GROUNDWATER FOR REFUGEES (GW4R)

Pilot project Burkina Faso

GROUNDWATER FOR REFUGEES (GW4R)

- Pilot project Burkina Faso -

SUMMARY

Refugee crises require rapid access to safe water supply. Required information on water resources, especially groundwater, is often not readily available. To contribute to the UNHCR mission, IGRAC, as a global groundwater assessment centre, suggested to assist in the gathering and interpretation of data potentially useful for a rapid and effective assessment of groundwater resources in areas struck by a refugee crisis. For that purpose, a three-step methodology was developed that utilises regional and local scale data analysis & interpretation. The outcome of the methodology is an optimal location recommendation for in-situ groundwater development. Special attention in the methodology is paid to scale effect on data analysis and interpretation.

The GW4R (groundwater for refugees) methodology is tested on a pilot area (proposed by UNHCR and the University of Neuchâtel) in the Soum province in Northern Burkina Faso, along the border with Mali (Fig. 1). This report contains three main sessions: presenting the purpose of this work, the implementation of methodology, and the outcomes. The methodology proved to be sufficiently robust and straightforward for replication elsewhere without major modifications required, if any. The piloting also confirmed the importance of an organized knowledge base; new groundwater data cannot be gathered quickly but existing data & information need to be known, accessible, harmonized, and well-structured in advance of any urgent need for groundwater development.

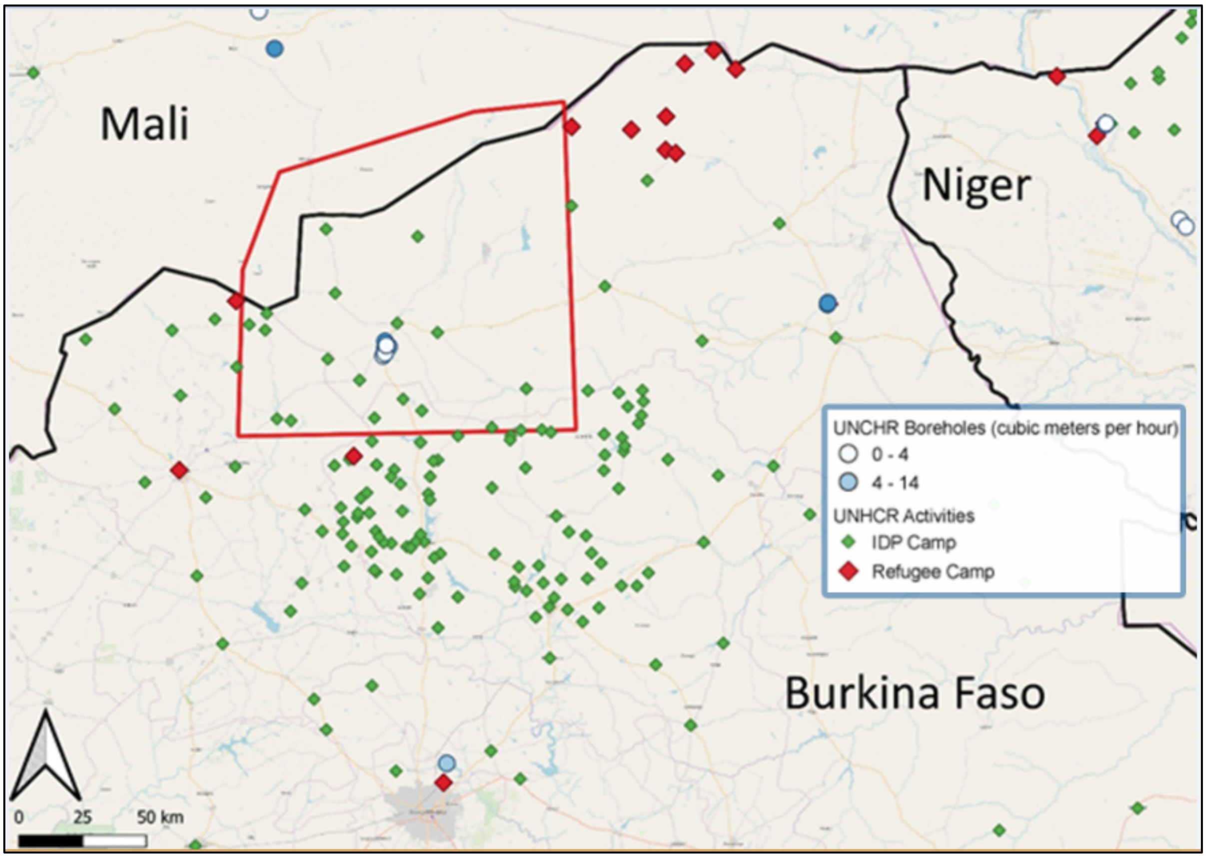

Figure 1 - Map of northern Burkina Faso with the pilot study area outlined in red. UNHCR Borehole yields are in m3/hour and UNHCR Activities are categorised as IDP (Internally Displaced People) Camp and Refugee Camp

TABLE OF CONTENTS

FIGURES

TABLES

1. RATIONALE

More than 68 million people worldwide have been forced to flee their homes at the end of 2017 as a result of persecution, conflict, poverty, violence, or human rights violations. Most are hosted by neighbouring developing countries where access to water is already a challenge. In emergency situations, immediate access to potable water is one of the most important considerations to refugee populations (UNHCR, 2018). To assist refugees, UNHCR has developed an Emergency Handbook (https://emergency.unhcr.org/) which includes guidelines for WASH interventions and thus an initial assessment of water needs and available water sources. Additionally, the University of Neuchâtel (CHYN) developed a methodology for rapid groundwater mapping in refugee settings, estimating water availability and potential demand. After initial consultations with UNHCR and CHYN, it appeared that IGRAC could contribute to these efforts, utilising its long-term experience in groundwater assessment. Accordingly, a close cooperation was established among these three organisations to ensure synergy of various approaches.

Availability of a local scale (i.e. the scale of groundwater development) data and information required for rapid groundwater assessment vary by location but is in general insufficient or lacking. Furthermore, accessing data can be time-intensive and data are often in formats that do not facilitate rapid analysis and interpretation (e.g hardcopies and excel files) necessary for a quick response to a humanitarian emergency. UNHCR has developed an on-line WASH portal containing georeferenced information on drilled boreholes and wells. There is a significant amount of regional hydrogeological information available, but it needs further refinement to serve as the basis for an assessment relevant to support UNHCR decisions on groundwater development in situ. This upscaling can be carried out for dedicated areas using additional/proxy information and local scale data. UNHCR's experience with refugee crises combined with IGRACs regional-to-local assessment experience, global groundwater information system (GGIS) and extensive international network, are advantageous for this kind of assessment.

The methodology developed by IGRAC outlines how groundwater potential zones can be identified through regional and field analysis. For that purpose, the methodology is split into three key steps: (i) a literature review on the groundwater resources in the specified area (sub-section 2.1); (ii) a regional analysis based on geology, precipitation, evapotranspiration, topography, UNHCR activities, roads network, land use, and potential groundwater contamination (sub-section 2.2); (iii) and a local analysis based on borehole yields, weathering thickness, drilling depth and groundwater level datasets (sub-section 2.3). The list of parameters used for regional and field-data analysis is not exclusive.

2. PILOTING THE GW4R METHODOLOGY

Accurate groundwater assessment for the purpose of groundwater development (usually involving borehole drilling) requires gathering a variety of data and information at the regional and local scale. Furthermore, in the context of a refugee crisis, the UNHCR criteria for water supply in camps needs to be taken in account. For example, the location of a new camp needs to be at least 15 km away from existing camps. WASH standards (water quality, boreholes' distance from the camp, access etc.) should be considered as well while estimating groundwater potential. Synchronised consideration of the political situation, available services and natural resources is essential.

2.1 Groundwater resources of Burkina Faso/Soum province

In Burkina Faso, groundwater challenges are often linked to a deficit or unequal distribution of water, agricultural pollution with pesticides, industrial and mining pollution, a lack of monitoring and a lack of awareness regarding the preservation of the environment. There is an urgent need to put in place measures to help preserve groundwater resources, especially in aquifers developed in the sedimentary rocks, where most of the water is exploited by industry and mining. Regarding the hard-rock basement aquifers, directed groundwater exploitation to ensure high yielding boreholes is essential as the resources are limited (World Bank, 2017). In addition, more than one million people are internally displaced and there are around 20,000 refugees (UNHCR 2020), adding pressure to the current challenges that the country is facing for sustainable use of groundwater resources.

Climate and hydrography

The climate in Northern Burkina Faso is categorized as semi-arid where more than 600 mm/y of precipitation is rare. It is an area characterized by a dry period from October to June, and a rainy month occurring mainly in August. The rainfall variability remains high spatially and temporally. Evapotranspiration (ETP) is highly correlated to the temperature variation and is maximal in June and minimal in December and January (DIRH, 1993).

Hydrographically, North Burkina Faso belongs mainly to the Niger basin with all the rivers being ephemeral, flowing from a few hours to 4 months maximum. The flow in many rivers is reducing due to the limited precipitation and high ETP intensity (DIRH, 1993).

Geomorphology

The country is flat with a mean altitude below 400m asl. Geomorphology reflects an ancient peneplane covered by weathered material whose thickness is largely defined by lithology. The plane surface is crowned in places with crusted entablatures 10 to 20 m high composed by laterite and saprolite with clay layers in the upper part of the saprolite at the top of the weathering profile.

Geology and Hydrogeology

In northern Burkina Faso, including the pilot area, the geologic formations are mainly Precambrian granite-gneissic or magmatic and volcano-sedimentary rocks. The granite-gneissic or magmatic formation is more specifically composed of migmatites and undifferentiated granites, and the volcano-sedimentary formation is mainly represented by schists (DIRH, 1993, World Bank, 2017) within the pilot area.

Close to the border with Mali, sedimentary formations of limestone and dolomites dated from the Precambrian to Cambrian-Ordovician and belonging to the sedimentary Taoudeni basin are found. Tertiary deposits from the continental terminal formation are also present in the north-western part of the pilot area. (Courtois et al, 2009, DIRH, 1993, World Bank, 2017).

Hydrogeologically, even though the sedimentary deposits have a higher groundwater potential, this zone is very conflicted by tensions with Mali and therefore the hard-rock aquifers are more of interest for this study. No detailed hydrogeological description was available at the pilot area scale. Nevertheless, based on DIRH (1993), the Precambrian granite-gneissic or magmatic system is the most important system in northern Burkina Faso, characterized by a weathering thickness that rarely surpasses 20m. Successful boreholes can be drilled at shallow depths (45 m) with water levels at less than 15m depth. In this system, the presence of orthose intercalation alone or linked with quartz dykes increases the change of successful drilling and should therefore be looked for in the field. In the volcano-sedimentary rock formation, the system presents a highly heterogeneous lithology. In this system, the weathering thickness is very important. Some layers/formations can be considered good reservoirs when fractured, but the presence of low permeability materials limits the productivity of this aquifers. Nevertheless, the presence of detritic intercalations and quartz dykes increases the potential of this reservoir. These two types of hard-rock aquifer correspond to fractured and discontinuous aquifers, with the productivity being closely linked to the presence of fractures and the nature of the hard rock. Indeed, the hard rock type leads to the development of specific fracturing and weathering that will lead to higher specific storage capacities and exploitation conditions (World Bank, 2017).

Based on the weathering profile of these two types of hard-rock formations, three overlaying systems can be found: a fractured system overlaid by a saturated weathered zone and the saprolite. Within these layers, the fractured bedrock, sometimes cut by quartz or pegmatitic dykes, is considered the most exploitable.

The saprolite is a shallow layer derived from prolonged in situ decomposition of the bedrock and is not viable for groundwater exploration due the drying up of this layer caused by climatic conditions (DIRH, 1993, World Bank, 2017). Weathered crystalline aquifer models from Africa and India (Dewandel et al. 2007) show that the fissured layers are the most permeable section of the aquifers and indicate that well productivity in hard rocks is linked to i) whether the well reaches the fissured layer and ii) the hydraulic conductivity of the fissured layer. Drilling in hard rocks in Africa should not continue beyond the fissured layer when considering drilling costs versus yield gain (Courtois et al, 2009). The study conducted by Courtois et al. (2009) concluded that in Burkina Faso the most productive section of the fissured layer in the hard-rock aquifers varies between 25 and 37 m depth.

There is an on-going debate on the importance of fractures and lineaments for groundwater potential. In Burkina Faso, numerous boreholes have been drilled based on the fracture and lineament development and have turned unsuccessful (Soro et al, 2017). Recent research highlights that effectiveness of borehole sitting in this context, lies on identification and study of the nature of the weathering profile rather than the fracture development. Soro et al. (2017) demonstrated that the value of hydraulic conductivity is likely linked to weathering processes as opposed to tectonic fracturing in this area.

Recharge and Discharge

Understanding recharge and discharge mechanisms is a key element in estimating areas of groundwater potential in the pilot area. These mechanisms are dynamic processes and their importance vary both spatially and temporally.

Based on DIRH (1993) three main types of recharge mechanisms have been identified in northern Burkina Faso:

- Direct recharge through homogeneous infiltration: in this system, precipitation infiltrates directly in the soils and slowly percolates to the aquifer.
- Direct recharge through preferred channel: rainfall percolates directly and quickly to the aquifer through fractures zones, quartz dykes or other conductive channels.
- Indirect recharge: in this system, the recharge occurs through runoff percolation in low topographical depressions. The recharge mechanisms can occur either through simple percolation through the soil, or though preferential channels as defined above.

It was found that the groundwater level is closest to the surface in the topographically lower areas (opposite to high slope where very little recharge occurs), making the low-lying lands the most viable areas for groundwater exploitation (DIRH, 1993, World Bank, 2017).

Regarding groundwater discharge, it occurs either by man-made abstraction, lateral groundwater flows or evapotranspiration. The quantity of groundwater abstracted represents only a small percentage of the groundwater discharge, making the ETP and lateral groundwater flow the main discharge mechanisms (DIRH, 1993).

Groundwater development in northern Burkina Faso

Various hydrogeological exploration methods have been successfully used in Burkina Faso to guide groundwater development, especially the boreholes in hard rock aquifers, achieving yields of 10-50 m3/h. The applied methodology consists of identification of faults systems and lineaments on aerial images, the lineaments' density via satellite images and the use of surface geophysical methods (electric, electro-magnetic and RMP) to verify air-born estimations (World Bank, 2017). Broad applicability of this approach is questioned by Soro et al (2017), claiming that borehole sitting should focus on analysis of weathering profiles rather than tectonic fracturing.

Although the use of surface geophysical surveys can be very valuable to determine groundwater potential zones, certain lithological characteristics can limit their potential (DIRH, 1993). On granitic bedrock, when the weathering thickness is less than 20m, using geophysics for the identification of fractures is unnecessary since the fractures are visible at the surface or via aerial images. However, between 20 and 40m these ground methods are very useful, while deeper than 40m limited information can be retrieved using geophysics. On the other hand, geophysics can be very useful to determine clayey and impermeable areas weathering profiles. Since geophysical investigations in geological formation of northern Burkina Faso were conducted, there have been advancements in geophysical methods. This could be considered as an option to collect further data if desirable.

2.2 Regional analysis

Datasets used to carry the regional assessment are listed in Table 1. The table contains the UNHCR criteria for refugee setting and various environmental variables.

UNHCR Criteria				
Criteria	Description	Dataset	Resolution	Conditions
UNHCR Activities	Refugee and internal displacement population (IDP) related activities	UNHCR	n.a.	>=15km away from other refugee/IDP camps
Roads	Open data for roads	OpenStreetMaps by Geofabrik	n.a.	<= 1km
Population	Spatially distributed population density	High Resolution Settlement Layer (HRSL)	30 m	
Environmental and Geographic Variables				
Variable	Description	Dataset	Resolution	Conditions
Evapotranspiration	Mean annual data from 2019	WaPOR (2018)	250 m	n.a.
Precipitation	Mean annual data from 1981 to 2018.	CHIRPS	~5 km	n.a.
Lithology	African lithologic information	BRGM lithologic data	1:10 M	n.a.
Elevation	Elevation data for a Digital Elevation Model	Shuttle Radar Topography Mission (SRTM)	30 m	Slope: 2-5 degrees
Land Cover	Land cover classification	Africa Land Cover 2016	20 m	n.a.
Streams	Stream by order	HydroRivers by the HydroSHEDS project	n.a.	n.a.
Arsenic	Map of potential zones of Arsenic over 10um	Bretzler et al, 2017	~5 km	n.a.

Table 1 - UNHCR criteria and environmental variables used in the analysed within the pilot area

QGIS in combination with Topo Toolbox was used for the regional analysis. Firstly, the regional lithologic and climatic (precipitation and evapotranspiration) information was used to indicate preferable areas for drilling the boreholes as per prior UNHCR investigations. However, no significant spatial variance was identified in these two regional datasets (Fig. 2), and thus other relevant hydrogeologic and geographic metrics needed identification to suggest areas where UNHCR could drill the boreholes in Northern Burkina Faso.

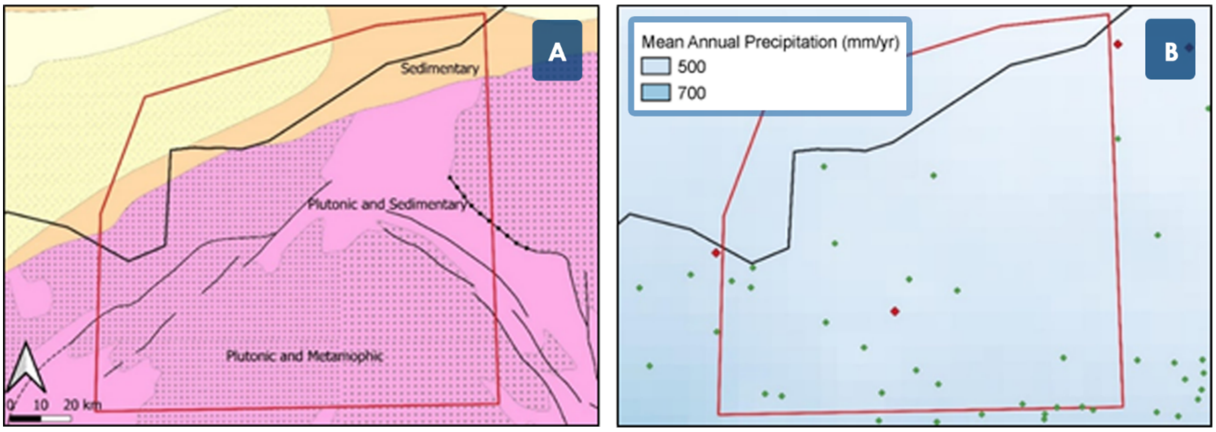

Figure 2 - A- main geological formations in the defined study area and B – Precipitation (mm/yr)

Because the UNHCR handbook on rapid environmental assessment for refugee situations explores areas of 15 x 15 km to build new camps, the resolution of the study was increased so that the findings would be relevant at scales necessary to inform a well sitting campaign (UNHCR, 2009). Areas near perennial surface water were avoided as they represent potential zones that could be contaminated through refugee camps. Zones with the potential for arsenic contamination were disregarded as groundwater quality might be poor. Furthermore, to ensure that the ground water was uncontaminated with nitrates, a population density map was used to select areas away from settlements and farmed land (BGS, 2002). Regional scale data on arsenic contamination of groundwater resources and population density informed decisions as to where a focus should be within the study area, but these data lack resolution to sit wells for a 15 x 15 km area. Finally, areas with roads were selected as per UNHCR criteria.

Based on the regional spatial analysis and in order to use the maximum data available, a focus area slightly larger than requested, of 20 x 20 km, was identified (Fig. 3) to estimate the most adequate locations for groundwater development in the given conditions of refugee crisis.

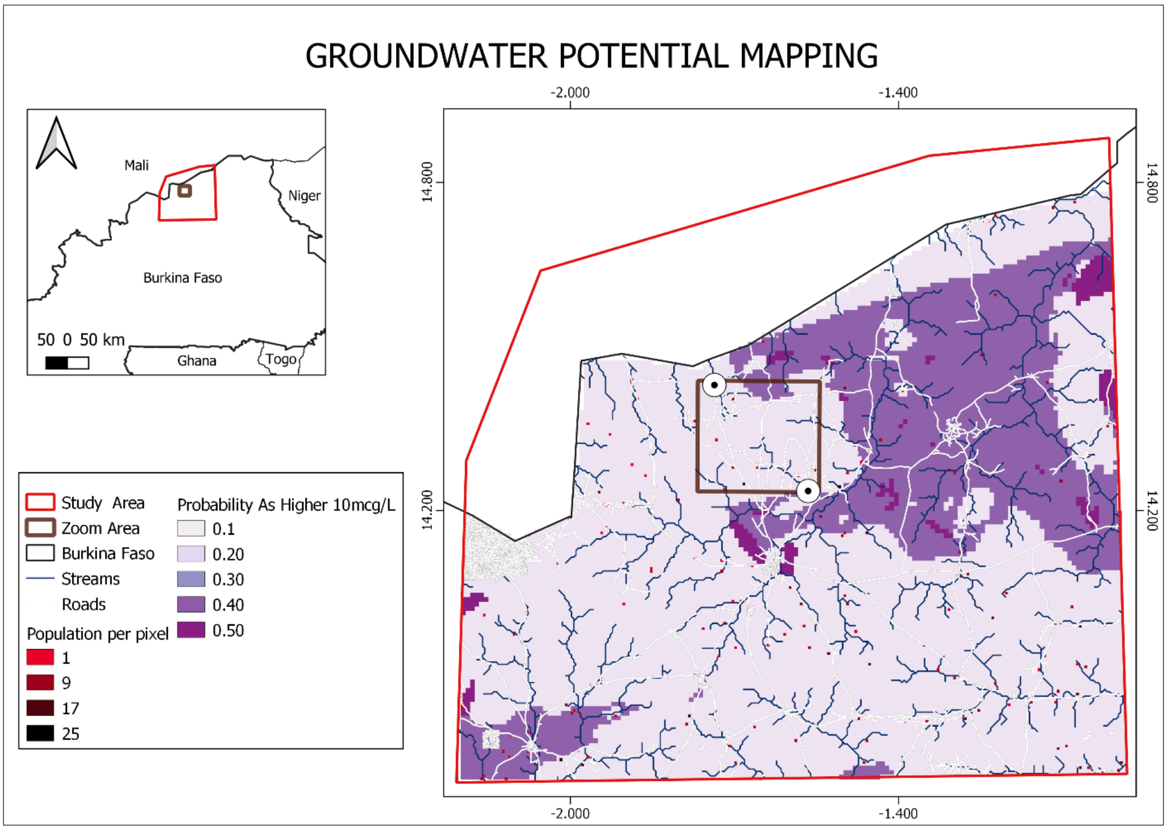

Figure 3 - Focused area defined after a macro special analysis of the described variables before

Within the selected "local" area, the data analysis focused on mapping the roads, land use and topographic features to determine potential zones for future wells. Areas within 1 kilometre of an existing road were chosen to guarantee rapid access for well drillers (UNHCR, 1992; UNHCR, 2009). A land use map was used to assess the potential of agricultural pollution and to identify potentially vacant areas. In addition, only areas on gentle slopes of 2-5 degrees were considered, as per the UNHCR rapid environmental response handbook. This study identified areas at least 15 km away from all existing camps as per UNHCR recommendations.

Finally, the SRTM 30 m digital elevation model was used to identify erosional geomorphic features within ephemeral channels. Areas with low levels of erosion are more permeable therefore allow more recharge to occur, making them a more suitable area for groundwater exploitation. *Topo Toolbox* was used to generate longitudinal stream profiles and chi plots of ephemeral channels within the small study area. Chi plots assist in detecting erosional signals in the landscape. Erosional features can be detected where the plot steepens. Two areas were identified as potential areas for further groundwater exploration (Fig. 4).

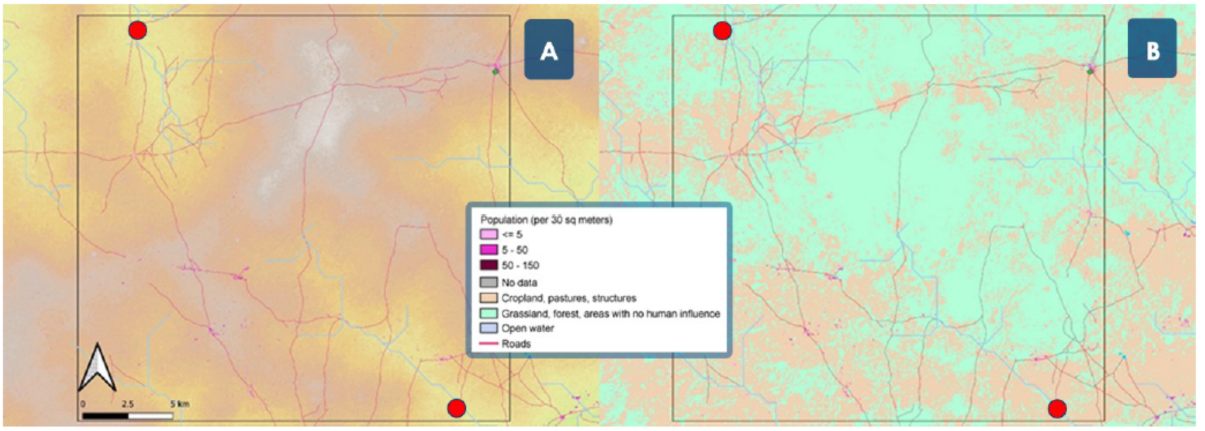

Figure 4 - Upscaling of areas where to have hydrogeological investigations. A – Location of the site relative to elevation and B relative to land cover

Both sites are on slopes of 2 to 5 degrees, do not have any significant human activity (including agriculture) in the vicinity, are near the roads, lack erosional features, and are more than 15 km from other UNHCR refugee or IDP sites. The site in the South East has a slightly larger drainage area relative to the other site located in the North West. This suggests the potential for more surface water, and therefore more groundwater recharge. However, the area in the North West has less farm and pastureland surrounding it.

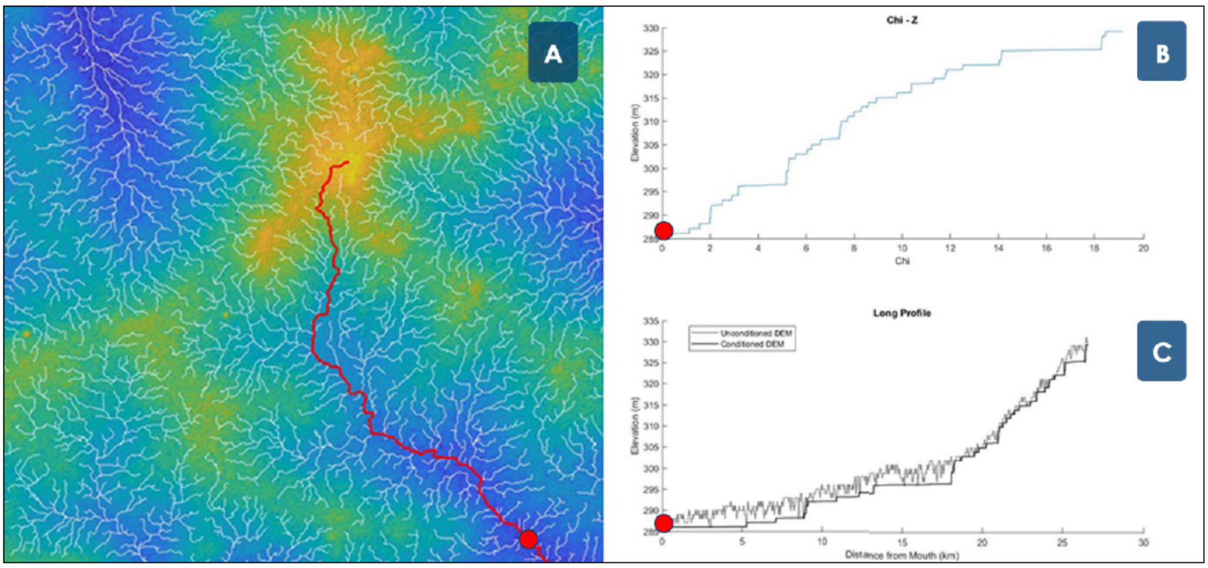

Figure 5 - A) A topographic map of the study area with the example stream channel in red and a red point denoting the proposed well location. The scale in this map is the same as in figure 4. B) A chi profile and C) stream profile showing that c channel steepen

The expected depth to the fissured, water bearing, layer at the proposed well site in the South is approximately 25 – 27 m, while in the North it is 27 – 31 m (Courtois, 2010). Within hard rock aquifers in Northern Burkina Faso, the depth to the more productive weathered zone is generally between 25 and 37 m. The saprolite in valleys cut by stream channels is likely more thin and fractured aquifers therefore lie closer to the surface.

2.3 Local analysis

A field dataset was received from ECOWAS, IGRAC's focal point in Burkina Faso. It comprised of data on boreholes construction as well as pumping test data from the North and East Province. 740 boreholes were located within the study area, not all of them with a complete dataset. Only variables with data available for most boreholes were used. Variables with erroneous data values (e.g. -1,0 or null values) were disregarded. The data used for the field analysis are listed in Table 2 below.

Variable	Unit	Number of BH with data
Thickness of the weathered zone	m	671
Borehole yield	m3/h	683
Total drilling depth	m	711
Groundwater level (after drilling)	m	418

Table 2 - Variables considered and number of boreholes in the study with valid values for each specific variable

Field data, specifically the thickness of the weathered zone, total drilling depth and water level after drilling were mapped with QGIS and classified using a Jenk's natural breaks classification. For the borehole yield the same classification as the one used in the work developed by the University Neuchâtel was applied. The Jenks Natural Breaks Algorithm divides data in classes based on the natural grouping inherent in the data. Data are thus organized in groups of similar values and boundaries break the set where big differences exist (ArcGIS, 2020). The variance within each class is minimal while the variance between classes is maximal (QGIS, 2020).

The borehole yield was classified in function of the type of pump to be installed and water demand. In the approach developed by the University of Neuchâtel, one of the specific requirements for groundwater mapping was that boreholes produce sufficient yield to install motorized systems as requested by UNHCR. Table 3 summarizes the ranges used to classify the field data with the Jenks natural breaks classification and Table 4 with the University of Neuchâtel classification.

Total drilling depth (m)	Weathered zone thickness (m)	Water level after drilling (m)
5 - 53	1-19	2 - 17
53 - 74	19 -38	17 - 30
74 - 132	38 - 81	30 - 62

Table 3 - Field data classified with the Jenks Natural Breaks Algorithm

Yield range (m3/hour)	Water supply potential	Water supply option
0.5-5	Low	Hand-pumps
5-10	Medium	Small motorized systems
>10	High	Large motorized systems

Table 4 - Table 4 – Borehole yield classification in function of the type of pump to installed, University of Neuchâtel classification

Once selected and classified, borehole field data were mapped (Fig. 6) and a spatial analysis carried out. Through this field study, the accuracy of groundwater potential assessment at a local scale was improved. The selected variables provide following insights in groundwater potential:

- Weathered zone thickness is an indicator of a groundwater storage in hard-rock formations; The analyses of this variable should be complemented with the analysis of fractures zones (in this case no local structural maps were available).
- Borehole yields are direct indicators on the groundwater potential and is a key variable for this assessment.
- Groundwater level and total drilling depth are parameters that are useful while in the field for borehole drilling carried out by drilling and hydrogeologist teams.

At the pilot area scale, boreholes are located mostly along ephemeral streams, restricting this borehole analysis to those areas; this because higher recharge (Section 2.1) occurs at lower elevation, downstream and in zones of lower slope (DIRH, 1993). However, data are scattered and a correlation among variables is not obvious, which is common for hard-rock aquifers.

It appears that wells located in volcano sedimentary formations and in main tectonic structures (SW-NE) have higher yields. However, other factors (e.g. drilling stopped once sufficient yield for hand pumps was achieved) could be causing lower yields to be found in other formations.

Within the pilot area the thickness of the weathered zone varies between 1 and 81m, borehole yields between 0 and 22m3/h, total drilling depths between 5 and 131m and depth to groundwater level between 2 and 62 m. There is no obvious link between higher borehole yields and thicker weathering zones. Therefore, the nature of the weathering should be further investigated using geophysical surface methods. In some areas where regional analysis indicates potentially high yields are high, other criteria are not satisfied such as the presence of arsenic or high population density.

The two sites suggested for borehole drilling in the regional analysis (section 2.2) are in an ephemeral streambed and downstream, have shallow slopes and high levels of groundwater recharge (Fig. 4).

Only two boreholes (yields between 0.5 and 5 m3/h) are located nearby the suggested site in the north-western part of the focus area (Fig. 7). Data from only two boreholes were available upstream. Along the south-eastern location, more data are available along the stream. Borehole yields on the volcano-sedimentary formation presented water levels above 20m and borehole yields between 5 to 10m3/h. On the outer zone of the focus area, in the S-E corner, and along the main faults and stream channel borehole yields exceed 10 m3/h (Fig. 6). However, borehole sitting in these outer sites is not recommended as high levels of arsenic have been reported (Fig. 3). Furthermore, the SE site is at the contact area between the granitic formation and the volcano-sedimentary formation (Fig. 7) which entails a higher fractured development and thus a specific location to look for once in the field.

A geophysical investigation to identify highly fractured local zones would be beneficial to identify the fractured bedrock which is considered the most productive layer of a granitic or volcano-sedimentary weathering profile. Other field data showed that at this selected site, the total drilling thickness varied mainly between 41 and 70 m with a weathering thickness between 12 and 22 m making this area a more optimal zone for drilling (Fig. 7). Based on the literature survey, fractured bedrock should be focused on to increase the chances of success for borehole sitting. However, a lack of borehole logs in this area will make it difficult to identify the geological strata that is exploitable. Through this spatial analysis, the S-E site identified with the regional analysis can be confirmed as a preferred groundwater potential zone to explore for borehole sitting and geophysical investigation. A field study would allow for confirmation of this conclusion.

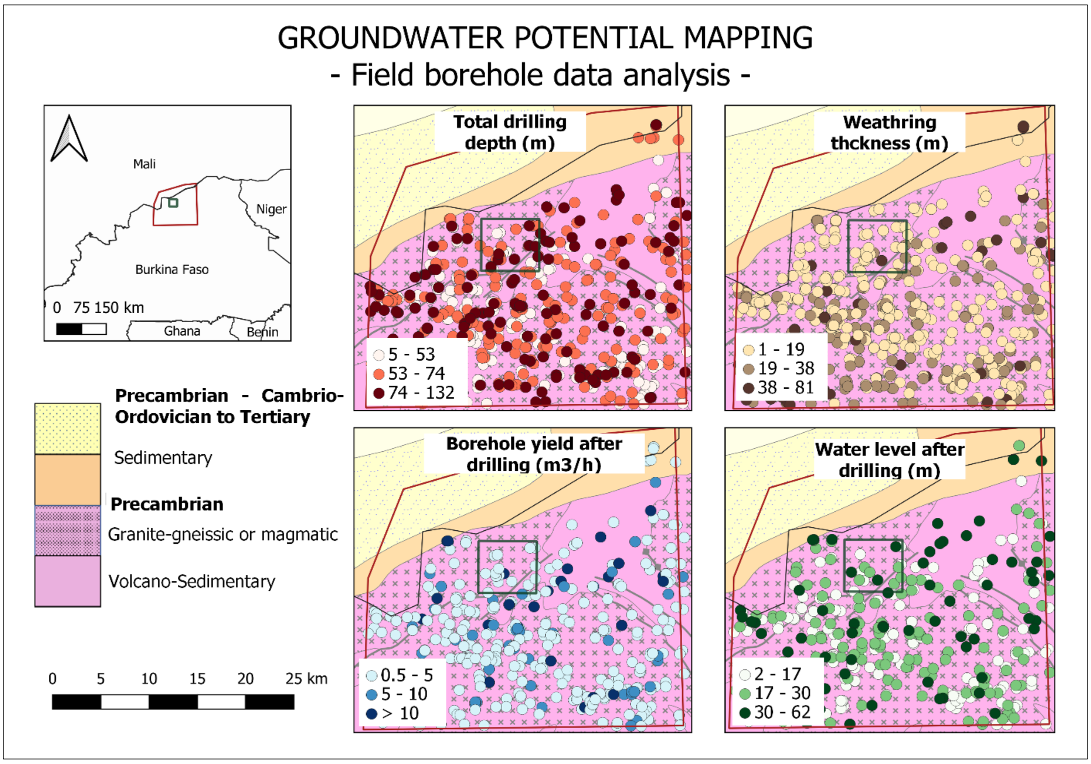

Figure 6 - Mapping and spatial analysis of boreholes data in the pilot area

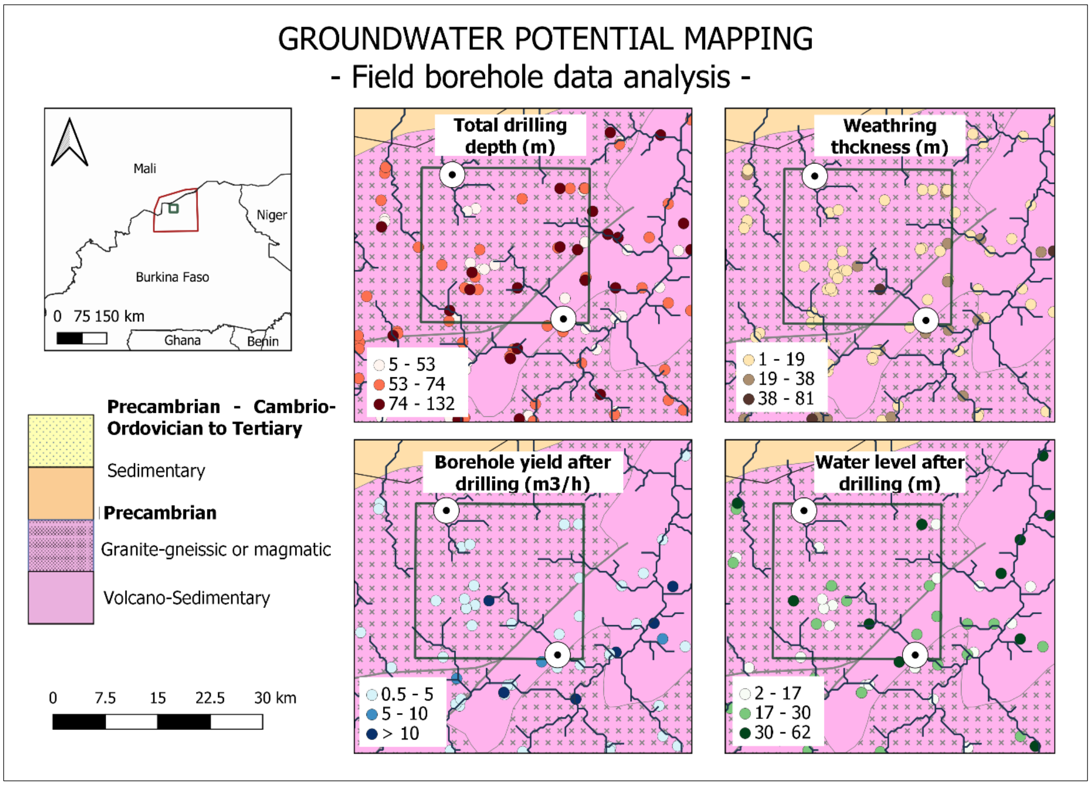

Figure 7 - Mapping and spatial analysis of boreholes data in the focus area

3. CONCLUSION AND FUTURE WORK

An effective and rapid groundwater assessment requires a wide variety of information and data at the regional and local scale alongside the integration of regional and field data analysis to provide a useful assessment for borehole sitting and geophysical investigation. This pilot study conducted by IGRAC in Burkina Faso provides a methodology aimed at improving the understanding of how different type of data can be used to assess for rapid groundwater assessment in a refugee's context for UNHCR. This methodology is free, open source, and can be replicated elsewhere.

Within the 20 by 20 km window, two sites were proposed using regional data as the best locations to explore for groundwater. Field data then suggested the site in the south east corner to have greater potential for borehole siting and geophysical investigation. Here, data from surrounding boreholes showed yields above 5 m3/h and thus suitable for the implementation of motorized pumps. Analysis of field data also highlighted that the previously studied linkages between weathering thickness and borehole yield do not necessarily correlate. It was not possible to analysis correlation between fracturing and borehole yield due to limited geological structural mapping in the area. This made it difficult to identify fracture zones of interest for further geophysical investigations. Soro et al. (2017) demonstrated that the value of hydraulic conductivity in this area is likely linked to weathering processes as opposed to tectonic fracturing and as such, we suggest that geophysical investigation in the SE corner of the area focus on assessing the weathering profile, lithology, and the fractures and lineaments that have developed in the rock to determine the most optimal location for borehole sitting.

This pilot highlights the need to consider a variety of data sources and scales. In the future, more data could be acquired to refine predictions. Reaching out to local governments, companies, and relevant institutions for data is recommended. Investigation into how seasonality and climate change could affect the interpretations in this study should also be explored. Finally, investment in new technologies like remote sensing, airborne geophysics, data interpolation and geo-statistical analysis methodologies could help increase the accuracy for successful borehole sitting.

As a final comment, the UNHCR criteria and conditions for water resources assessment (in particular water supply infrastructure requirements), could be better adapted to reflect the complexity of groundwater systems without compromising water supply safety in emergencies.

4. REFERENCES

ArcGIS, 2020. Retrieved from https://pro.arcgis.com/en/pro-app/help/mapping/layer-properties/data-classification-methods.htm#ESRI_SECTION1_B47C458CFF6A4EEC933A8C7612DA558B

BGS, Groundwater Quality Information Burkina Faso (2002). Retrieved from http://earthwise.bgs.ac.uk/

Bretzler, A., Lalanne, F., Nikiema, J., Podgorski, J., Pfenninger, N., Berg, M., & Schirmer, M. (2017). Groundwater arsenic contamination in Burkina Faso, West Africa: Predicting and verifying regions at risk. Science of the Total Environment, 584–585, 958–970. https://doi.org/10.1016/j.scitotenv.2017.01.147

Chilton, P.J., and S.S.D. Foster. 1995. Hydrogeological characterisation and water-supply potential of basement aquifers in tropical Africa. Hydrogeology Journal 3, no. 1: 36–49.

Clark, M. P., Nijssen, B., Lundquist, J. D., Kavetski, D., Rupp, D. E., Woods, R. A., … Rasmussen, R. M. (2015). Water Resources Research. 2498–2514. https://doi.org/10.1002/2015WR017200.A

Courtois et al., 2010 N. Courtois, P. Lachassagne, R. Wyns, R. Blanchin, F.D. Bougaïré, S. Somé, A. Tapsoba Large-scale mapping of hard-rock aquifer properties applied to Burkina Faso Ground Water, 48 (2) (2010), pp. 269-283

Dewandel, B., Gandolfi, J.-M., Zaidi, F.K., Ahmed, S., Subrahmanyam, K. 2007. A decision support tool with variable agro-climatic scenarios for sustainable groundwater management in semi-arid hard-rock areas. Current Science 92, 1093–1102.

Elbeih, S. F. (2015). An overview of integrated remote sensing and GIS for groundwater mapping in Egypt. Ain Shams Engineering Journal, 6(1), 1–15. https://doi.org/10.1016/j.asej.2014.08.008

Fan, Y., Li, H., & Miguez-Macho, G. (2013). Global patterns of groundwater table depth. Science, 339(6122), 940–943. https://doi.org/10.1126/science.1229881

Gleeson, T., Marklund, L., Smith, L., & Manning, A. H. (2011). Classifying the water table at regional to continental scales. Geophysical Research Letters, 38(5), 1–6. https://doi.org/10.1029/2010GL046427

MATLAB based software for topographic analysis. *https://topotoolbox.wordpress.com/*

Ministère de l'Eau Direction de l'Inventaire des Ressources Hydrauliques (DIRH) & Directorat General de la Cooperation au Développement (DGIS). (1993). *Notice explicative de la carte hydrogeologique du Burkina Faso, echelle 1:500.000*. Ministère de l'Eau Direction de l'Inventaire des Ressources Hydrauliques (DIRH). https://edepot.wur.nl/488047

QGIS, 2020. Retrieved from
Https://docs.qgis.org/3.10/en/docs/user_manual/working_with_vector/vector_properties.html?highlight=jenks

Soro, D. D., Koïta, M., Biaou, C. A., Outoumbe, E., Vouillamoz, J. M., Yacouba, H., & Guérin, R. (2017). Geophysical demonstration of the absence of correlation between lineaments and hydrogeologically usefull fractures: Case study of the Sanon hard rock aquifer (central northern Burkina Faso). Journal of African Earth Sciences, 129, 842–852. https://doi.org/10.1016/j.jafrearsci.2017.02.025

Tirogo, J., Jost, A., Biaou, A., Valdes-Lao, D., Koussoubé, Y., & Ribstein, P. (2016). Climate variability and groundwater response: A case study in Burkina Faso (West Africa). Water (Switzerland), 8(5), 1–20. https://doi.org/10.3390/w8050171

UNHCR. (2018). *Forced displacement at record 68.5 million.* Retrieved from https://www.unhcr.org/news/stories/2018/6/5b222c494/forced-displacement-record-685-million.html

United Nations High Commissioner for Refugees (UNHCR). (1992). *Water Manuel for Refugee Situations.* Retrieved from https://www.unhcr.org/publications/operations/3ae6bd100/unhcr-water-manual-refugee-situations.html

United Nations High Commissioner for Refugees (UNHCR), & CARE. (2009). *FRAME Toolkit: Module III Rapid Environmental Assessment. FRAME Toolkit: Framework for Assessing, Monitoring and Evaluating the Environment in Refugee-Related Operations.* Retrieved from http://www.unhcr.org/4a9690239.html

World Bank. (2017). *Amelioration de la connaissance et de la gestion des eaux au burkina faso - p162723.* Retrieved from http://documents1.worldbank.org/curated/ar/445991522099361916/pdf/Rapport-de-Synthese.pdf

Westvest 7
2611AX Delft
The Netherlands

T:+31 15 215 2325
E: info@un-igrac.org
I: www.un-igrac.org