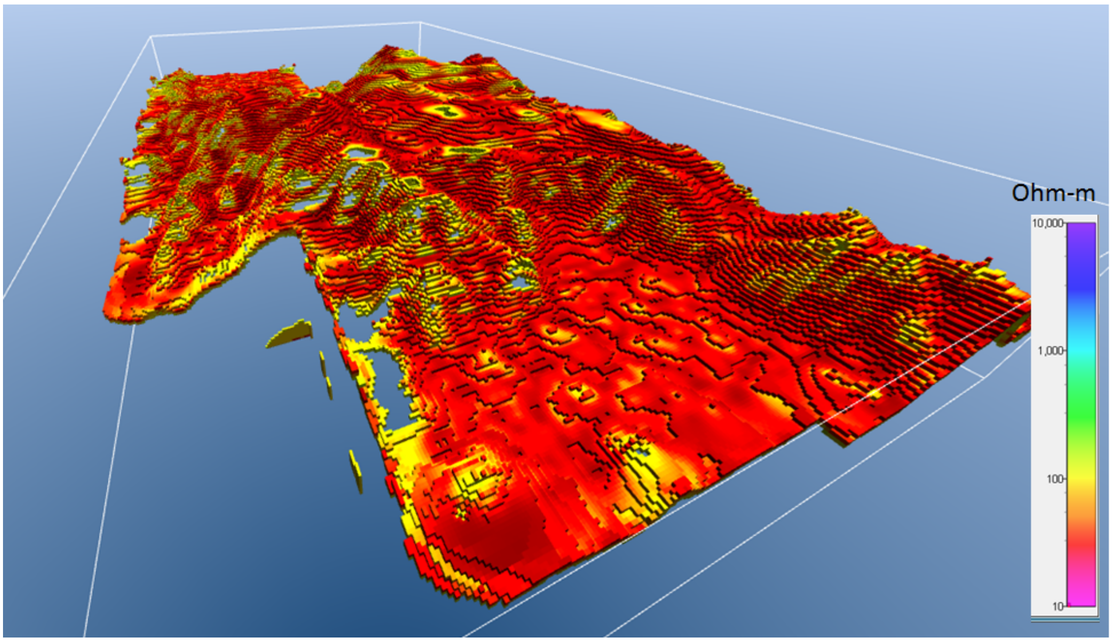



**Figure 75**. 3D conceptual model of the regolith from AEM data processing
Explanation: Resistivity variations based on processing of AEM, viewed from the southwest.

## Pilot study conclusions

The re-processing of existing VTEM data has provided useful info for the hydrogeological study carried out for the SALWACO project: maps of regolith thickness, geometry and its resistivity have been produced. Further analysis including stratigraphic data, chargeability response, groundwater quality could improve any further hydrogeological interpretation.

These results clearly demonstrate the potentiality of this geophysical methodology in providing quantitative high-value information for hydrogeological characterization and modelling. A complete three-dimensional reconstruction of the geometry of permeable units has been obtained, with a thickness accuracy on the order of 1 m. When large resistivity contrasts exist, as in the Nimini area, the airborne electromagnetic is capable to provide the subsurface architecture down to large depth, till to 300-400 m.

From a strategic point of view, it can be concluded that the Nimini pilot area can be characterized as having insufficient groundwater potential to warrant any major development in the future, other than additional localized investigation to support minor small scale supply projects.

From a hydrogeological point of view, we find that the geomorphological setting (a hill), the location (it not within the priority areas), and the areal extent does not justify further intense research. However, testing this methodology and processing the outcomes have been of paramount importance, not only because it allowed us to come to this scientific judgement of groundwater potential, but also because it demonstrates the application for future projects of aquifer characterization in Sierra Leone. The specific application has undoubtedly revealed that AEM delivers significant advantages in characterizing the hydrogeological system in challenging environments and in medium to large zones, up to the entire country scale as demonstrated by other examples available in the literature, for example Denmark. A proper integration of AEM survey with several (relatively few) in-situ investigations (borehole stratigraphy and pumping tests) will allow to develop a hydrogeological model usable to properly manage the groundwater resources in Sierra Leone.

## Recommended Further Investigation of the Selected Areas

The overall goal of this additional exercise has been to improve the understanding of hydrogeology in four areas of interest and provide guidance to the government authorities on what steps are needed to find new sources of high-quality water and achieve productive water supply wells in the most suitable locations. In this section, we present a sequence of specific investigative actions that we recommend following to assist in determining best sites and designing production boreholes in the four AOI's discussed above. The steps provided here take into account, and if implemented should preclude, a program to design and construct boreholes. Though this section has an exploratory focus, it is important to emphasize that these suggested investigations will generate new data that should contribute to the national database (SALGRID) and eventually help refine and update the Hydrogeologic Atlas and tools developed by this study.

### The investigative process

For future investigation of new water resources in Freetown, Makeni, Kabala and Musaia, we have designed an investigation programme with four essential phases. In general, this approach can be applied to any area in Sierra Leone where the focus is developing new water supplies.

#### *Phase 1 – Desk Study*

The suggested investigation begins with a review of historical records and documents for each of the AOI's. A good starting point will be the national scale maps and information generated by this study, but also the SALGRID database tool.

We also suggest conducting a site-specific analysis of remote sensing data. This study developed new remote-sensing tools that should be used as a starting point. Furthermore, a skilled expert should interpret and analyze existing imagery, such as those provided under this project, and procure new imagery if needed to update the seasonal changes and give new details. The desk study should also include an analysis of local morphology and geomorphology, using existing maps and data available.

#### *Phase 2 – Field Hydrogeology*

This phase of investigation aims to gather *in situ* hydrogeologic data and establish the baseline of hydrogeologic resources in the study area. The main activities in this phase are: field reconnaissance, water point inventory, water level measurements and data processing. A site reconnaissance is the first step, providing a preliminary evaluation of the hydrogeologic conditions. Next, the hydrogeologist will perform an inventory of the existing boreholes and hand-dug wells in the study area, taking GPS and elevation. The inventory should be compared and aligned with the new SALGRID borehole database, and new data should be uploaded to the database.

Water level measurements should also be taken from all water points of interest in the area, such as existing boreholes and hand-dug wells. Many boreholes in Sierra Leone are capped, preventing measurements to be taken. If possible, effort should be made to access boreholes that are capped.

Next, the data collected and compiled in during desk review and field hydrogeology will need to be processed and evaluated with a view to identify more focused areas with favorable conditions. The hydrogeologist should strive to produce local maps of groundwater potential for the AOI for at least two recent seasons. Also part of the data processing, we suggest when possible to construct numerical models in favorable zones as a method to optimize and test the sustainability and viability of proposed boreholes within a given area. Numerical modeling, however, relies on sufficient data to be useful.

*Phase 3 – Hydrogeophysics*

As highlighted in the above analysis of AOI's, the geoelectrical resistivity soundings performed under the present study yielded limited information on the basement depth in only a few spots. Additional data will be needed. Following the desk review and field hydrogeology, hydrogeologists will identify smaller favorable areas that will need to be further studied and refined. Field investigation will enable more precise planning of hydrogeophysical surveys, a good method in detecting depth of the basement rock, average thickness of the aquifer and studying fractures. Two types of hydrogeophysics are suggested in this phase: surface geophysical investigations and airborne electromagnetics.

The investigation should consider using one of two types of surface geophysical methods on spot locations: **Vertical electrical sounding (VES)** or **electrical resistivity tomography (ERT)**. The choice will depend on the type of information being targeted. VES can give information referring to the resistivity layers below the central point of the arrangement and help characterize the material as clay, silt, sand, gravel or consolidated rock. ERT can give a quasi 2D model along a profile. VES requires a higher number of soundings compared to ERT to reach similar results. Also, the use of VES in densely populated areas (urban areas) can give unreasonable results due to undetected electric cables or water pipes.

Surface geophysical surveys must be calibrated with a nearby borehole with a known lithological log, either an existing borehole or a planned exploration well in the same programme (eg. Phase 4 below). In the absence of such data, the geophysical interpretation of the sub-surface is essentially blind, hindering characterization of basement depth and aquifer thickness.

**Airborne Electromagnetic (AEM):** The advantages of AEM were discussed under the section above on Nimini pilot area. Its greatest value for borehole siting and design is the capability to rapidly characterize groundwater potential of large regions with great detail at a depth range of 20 – 300 m—the critical strata where current drilling methods can reach perched aquifers and new water resources. For all four areas, AEM will deliver the following: 3D resistivity distribution, distribution and thickness of regolith, and detection of potential perched aquifers and conductive fractures. In coastal areas, such as Freetown, AEM can also model a good resolution of seawater intrusion dynamics. AEM technology is very costly, namely due to aircraft costs, and should be used in areas that have been already identified as having favorable conditions for groundwater exploration. For each of the four areas, the AEM survey areas and flight pattern density will factor in available budget and the need to study the largest area possible.

*Phase 4 – Exploration drilling*

The overriding goal of the exploration drilling phase is to collect subsurface data so that a final judgement can be made on the suitability of a site for production well. Drilling of exploratory boreholes is the most direct and best method to understanding the character of subsurface geology and test the potential success of a new water supply well, though it is a more costly method of exploration, so it needs to be used wisely. By this stage, the hydrogeologist has analyzed the data and information from the preceding three phases of investigation as well as national data, and is able to identify aquifers and sites that indicate favorable conditions and which justify being tested in this phase. When conducting an exploration program, it is important to select the correct method of drilling to ensure that proper data are collected. The Drilling Physical Suitability Map of Sierra Leone provided by the current study is a good reference for this purpose. Furthermore, the Groundwater Exploration Suitability of Sierra Leone map will be an important tool for determining sites.

For each of the AOI's, we recommend as a minimum drilling least two exploratory boreholes -- one to be converted into a piezometer (PZ) and one that can serve as a water production well (PW), with the aim of getting the stratigraphic succession and perform an aquifer test. The PW will serve to perform a long duration aquifer test while the drawdown and recovery will be measured in the pump well itself and the piezometer. The latter will consist of a cased well screening all the aquifer and without a pump. Before, during and after the test, atmospheric pressure, and water table levels will likely be recorded through water level transducers to account for natural or induced effects.

The main scope of the aquifer tests, is the collecting of more reliable values of the most important hydrogeologic parameters as transmissivity (T = kb), Storage and/or porosity (S, n), influence radius (R), hydraulic conductivity (K). This must be considered as a necessary step for any further evaluation of the aquifer potential and long term pumping effects.
More precise information for a correct aquifer management will be the assessment of several piezometric maps in different periods and the continuous monitoring of a net of existing piezometers. Suffice to say that the exploratory boreholes drilled during this phase of investigation could be used in the future for delivering potable water to local users.

## Recommended investigative programme for Freetown, Makeni, Kabala and Musaia

Applying the basic investigative framework summarized above, this section describes the recommended actions to investigate groundwater sites in each of the four AOI's. The table below summarizes the recommended programme for all four areas.

**Table 25. Recommended investigations for Freetown, Makeni, Kabala and Musaia**

| Investigation | (1) Freetown | (2) Makeni | (3) Kabala | (4) Musaia |
|---|---|---|---|---|
| **Phase 1 – Desk study** | | | | |
| 1. Desk study of existing information | ✓ | ✓ | ✓ | ✓ |
| 2. Remote sensing analysis | ✓ | ✓ | ✓ | ✓ |
| 3. Morphology/geomorphological analysis | 1 week | 1 week | 1 week | 1 week |
| **Phase 2 – Field hydrogeology** | | | | |
| 4. Field reconnaissance | 5 days | 3 days | 3 days | 3 days |
| 5. Water point inventory | 5-7 days | 5 days | 5 days | 5 days |
| 6. Water level measurements | 4 + 4 days, two seasons | 2+2 days, two seasons | 2+2 days, two seasons | 2+2 days, two seasons |
| 7. Data processing and groundwater mapping for both wet and dry seasons | 2 weeks | 2 weeks | 2 weeks | 2 weeks |
| **Phase 3 – Hydrogeophysics** | | | | |
| 8. Surface geophysical surveys (VES or ERT) | 10 x VES soundings / 5 ERT points | 10 x VES soundings / 5 ERT points | 10 x VES soundings / 5 ERT points | 10 x VES soundings / 5 ERT points |
| 9. Airborne Electromagnetic surveys (AEM) | 1x 150 $km^2$ zone (5 x 30 km)<br>1 x 324 $km^2$ zone (18 x 18 km) | 1 x 400 $km^2$ zone (20 x 20 km) | 1 x 400 $km^2$ zone (20 x 20 km) | 1 x 400 $km^2$ zone (20 x 20 km) |
| **Phase 4 – Exploration drilling** | | | | |
| 10. Exploratory boreholes | 3 x horizontal<br>2 x conventional<br>3 x deep boreholes | 2 x conventional exploration boreholes | 2 x conventional exploration boreholes | 2 x conventional exploration boreholes |

### *Freetown*

A major focus for exploration in Freetown is for the siting of productive boreholes in or near the populated areas on the peninsula and in the marsh areas east of Freetown in Koyo Chiefdom, Port Loko District where water-table elevations and basement depth appear to increase in an eastwardly trend. Existing data does not give evidence of a thick unconsolidated deposit in this area, but this investigation process would identify any potential sites available.

Desk review of the area would benefit greatly from the procurement and interpretation of seismic data from offshore petroleum E&P industry for deeper exploration (deeper than 300 m), which has been identified by the bibliographic review of this study.

At a minimum, the surface geophysical programme for Freetown will include a 1-week survey of 10 VES soundings or 5 ERT points of the 100-150 m strata. Additional soundings should be conducted if more resolution is required. Two AEM surveys could be planned: A zone of 150 $km^2$ (5 x 30 km) along the densely populated eastern coast of the peninsula, and a zone of approximately 324 $km^2$ (18 x 18 km) in the Koyo Chiefdom marshes. The key deliverables will be a 3D resistivity distribution, distribution of the shallow aquifer, detection of sandy-gravel aquifers in the Bullom Group, detection of potential perched aquifers and fractured aquifers within the gabbroic basement formation, and a seawater intrusion model along the coastal area.

For the exploration drilling phase, opportunities for exploratory horizontal boreholes should be studied in the Freetown peninsula, which are a great method for collecting groundwater in high-relief terrain (see figure below). We recommend drilling three exploratory horizontal wells of 200-250 m length (80-120 mm in diameter). If successful one or more production wells could be sited with this method.

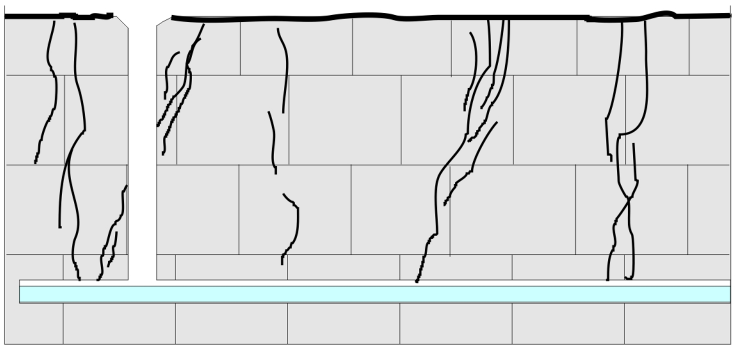


**Figure 76**. Diagram of a horizontal well proposed for Freetown peninsula
Explanation: Figure shows a drainage gallery modeled in Trogir, Croatia. The horizontal tunnel is located at 80 m depth at the bottom of a sinkhole in the limestone formation. The gallery direction is perpendicular to main fractures. Water of good quality and yield is collected by gravity and the system is not influenced by salt water intrusion despite the proximity to the sea. Source: Borivoje, Mijatovic.

We also recommend at least drilling one pilot well of small diameter to be used as calibration for geophysics and one exploration well that can be converted into a production well. The two boreholes will serve for conducting an aquifer test to obtain transmissivity (T = kb), Storage and/or porosity (S, n), influence radius (R), hydraulic conductivity (K).

Depending on the results of the AEM, we also recommend a cautious approach to confirming the presence of perched aquifers and fractured formations in the marshes of Koyo Chiefdom, and therefore suggest drilling 1-3 deep exploratory boreholes (60-300 m deep) near the shore.

Other important guidelines for exploratory drilling in Freetown area include:

- Hydrogeologists should locate the boreholes so as to avoid sources of contamination in the Freetown area (see section on groundwater vulnerability above).
- Drilling in marshland close to the sea must be conducted with proper care to avoid salt water mixing with confined aquifers underneath; same consequences can be induced due to a long term pumping

### *Makeni, Kabala and Musaia*

The prescription for investigation for the three areas is the same due to their similar hydrogeological contexts and the need for similar types of data to inform decisions about siting and designing new boreholes. See sections above on the specific analysis of the individual areas. The focus of exploration is to identify sites for groundwater development within the vicinity of the core population centers of those communities, maximum 10 km from town center.

Desk review and field hydrogeology phases for these areas could be undertaken over a period of approximately two months, individually, not taking into account the need to collect multi-seasonal data. Water point inventory will be critical to calibrate and plan properly the hydrogeophysical surveys, something that was hindering the present study in these areas.

The hydrogeogeophysical programme for Makeni, Kabala and Musaia will entail for each site a 1-week surface geophysical survey to investigate 100-150 m depth either with minimum 10 VES soundings or 5 ERT points. Additional soundings may be planned if more data resolution is needed, making sure that they are positioned within a close vicinity of existing boreholes with hydrogeological logs.

AEM surveys of a 400 $km^2$ zone (20 x 20 km) can be planned for each of the three sites, though implementation may need to be prioritized due to high cost of running AEM. We suggest surveying Makeni area as a minimum due to the urgency of the government to develop new water resources in that area.

The exploration drilling phase of investigation for these three areas includes drilling at least one pilot well of small diameter to be used as calibration for geophysics and one exploration borehole that can be converted into a production well. The two boreholes will enable hydrogeologists to conduct an aquifer test to obtain transmissivity (T = kb), Storage and/or porosity (S, n), influence radius (R), and hydraulic conductivity (K).

# Summary and Conclusions

The availability of hydrogeologic maps for Sierra Leone is important to hydrogeologists, groundwater specialists, and water resources managers and planners. These maps, in combination with the insights generated by this study and the associated SALGRID online database tool, serve as an important source of information by providing baseline hydrogeologic science in a concise user-friendly format. The Hydrogeologic Atlas and associated maps can serve as a reliable source of information for hydrogeologic investigation and groundwater development at national and regional levels when used in conjunction with other relevant maps and data. It is also an invaluable reference and a useful educational tool at all levels.

Sierra Leone covers a total area of 71,740 $km^2$. Of this total area, about 54,000 $km^2$ (75-78%) are underlain by hydrogeologic systems that are classified as crystalline basement complex. Porous aquifers are the principal aquifer system along the entire coastal area. Considering the many assumptions made, and applying a simple calculation method, we can estimate the volume of total renewable groundwater resources in Sierra Leone to be no greater than 18.3 $km^3$ accounting for storage volumes and recharge, or 0.25 m volume per unit.

The potential development of untapped groundwater resources in Sierra Leone is significant. As it stands, the influence of current abstraction practices on available volumes of groundwater systems seems to be minimal, indicating a great potential for further development of groundwater resources. This deeper, fractured aquifer zone is typically a more sustainable groundwater source than the upper weathered zone. It also has more potential for the natural attenuation of contaminants, because of the overlying clay zone and the longer pathways. Quality will continue to be an issue, with much of the country being highly vulnerable to surface contamination.

## Study Limitations

Data limitations are a significant concern for any study, and particularly so for regional and national scales. This study has been an opportunity to take stock of Sierra Leone's existing hydrogeological data and suggest remedies to improve the overall science and methods. The limitations have been highlighted throughout the current report; however, the most significant data limitations in hydrogeology in Sierra Leone are in the following areas: groundwater quality, borehole logs and yield, climate, stream flow, geology, and socio-economic parameters. Better qualitative and quantitative data would have resulted in more detailed concepts, such as the classification of lithology types, groundwater quality mapping, groundwater balance, or the analysis of basic parameters in the Areas of Interest.

Despite these limitations on hydrogeologic data, it was possible to give a general, but still valid, description of the aquifers of Sierra Leone. This study also demonstrated modern investigation and exploration technologies, such as integrated sub-surface characterization, advanced modeling and data processing techniques, which helped to overcome the constraint of limited data and achieve new reliable maps and information about groundwater at the national scale—something that had been lacking prior to this study, and one of its flagship achievements. When needed, the study also highlighted the uncertainty of these methods and gave guidance to users on how to interpret them (eg. average estimate of water table elevations, GES mapping). The information generated by this study now represents the new national baseline of groundwater, a new starting point reference for future investigation and research.

## Recommendations

This study has put forward recommendations on a number of important aspects, notably those on improving water quality data and mapping (section "Water Quality"), improving water balance assessments (section "Annual renewable groundwater resources") and those on further investigations in the Areas of Interest (section "Recommended Further Investigation on Selected Areas"). Going further, and taking stock of the information and tools developed out of this study, the Government of Sierra Leone, the Consultant and a group of national stakeholders, having met at occasion of the study validation workshop on 15 June 2017 in Freetown, have agreed to the following overarching recommendations for follow-up to this study:

1. **Expand the scope of future investigation at both the level of local priority areas and at the national scale, including the national network of groundwater monitoring stations.** More specifically, it is highly recommended to implement a second phase (Phase 2) of the study that would focus on detailed exploration of groundwater resources in priority areas (eg. Freetown, Makeni, etc.) with the use of advanced groundwater prospection techniques, such as airborne electromagnetic (AEM), exploratory drilling, localized modeling, combined with the siting, design and construction of water supply boreholes.

2. **Improve data collection standards for more reliable, homogeneous and robust national datasets.** The Ministry of Water Resources plays a leading role in collecting hydrogeologic data and effort to build institutional capacity to collect data should be supported. Similarly, the National Water Resources Agency (NWRA) should play a central role in the future in issuing and enforcing hydrogeological data standards. Furthermore, the SALGRID tool delivered by the Consultant in this project should be used to disseminate standardized data collection forms to relevant stakeholders, and serve as the central tool for archiving groundwater data and coordinating data exchange in Sierra Leone.

3. **Utilize tools and build skills in groundwater management,** including the construction and implementation of numerical models for the aquifer unit levels as a tool to establish policies for maximum withdrawal rates and other enforceable measures to promote the sustainable use of groundwater nationwide.

4. **Update the national study every four (4) to five (5) years.** Stakeholders recommend the government undertake an update of the maps and the report around the year 2021 and no later than by December 2022.

5. **Expand data collection and the national observation network to build on the study to improve the certainty of some of the estimates and models.** More specifically, it is recommended that reliable time-series data on the following parameters be collected and/or estimated for future hydrogeologic studies at national scale:

   a) GPS location for validated, reliable data, using a common coordinate system
   b) Evapotranspiration (ET)
   c) Water quality data (see Table 11)
   d) Depth-to-groundwater
   e) Specific Yield
   f) Effective aquifer thickness
   g) Socio-economic parameters

6. **Undertake policies and measures to protect groundwater from surface contamination.** This will need to include conducting future mapping and studies focused on groundwater quality and key groundwater vulnerability areas, building on the maps provided by this study. See section of this report on specific recommendations for improving groundwater quality data and Table 11. Furthermore, it is recommended to develop groundwater conservation policies and measures, particularly in areas most vulnerable identified by the study.

7. **Give high visibility and wide access to the information and SALGRID tool.** The SALGRID should be consolidated as the nation's online tool to apply national data collection standards and provide a centralized data repository for official data submissions. Use of data form templates can assist, as well as establishing a team of data reviewers to ensure that new data meets the required standards for quality.

8. **Institutionalize the results of this study,** namely through the following actions:

   a) Institutionalize and strengthen groundwater management under the auspices of a single national authority, ie. the **National Water Resources Agency (NWRA).** The NWRA will play a central role in issuing and enforcing hydrogeological data standards.

   b) From the professional sector, the existing **Sierra Leone Institution of Geosciences (SLIG)** can play a role in disseminating the study's information.

   c) It was also recommended that the study be assimilated by the pool of Sierra Leonean professionals working in the field of groundwater. As such, the stakeholders recommended that a new national chapter of the International Association of Hydrogeologists (IAH) be formed in order to further the understanding, wise use and protection of groundwater resources in Sierra Leone (see: https://iah.org/groups/national-chapters). A new **"IAH Sierra Leonean Chapter"** would play a role in building on the national study, and help promote and coordinate hydrogeologic studies in the country, as well as link national studies with regional and international research. The stakeholders deem Dr Mustapha Thomas (Fourah Bay College), senior professor in geology and researcher in hydrogeology, as the person who is best positioned to assist in bringing this initiative to fruition.

9. **Build national capacities of Sierra Leonean experts in utilizing and applying the main products of the national study.** In order to enhance the sustainability of this project, the stakeholders recommend that a robust capacity building programme be implemented to train a critical mass of government experts and stakeholders to properly use the maps and information delivered by this project. Each national scale map provided by this study is not designed to be taken as a stand-alone basis for a specific action at the local level, and should be used in conjunction with additional local investigations and tools.

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