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Groundwater potential in Sierra Leone: hydrogeological mapping and preliminary aquifer parameter evaluation

Potenzialità degli acquiferi in Sierra Leone: Cartografia e valutazioni preliminari dei principali parametri idrogeologici dell'acquifero

Alessio Fileccia, Desmond Alie, Mohammed Sahr E. Juanah

Riassunto: In quasi tutto il continente africano, l'acqua sotterranea è la prima fonte di acqua potabile relativamente sicura. Ciononostante poco si sa ancora sulla potenzialità degli acquiferi in molti paesi. La Sierra Leone ha valori di precipitazione fino a 5000 mm/a ed una rete capillare di corsi d'acqua, ma l'aspetto idrogeologico non è mai stato preso in considerazione in precedenza. Tra il 2016 e 2017, HydroNova (USA) ha condotto un'intensa ricerca su tutta la documentazione idrogeologica esistente nel paese. Il prodotto finale di questo lavoro è l'Atlante Idrogeologico della Sierra Leone, una serie di 20 carte tematiche, corredate da elaborazioni tecniche, sia in versione digitale che cartacea. Il progetto ha mostrato che la maggioranza dei quasi 29000 pozzi nel paese, è posizionata in acquiferi liberi, di limitata estensione e di tre diverse tipologie: sospesi, lungo i grandi corsi fluviali; porosi, comuni in tutto il paese e lungo costa e fratturati, di solito al di sotto dei precedenti nelle rocce del basamento cristallino. Il flusso di falda va da NE verso SW seguendo i corsi principali ed è in genere correlato con la topografia. Il basamento costituisce quasi sempre il letto dell'acquifero, tra 15 ed 80 m di profondità. La portata di utilizzo è di 0.3 - 0.6 l/s, eccezionalmente 3 – 6 l/s. La trasmissività è bassa (2-3 m^2/s) e costringe a lasciare fermo il pozzo per qualche ora per permettere il recupero del livello. La relazione di progetto ed altri lavori legati a questo articolo possono essere consultati tramite il seguente link: http://www.salgrid.org

Keywords: *Sierra Leone, aquifer, water budget, hydrogeologic map, transmissivity, recharge.*

Parole chiave: Sierra Leone, acquifero, bilancio idrico, carta idrogeologica, trasmissività, ricarica.

Abstract: *Groundwater is a major source of safe drinking water throughout Africa. Despite this, little quantitative information on aquifers potential is known in many countries. Sierra Leone has annual precipitation rates of as much of 5000 mm/yr and a capillary net of surface streams, but the hydrogeological aspect was never taken into serious consideration. Between 2016 and 2017, HydroNova (USA) conducted an extensive survey on all existing hydrogeological data in the country. The flagship product of this study was the Hydrogeologic Atlas of Sierra Leone, a series of 20 maps complemented with textual notes, published in official digital and hardcopy formats. The project showed that the majority of nearly 29000 wells, from the national survey, are located in unconfined aquifers of limited extent and of three different types: perched (along large river banks), porous (widely distributed across the country and along the coast) and fractured (in the crystalline basement). The latter are generally deep and often covered by the lateritic soils. The water table flows from NE to SW following the main water courses and is generally correlated to the topography. The crystalline basement is the common layer at the bottom of the aquifer at depth of 15-80 m. Well yield is normally in the range of 0.3-1.5 l/s and exceptionally 3-6 l/s. Transmissivity is also low (2-3 m^2/d). As a consequence many boreholes must remain unpumped, for some hours, to recover an exploitable water level. The entire report and other publications related to this paper can be accessed via the following link: http://www.salgrid.org*

Alessio FILECCIA ✉
Hydrogeologist HydroNova LLC
Texas, USA
geofile@libero.it

Desmond ALIE
Hydrogeologist Edal Drill. Co
Sierra Leone
aliedesmond@yahoo.com

Mohammed Sahr E. JUANAH
Head of Water Resources (MOWR)
Sierra Leone
msejuanah@hotmail.com

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Introduction and scope

As surface water supplies in Sierra Leone, especially the capital Freetown and other big cities, become subjected to increasing pressure from pollution, climate change conditions and growing demand, a goal of the government is to develop groundwater as a complementary 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, dry borehole situation and water quality deterioration. National agencies and local water supply entities, are in need

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of reliable, easy-to-access information that might help them to properly manage the water resources of Sierra Leone. This paper illustrates some of the many hydrogeological issues affecting Sierra Leone and highlighted during the project for the national Ground Water Mapping performed by HydroNova between 2016 – 2017.

Previous work and limitations

Prior to the present study, no comprehensive hydrogeological mapping or investigation had been undertaken at the national scale. Similarly, related parameter 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, surveyed by the Survey and Lands Department, Freetown. 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 28850 water data points collected from the government's 2012 national survey of water points (Ministry of Energy and Water Resources 2012). 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 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. 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. On a general point, useful resources were those from the British Geological Survey that performed several studies on the basement complex aquifers in Africa (MacDonald A M, Davies J 2000). Whenever possible, ground truthing (field checking) was applied to validate data on site.

Materials and methods

Hydrogeological maps are widely considered as a useful basic documents for rational planning of water resources, to serve for agriculture, industry and public supply. The tool is in use since early '40s with continuous implementation on survey techniques and symbol uniformity (IAH 1995).

The maps represent a complex three dimensional system made of rocks and water, but also changing in time. This leads to the fact that they have to include a combination of hydrogeological parameters and be prepared in different periods of time. Due to the complexity of the environment being represented, hydrogeologic maps are several and are generally adopted to specific purposes and budgets. The hydrogeological maps are divided in two main categories (IAH 1995)

- General maps describing the groundwater systems used as a reconnaissance tool and derived from preexisting maps or satellite images
- Parameter maps, generally prepared for smaller areas and based on specific field tests; they describe spatial variation of some important hydrogeologic parameters and are more useful for planning and management

Both groups are complementary and should be considered in development project.

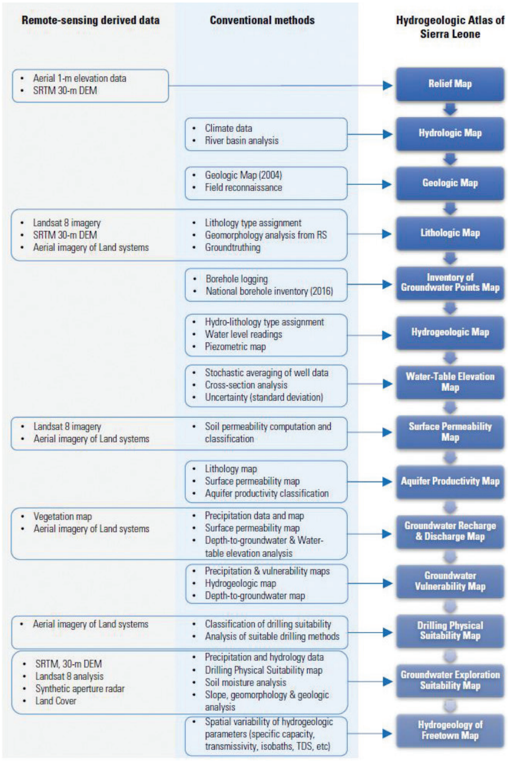
Today, many spatial data derive from satellite image interpretation, processed using Geographic Information Systems and digital hydrogeologic maps are the final product, well suited for water resources planning. Other common techniques used to acquire field parameters, refer to the classic logs from drillings, aquifer tests and geophysical methods such as FEM, TEM, GPR, the classic vertical electrical sounding (VES) and the AEM, airborne electromagnetic. This last method, particularly, has increased over the past ten years, proving how these systems are appropriate for large-scale and efficient groundwater surveying. One of the major reasons for its popularity is the time and cost efficiency in producing spatially extensive datasets that can be applied to multiple purposes. As an example a pilot application of AEM technology for groundwater exploration was undertaken during the execution of the project, by re-processing data in an area of Kono district (Nimini Mining Ltd. 2010, unpublished data)

As a general task the Groundwater Mapping of Sierra Leone was to examine, optimize and finalize all available hydrogeological data, scattered in different agencies and companies. Due to this, time and budget constraints, the job had not the same detail all over the country, but allowed nevertheless to demarcate groundwater characteristics at a national scale, through a range of general parameter and specialized maps. The approach was integrated with existing ancillary data, advanced remote-sensing and modern mapping and investigation methods applied in the GIS environments (ArcGIS and QGIS). The twenty hydrogeologic maps of Sierra Leone were developed according to IAH standards and guidelines, (Struckmeier 1995) see Table 1, summarizing the overall methodology.

DOI: 10.7343/as-2018-330

Tab. 1 - Mapping methodological framework.

Tab. 1 - Sintesi delle diverse fasi di lavoro e redazione della cartografia.



One of the main starting point was the Geologic Map (Keyser, Mansaray, 2004) an unreplaceable tool for developing some derived maps (e.g. lithological map).

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 local geological and hydrogeological characteristics such as: lithology, aquifer classification, drainage and lineament patterns, surface permeability, water table surface, depth to groundwater, water points distribution, recharge and discharge areas, aquifer productivity and vulnerability.

Furthermore, detailed field investigations of Freetown peninsula allowed the preparation of three more maps for the specific capacity, water table surface and depth to basement.

The project was completed with the acquisition of resistivity data through field surveys in 4 areas of special interest (AOI): Freetown, Musaia, Kabala, Makeni.

An overall dataset of nearly 29000 records was reviewed, and a final sample of 1033 boreholes and hand dug wells were found to contain sufficient and reliable information for hydrogeologic analysis (Fig. 1).

Furthermore, tenths of drilling reports submitted by private companies, were examined to obtain more data on the basic parameters, such as transmissivity, specific capacity, re-charge, static water level.

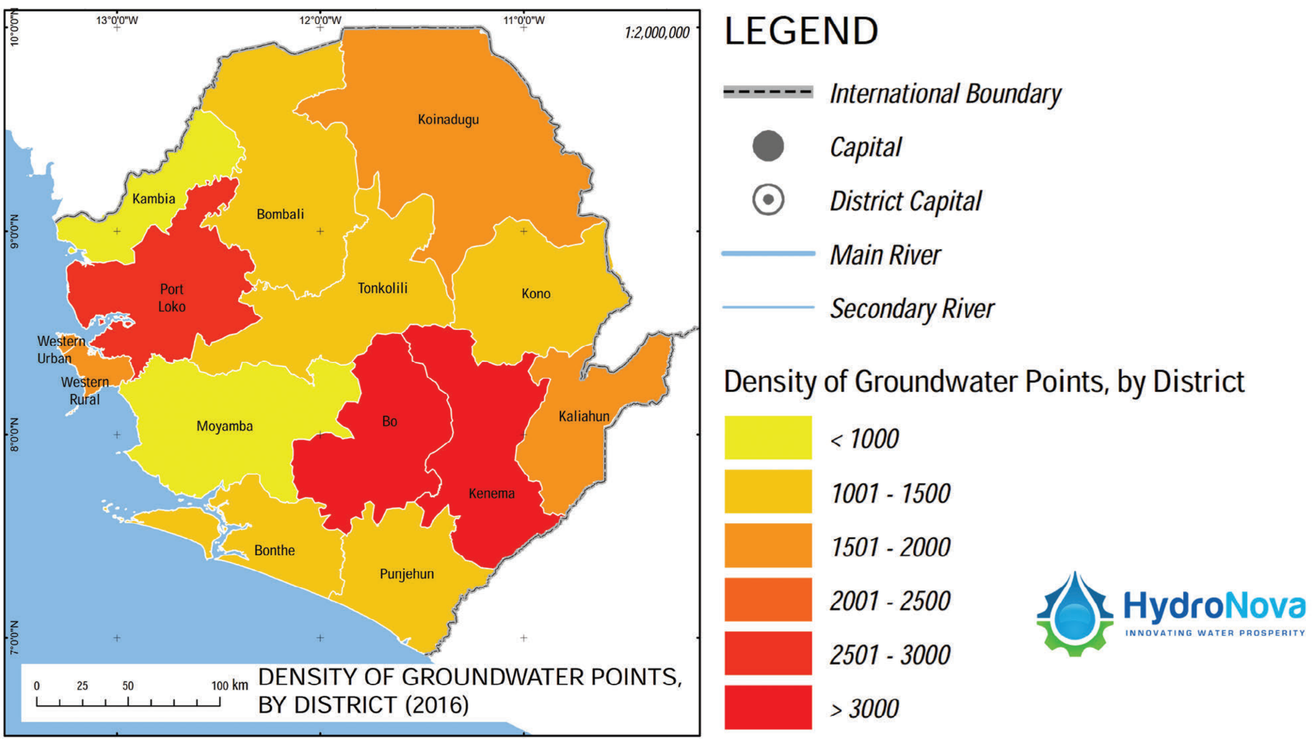


Fig. 1 - Density of groundwater points for each district in Sierra Leone. The figure is derived from the national database prepared by WASH in 2012. The number of hand dug wells and boreholes is 28845.

Fig. 1 - Densità dei pozzi per distretto in Sierra Leone. La figura è elaborate da una ricerca di WASH nel 2012 su 28845 pozzi a mano o perforati.

General setting

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. The total land area of the territory is 71740 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.

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, with moderate elevations (700 m) set against large areas of low coastal plains. The coastal plain is a strip approximately 50 km wide, covering about 15% of the country, giving way to inland plains and plateaus in the interior. The lower plains rise from 50 m in the west to 200 m in the east and host a long strip of swampy areas (bolilands). Further to the east and Guinea boarder, the terrain becomes rugged with hills and mountains up to the highest peak, Bintumani at 1948 m. The plains and plateaus 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 (also called laterite). 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.

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). Precipitation is greatest in the Freetown Peninsula, due to the influence of relief, at 5200 mm/yr on the seaboard banks. The southeast receives also a significant amount of rain, with about 4200 – 3200 mm/yr. Along the coast, rainfall varies from 3000 – 4000 mm/yr. The northern region receives the least amount of rainfall, less than 2400 mm/yr.

Sierra Leone has 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/Rokel is the longest river (424 km), with its headwaters beginning in the highlands of Guinea. The largest basin is the Sewa (19022 km^2). Four of Sierra Leone's primary basins are shared with its neighbors – the Great Scarcies, Little Scarcies, Moa (Guinea) and Mano (Liberia). From the geological view, Sierra Leone occupies the central portion of an Archean craton that was disrupted by the opening of the Atlantic Ocean. The eastern unit is part of the stable Precambrian West African Craton and consists of high-grade metamorphic rocks and granitic gneisses. (Fig. 2)

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 (gravel, sand, clay). Prior to the deposition of the Bullom Group, two periods of intensive igneous activity occurred in the Mesozoic. The intrusions gave rise to the Freetown gabbro complex and a series of dolerite sills and dykes trending NW-SE.

The famous kimberlite dykes and pipes date back to 90 Ma ago and are found mainly in the interior of the country. (Fig. 3).

Locally, laterites occur within the relatively unconsolidated sediments and form resistant outcrops, such as along the Bullom shore. 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 (Tab.2).

Tab. 2 - Main geologic units of Sierra Leone.

Tab. 2 - Unità geologiche principali della 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 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)

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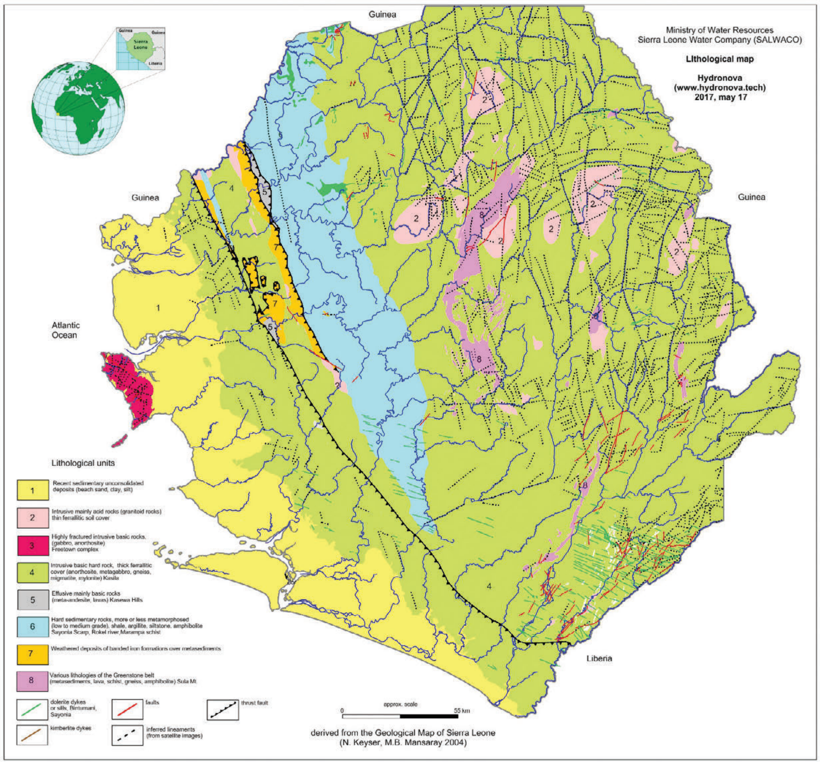

Fig. 2 - The Lithology of Sierra Leone map represents an intermediate step between the geologic and hydrogeologic point of view, depicting the distribution of geologic units classified as mainly type of rock composition and texture. Main trends in lineaments are also illustrated. In essence, the lithological map excludes information on formation age and environment, facilitating the differentiation of porous and fractured formations. This map used the Geology of Sierra Leone (Keyser, Mansaray 2004) map as a starting point; the 28 geologic units were interpreted as nine lithological units. Lineation (lines) was added to show formation contacts and folding, following the analysis by remote sensing and field ground truthing. Geological structures and morphology generally show a good degree of correlation, particularly for the younger intrusions and linear elements.

Fig. 2 - La Carta Litologica della Sierra Leone rappresenta una fase intermedia tra quella geologica ed idrogeologica. Le unità geologiche sono distinte in base al tipo di roccia, insieme alle principali lineazioni. In sintesi la Carta Litologica non considera l'età delle formazioni e l'ambiente, facilitando la distinzione tra materiali porosi e fratturati. Questa Carta utilizza di partenza, la Carta Geologica della Sierra Leone (Keyser, Mansaray 2004). Le 28 unità geologiche sono state condensate in 9 unità litologiche. Per evidenziare i contatti ed il sistema di pieghe sono state aggiunte le lineazioni ottenute da analisi satellitari e controlli in campagna. Le strutture geologiche e la morfologia, mostrano in genere una buona correlazione, in particolare per quanto riguarda le intrusioni recenti e gli elementi lineari.

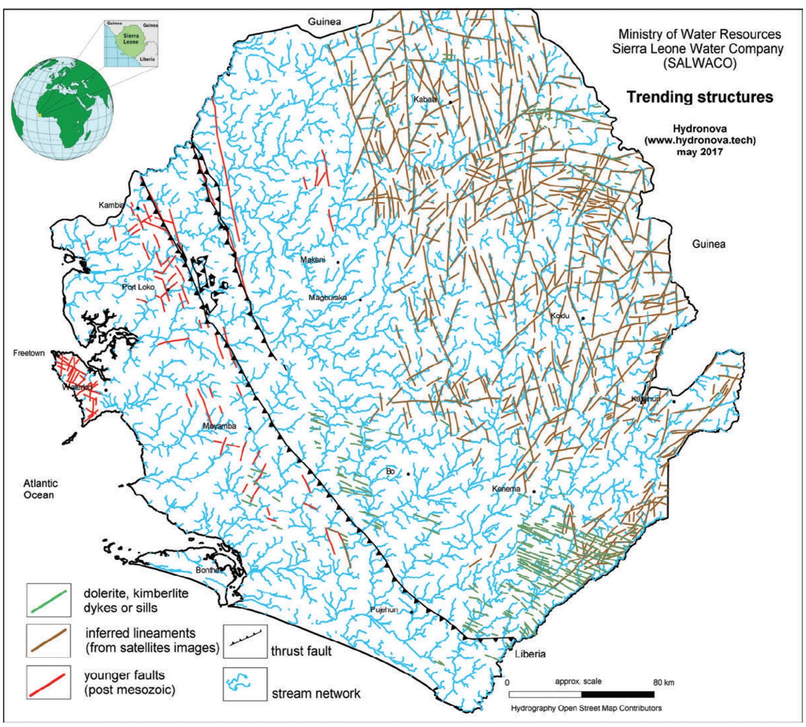

Fig. 3 - Drainage and lineament patterns. Faults and fractures in brown color are mainly Precambrian in age while red lineations are more recent (Mesozoic). The latter are related to the opening of the Atlantic Ocean and the similar transform systems in Guinea and Liberia. Dykes have dated to a recent magmatic activity. The Polar graph was 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.

Fig. 3 - Assi di drenaggio e strutture lineari. Faglie e fratture in colore marron sono principalmente precambriane, mentre le linee in rosso sono più recenti (Mesozoico). Le ultime sono collegate alla formazione dell'Oceano Atlantico e sistemi trasformi simili, in Guinea e Liberia. I dicchi risalgono all'attività magmatica più recente. Il grafico a rosa è stato ottenuto da analisi di immagini satellitari su 708 sistemi lineari. La direzione principale è N165°E per quanto riguarda la tettonica precambriana (frequenza 13%), mentre i dicchi più recenti si sviluppano con direzione N120°E.

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Hydrogeological units

Recalling the main geologic units presented in the previous section, Adekile (MOWR, 2015) provided a simplified hydrogeological classification with four categories corresponding to four geological units. 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 (Tab.3).

1. Unconsolidated sedimentary deposits

They are subdivided into alluvial (valley fill) and coastal deposits of the Bullom Group formation. Alluvial sediments are sands, gravels and clays 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 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).

2. 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.

3. 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.

4. 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

Tab. 3 - Main hydrogeological units and aquifer parameters from various sources in Sierra Leone.

Tab. 3 - Unità idrogeologiche principali e parametri dell'acquifero per la Sierra Leone, da vari Autori.

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) 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.

Hydrogeological parameters

There are, indeed, very few published records of aquifer properties for Sierra Leone and no national scale research on the distribution of aquifer parameters as 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 a proxy for 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 in the Weathered Basement Complex in other parts of Africa as follows:

- 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 (MOWR, 2015). 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.

Main results

Results obtained from this project are many and not all can be illustrated in this paper, but the main are:

A. The assesment of a set of thematic hydrogeologic maps for the entire country
B. A better delineation of aquifer parameter distribution in many districts and a more precise definition of the conceptual model and the various hydrogeologic schemes
C. A general assessing of the water balance and groundwater potential
D. The accessibility to all data, through SALGRID online database

A side aspect was also, the opportunity offered to SALWACO engineers to attend specific training courses and take actively part to the field surveys. This paper will illustrate some outcomes dealing with points B. and C. adding a few notes on water quality. The aquifer parameter evaluation comes from a limited number of boreholes and hand dug wells (1033) where simple aquifer tests have been performed. The higher percentages of processed data are in Bombali, Port Loko, Pujehun and Bo. Simple pump tests or yield records were available for only 98 of them. 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. The basement is 37 m deep, on average (Table 4). Pump tests were available for a smaller percentage of this inventory. Direct measurements of transmissivity and porosity are scarce in Sierra Leone. As an alternative, this study used proxies,like yield and specific capacity (SC) where pump test data were of poor quality. In all other cases interpretation was performed using Jacob-Cooper (residual, recovery) or Moench methods. 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

Tab. 4 - Hydrogeological parameters in Sierra Leone, extracted from 1033 boreholes and hand dug.

Tab. 4 - Principali valori di parametri idrogeologici in Sierra Leone, sintesi di 1033 perforazioni e pozzi a mano.

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

Hydronova LLC, 2017

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Tab. 5 - Average values for Specific Capacity (SC) drawdown and discharge in various Districts.

Tab. 5 - Valori medi di Portata Specifica (SC), abbassamento e portata nei vari distretti.

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

Hydronova LLC, 2017

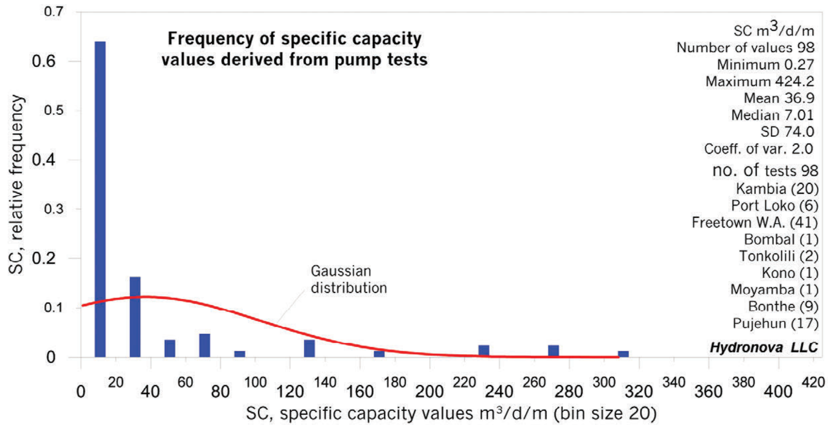

Fig. 4 - Frequency of Specific Capacity (SC) in Sierra Leone, with statistical analysis.

Fig. 4 - Frequenza dei valori di Portata Specifica in Sierra Leone e sintesi statistica.

generally preferred over those performed in the laboratory. From the hydrogeologic inventory, the specific capacity (SC) was calculated at national scale, with a reasonable mean value of 70 m^3/d/m (Table 5). 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 largely applied, and results are illustrated on Figure 5. Among the data recovered, 46 pump tests were available and interpreted using the Jacob "straight line" or Moench method, while the remaining 42 boreholes were processed to calculate SC and the derived T. Figure 6 illustrates one common test (Step Drawdown Test) and the associated curves, used to calculate the transmissivity when residual drawdown readings were made available.

As a conclusion, values for aquifer properties of the unconfined fractured aquifer can be considered rather low. 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. Concerning the water wells and water-table fluctuations, the number of in-use groundwater

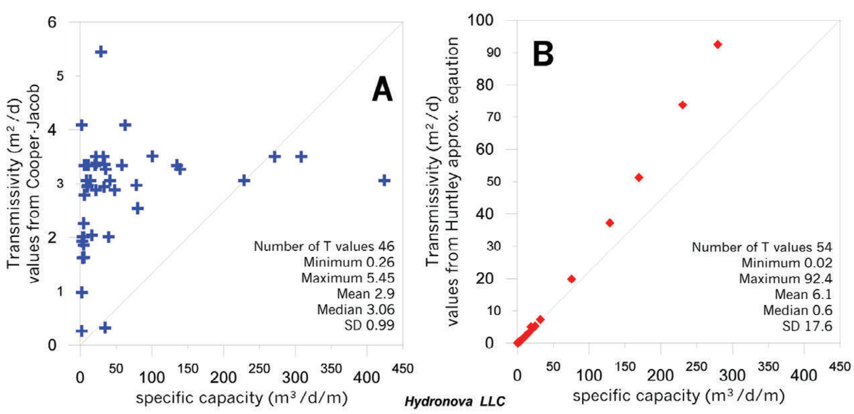

Fig. 5 - Scatter plot of transmissivity (T) and specific capacity (SC). (A): T calculated from Cooper-Jacob straight line method on 46 tests (MOWR), T and SC are obtained independently; (B): T calculated with Huntley approx. formula using SC values, for the remaining 42 sites.

Fig. 5 - Scatter plot della trasmissività (T) e portata specifica (SC). A: valori di T calcolati con la procedura Cooper-Jacob su 46 prove (MOWR) indipendentemente da SC; B: T calcolato con la formula approssimata di Huntley, partendo dai valori di SC, su 42 prove.

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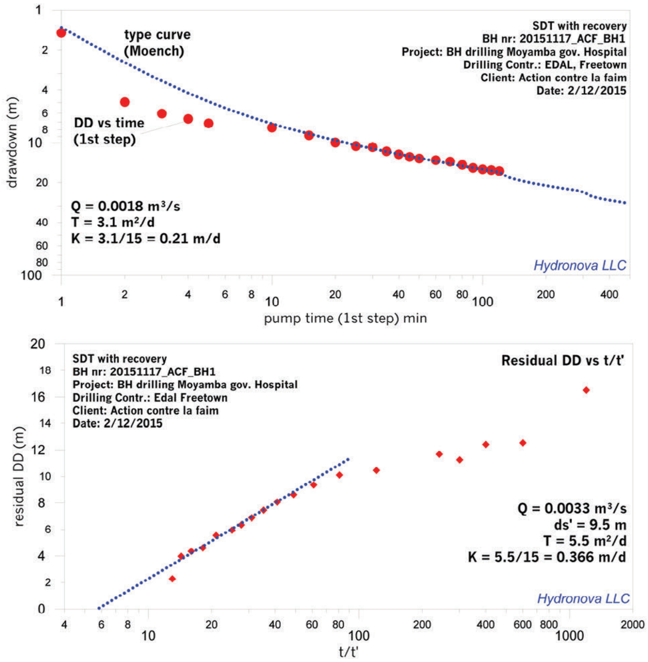

Fig. 6 - Typical pump test interpretation from raw data collected by Edal. Whenever possible transmissivity value was checked again during recovery.

Fig. 6 - Esempio di interpretazione partendo da dati raccolti da Edal. Quando possibile i valori di T sono stati elaborati anche durante la risalita.

points is close to 19000, out of which. 7700 are seasonal and get dry several months of the year. 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). 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. 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 availability of water table fluctuation data made also possible to evaluate the recharge in some localities through the WTF method (USGS). Values for specific yield were extrapolated from stratigraphic logs or pump tests when available (Fig. 7).

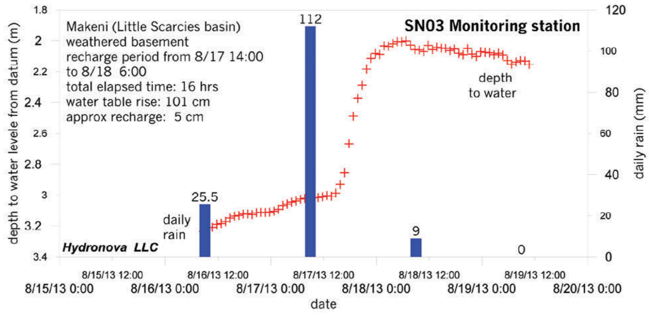

Fig. 7 - Extrapolated data from SN03 station (Makeni). Water table (red cross) respond rapidly to the rain (blue bars) indicating a shallow aquifer and a fairly good hydraulic conductivity. The application of the WTF method considering a specific yield of 0.05, gives a recharge of 5 cm for this particular event.

Fig. 7 - Variazioni di livello piezometrico e pioggia per il pozzo SN03 (Makeni). La falda (croci rosse) risponde rapidamente alla pioggia (barre in blu) ed indica un acquifero superficiale con buona conducibilità idraulica. Applicando il metodo WTF per una porosità efficace di 0,05, si ottiene una ricarica di 5 cm per il particolare evento piovoso.

Water Quality

Few information are available on the groundwater quality of Sierra Leone. Most of the analysis were performed for Freetown, Tonkolili, Port Loko and Moyamba districts. Water points positons were not recorded, preventing any interpolation method to study chemical distribution and variation in space. Some investigations (Massally et alii, Edal, 2015) show that two third of the samples are within WHO limits for turbidity. A low percentage (5-10%) exceeded WHO guidelines for electrical conductivity, while 12 to 25% had iron and manganese values in excess of WHO standards. A fairly great problem arise with bacteriological contamination, expecially in Freetown area, where faecal and non-faecal coliforms where retrieved in 30% of the wells. Generally speaking, groundwater quality is fairly good and drinkable all over the country with rather higher values for iron and manganese or specific metals close to mining sites. Bacteria are a common issue near populated areas where a large amount of hand dug wells are present, facilitating the infiltration of polluted water from surface.

The Conceptual Model and the hydrogeologic schemes

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. The hydrogeologic conceptual model for Sierra Leone is based on a set of main assumptions, listed below and will 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.

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;

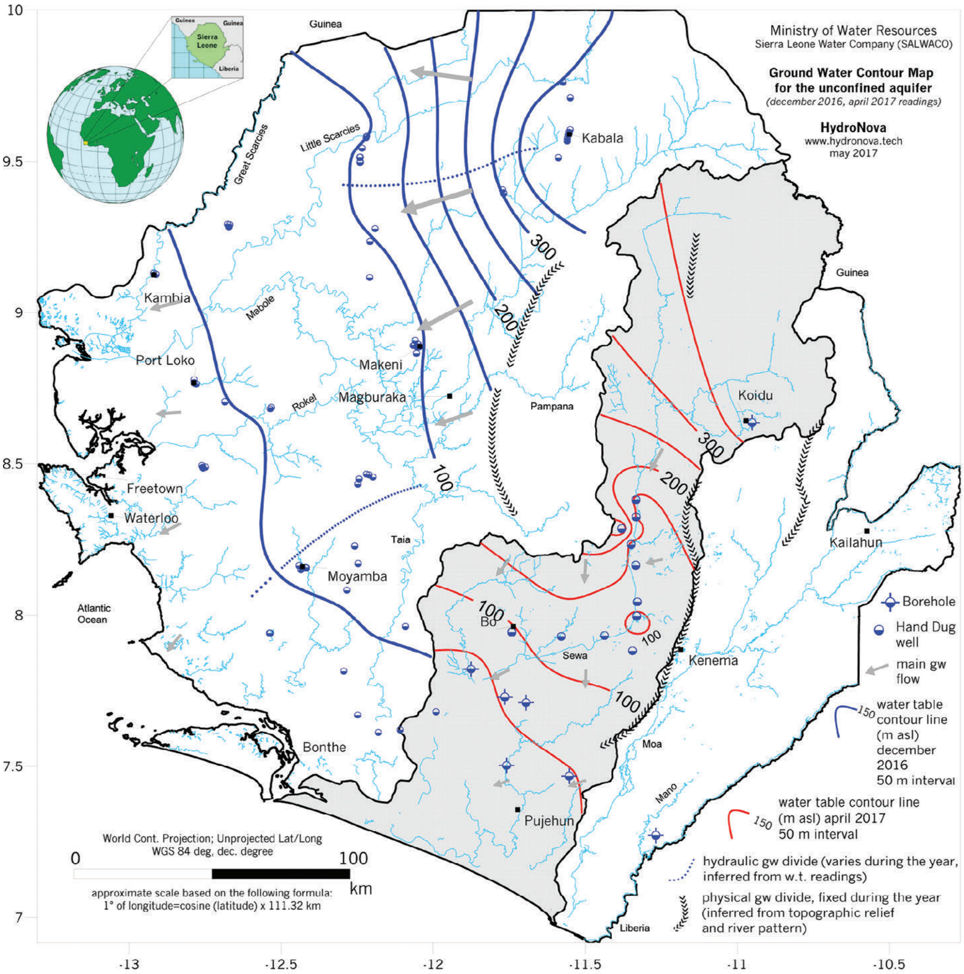

Fig. 8 - Water table contour map. Due to the extent of the territory, the map is based on field readings in two different periods: december 2016 (blue lines) and april 2017 (red lines). The data were also used to prepare the Rest Water Level map (depth to groundwater) and the Recharge Discharge map. The general flow direction is from the high elevated inland areas towards the sea. Hydraulic boundaries can be traced in the northern, central and southern parts of the country. The map was also prepared considering some physical impermeable boundaries, like the central range of Sula Mountains and Kangari Hills and the Kambui hills west of Kenema. Sewa river is clearly draining the aquifer SW of Koidu. The depth of water below surface lays in general between 9 and 42 m, with much closer figures along a wide strip parallel to the coast.

Fig. 8 - Carta piezometrica. A causa dell'estensione del territorio la Carta è stata preparata in due diversi periodi: dicembre 2016 (linee blu) ed aprile 2017 (linee rosse). I dati hanno poi permesso di redarre anche la Carta della Soggiacenza. Il deflusso principale è dalle aree montane all'interno verso il mare. Alcuni limiti idraulici si possono esistono nella parte settentrionale, centrale e meridionale. Come limiti fisici impermeabili sono stati considerati, le Sula Mountains, Kangari e Kambui hills ad ovest di Kenema. Il fiume Sewa effettua un'azione drenante a partire da SW di Koidu.

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 2400 and 5000 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 vegetation 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. The vegetation cover on surface water should be viewed, on average, as an advantage other than disadvantage, because most known streams have gone dry due to the destruction/removal of forested areas;

g. Transmissivity is generally low for the fractured and porous formations and weathered surface layer, 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 (Fig.8).

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

1. Shallow, unconfined aquifers are prevalent. These aquifers are partly confined in some areas near the coast.
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 watertable may drop, and can fragment entire aquifers into smaller ones;
7. The surface layer and the fractured rock are characterized by high heterogeneity and anisotropy with hydraulic conductivity (K) dependent of direction. Due to different K values between the weathered and the fractured formations the aquifer response to seasonal variations is like that of a medium with double porosity;
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. (Fig.9). 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 deep, depending on the thickness of the weathered zone.
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 Fig.10 at a position near Lungi where groundwater leaves the silty sand formation at the base of a cliff with height of 15 m. 10. On a more general note, 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 general water budget and renewable groundwater resources

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

Zone 1: A shallow (regolith) groundwater zone, accessed by hand 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 basement 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). Using the simple water balance equation, 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.

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 and an excessive lowering of the groundwater table. Calculations are normally made for a single year and 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

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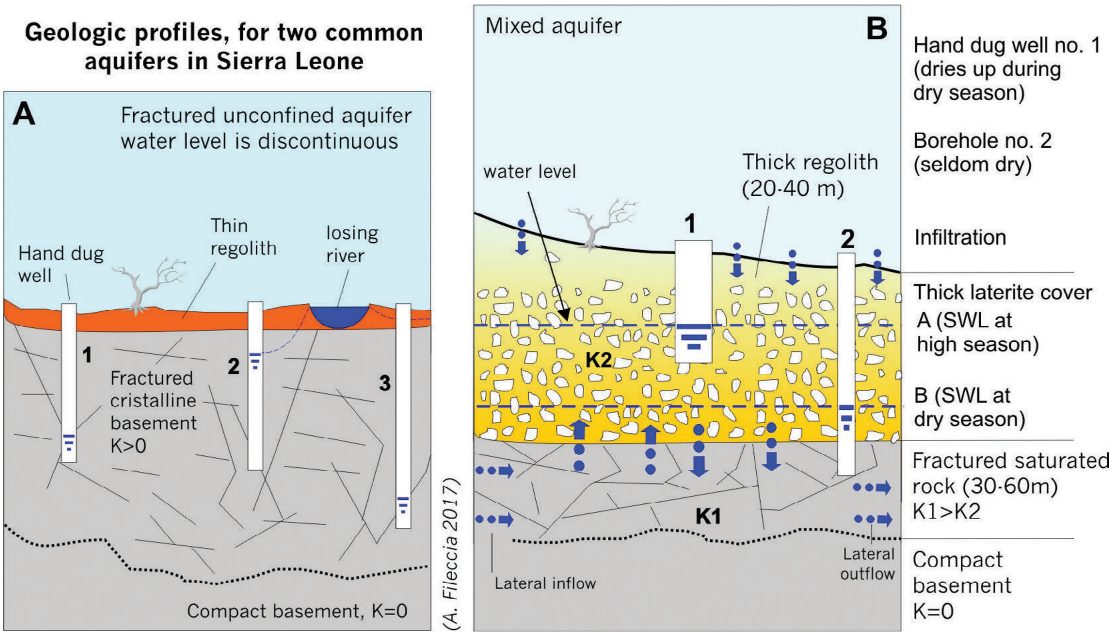

Fig. 9 - Schematic diagrams of two typical aquifer types in Sierra Leone. (A) Groundwater flow in a fractured aquifer with thin regolith cover. Recharge can derive from rain (water wells 1-3) and river infiltration (fractures connect river and hand dug well no. 2). The different situations can lead to long or short water availability during the year. (B) 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, but after a few weeks the levels compensate each other. 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 at two different lower elevations, alternatively only the lower aquifer has water. The most frequent situation encountered is that where hand dug well no. 1 is sustainable for a limited period of the year, while borehole no. 2 supplies water all year round.

Fig. 9 - Sezioni tipo di due acquiferi molto comuni in Sierra Leone. A: l'acqua scorre in un acquifero fratturato con un regolite poco potente. La ricarica può derivare dalla pioggia (pozzi 1-3) e/o da infiltrazioni da fiumi (le fratture collegano il fiume ed il pozzo n.2). Le due situazioni possono portare a diversa disponibilità idrica durante l'anno. B: in un acquifero misto con un regolite potente, l'acqua scorre in due mezzi a diversa conducibilità idraulica. I due acquiferi sono entrambi liberi ma la loro comunicazione avviene attraverso lo strato superiore alterato. Durante la stagione piovosa, l'acqua viene fornita diversamente in base alle condizioni idrogeologiche locali: dalle piogge, dal fiume o da entrambi. All'inizio della ricarica possono esserci contemporaneamente due diversi livelli piezometrici che si compensano dopo un certo periodo. Durante il periodo di recessione, l'acquifero fratturato, più permeabile, si svuota più velocemente, soprattutto se in collegamento con un fiume. L'acquifero poroso superiore si svuota più lentamente. Al termine della stagione secca B, di solito in aprile, i due livelli piezometrici sono differenti od esiste solo quello inferiore. La situazione più frequente che si incontra è comunque quella che il pozzo n°1 è utilizzabile per un breve periodo di tempo 4-6 mesi, mentre il n°2 per tutto l'anno.

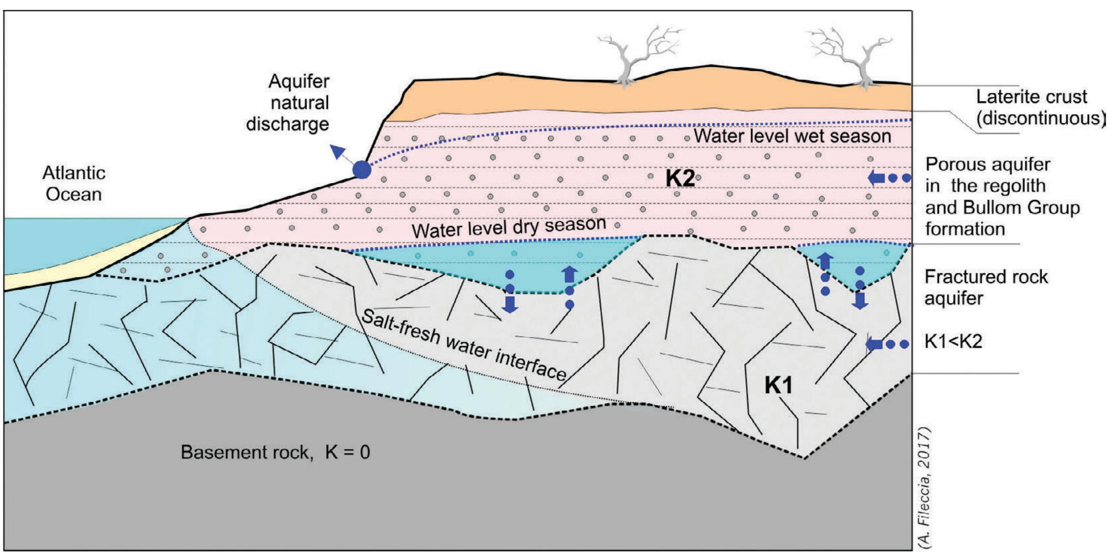

Fig. 10 - Simplified aquifer structure in the coastal zone of Sierra Leone. Example given is the Bullom Group formation near Lungi. The unconsolidated aquifer discharges naturally, not far from the Atlantic at the base of a long cliff. Here, the highest discharge rates have been noted (up to 6-7 l/s) during the recession period. In the dry season, several separated aquifers can be present due to the undulating morphology of the basement.

Fig. 10 - Struttura idrogeologica semplificata lungo la zona costiera della Sierra Leone. L'esempio si riferisce alla formazione d Bullom nei pressi di Lungi. L'acquifero alluvionale scarica le sue acque lungo le rive dell'Atlantico, alla base di una lunga parete. Le portate naturali raggiungono in certe zone 6-7 l/s (0,06 l/s/m), durante la fase di recessione. Nel periodo asciutto, causa l'abbassamento dei livelli piezometrici e l'irregolarità del letto, può verificarsi la presenza di molti piccoli acquiferi.

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aquifer below), often measured indirectly or obtained through a coefficient accounting for the type of unsaturated surface layer (potential infiltration coefficient). FAO (Aquastat) estimates Sierra Leone's total renewable water resources as 160 km3/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. Data for precipitation (P) puts the estimate at 2.5 – 3 m/yr (2500 – 3000 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 (Fig. 11).

Studies have shown that evapotranspiration rates vary from 30% to 90% 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 ground truthing. 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 30417 km^2 , the measured average flow is 24642 x 10^6 m^3/yr (1970 -1976). Extrapolating the runoff volume for all the country (71740 km^3), we assume a total runoff of 74000 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.

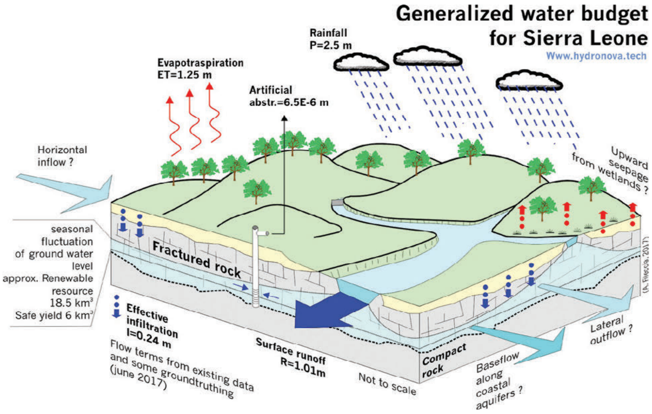

Fig. 11 - Generalized water budget for Sierra Leone. The very simplified block diagram was prepared coupling the available data with expert judgement. The effective infiltration, water entering the aquifer from the upper unsaturated soil, is almost equal to the seasonal variation in water table level, considering an overall specific yield of 0.05 and seasonal variation of 5 m. One of the main unknown is due to the widespread vegetation (high forest) contributing to maintain river flow, long after the end of the rainy season (2-3 months) thus extending the recharge period.

Fig. 11 - Schema generale del bilancio idrogeologico per la Sierra Leone. Il diagramma, molto semplificato, è stato preparato utilizzando i dati esistenti e valutazioni di vari casi studiati in campagna. L'infiltrazione efficace dallo strato insaturo superiore, è all'incirca uguale alla variazione annuale di livello piezometrico (5 m), con una porosità efficace di 0,05. Una delle incognite è dovuta alla vegetazione estesa che mantiene un'elevata umidità e quindi la persistenza dei corsi d'acqua e della ricarica, anche 2-3 mesi dopo la stagione delle piogge.

Conclusions and study limitations

The project described 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 maps, in combination with the associated SALGRID online database tool, serve as an important source of information by providing baseline hydrogeologic science in a concise user-friendly format.

Sierra Leone covers a total area of 71740 km^2 . Rain precipitation is between 2400 and more than 4000 mm/yr while surface river net is spread over the entire country. About 54000 km^2 (75-78%) are underlain by hydrogeologic systems that are classified as crystalline basement complex at an average depth between 10 and 80 m. Porous aquifers are the principal aquifers along the entire coastal area, while fractured ones prevail inland. A common figure for the specific yield is 0.05 and for transmissivity 3 to 6 m^2/d, while the borehole yield is in the range of 1 – 6 l/s, in accordance with the more general measurements obtained by other authors on the crystalline basement in Africa (MacDonald, 2000, 2002). Considering the many assumptions made, and applying a simple calculation method, the volume of total renewable groundwater resources in Sierra Leone is estimated to be

18.3 km^3, accounting for 0.25 m of recharge. 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. The most significant data limitations are in the following subjects: groundwater quality, borehole logs and yield, stream flow, hydrogeological parameter and aquifer monitoring . 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 specific areas. As a simple step to improve the conceptual model described so far it is advisable 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.

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