Department of Earth and Environmental Sciences
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Integration of hydrogeological investigation, remote sensing and terrain modeling for the analysis of shallow aquifers in West Africa and the identification of suitable zones for manual drilling

Phd dissertation

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This research is dedicated to the warm, friendly people met in the villages of Guinea and Senegal in the last years. I received many lessons meeting them. I hope that this study can support their struggle to have adequate water supply, especially in those areas where the outbreak of Ebola worsened dramatically their situation. I look forward to reach them again in the next years.

Acknowledgement

25 years ago, as a young student, I start my dream to mix science and exploration in Africa with Roberto, in Mali. And now I am still here, exploring the geology of Sahel, with him. I was surprised that after many years doing international cooperation in Africa, I went back to the University. sharing this new adventure and receiving support from Roberto and Tullia (who was hunting ancient glaciers with me not in Africa, but in the Alps); this was an important aspects of my return to the University after so many years.
I acknowledge the support of the staff of the university for the implementation of the research project in Africa, prof. Marco Vighi who coordinated the PhD and Prof. Pierre Perrochet who was ready to advise me during the progress of this study.

But other friends and colleagues of past years shared with me this adventure. Cheikh and Barry supported me during my work in Senegal and Guinea and shared my wonderful experience when we worked for the UNICEF program of manual drilling; their presence showed me different lights about the personality of Western Africa and taught me a lot. They were the key persons who made possible to find good partners in their country and thanks to them that this project could be arranged. I am grateful to the staff of UCAD and SNAPE who collaborated in the different activities.

In Italy different persons supported me in the research and shared part of this adventure: Letizia arrived in this research only in the second phase, but she was not only deeply appreciated by me, but she became soon a symbol of strength and smile among the team in Senegal. Francesco went to Senegal with me only at the beginning, but then he was always present, supporting me with advise and mumble, always appreciated. Biagio put his energy in the exploration of statistics between satellites and boreholes, a difficult story. Tommy was modeling the growth of trees in the desert. And all the remote sensing lab, it means Marco Micol Cinzia Sergio Chiara Roberto, Claudio. Thanks very much for your effort and continuous support.

Other friends also participated with their contribution. Margherita with complex procedures of morphometric analysis, Marta tried as much as possible to transfer her deep knowledge of statistics, Silvia was present, physically distant, from Portugal, but always in contact,; Giuseppe from his new life in London, and my sister Cristina with her revision of translation.
In the last part of the project, a great support in the dissemination of the project was provided by a volcanic Kerstin Danert and the UNICEF group in New York (Jose Gesti Canuto) and in the regional office in Dakar (Kelly Naylor and Kadjo Dao). Thanks very much for your effort.
The presence of my family and friends was essential to encourage me to go on with this research.
This project was possible thanks to NERC that financed all this project, and I want to acknowledge their essential support

Abstract

In several countries of the World the situation of access to improved water sources (supplying an adequate quantity and protected from contamination) is still critical. In this context UNICEF is promoting manual drilling as a suitable low cost technical solution to increase the use of groundwater.

Manual drilling refers to several drilling methods that rely on human energy to construct a borehole and complete a water supply. These techniques are cheaper than mechanized boreholes, easy to implement and able to provide clean water if correctly applied. Unfortunately manual drilling can be used only in areas where formations are quite soft and groundwater is relatively shallow. Mapping of suitable zones has been carried out in several countries in Africa, but previous methods are based on a qualitative approach, depending from availability of data and not structured.

The main aim of this research is to develop an improved methodology for the characterization of shallow geological conditions and for the identification of suitable zones for manual drilling, by integrating the analysis of existing information from water point database with parameters derived from remote sensing and terrain modelling.

This study has been carried out in two different areas, in Senegal and Guinea (West Africa), in the framework of the UK funded project "Use of remote sensing and terrain modeling to identify suitable zones for manual drilling in Africa and support low cost water supply", within the scientific cooperation of partners from Italy, Senegal and Guinea.

The first part of the research focused in the definition of a well-structured and semi-quantitative conceptual model to estimate suitability for manual drilling, based on the knowledge of depth of water, depth of hard rock, thickness of lateritic layers and hydraulic transmissivity of shallow aquifer.

In the second part this conceptual model has been applied in the two study areas

A specific software (TANGAFRIC) to process borehole data has been elaborated, taking into consideration the existing water point database in both countries and the experience of stratigraphic analysis with software TANGRAM at University Milano Bicocca.

Using TANGAFRIC with a procedure of manual codification of stratigraphic data and automatic analysis, it was possible to estimate hydro-geological parameters of shallow aquifer at borehole positions. In the mean time a set of variables have been obtained from three categories of data:

- geology, geomorphology, soil and land cover, obtained from existing thematic maps;
- vegetation phenology, apparent thermal inertia, and soil moisture, obtained from analysis of multitemporal optical and thermal satellite MODIS data and radar (ASAR) data;
- morphometric parameters, obtained from public digital elevation models (ASTER GDEM).

These variables have been combined using multivariate statistical methods in order to evaluate their relationship with hydrogeological parameters obtained from borehole data: this analysis allowed to extrapolate the information about geometry and hydraulic parameters of shallow exploitable aquifers with manual drilling from borehole position to the whole study area, and finally identifying those zones with potentially suitable conditions.

The final result of this research was a comprehensive mapping of suitable zones for manual drilling in the regions under study. The maps thus produced are important tools for a correct planning of water programs by UNICEF and local institutions.

The proposed methodology allows the integration of layers of information available in each region that show meaningful relation with those parameters required for the evaluation of suitability for manual drilling (R2 = 0.73 with groundwater depth in Senegal), therefore they can improve the interpretation of shallow hydrogeological context. Furthermore the software TANGAFRIC could be a valid support to local institutions for the organization and analysis of hydrogeological data.

Table of contents

LYST OF ACRONYMS

DFID: Department of International Development of UK Government
DGIS: Directorate-General for International Cooperation of Dutch Government
DGPRE: Direction de la Gestion et de Planification des Ressources en Eaux (Senegal)
EW: Enterprise Works
PEPAM: Programme d'eau potable et assainissement du Millénaire
RWSN: Rural Water Supply Network
SKAT: Swiss Resources Centre and Consultancies for Development
SGPRE: Service de Gestion et de Planification des Ressources en Eau
SNAPE: Service Nationale de Points d'Eau de Guinée
UCAD: Université Cheik Anta Diop - Dakar
UNICEF: United Nations International Children's Emergency Fund

Chapter 1. Introduction

In 2000 United Nations (UN) formulated the Millennium Development Goals (MDG), a series of 8 targets covering different aspect of human living condition that all the members of UN committed to achieve before 2015. One of this target (MDG nr. 7) concerned environmental sustainability and included a specific target for water and sanitation (7.C: halve the number of people without safe access to drinking water and sanitation).

From that declaration, over 2 billion people have gained access to improved sources of drinking water, and 116 countries have met the MDG target for water. Despite strong overall progress, 748 million people still did not have access to improved drinking water in 2012, 325 million (43%) of whom live in sub-Saharan Africa. (WHO/UNICEF, 2014).

Groundwater has proved the most reliable resource for meeting rural water demand in sub-Saharan Africa. It can derive from the exploitation of different type of aquifers: basement (and weathering layer), volcanic rocks, sedimentary rocks, unconsolidated sediments.

Unconsolidated sediments cover 22% of South Saharian Africa, and at least 60 million people in rural areas obtain water from this type of aquifer (MacDonald and Davis, 2000).

Justification of the research

In the framework of the Program for the achievement of MDG (Millenium Development Goals) for water supply, UNICEF is promoting manual drilling throughout Africa, with different activities: advocacy, mapping of suitable zones, technical training and institutional support.

Manual drilling refers to those techniques of drilling boreholes for groundwater exploitation using human or animal power (not mechanized equipment). These techniques are well known in countries with large alluvial deposits (India, Nepal, Bangladesh, etc). They are cheaper than mechanized boreholes, easy to implement as the equipment is locally done, able to provide clean water if correctly applied.

But manual drilling is feasible only where suitable hydrogeological conditions are met:

- the shallow geological layers are not too hard (soft sediments or rocks having limited resistance) and have good permeability;
- the depth where it is possible to find exploitable water is limited

For this reason mapping of suitable zone for manual drilling has been one of the first step in UNICEF program. The identification of suitable zones resulted extremely important to optimize the following steps; in particular to define whether in a specific country the introduction of manual drilling in the national water strategy could have contributed to improve water access and, in this case, determine those zones with highest priority in terms of potential results of manual drilling and uncovered needs of the population; here the national water authority and UNICEF had to concentrate the following activities aiming to create new water points and local capacity to implement manual drilling at high quality standard.

The activity of identification of suitable zones for manual drilling at country level has been already completed by UNICEF in 15 African Countries, between 2008 and 2012 (almost all report and maps can be found in the website of UNICEF (http://www.unicef.org/wash/index_54332.html.
On the basis of the results of these studies, different countries have run the following steps of the program of promotion of manual drilling (technical training, institutional support and advocacy, provision of equipment for manual drilling and financial support to construction of water points).

The method for the identification of suitable zones at country level in the main study conducted in Africa (UNICEF, from 2008 to 2013) is based on the analysis of existing hydrogeological data (in form of maps, report, national database of water points); all these sources of information are compared with qualitative information coming from meetings with local experts having direct field experience and limited field survey

The method that has been used has some aspects to improve:
- The definition of a more structured and semi-quantitative approach in the definition of suitability for manual drilling;
the needs to downscale the analysis, from a general identification of potentially suitable regions to a more precise identification of drilling locations in those areas classified with high potential;
- The integration in the procedure of other sources of data that can give indirect information on shallow geology in those zones where direct data coming from existing boreholes or detailed geological studies are limited.

This research aims to give specific contribution to the improvement of this method. It has been developed as part of the project entitled "Use of remote sensing and terrain modelling to identify suitable zones for manual drilling in Africa and support low cost water supply"; it is financed by

NERC (National Environment Research Council, UK) in the framework of the program UPGRO (Unlocking the Potential of Groundwater for the Poors), with the collaboration of different partners from Italy, Senegal and Guinea.

Objectives

The main aim of this research is to develop an improved methodology for the characterization of shallow geological conditions and for the identification of suitable zones for manual drilling, by integrating the analysis of existing information from water point database with parameters derived from remote sensing (optical, thermal and radar data) and terrain modelling.

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Study area

Two study areas have been selected for this research, in Senegal and Guinea (Figure 1). The study area in Senegal corresponds to the administrative region of Louga, in the north-western sector of the country, while the area in Guinea has been selected in the eastern part of the country, between the regions of Kankan and Faranah.

Both study areas have been selected taking into consideration the existence of potentially suitable zones for manual drilling, as indicated in previous study for the identification of suitable zones (Kane et al, 2013 GRAIA, 2012; Fussi et al., 2014a). Furthermore the study area in Guinea has high priority for the implementation of manual drilling in the country promoted by UNICEF and SNAPE.

Country	**Description**	**Latitude (min/max)**	**Longitude (min/max)**	**Extension (square km.)**
SENEGAL	Administrative region of Louga	14.5 / 16.2 N	-16.7 / -14.2	29909
GUINEA	Selected area in Kankan and Faranah regions	9.1 / 10.4	-10.7 / - 9.4	15444

Table 1 ***Study areas in Senegal and Guinea – general information***

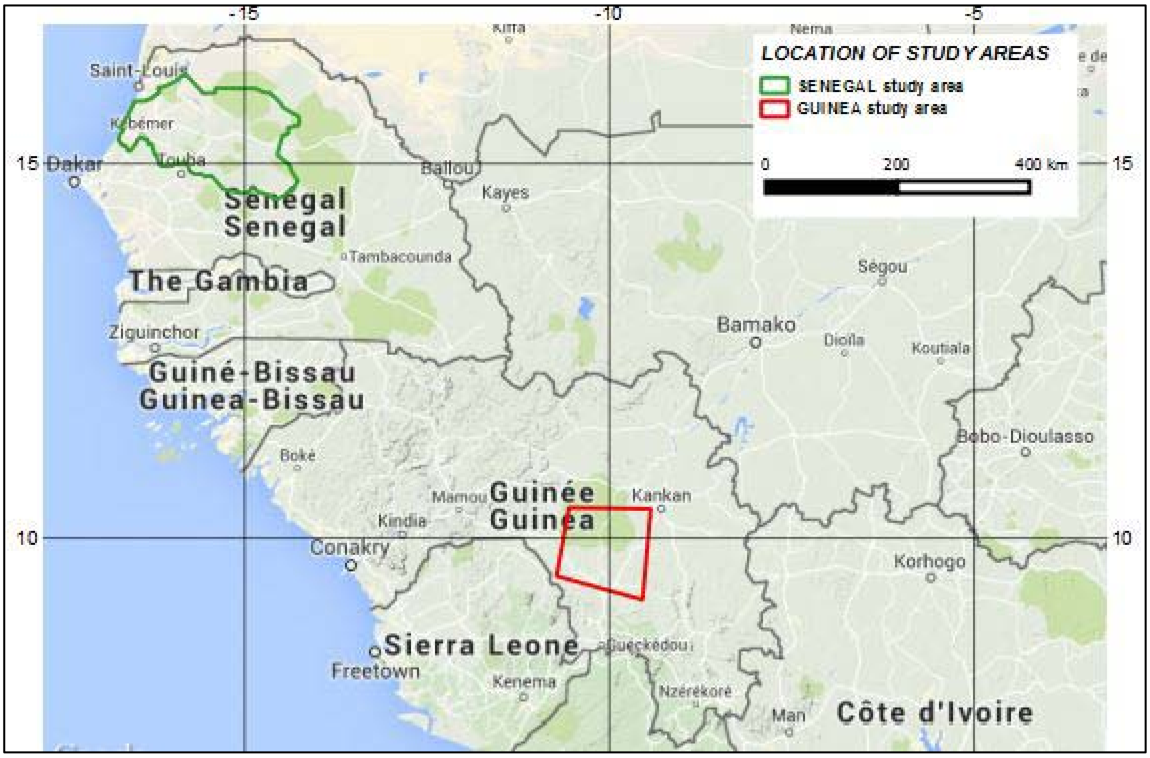


Figure 1 *Location of study areas*

The two areas have different rainfall regime: in Senegal we have a low yearly rainfall (Table 1) and precipitation concentrated between July and September (Figure 3), while in Guinea there is a much higher value for the yearly rainfall, with precipitation distributed in a longer period (Figure 4).

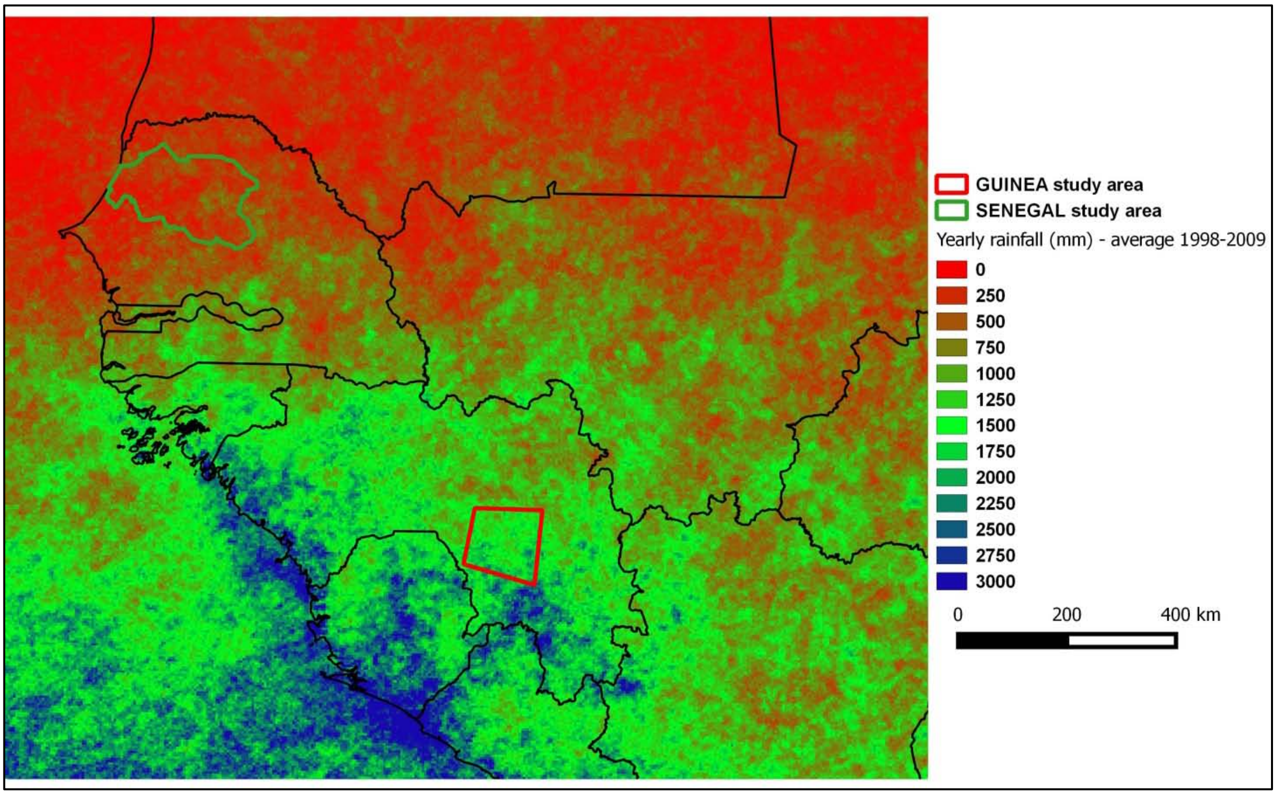


Figure 2 ***Yearly rainfall in Western Africa – average 1998-2009. Source: Bookhagen, B. (in review)***

	Mean	**Median**	**Standard Deviation**	**Minimum**	**Maximum**
SENEGAL	331	316	146	39	851
GUINEA	1553	1535	230	726	2643

Table 1 ***Yearly rainfall in Senegal and Guinea study areas***

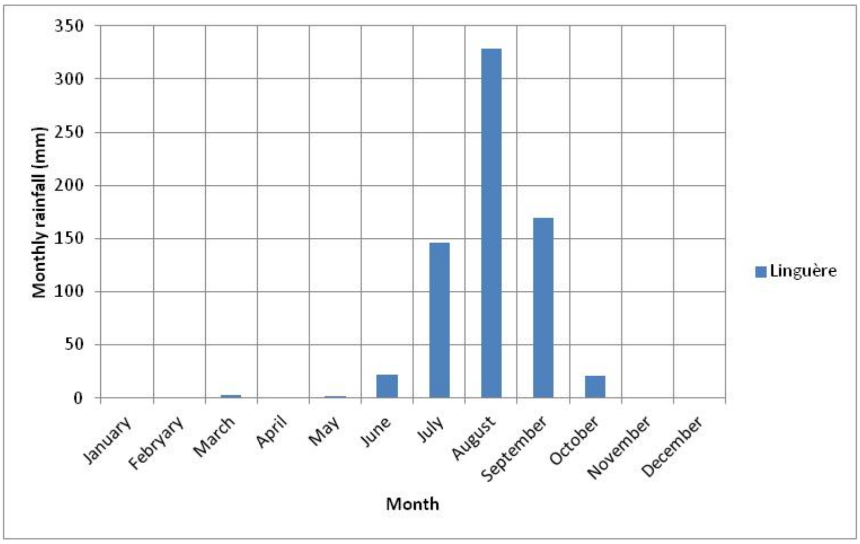


Figure 3 ***Monthly rainfall in Senegal study area (average 2008-2012). Source: http://www.weatheronline.co.uk***

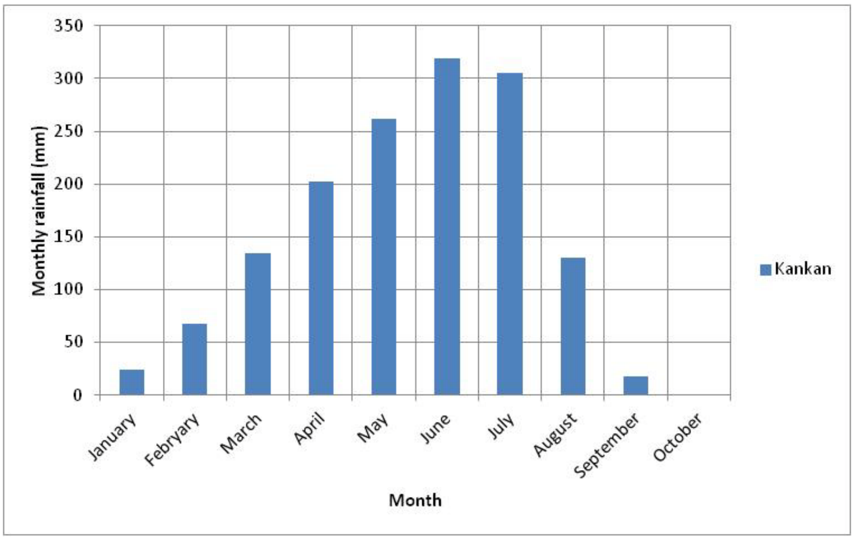


Figure 4 ***Monthly rainfall in Guinea study area (average 2008-2012). Source: http://www.weatheronline.co.uk***

The study area in Guinea is geologically characterized (Figure 7) by a large gneissic complex in the central and southern part, with intercalation of other formation granitic and gneissic and doleritic intrusion (Figure 5). This geological context is extended for almost the whole south-eastern part of the country (Guinee forestiere). In the north-eastern part of the study area there is the limit with the sedimentary units of sandstones and shales, this unit covers the north-eastern part of the country, from Kankan to Siguiri.

The morphology is dominated by the hilly area of Gueckedou – Kissidogou in the South, shifting to the gentle sloping and flat region in the northern part, crossed by rivers flowing to the north (Figure 6).

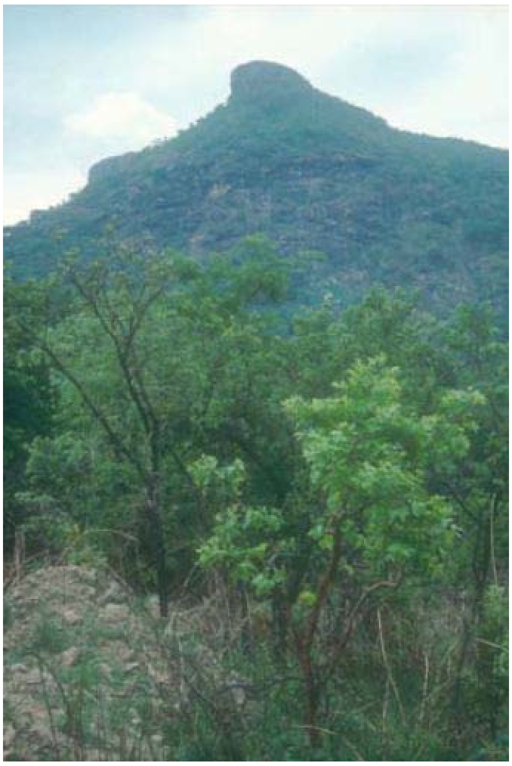


Figure 5 ***Doleritic hill emerging from the gently ondulated gneissic zone of Kissidogou region (Guinea)***

Figure 6 ***River Niger flowing northward in Kourossa (Guinea)***

The study area in Senegal is characterized (Figure 8) by a quite homogeneous coverage of sandy deposits in the western (with more pronounced dunes along the coast, Figure 9) and central part (with a predominantly flat morphology). In the eastern part the sandy layer is thinner and discontinuous, with outcrops of the sedimentary substratum and presence of lateritic hard layers.

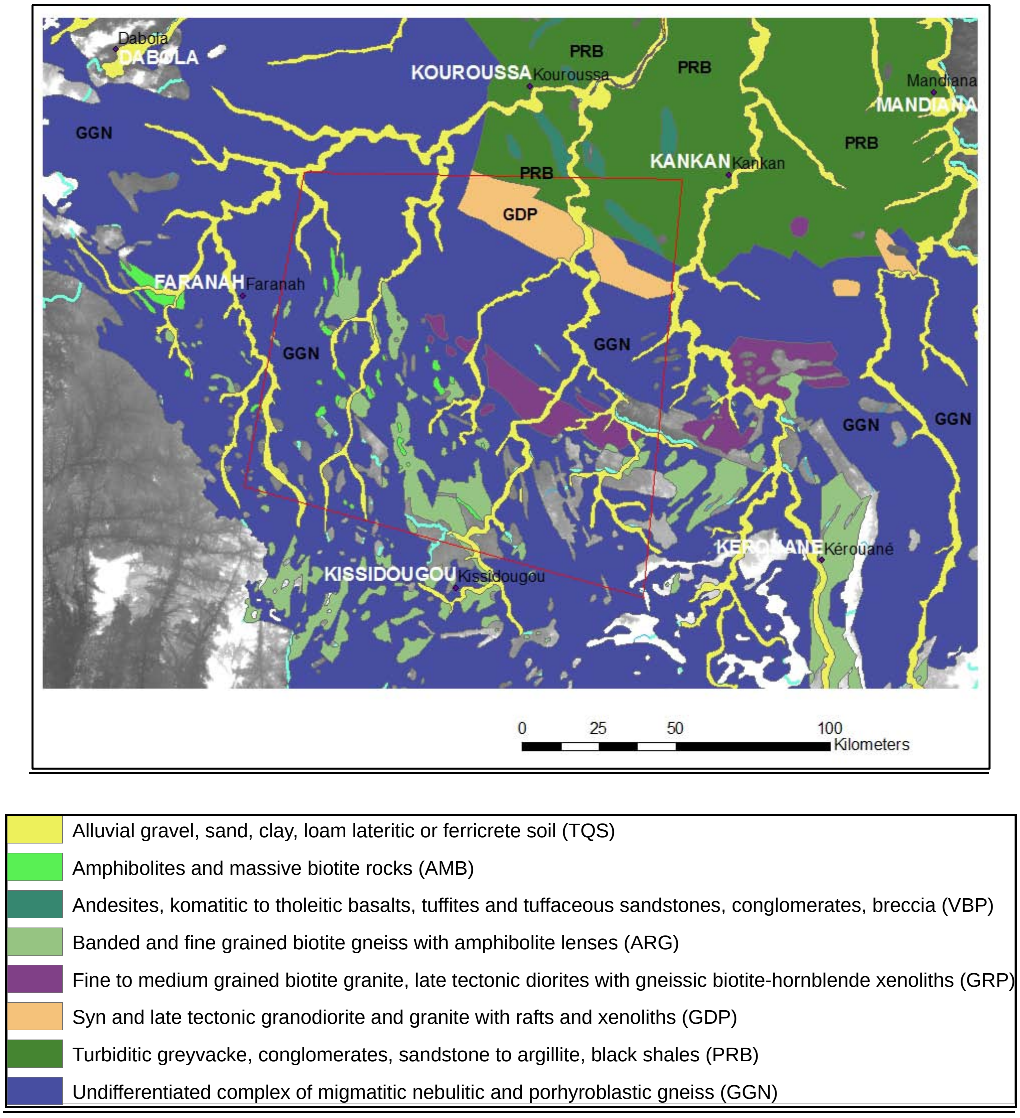


Figure 7 *Guinea study area – Geological Map*

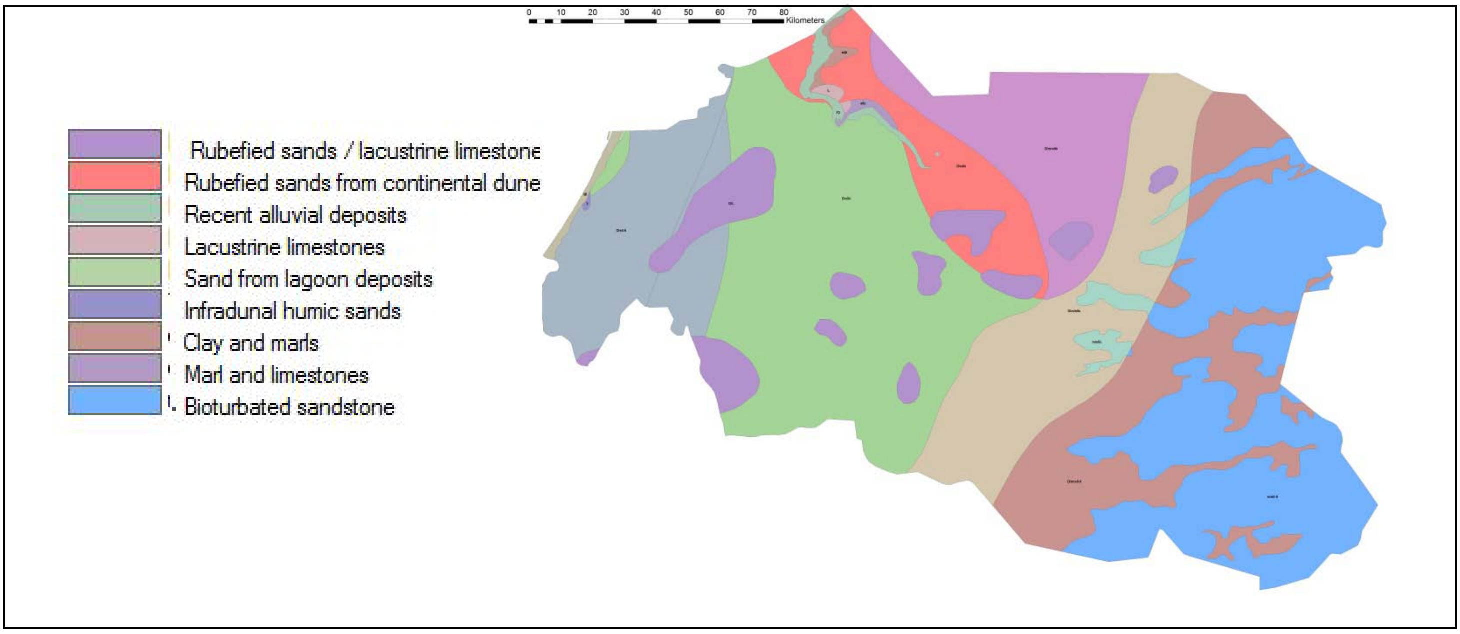


Figure 8 *Senegal study area – Geological Map*

Figure 9 ***Sandy dunes with shallow water table in the coastal region of Senegal***

Chapter 2. Manual drilling

Nyallugol taaradè maayo no bhuri dawgol yooladè

(It is better to follow the river all day than drown early morning)

Introduction

Manual drilling refers to several drilling methods that rely on human energy to construct a borehole and complete a water supply (Danert, 2015). These techniques use human energy or a small pump to open a hole.

Manual drilling can provide low-cost but high quality water supply. The main advantages are (Danert, 2015):

- **Cost**: manual drilling costs 10 to 25% of the cost of a machine drilled borehole, therefore it is economically feasible even for small communities or households;
- **Accessibility**: the equipment for manual drilling are light and easy to transport, therefore it can be used in areas with difficult access (remote areas, emergency context);
- **Local economic development**: manual drilling is “labour intensive” and does not require large investment in expensive machinery. It facilitates local employment and promote productive uses of water;
- **Time savings and safety**: with manual drilling techniques it is possible to construct shallow wells much faster and in much safer conditions than with hand dug well.

Existing techniques and criteria for their implementation

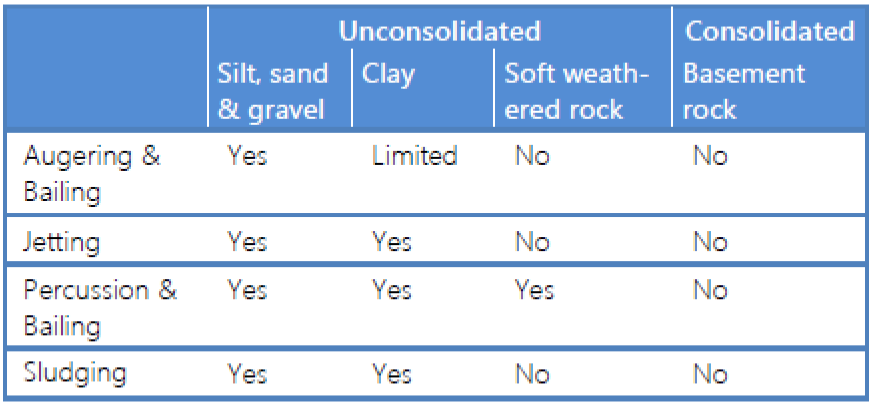
Different methods are currently used for manual drilling (Danert, 2015):

- **Augering and bailing**: penetrating the soil with a cylindrical or helical soil auger; the loos materials are removed with the auger itself or a bailer;
- **Jetting**: injection of fluid (water sometimes mixed with some thickener) down and around the bottom of a drilling pipe, this fluid remove the loose fragment through the annular space between the drilling pipe and the hole, the fluid is injected manually or with a small pump;
- **Percussion and bailing**: lifting and dropping a cutting tool suspended at the end of a rope; cuttings are generally removed with a bailer. It requires a considerable amount of water;
- **Sludging**: the drilling stern, fitted with a cutting shoe, is lifted and dropped into the hole to loose the formation. Drilling fluid flows into the annular space between drilling pipe and the hole, and rise through the drilling pipe, bringing the cuttings to the surface. A hand placed at the top of the drilling pipe act as a flap valve to release the drilling fluid. It requires considerable amounts of water.

Since manual drilling cannot open holes in hard rock and cannot generally reach high depth (although experiences of manual drilling up to 100 m are registered), it requires specific hydrogeological conditions for its application:

- Shallow geological layer formed by unconsolidated deposits;
- Exploitable groundwater not too deep.

These general criteria can be more specific according to the different methods of drilling (see Figure 10).



	Unconsolidated			Consolidated
	Silt, sand & gravel	Clay	Soft weathered rock	Basement rock
Augering & Bailing	Yes	Limited	No	No
Jetting	Yes	Yes	No	No
Percussion & Bailing	Yes	Yes	Yes	No
Sludging	Yes	Yes	No	No

Figure 10 ***Suitable formations for manual drilling methods (source: Danert, 2015)***

Given these limitations, it is therefore important before the start of a manual drilling program to assess the compatibility of hydrogeological and identify those zones considered suitable for its application.

Manual drilling in the world

Despite mechanized drilling appeared approximately at the end of 19th century, the exploitation of groundwater had already been a common strategy in human society for many centuries, using hand digging and manual drilling.

Manual drilling is a well established technology in Bangladesh, Bolivia, India, Kenya, Niger, Nigeria and Madagascar (Danert, 2015).

The largest example of application of manual drilling is in alluvial deposits and unconsolidated weathered layer in India and nearby countries (Nepal and Bangladesh). Tube-wells, largely hand drilled, are the most common source of water. In India the percentage of the population using tube wells is increasing (43% in 2011, compared with 30% in 1991, see Figure 11). At the moment almost 500 million of Indians rely on tube wells. Dave (2014) estimates that a million new tube-wells drilled manually are completed in India every year.

Figure 11 ***Sources of Drinking Water in India. Source: Danert 2015, based on WHO/UNICEF, 2014)***

Manual drilling methods are being used to provide water for drinking and other domestic needs in at least 31 countries (Danert, 2015), distributed in Asia, Africa, Southern and Central America (Figure 12).

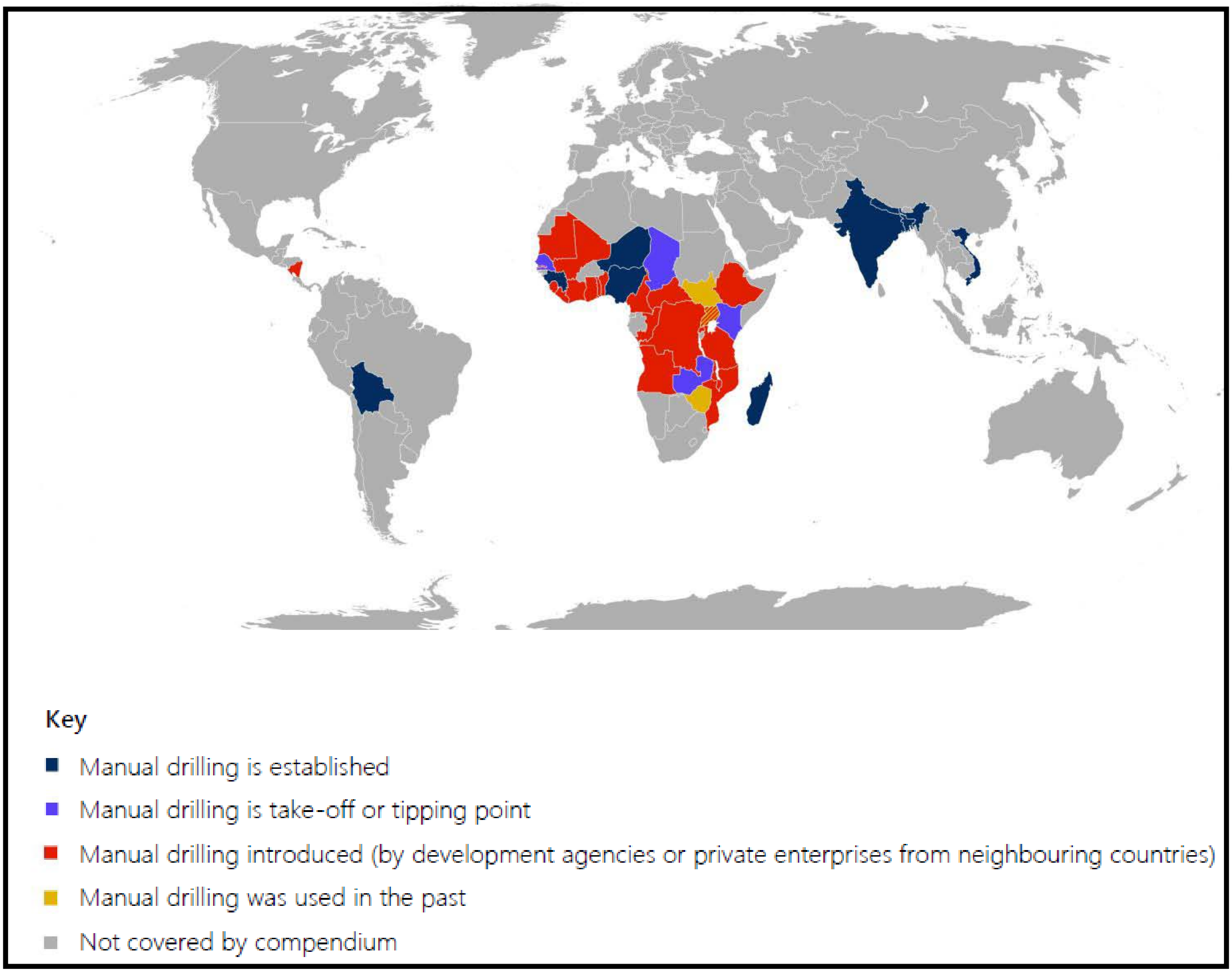


Figure 12 ***Extent of Manual Drilling for Domestic Water Supplies today (source: Danert, 2015)***

Manual drilling in Senegal

Low Cost drilling techniques were first introduced in Senegal in the early 90's (Danert, 2015).

In 1997 hand augering was introduced by Enterprise Work in areas with shallow aquifer and sandy soil. From the original small group of private drillers it is estimated that now there are 40 teams applying this technique in Dakar, Thies and Ziguinchor.

In 2002 sludge and rota-sludge techniques were introduced by EW and PRACTICA in Ziguinchor; this experience, however, remain limited and sludging was not implemented in other areas.

The largest effort to promote manual drilling was carried out between 2009 and 2014 in the framework of USAID/PEPAM Millenium Water and Sanitation program: 13 well-drilling teams were trained to manually drill wells using hand augering, manual percussion, and rotary jetting

(Naugle and Mamadou, 2013). They completed more than 300 hand drilled boreholes till 2013 in Casamance (Ziguinchor, Sédhiou, and Kolda) and Tambacounda.

In Senegal the national water authority DGPRE and UNICEF have not considered the promotion of manual drilling as one of the key action in the national strategy for water supply. In fact these techniques are still limited in certain regions and no trained team is present in the northern part of Senegal. After the end of USAID/PEPAM project (2013) those private drillers trained in manual drilling are still active in their regions, but there is not any program to support them and expand their action.

Manual drilling in Guinea

Manual drilling was not practiced in Guinea (Fussi et al., 2014b). In 2011 UNICEF carried out a first test: 11 hand drilled wells were completed in the north coast (Tougnifily and surrounding zones). The positive results raised interests for these techniques from different stakeholders (local institutions, ngos, international organizations and donors). At that time UNICEF and SNAPE agreed to introduce manual drilling in the national water strategy and promote it through different actions.

At the end of 2011 the study for the identification of suitable zones at country level started; the final maps and reports were available in 2012. At that point this study was considered the basis to define the geographic priorities for the program of promotion

At the moment (April 2015) 10 drilling team scattered in the whole country are trained in the application of high quality manual drilling techniques); 4 teams (in Conakry, Kankan, Faranah and Nzerekore') are trained in the construction of drilling tools for drilling. The techniques that are applied are rota-sludge and jetting. 152 hand drilled wells have been completed, in the coastal region, in Nzerekore' et Kankan/Faranah (Figure 13)

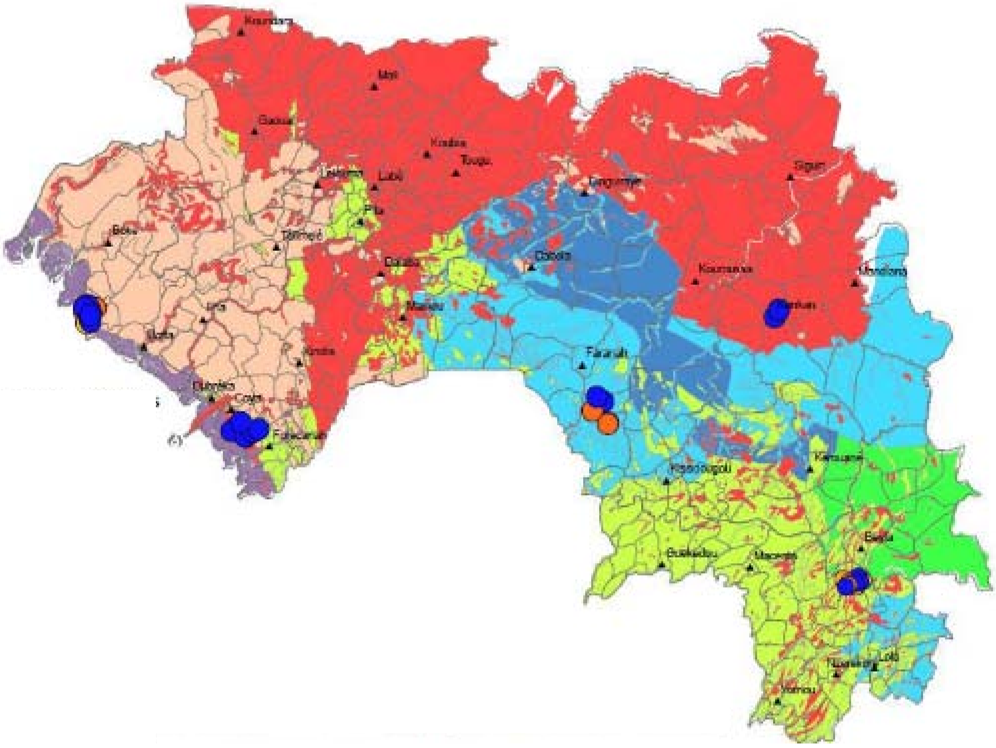


Figure 13 ***Localisation of hand drilled wells completed in Guinea after 2011. In blue positive wells***

Chapter 3. Identification of suitable zones for manual drilling - state of the art

Ko surusuru hebbinta maayo

(They are fine regular rains which cause flooding of major rivers)

A preliminary approach to recognize suitable zones was tested in Chad using the water points database at the national water authorities (Direction de l'Hydraulique) and a simple procedure of visual interpretation (PRACTICA, 2005). Results of this study were used for an intense program of promotion of manual drilling by UNICEF and the national water authority: as a results in 2014 thousands of excellent hand drilled wells are present in the country (Danert, 2015), with a network of private contractors trained in high quality techniques.

UNICEF tried to give a schematic method that was applied, with some modifications, in 12 countries between 2008 and 2010 (Fussi, 2011; Fussi, 2013) to produce maps of suitable zones at country level. The general suitability derived from cross analysis of three parameters: geological suitability (depending on thickness and permeability of shallow layers), water depth suitability (depending on static water level), morphological suitability (based on the existence of landform that facilitate accumulation of unconsolidated sediments or erosion). This method was based on the analysis of water point database, geological map and SRTM digital elevation model, integrated with qualitative experience of local hydrogeologists.

A similar approach derived from cross analysis of shallow geology (obtained from simplification of geological map) and water depth (assigning an estimated range of this parameter to category of landforms obtained by processing SRTM digital elevation model model) was used in Madagascar (Voahary Salama, 2008).

A different method was applied in Tigray, Northern Ethiopia (Huisman Foundation, 2014). It is based on direct field survey, observation of hand dug wells and soil condition, discussion with local expert.

The map of suitable zones for manual drilling in Senegal

The map of suitable zones for manual drilling in Senegal was completed in 2010. As the territory is generally flat or smoothly undulated, morphology has limited influence on the hydrogeological context (with the exception of south-eastern part of the country). Therefore the combination of the other two factors (depth of groundwater and geological features of shallow layers) determine the degree of suitability for manual drilling. Four classes of suitability were discriminated (Kane et al., 2013):

- ***Very favourable ("Tres favorable" on the map)***: refer to areas where both parameters (geological formations features and depth of ground water) are favorable;
- ***Favourable ("Favorable" on the map)***: refer to areas where one parameter shows an average aptitude for manual drilling use, and on the other is rather favorable;
- ***Little favourable ("Peu favorable" on the map)***: refer to areas where both parameters show an average aptitude (i.e. favorable with some limitations); in these areas manual drilling techniques may be used depending on topographic conditions, however in general these areas have constraints for implementing these techniques. For instance in the eastern part of the country, undulating topography (with low altitude zones) and weathered layers occurrence may provide specific environment for positive implementation of manually drilling techniques, but only in selected locations;
- ***Not favourable ("Pas favorable" on the map)***: refer to areas where, either one or both parameters have suggested unfavorable conditions for manual drilling; therefore these techniques are generally difficult to use.

In general thickness and permeability of the unconsolidated sediments don't represent limiting factors for the suitability for manual drilling for almost the whole country. The main constraints are represented by the depth of ground water and the presence of thick hard lateritic layers.

Ground water is not deep along the coastal region, in the valley of Senegal and in Casamance. At the contrary depth of ground water is considered excessive for a common practice of manual drilling in the whole central part of the country (a limit of 25 m for groundwater depth was considered to discriminate the feasible zones).

Laterite is frequent in central and southern Senegal . In some cases thickness of hard layers makes extremely difficult, if not impossible, the completion of a positive hand drilled wells.

Considering these two constraints we can affirm that in Senegal manual drilling can give positive results in large areas at the moment considered not suitable once specific techniques and tools that make possible to achieve deeper layers and break hard intercalation are introduced in the country.

The main areas considered highly suitable to manual drilling are:

- The valley of Senegal river, with very shallow ground water and unconsolidated sediments, with important presence of clay, therefore this area is suitable for manual drilling but low yield can occur
- The northern coastal strip, from Dakar to Saint Louis, generally favourable in terms of hydrogeological context but with important risk of salt intrusion in ground water in some localities

- The coastal area of Fatick region, with generally favourable conditions but low yield expected
- Casamance, in particular in the western part (Ziguinchor) where water table is shallow and sediments are composed by sand or sandy clay, although a frequent presence of laterite could force to use percussion techniques to break it.

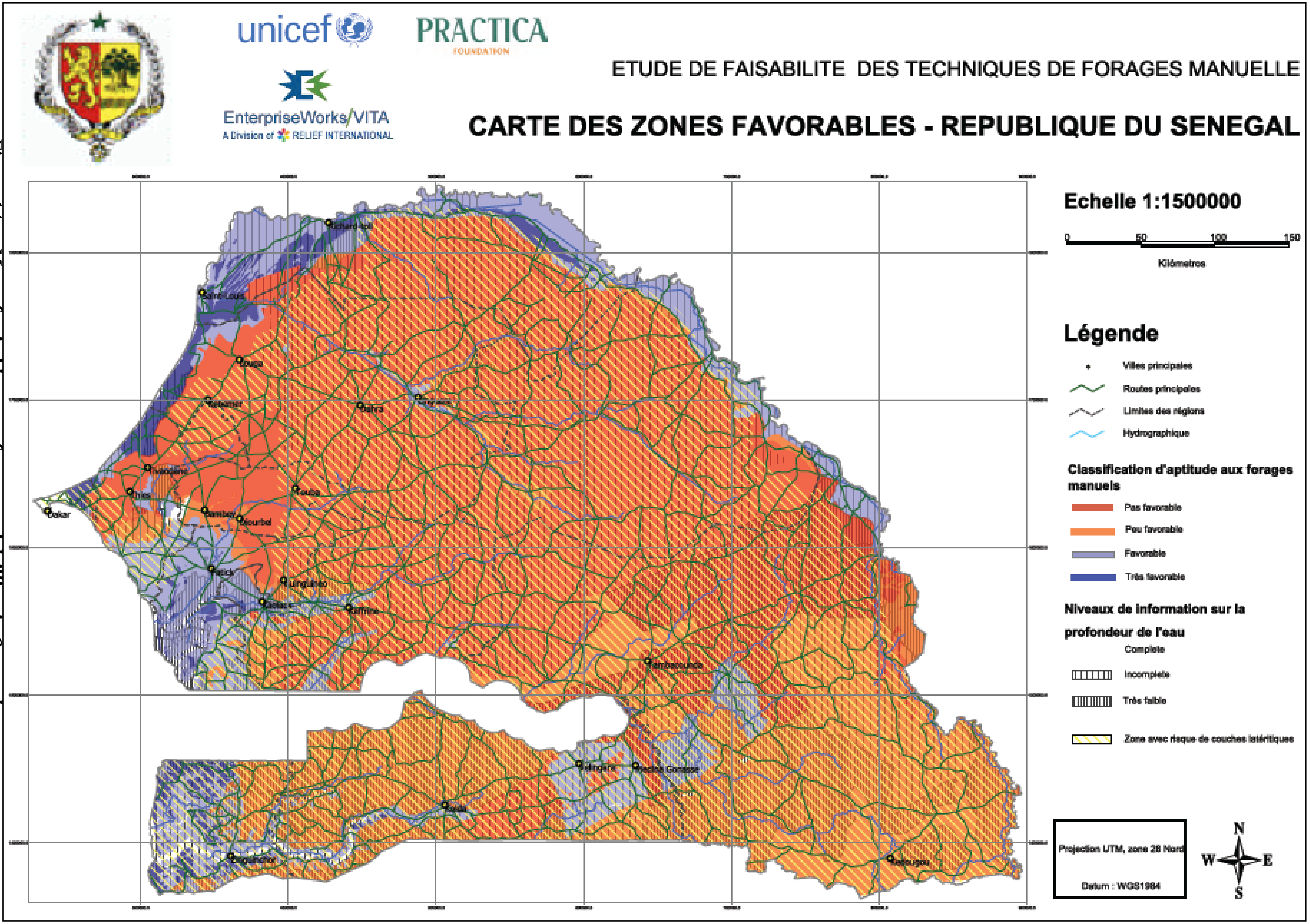


Figure 14 ***Map of suitable zones for manual drilling in Senegal***

The map of suitable zones for manual drilling in Guinea

The map of suitable zones for manual drilling in Guinea was completed in 2012.
The geology and morphology of Guinea are more diversified compared to Senegal. The most important constraints in Guinea for the implementation of manual drilling are:

- the presence of hard rocks at shallow depth (in particular in the central part of Guinea and in the mountainous regions);
- the low permeability of the weathered layers, especially in the north-eastern part of the country;
- the presence of discontinuous hard laterite in central, northern and western Guinea.

The regions with the highest potential are located:

- along the coast (where a risk of salt intrusion exists, particularly in the northern coast of Boke and Boffa)
- the eastern and south-eastern part of the country, where a clay and sandy weathered layer covers the gneissic and granitic basement.

In Guinea the UNICEF study produced also some regional maps where it was taken into consideration local morphological conditions. In fact in Guinea morphology has a strong influence in the nature and thickness of weathered aquifers.

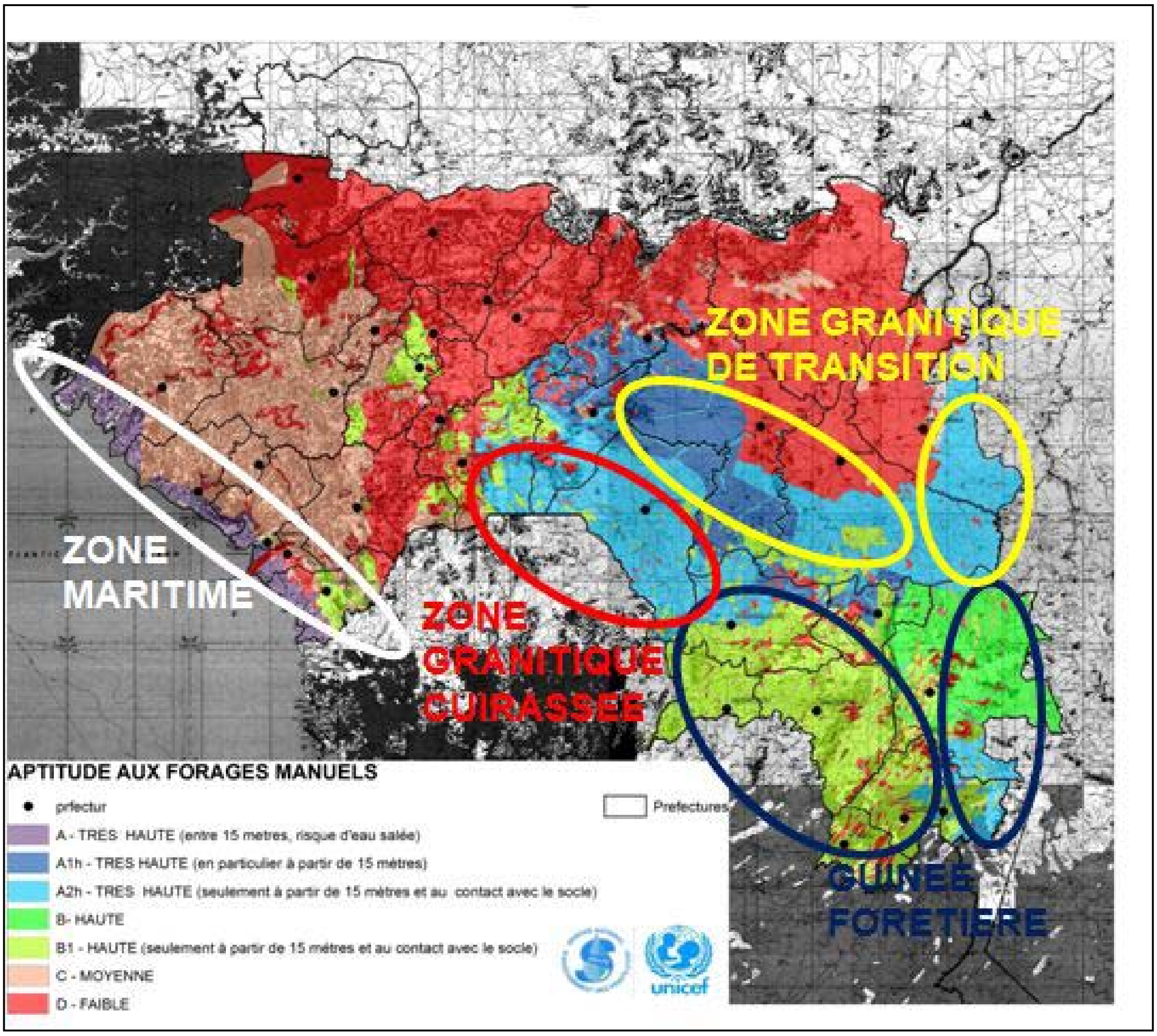


Figure 15 ***Map of suitable zones for manual drilling in Guinea***

Chapter 4. A proposed methodology for the identification of suitable zones for manual drilling

Ndihal ko è looppoye dembata

(Water remains undrained only in the muddy zones)

The methodology proposed in this research to estimate suitability for manual drilling is based on a structured and semi-quantitative cross analysis of the distribution of a set of geological and hydrogeological parameters, extracted from borehole logs or extrapolated to the whole area.

The method can be applied in three steps: 1) assessment of feasibility, 2) estimation of potential for exploitation, 3) final classification of suitability.

Assessment of feasibility

The assessment of feasibility of manual drilling requires evaluating if in a specific location the existing hydrogeological conditions make possible to complete a hand drilled well (with the different set of techniques available); this assessment is carried out by analyzing two main parameters extracted from borehole logs: presence of hard layers and depth of water.

Hard layers can be composed by hard rock or laterite and they have different interpretation:

- in case of hard rock, generally the shallower hard layer observed in the stratigraphic log correspond to the upper limit of the basement underlying unconsolidated materials. From that point downward, all the layers are hard, therefore manual drilling cannot go deeper than that limit;
- in case of laterite, a hard layer can be intercalated between soft sediments. If this layer had limited thickness, it can be broken with special techniques of manual drilling and the well can continue deeper.

Based on this consideration, the procedures to assess feasibility for manual drilling can be schematized as a sequence of three conditions, evaluated through Boolean operators (Yes/No):

- Condition 1 - Depth of hard rock: the presence of hard rock at the surface or shallower than 10 metres makes manual drilling not recommended: even in case of water table close to the ground, a maximum depth of 10 metres leads to unreliable water supply from the wells (too small water column), especially during dry periods (when water table become deeper). Therefore in this situation a complete and successful hand drilled well is considered not feasible.
- Condition 2 - Depth of water: although manual drilling has been tested in specific conditions up to 100 meters, it could be estimated that it is quite unlikely that these techniques can be widely applied when it is required to drill more than 40 or 50 meters. In this research we have assumed that maximum drilling depth is 50 m (considering that in Senegal unconsolidated layers are easy to penetrate, as shown by the large presence of hand dug wells as deep as 40 m or even more) and a limit of maximum water depth of 40 m for the feasibility of manual drilling (considering that few meters of water column must be present inside the well above the pump).
- Condition 3 - Presence of hard laterite: in case of presence of thin hard layers, they can be perforated but special techniques (e.g. percussion) are required. Based on direct experience of manual drilling experts, it is estimated that perforation is possible for hard layer thinner than 5 m.

The sequence of three conditions applied is schematized in Figure 16:

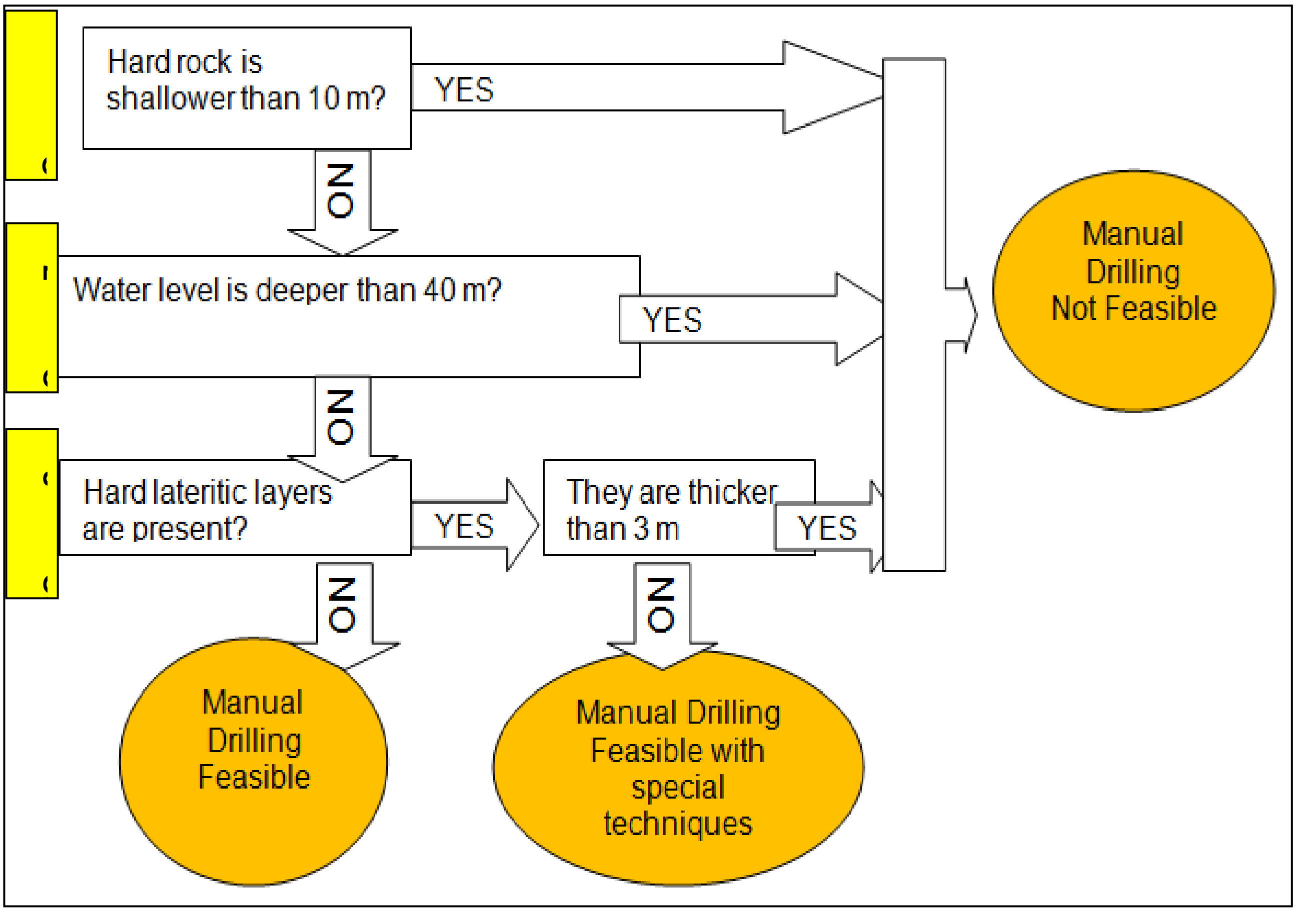


Figure 16 *Schematization of the procedure to assess feasibility for manual drilling*

With this procedure, three classes of feasibility are discriminated (Table 2):

Class of feasibility	Description
NF (Not Feasible)	Not feasible because presence of shallow hard rock, high depth of water, thick lateritic hard layer
F (Feasible)	Manual drilling can be successfully done in this hydrogeological context
FS (Feasible with special techniques)	Manual drilling can be done, but the presence of hard intercalated layers oblige to use at certain depth special techniques (e.g. percussion) to break it, together with other common methods to drill in unconsolidated sediments

Table 2 *Class of feasibility for manual drilling*

Estimation of potential for exploitation

After having identified where manual drilling is feasible, it means classes F and FS (with the option of special techniques required), the second step is the estimation of the potential for exploitation with manual drilling in these zones. This can give an indication of the expected yield, reliability in dry season, type of pump and size of the population served.

Potential for exploitation with manual drilling is obtained from the hydraulic transmissivity in the exploitable interval (Tex).

$$T_{ex} = K_{ex}{*}\, H_{ex} \qquad \text{[eq. 4.1]}$$

where:

T_{ex} = hydraulic transmissivity (m2/s) of the exploitable layer by manual drilling (it means up to 50 m deep)

H_{ex} = thickness (m) of the saturated exploitable layers, corresponding to: a) the difference between static water level and 50m, in case upper limit of hard rock is deeper than 50m, b) the difference between static water level and upper limit of hard rock layers, when this is less than 50m.

K_{ex} = average hydraulic conductivity (m/s) in the saturated exploitable layer.

Defining threshold to Tex, each zone is classified into 5 classes of potential for exploitation: Null, Low, Moderate, Good and Excellent (Table 4). In the definition of these class of potential, the performance of different type of pumping systems in terms of expected yield are considered (Table 3):

:

Handpumps are the most common pumping system for manual drilled wells. Regardless of the potential yield of the well, it is estimated that the expected yield from handpumps is approximately 0.2 l/s, with maximum limit of 0.4 l/s in optimal condition. They are suitable for the whole range of depth of static water level considered as feasible for manual drilling (maximum depth of static water level = 40 m) and they can provide water for groups of approximately 250 users.
Solar pumps can be installed in high productive manual drilled wells. They can supply water for a larger community (and eventually connect to small distribution systems. Their yield depends on the power generated by solar panels (whose extension and power production can vary considerably); as a reference value we consider 1 l/s as a reasonable yield for a solar pump providing water to 1000 users.
Rope pumps are suitable and cheap systems to collect water from manual drilled wells in case of small communities. They have a low yield (0.1 l/s as reference value), but they can be installed only where static water level is not deeper than 15 m

Table 3 ***.Type of pumps usually installed on hand drilled wells and their expected yield***

With an approximate estimation of the relation between transmissivity of aquifer and expected drawdown using different pumps, different class of potential have been defined, according to the potential yield (therefore the possibility to provide water for handpump or solar pumps) and the capacity to ensure water supply for extended and intense pumping.

Although this approach can be generalized to different regions, threshold values are defined on the basis of site specific characteristics of aquifers, depth of water table, seasonal fluctuations, etc.

Class of potential	**Description**
NP - potential null	Physically the hand drilled can be done, but it results dry, since water level is deeper than the depth of hard rock, therefore the porous aquifer is completely dry (H_{ex} =0)
LP - Low potential	Hand drilled wells can be equipped with handpump, but expected yield is low. After intense pumping, or in case of decrease of water level, the well is likely to get dry
MP - Moderate potential	Hand drilled wells can be equipped with handpump and provide a reliable water supply; pumping cannot be continuous for a long time. Not suitable for intense utilization by large groups
GP - Good potential	Hand drilled wells can provide continuously water supply, with adequate yield for handpump. Suitable for medium community
EP - Excellent potential	Hand drilled wells can provide an excellent yield for a continuous utilization of handpump, and can even be equipped with solar pump in some cases, as they can supply a higher yield

Table 4 ***- Class of potential for manual drilling***

Assigning the final class and overall group of suitability

The final suitability derives from the combination of feasibility and potential for exploitation. With this method 11 classes of suitability (Table 5) are defined, with three overall groups; not suitable, suitable with poor results, suitable.

Feasibility	Potential	Class of Suitability	Overall group
NF		NF	Not suitable
F	NP	F-NP	Not suitable
F	LP	F-LP	Suitable with poor results
F	MP	F-MP	Suitable
F	GP	F-GP	
F	EP	F-EP	
FS	NP	FS-NP	Not suitable
FS	LP	FS-LP	Suitable with poor results
FS	MP	FS-MP	Suitable
FS	GP	FS-GP	
FS	EP	FS-EP	

Table 5 ***- Final classification of suitability for manual drilling***

The overall group indicates where hydrogeological conditions are definitely not suitable for manual drilling, where they are feasible but with extremely limited results or where conditions are considered adequate to implement manual drilling.

In this last case, we can observe the class of suitability: here we can estimate the potential range of yield achievable, the type of pumps that can be installed and finally the potential needs of specific techniques (mainly percussion) that are required to break hard layers during drilling.

Limitations of the approach to the estimation of suitability for manual drilling

The proposed approach tries to give a semi quantitative structured method to evaluate the feasibility of manual drilling and the expected yield (through the evaluation of transmissivity of shallow aquifer and acceptable drawdown).

There are few aspects that must be taken into consideration:

- The efficiency of a hand drilled wells and the rate of pumping that can be applied without drying up the well are arbitrary. They depend from the specific type of pumps, the depth of water, and the quality of the well;
- The assumptions considered to define the condition of feasibility can be modified according to the technological level in each country and the type of sediments. In some countries there are manual drillers well trained in the application of specific techniques to reach more than 50 m, while in other countries there is no experience on that. Furthermore, according to the type of sediments (texture, degree of compactness, presence of stones, etc) manual drilling has a different level of difficulties and a maximum reasonable depth that can be achieved;
- The potential has been evaluated on the basis of the trasmissivity, deriving from the product of thickness and hydraulic conductivity (K) of the saturated aquifer. But K can vary along a much extended ranges of values (for example between 1*10-4 and 1*10-6 m/s, it means with a factor of 100) while the exploitable saturated thickness has a range of variations more reduced. Therefore in the final evaluation of potential according to the proposed method a higher importance is assigned to K (whose estimation can be extremely imprecise). Even with a high K, it will be difficult to have efficient wells in case the thickness of exploited layers is less than 2 or 3 m. Furthermore, the saturated thickness changes during the year, because of seasonal fluctuations of water table;
- Suitability is estimated on the basis of the physical feasibility of drilling and the expected yield. In this approach is not considered the quality of water; this aspect can have high

relevance in the decision about the implementation of hand drilled boreholes. The main factors to consider are the possibility of inadequate physico-chemical composition of the water (for example like high salinity, affecting ground water in the coastal zone of Guinea) or the exposure to microbiological contamination caused by infiltration of pollutants from the surface (extremely dangerous, in particular in densely inhabited zones or presence of animals). In general physico-chemical data of shallow groundwater are not available in national inventory of water point or other systematic and extended source of information; therefore this aspect can be explored on the basis of previous hydrogeological studies, local experience of the population and field water analysis in specifically target areas. It would be difficult to include in this standardized and semi-quantitative procedure to assess the suitability of manual drilling.

Chapter 5. Characterization of subsurface hydrogeology at selected location and estimation of suitability for manual drilling

In the previous chapter we have proposed a schematic procedure to estimate the suitability for manual drilling based in the cross analysis of a set of geological and hydrogeological features. This procedure allows defining in each location the degree of suitability, once we have the different parameters required by this suitability model.

Extraction of hydrogeological parameters from water point data and classification of suitability

In this chapter specific tools and methods to process existing water point data are presented; the results of their application is the estimation of the input parameters at water point location and the estimation of the class of suitability at that position.

Source of information

In both countries the main sources of information were the inventory of water points held by national water authorities, it means DGPRE in Senegal and SNAPE. The structure of the two databases are similar, based in the data architecture of the software PROGRES (ANTEA/BURGEAP, 2007), although there are differences in the type of information obtained.

Furthermore in Senegal it was possible to carry out to field campaigns to collect different types of direct data (observation of large diameter wells and recording water level, pump and recovery test, geophysics); these direct data resulted important in the validation of the results obtained through semiautomatic analysis of water point data, as explained later. Unfortunately direct data collection was cancelled in Guinea because of Ebola outbreak.

In Senegal the water point database of DGPRE (7138 water points recorded and 1419 borehole logs) is part of the geographic information system of water resources SGPRE (République du Sénégal, 2000). 3 categories of data have been obtained from water point database in Senegal:

- General inventory of water points (1277 in the study area): position, total depth, depth of static water level and in some cases, yield for the pump test (this information was available only for boreholes). They cover all the study area, although there is much higher concentration in the western side (Figure 17);

- Piezometers (45 in the study area): as for the general water points, plus main aquifer and data on periodical monitoring of water table, yield for the pump test and drawdown. They are almost completely concentrated in the coastal region, not farther than 50 km from the sea (Figure 18, left);
- Stratigraphic logs of boreholes (131 in the study area): as for general water points, plus lithological description of different layers found during the drilling. No stratigraphic log is available for hand dug well. They are mainly concentrated in the west side, although there are limited stratigraphic data scattered in the whole study area (Figure 18, right).

Figure 17 ***Distribution of total water points with data on water level in the study area of Senegal***

Figure 18 ***Distribution of piezometers (left) and boreholes with stratigraphic logs (right) in the study area***

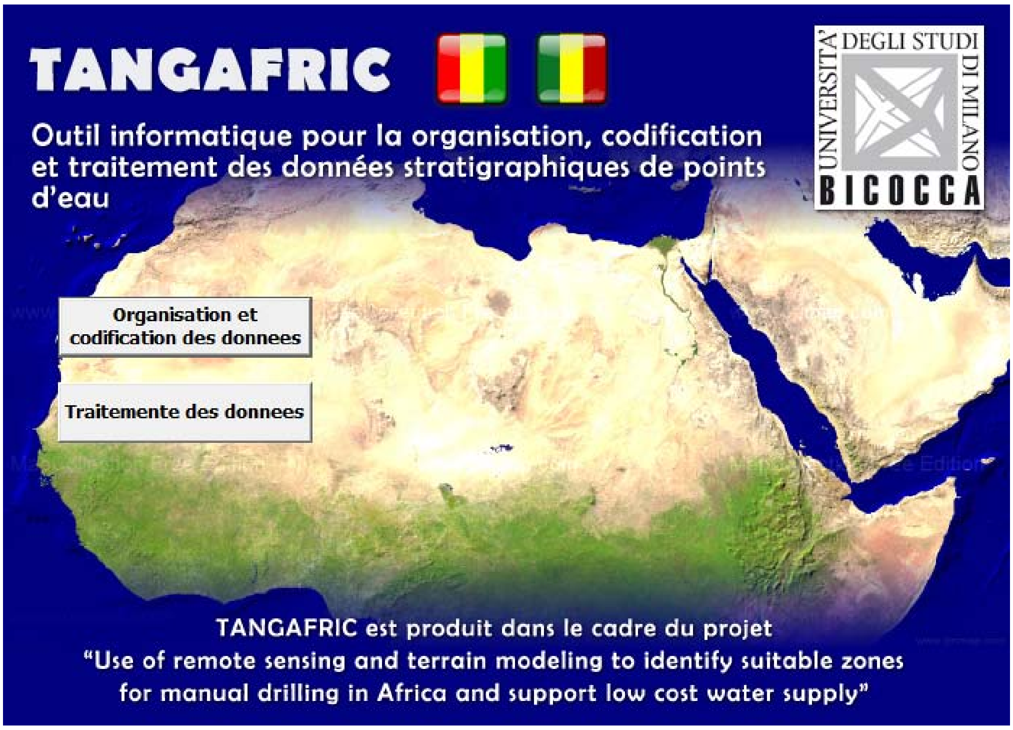
In Guinea the national database includes more than 16000 water points, but there are frequent mistakes or incompleteness. Furthermore, in the last years, SNAPE hydrogeologists collected data from specific rural water supply programs, but this information was not transferred and centralized in the national database. For this reason it is difficult to estimate the total number of water points recorded and identify duplicated data. The Guinean database contains only information about deep boreholes (499 in the study area), with a subset of data including complete stratigraphic logs in specific tables (90 in the study area). Differently from Senegal, there is no data about large diameter wells and piezometers.

Data processing

Processing borehole logs data have been done using a specific software (TANGAFRIC) produced during the research. This software (Fussi et al., 2014a) has two main modules that can be activated from the opening window (Figure 19):

- the first module (data input and codification) displays the list of water points with associated borehole logs contained in the national database (Senegal or Guinea, depending on the choice of the country that the operator has to select when TANGAFRIC starts) with general information (position, administrative codification), water level and sequence of stratigraphic layers (with the indication of upper and lower limit of each layer and the original geological description as reported in the national database). In a separate window the operator can select the nouns and adjectives to assign the stratigraphic codes to each layer, in order to standardize stratigraphic data;
- the second module process the results of borehole logs codification and extract textural and hydraulic parameters, using the procedure described later.

In the mean time for each borehole log we have position (X and Y coordinates), elevation, total depth, static water level and administrative units (village and district).



TANGAFRIC

Outil informatique pour la organisation, codification et traitement des données stratigraphiques de points d'eau

TANGAFRIC est produit dans le cadre du projet "Use of remote sensing and terrain modeling to identify suitable zones for manual drilling in Africa and support low cost water supply"

Figure 19 ***TANGAFRIC – opening window***

Data processing has followed 4 steps:

- standardization and identification of common categories;
- manual codification;
- extraction of textural composition of layers;
- estimation and extraction of hydraulic conductivity.

Standardization and identification of common categories

In order to identify the possible categories for each code, the whole set of borehole logs from Senegal and Guinea were considered, identifying those definitions that were more frequent (repeated at least 5 times in the whole data set). In this way the first set of nouns and adjectives to be used as possible categories for the codification process was defined (this list was slightly updated during the codification of data). One aspect to take into consideration in the process of drafting the list of categories common to Guinea and Senegal is that there are different definitions used to describe the same type of geological layer in the borehole logs (for example, in case of hard lateritic layers intercalated in unconsolidated materials, quite common in certain regions of both countries, in Guinea it is generally described as "cuirasse latéritique", while in Senegal it is often defined simply as "latérite"). Therefore we need to introduce different categories, although they refer to the same type of geological material.

Manual codification

The method of coding stratigraphic layers used in TANGAFRIC was adapted from the procedure used in software TANGRAM at the University Milano Bicocca, consisting in a 8-digit code describing the characteristics of each layer (Bonomi, 2009; Bonomi et al., 2014). The original system was modified and a 5-digit alphanumeric code was adopted; the first 3 digits describe the texture of the layer (noun of main component, noun of secondary component, adjective), while the last 2 digits describe the status (a qualitative characteristic like fine, fractured, weathered) and a colour.

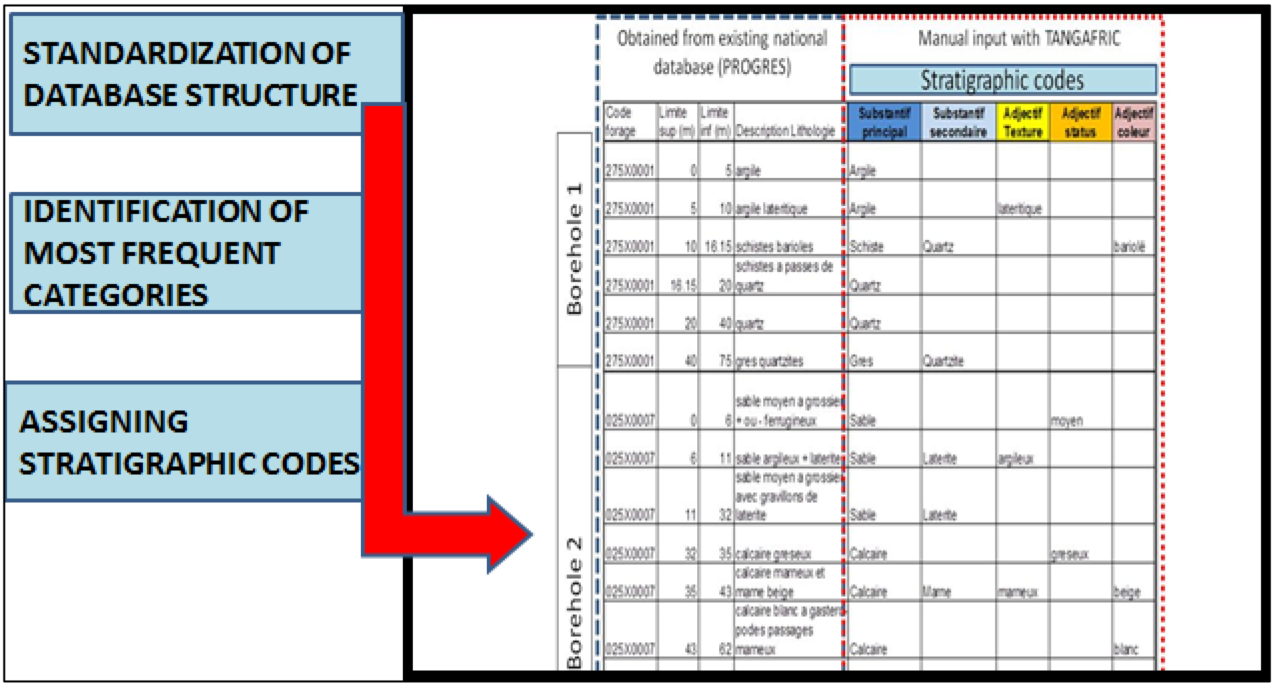
Table 6 shows an example of the codes corresponding to three layers:

Description	Main texture component	Secondary texture component	Texture adjective	Status adjective	Colour adjective
Sand	Sand				
Sandy clay	Clay		Sandy		
Fine yellow sand and laterite	Sand	Laterite		Fine	Yellow

Table 6 **- *Example of description of layers and corresponding codes***

Although the identification of categories was done considering the whole set of borehole logs in Senegal and Guinea, codification was carried out in a subset of data located in the two study areas (131 in Senegal, 90 in Guinea).

Once the categories were selected, two groups of hydrogeologists, in Senegal and Guinea, carried out manual codification of each layer of the logs registered in the study area. In case the stratigraphic description was already in the database, they had to import in TANGRAFRIC, displaying the description of each layer and assigning the most appropriate codes. As in part of the study area there were few stratigraphic logs in the database, they selected from their bibliographic archive the original hard copy documents containing the description of the boreholes, filled a table with inventory of new logs and the description of each layer, and then they followed the same steps as before (displaying each layer's description and assigning codes). The complete process of identifying stratigraphic codes and assigning to borehole logs’ layers is shown in Figure 20.

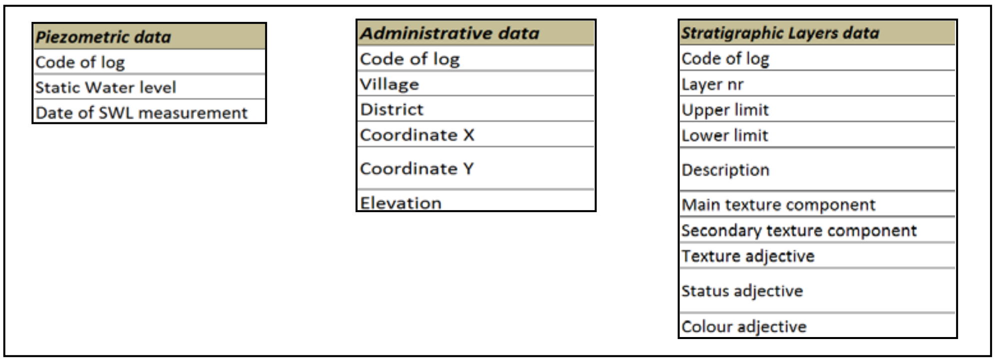


Code forage	Limite sup (m)	Limite inf (m)	Description Lithologie	Substantif principal	Substantif secondaire	Adjectif Texture	Adjectif status	Adjectif coleur
275X0001	0	5	argile	Argile				
275X0001	5	10	argile lateritique	Argile		lateritique		
275X0001	10	16.15	schistes barioles	Schiste	Quartz			bariolé
275X0001	16.15	20	schistes a passes de quartz	Quartz				
275X0001	20	40	quartz	Quartz				
275X0001	40	75	gres quartzites	Gres	Quartzite			
025X0007	0	6	sable moyen a grossie + ou - ferrugineux	Sable			moyen	
025X0007	6	11	sable argileux + laterite	Sable	Laterite	argileux		
025X0007	11	32	sable moyen a grossie avec gravillons de laterite	Sable	Laterite			
025X0007	32	35	calcaire greseux	Calcaire			greseux	
025X0007	35	43	calcaire marneux et marne beige	Calcaire	Marne	marneux		beige
025X0007	43	62	calcaire blanc a gaster podes passages marneux	Calcaire				blanc

Figure 20 ***Schematic representation of first two steps of processing borehole logs data with TANGAFRIC***

The result of this process is a database where the data of borehole logs are stored in three different tables (Figure 21).

The table of piezometric data and administrative are in 1 to 1 relationship (each record is a borehole log), while data are in 1 to many relationship with the table of stratigraphic layers data (where each record is a specific layer inside a borehole log).



Piezometric data
Code of log
Static Water level
Date of SWL measurement

Administrative data
Code of log
Village
District
Coordinate X
Coordinate Y
Elevation

Stratigraphic Layers data
Code of log
Layer nr
Upper limit
Lower limit
Description
Main texture component
Secondary texture component
Texture adjective
Status adjective
Colour adjective

Figure 21 ***Structure of database generated by TANGAFRIC***

Extraction of textural composition of layers:

The procedure to extract textural composition of layers used in TANGAFRIC adopts a similar method of the software TANGRAM; some modifications have been introduced because of the different system to assign stratigraphic codes.

Textural composition is obtained from the interpretation of 3 first digit of layer's code, corresponding to main texture component, secondary texture component and texture adjective. The last 2 digits (status adjective and colour adjective) are not taken into consideration in this process.

First of all, the list of nouns and adjectives corresponding to all the possible textural categories allowed in the coding process are divided in 4 groups (Table 7), discriminated on the basis of grain size of unconsolidated materials, plus hard layers in a separate group (coarse, medium, fine and hard texture).

GROUP	CATEGORIES (NOUNS AND ADJECTIVES)	ENGLISH VERSION
Coarse texture	arène, sable, gravier, sableuse, sableux	1st or 2nd digit: Sand, Gravel 3rd digit: Sandy
Medium texture	marne, marneuse, marneux, silteuse, silteux	1st or 2nd digit: Marl, Silt 3rd digit: Marly, Silty
Fine texture	argile, couche vegetal, lignite, argileuse, argileux, lateritique, laterite, altérites	1st or 2nd digit: Clay, Vegetal layer, Lignite, Laterite, Alterite 3rd digit: Clayey, lateritic
Hard	basalte, calcaire, dolerite, gabbro, granite, grès, gres, quartz, quartzite, schiste, silex, cuirasse, cuirasse lateritique	1st or 2nd digit: Basalt, limestone, Dolerite, Gabbro, Granite, Sandstone, Quartz, Schist, Silex, Cuirass

Table 7 - ***Groups defined to extract distribution of class of grain size***

The software processes the stratigraphic data, and extracts the percentage of each group for a sequence of intervals with a regular step (in the research it was defined a 2 m step, but this can be adjusted) with the same criteria:

a) if only the main texture component is indicated (1st digit) and 2nd component and adjective are empty, then the texture will be 100% corresponding to the group of main component;

b) if main and secondary component are indicated (1st and 2nd digit), and no texture adjective is present, the texture will be 60% from main component and 40% from secondary component;

c) if main component and texture adjective are indicated (1st and 3rd digit) but not the secondary component, texture will be 70% from main component and 30% from adjective;

d) if all the 3 digits are filled, then the final texture will be 50% from main component, 30% from secondary component, 20% from texture adjective.

The combination of dividing in regular steps and assigning texture for each interval through the above described weighted procedure will give an output table where the percentage of each group is indicated for each layer of 2 m. Table 8 shows an example of a log with "Sand" between 0 and 4 m, "sandy clay" between 4 and 10 m (whose stratigraphic codes correspond to the first two layers in Table 6).

Depth (m)	Texture	From	To	% coarse	% medium	% fine	% hard
From 0 to 4	Sand	0	2	100	0	0	0
		2	4	100	0	0	0
From 4 to 10	Sandy clay	4	6	30	0	70	0
		6	8	30	0	70	0
		8	10	30	0	70	0

Table 8 ***- Example of output table of TANGAFRIC with distribution of grain size groups for each layer***

Repeating the same process with different grouping of texture categories and joining the resulting tables, we obtained for a set of borehole logs and intervals of 2m the percentage of:

-unconsolidated coarse fraction;
-unconsolidated medium fraction;
-unconsolidated fine fraction;
-consolidated hard lateritic material;
-consolidated hard rock material.

With TANGAFRIC is also possible to modify:

a) the list of borehole logs in the database (it means aggregating stratigraphic data not included in the original inventory);
b) the list of possible nouns and adjectives used for the stratigraphic codification of layers;
c) the classification scheme used in the processing module (therefore putting emphasis on specific characteristics of the lithological description, like the presence of a specific component);
d) the step used by the processing module to extract percentage of different class for each interval.

These data can be manipulated with aggregate functions of any DBMS software and extract textural composition for specified intervals according to our target (e.g. average textural distribution from 0 to 50 m, from static water level to depth of hard rock).

Estimation and extraction of hydraulic conductivity

Hydraulic conductivity (K) represents the water's ease of flow through the porous or fractured media, and depends on texture (in case of unconsolidated materials) or characteristics of fracturing (in case of rocks). Ideally hydraulic conductivity of geological layers must be defined through direct measurements on site specific sample (in laboratory), or in situ measurements (e.g. pump test).

When this information is not available, K can be estimated from hydrogeological knowledge of the region and published values of K measured in similar context for the same type of layers.

In this research the available site specific information on shallow aquifers was very limited for the following reasons: a) data of existing pump test carried out in boreholes (from national database of DGPRE and SNAPE) indicates values of K, but they generally can be referred to deep fractured hard rock, as previously explained and b) hydrogeological studies in this region are limited and also they focus their attention in fractured aquifers of the basement.

Different methods are available to estimate hydraulic conductivity from grain size of sediments. In this study we used reference value of K for lithological class obtained from the sources of information used in TANGRAM (Bonomi 2009; Fetter, 1994; Freeze and Cherry, 1979). In the present research we assigned a K value for each group used in the calculation of percentage of texture:

- for coarse material (corresponding to sand deposits in this region as no gravel is present) we assumed K= 10^{-4} m/s;
- for medium texture material we assumed K= 10^{-5} m/s;
- for fine texture material we assumed K= 10^{-6} m/s.

In case of consolidated hard materials we assumed K= 10^{-6} m/s (considering the presence of unconsolidated sediments filling the empty space of the hard layer). However they are often representing the upper layer of the basement and they are not perforated by manual drilling; in this case they are not considered in the estimation of exploitable transmissivity.

In this way we estimated K value for each interval of 2 meters, obtaining from the weighted average of log[K] of each group multiplied by its percentage (eq.5.1):

$$\log[K]_{interval} = \log[K]_{coarse}*\%_{coarse} + \log[K]_{medium}*\%_{medium} + \log[K]_{fine}*\%_{fine} + \log[K]_{cons.}*\%_{cons.} \qquad \text{[eq. 5.1]}$$

where $\log[K]_{interval}$ indicates log[K] of the estimated hydraulic conductivity of the interval composed by a mix of different textural categories.

For example, in case of an interval with 30% coarse and 70% fine (like sandy clay), the estimated log[K] will be:

$\log[K]_{interval} = \log[K]_{coarse}*0.3 + \log[K]_{fine}*0.7$

$\log[K]_{interval} = (-4*0.3)+(-6*0.7) = -5.4$

$K_{interval}= 1*10^{-5.4} = 4*10^{-6}$ m/s

where $K_{interval}$ indicates the estimated hydraulic conductivity of the interval composed by a mix of different textural categories.

A schematic presentation of the process to obtain hydraulic conductivity from the original stratigraphic description is shown in Figure 22

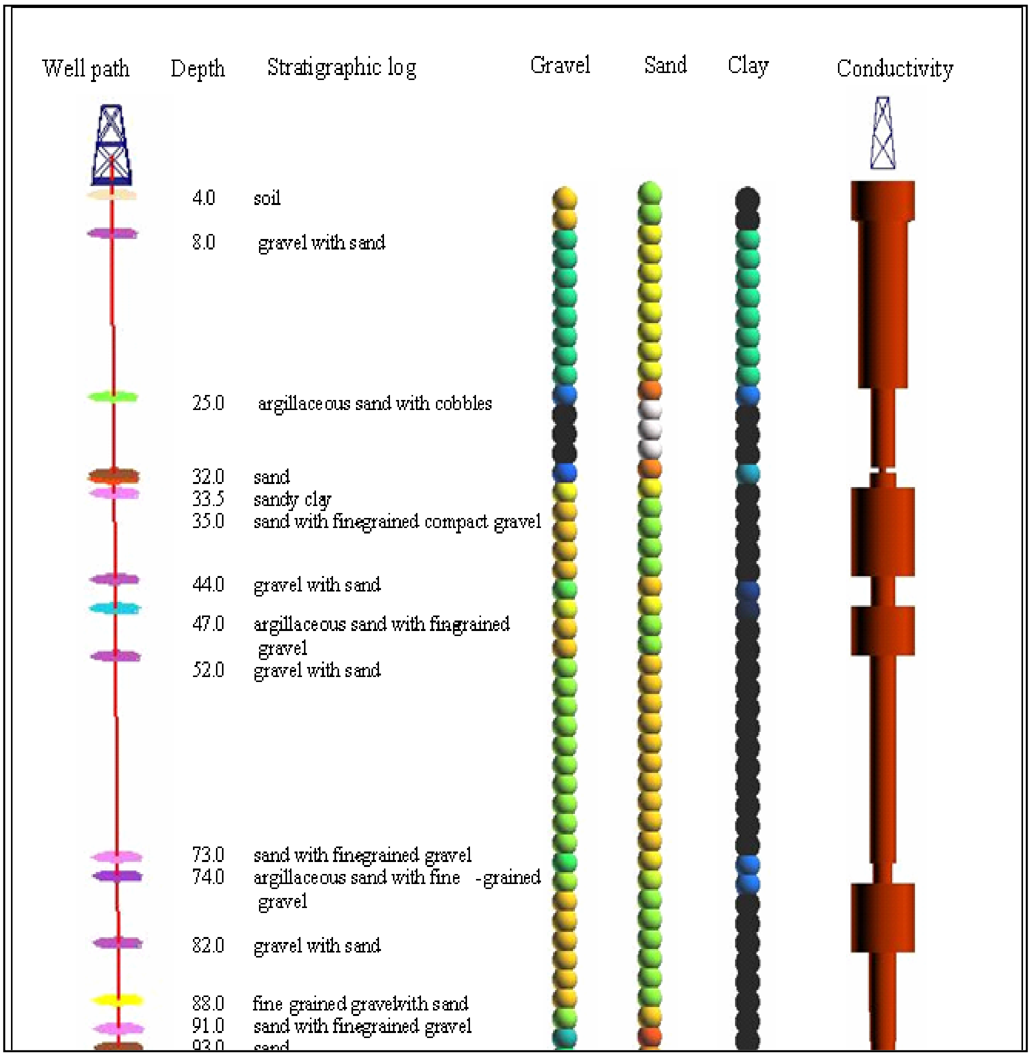


Figure 22 ***Representation of the process to obtain hydraulic conductivity from stratigraphic description***

Estimation and extraction of trasmissivity

As shown in the conceptual model to estimate suitability for manual drilling, this parameter is defined from the combination of two factors: a) feasibility, obtained with a logical procedure of analysis from depth of hard rock, depth of water and presence of laterite; b) potential for exploitation, obtained from a classification based on the trasmissivity in the exploitable layer, T_{ex}.

In order to calculate T_{ex} it is necessary to obtain: a) the thickness of the exploitable saturated layer (H_{ex}), it means the layer between the upper limit defined by the depth of water (above this level the aquifer is not saturated) and the lower limit corresponding to the maximum depth that manual drilling can reach in that position; b) average K in the exploitable saturated layer ((K_{ex}).

The maximum depth for manual drilling in a specific location can be 50 m (this is the standard value adopted as maximum reachable depth) or less, in case depth of hard rock is shallower than 50 m.

if DHR > 50m, then MD=50 m
if DHR < 50m, then MD=DHR

Hex (m) = MD - DGW (if MD > DGW)
Hex (m) = 0 (if MD < DGW)

Where:
MD = maximum depth of manual drilling in a specific location (m)
DHR = depth of hard rock (m)
DGW = depth of groundwater (m)

Since the transition from unconsolidated layers to hard rock is often not sharp, in this research we assumed that depth of hard rock corresponds to the upper limit of layers having consolidated hard rock component > 50%

K_{ex} = average K in the range between DGW and MD (obtained with aggregate functions from the K values extracted for each step of 2 m)

And finally

$$T_{ex} = H_{ex} * K_{ex} \quad \text{[eq. 5.2]}$$

Estimation of potential for exploitation with manual drilling

Once borehole logs data have been organized and processed as described above, it was possible to obtain the following parameters for each log:

- depth of hard rock,
- depth of water
- thickness of hard lateritic layers
- transmissivity of exploitable layer (T_{ex})

The first three parameters are used to define the class of feasibility (Table 1): depth of rock for condition 1, depth of water for condition 2, thickness of exploitable layers for condition 3

T_{ex} is used to classify the potential according to site specific threshold values.

Considering the hydrogeological context of the study area in Senegal, it was assumed the following threshold of T_{ex} (Table 9):

Class of potential	**Range of T_{ex} (m^2/s)**
NP - potential null	0
LP - Low potential	Between 0 and 3·10-05
MP - Moderate potential	Between 3·10-05 and 5·10-05
GP - Good potential	Between 5·10-05 and 1.3·10-03
EP - Excellent potential	More than 1.3·10-03

Table 9 ***- T_{ex} limits of the five class of potential for manual drilling in Senegal***

Results of borehole logs processing in Senegal and Guinea

Results of the semiautomatic analysis of borehole logs (and the comparison with direct field measurements) show the distribution of the different hydrogeological parameters considered in the proposed method to estimate suitability for manual drilling (Figure 4) and define the class of suitability at borehole logs position.

SENEGAL

Depth of hard rock

Almost in the whole study area the limit of hard rock is deeper than 10 m (as shown in the histogram of Figure 23), therefore satisfying the criteria defined in the feasibility model for manual drilling (class F and class FS).

Three cases can be identified:

- depth of hard rock is > 50m, in this case manual drilling is feasible (according to condition 1) and can be developed till the maximum depth reachable with this technique; it include 52% of cases;
- depth of hard rock is between 10 and 50 m, manual drilling is feasible but drilling depth is variable, limited by the thickness of unconsolidated layer (42.3% of cases);
- depth of hard rock is less than 10 m, manual drilling is not feasible (they are in class NF). It include 5.7% of cases, located in the NE part of the study area, and in a small band toward east of Louga.

The average value of depth of hard rock is 69 m, with a standard deviation of 54,1. It is clear that a large part of the study area is covered by a relevant layer of unconsolidated mater sediments, whose thickness is variable.

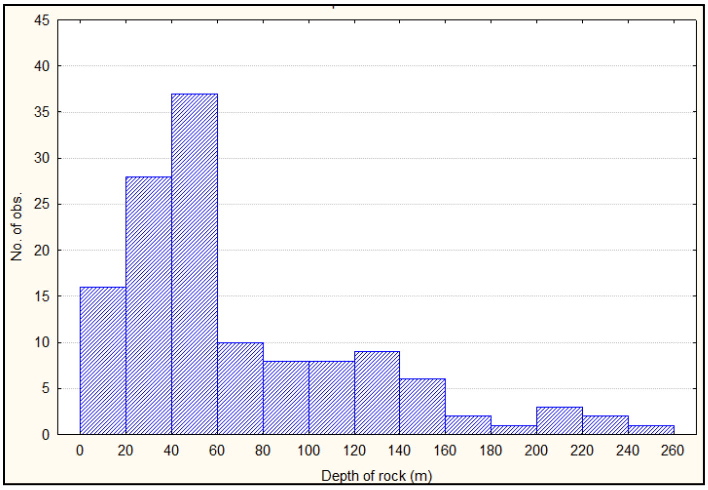


Figure 23 ***Frequency histogram of depth of hard rock in borehole logs in Senegal***

Thickness of unconsolidated shallow layer shows a general decrease moving eastward and northward (Figure 24), it means from the zones with limestone basement, to the zones with predominant sandstone basement. As a consequence, we expect limitations in the exploitable water column in manually drilled wells.

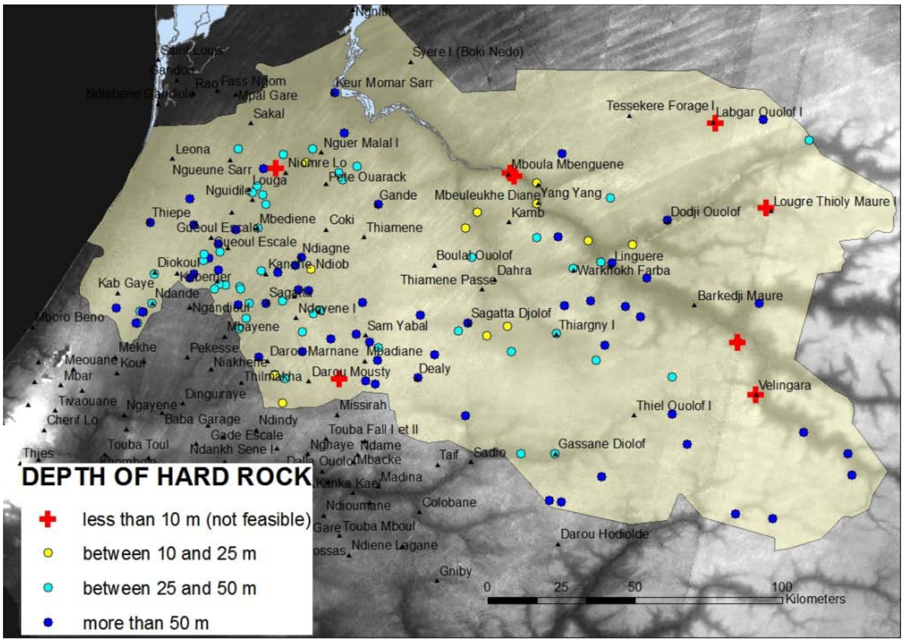


Figure 24 ***Map of depth of hard rock extracted from borehole logs in Senegal***

Depth of water

Depth of water is the most important limiting factor for the implementation of manual drilling in the study area. 45% of the logs show a static water level deeper than 40 m (Figure 25), therefore in this situation manual drilling is considered not feasible (NF) according to the limits defined in the proposed classification model (Figure 16, condition 2). The average value of water depth is 35 m, with a standard deviation of 10.3. However the estimation of depth of exploitable water (not recorded in the data) based on the information on static water level stored in the national database can be unreliable in case of confined deep aquifers covered with thick clay layers. This situation is frequent in the central and eastern sector of the study area, where information concerning water level in large diameter well (indicating the depth of shallow water table) in the database is limited; in this case field validation with direct observation of presence and depth of open wells is important.

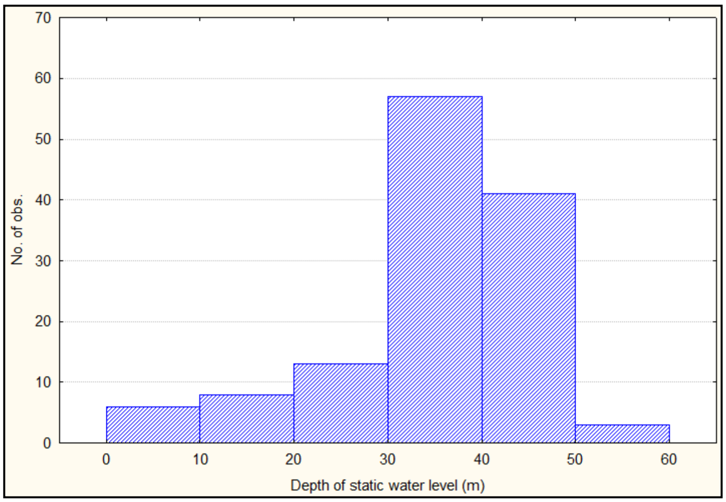


Figure 25 ***Frequency histogram of depth of static water level in borehole logs in Senegal***

The most critical zones is located SE of Kebemer, in the SW sector of the study area (Figure 26), while moving in the NE sector water level is generally shallower (although the limitation in drilling depth because of the presence of hard rock can make difficult to have a sufficient water column in the well).

The coastal strip has no borehole log data, but there is a large presence of water points (including several open hand dug well) with shallow water level. The amount of data concerning depth of water in the whole inventory of water points is much larger than boreholes logs, therefore they can be used separately to analyse this aspect, although they are not codified and elaborated with TANGAFRIC in order to extract hydraulic parameters (as no stratigraphic description is given for these points)

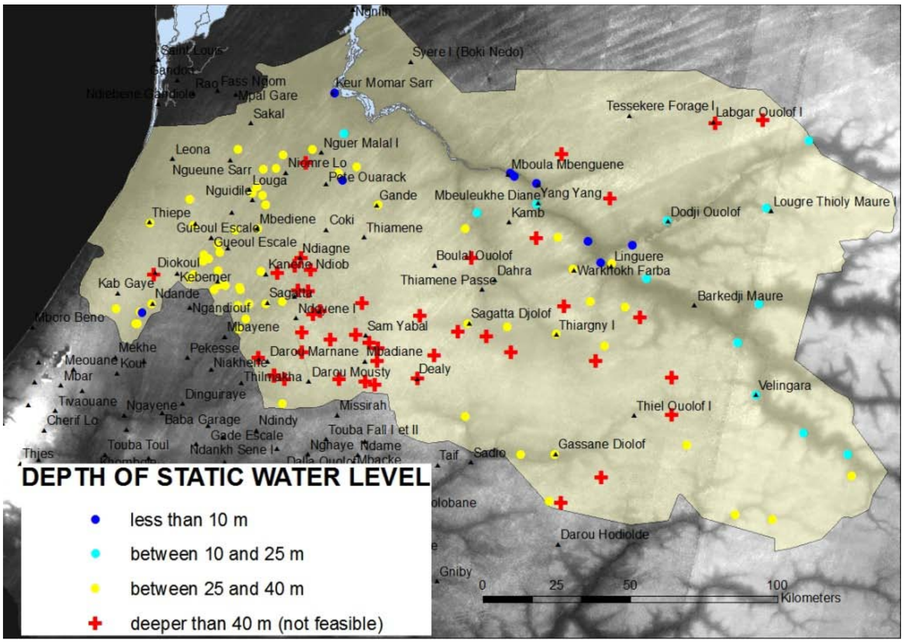


Figure 26 ***Depth of static water level in borehole logs in Senegal***

Thickness of hard laterite

Hard laterite is not frequent in the study area (Figure 27), therefore it doesn't represent in general a limiting factor for the implementation of manual drilling (Figure 16, condition 3). The presence of thick hard lateritic layers can represent an obstacle to the feasibility (when laterite is thicker than 5 m the condition is considered not feasible, class NF) only in the south-eastern side of the study area, around Patakour, and in some location around Linguere, in the centre. Furthermore in the southern band of the region there are a number of logs showing the presence of laterite with thickness less than 5 m; the condition of feasibility (if depth of rock and depth of water are favourable) are assigned to class F-SP, with the needs of percussion techniques to break this hard intercalated layers

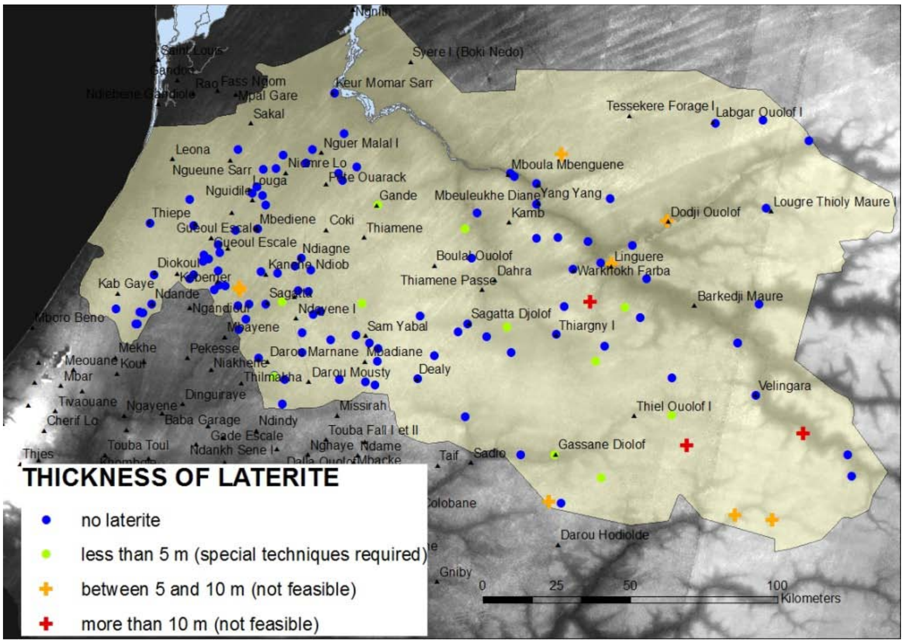


Figure 27 ***Thickness of laterite in stratigraphic logs in Senegal***

<u>Assessment of feasibility for manual drilling</u>

After having calculated the three previous parameters (depth of rock, depth of water, thickness of laterite) it is possible now to assign a specific class of feasibility for each borehole logs, following the procedure explained in Figure 16.

In the whole study area, 62% of the borehole logs show feasible conditions for manual drilling. Along the western coastal strip there are feasible conditions almost in the whole group of logs, while in the Ferlo valley the trend is mixed, although a predominance of feasible conditions. As we can observe (Figure 28), limitations in the feasibility of manual drilling in the study area are present in the southern part (mainly because of depth of water level) and the NE sector (in this case the main constraint is represented by the limited thickness of unconsolidated layers).

It is important to underline that the presence of confined aquifers and the lack of direct data about water level in the shallow water table can lead to a unreliable estimation of depth of water in the eastern part of the study area and finally the feasibility of manual drilling

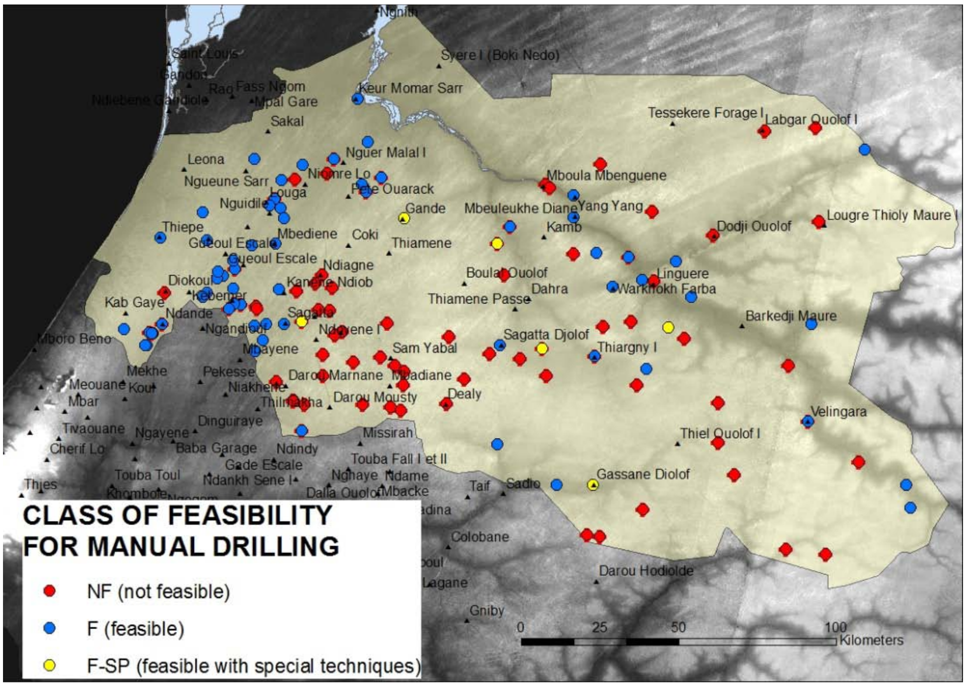


Figure 28 ***Class of feasibility for manual drilling at borehole logs position***

Hydraulic conductivity of exploitable layers

Depth of rock, depth of water and thickness of laterite are the three parameters required to define the feasibility for manual drilling at selected positions. At this point we shift to evaluate the potential for exploitation, this require that hydraulic conductivity and trasmissivity of exploitable layer are determined.

The estimated hydraulic conductivity of porous shallow aquifer in the exploitable layer shows log(K) values characteristic of an intermediate texture class (considering that the medium grain size fraction is limited, K value can be attributed to a mix of sandy deposits with an important clay fraction). Frequency distribution of Log(K) value has almost a normal trend (Figure 29). Average Log(K) is -4.83 (corresponding to K = 1.5·10-05 m/s), with a standard deviation of 0.4

The lowest K values in the exploitable layer are found SE of Kebemer and in the eastern sector of the study area (Figure 12).The highest values are in the coastal zone. Furthermore, few boreholes shows high estimated K value in the exploitable layer along the river valley NW of Linguere.

In general hydraulic conductivity in the first meters is higher than in the deeper part of porous aquifer: the average value of Log (K) between 0 and 10 m deep is -4.4 (K = 4·10-05 m/s), while between 20 and 30 m is -5 (1·10-05 m/s); in both cases standard deviation is 0.4 or 0.5. This is related to a general trend (90% of the whole data set) to decrease the coarse textural fraction in the deeper layers of the shallow porous aquifer. The ratio:

$$\frac{\text{\% of coarse fraction between 0 and 10 m deep}}{\text{\% of coarse fraction in the whole porous aquifer}}$$

has an average value of 2.64, and a median of 1.95.

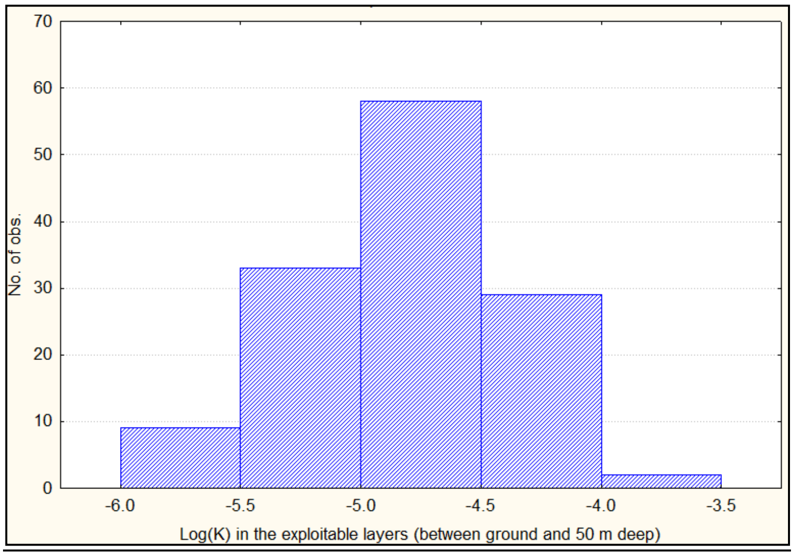


Figure 29 ***Frequency histogram of Log(K) in exploitable layers (up to 50 m deep) in borehole logs in Senegal. K expressed in m/s***

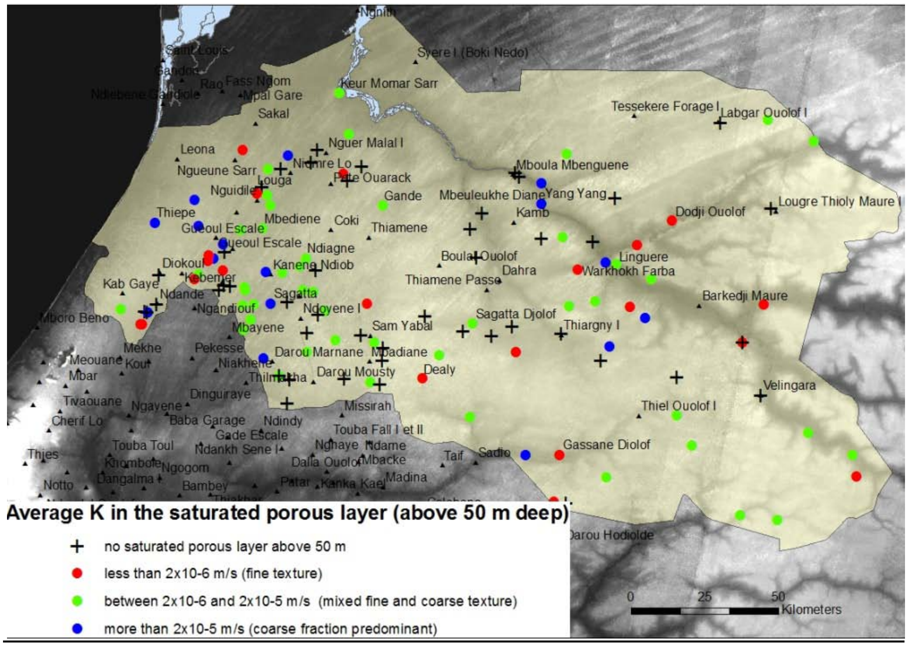


Figure 30 ***Map of hydraulic conductivity in the exploitable layers at borehole logs position***

Overall suitability for manual drilling

On the basis of the different hydrogeological parameters described above, it has been possible to classify each borehole log in terms of feasibility and potential for manual drilling, as described in the conceptual model proposed, and finally assign it to an overall group of suitability (Figure 31).

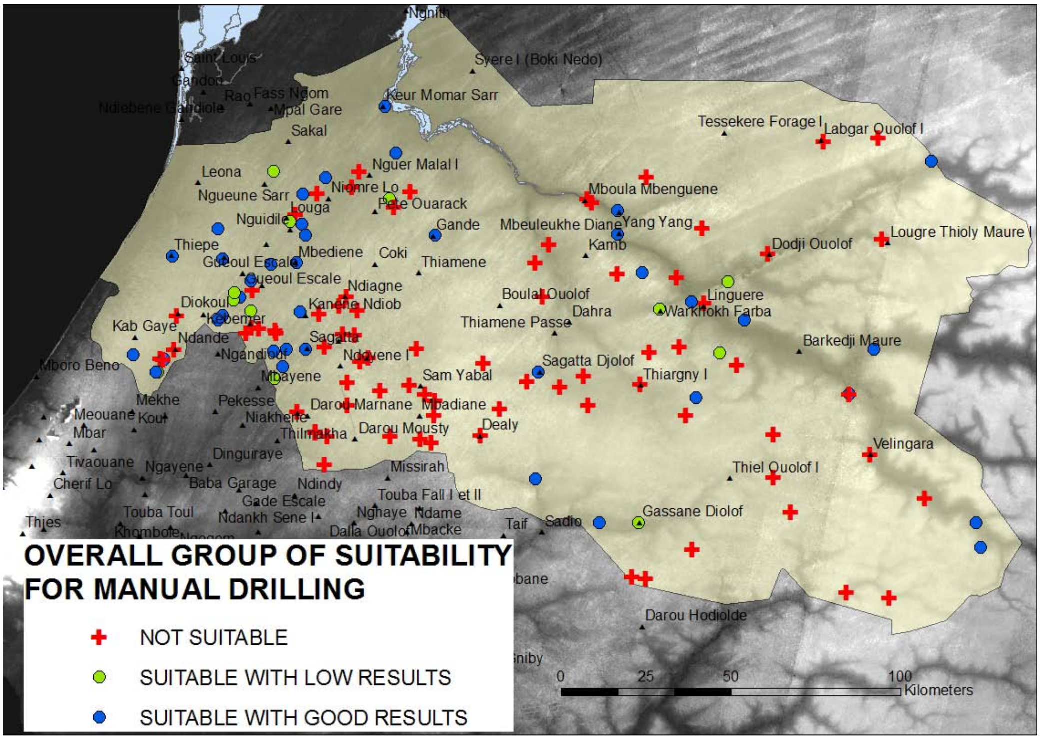


Figure 31 ***Overall group of suitability for manual drilling at borehole logs position***

In those areas where manual drilling is considered feasible, we can observe a good potential in the coastal area and in the Ferlo river valley around Linguere (although in this area the uncertainty about the depth of water level in the porous aquifer would suggest the comparison with other information not recorded in the national inventory of water points or other available source of data , as previously explained). On the other hand the area eastward from Kebemer (located in the SW sector of the study area) has several places with low potential, for the double effect of the depth of water (therefore a small water column in the well, if maximum depth is 50 m) and a higher percentage of fine materials (with low value of K).

In case of drilling deeper than 50 m, both estimated feasibility and potential would improve in the region of Kebemer (in the SW corner of the study area), while in the NE sector the limitations imposed by the presence of shallow hard rock would not change the estimation.

The estimation of feasibility depends on the limits assumed as a maximum depth for manual drilling, that depends on an estimation based on the experience of drillers. In this research we assumed a maximum depth of 50 m (and a maximum depth of water of 40 m). However 20% of the data shows a water depth between 40 and 50 m. Class of feasibility for these points would change in case of increasing of 10 m the maximum estimated depth of drilling (they would be considered feasible).

GUINEA

In Guinea all the boreholes logs showed depth of static water level in the range of feasibility for manual drilling (Figure 32). Although no information is available from open large diameter wells, we can assume that static water level in the boreholes correspond to the depth of ground water exploitable by using manual drilliing

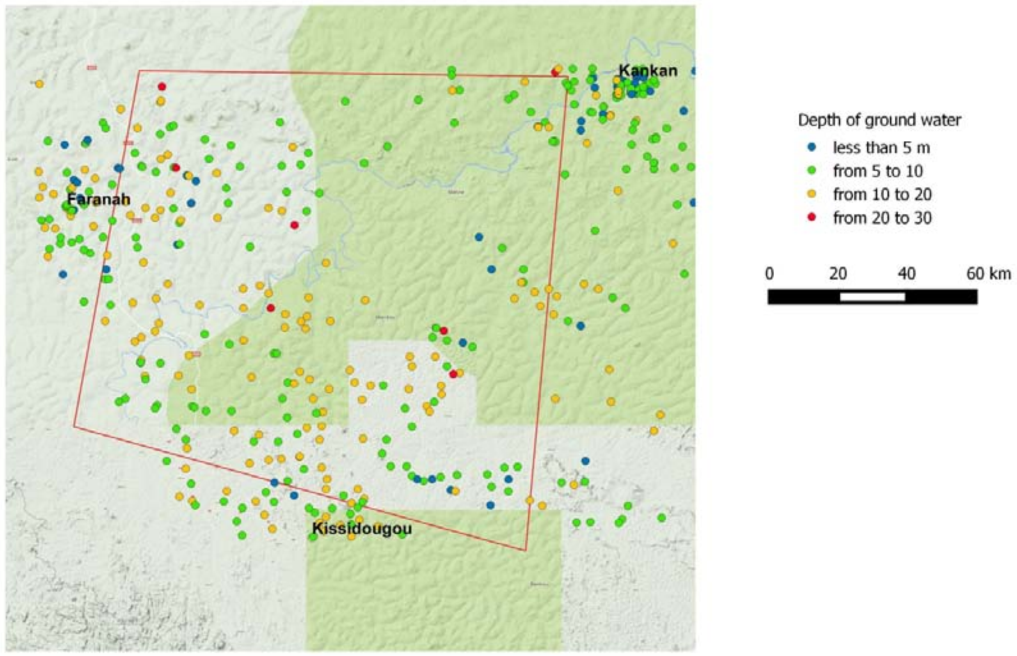


Figure 32 ***Depth of static water level in borehole logs in Guinea***

Concerning depth of hard rock (Figure 33), we can also assume that it is compatible with the execution of hand drilled wells; however these wells cannot reach the maximum depth potentially achievable; in most of the situation they are stopped at around 20 m.

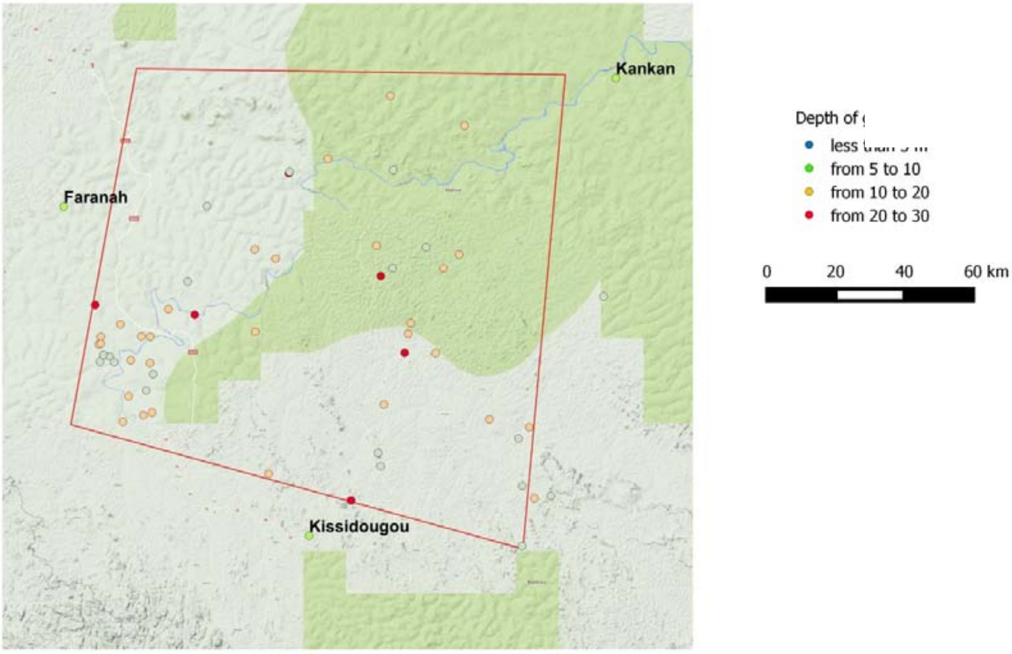


Figure 33 ***Depth of hard rock level in borehole logs in Guinea***

The hydraulic conductivity of unconsolidated sediments (Figure 34) is quite low, as a high presence of clay is observed. However a high permeable thin sandy layer is generally present at the contact with hard rock. If manual drilling is carried out up to the limit of the rock, the potential yield would be sufficient for small communities.

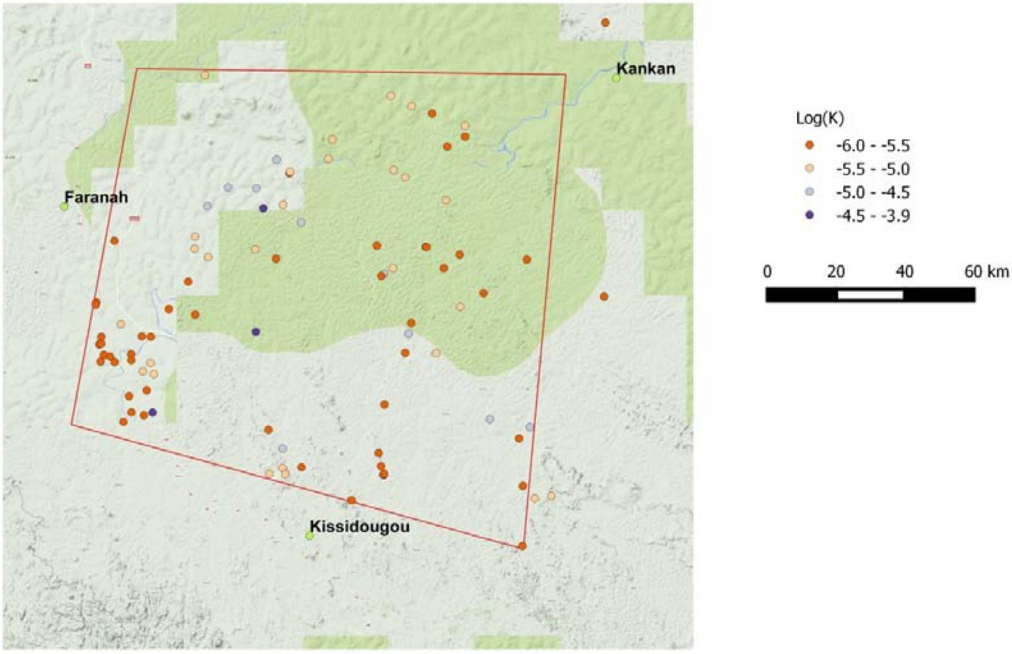


Figure 34 ***Log(K) for porous materials up to 50 m deep in borehole logs in Guinea***

Field observation, pumping tests and geophysics

The stratigraphic model obtained from borehole logs processing and the estimated values of hydraulic parameters were compared with measured parameters obtained from two field campaign (May 2014 and March 2015) in Senegal study area. The first campaign was mainly dedicated to improve the methodology of pump tests in large open well and the exploration of thewestern side of the area, while in 2015 the field observations were extended throughout the study area, increasing the number of measured data and verifying the potential factors determining the distribution of remote sensing parameters extracted from multitemporal series of satellite data.

All the planned field activities in Guinea were eliminated because of Ebola outbreak in the study area.

During the two campaigns in Senegal it was possible to complete 11 pump tests and 18 VES, distributed mainly in Western and Central part of study area and covering the different geological units (Figure 35). It was not possible to carry out pump tests in the eastern part of the region since here large diameter wells are extremely rare. Furthermore, water is deeper than 50 m in the few open wells; this resulted too deep to carry out pump test with the available equipment in the field.

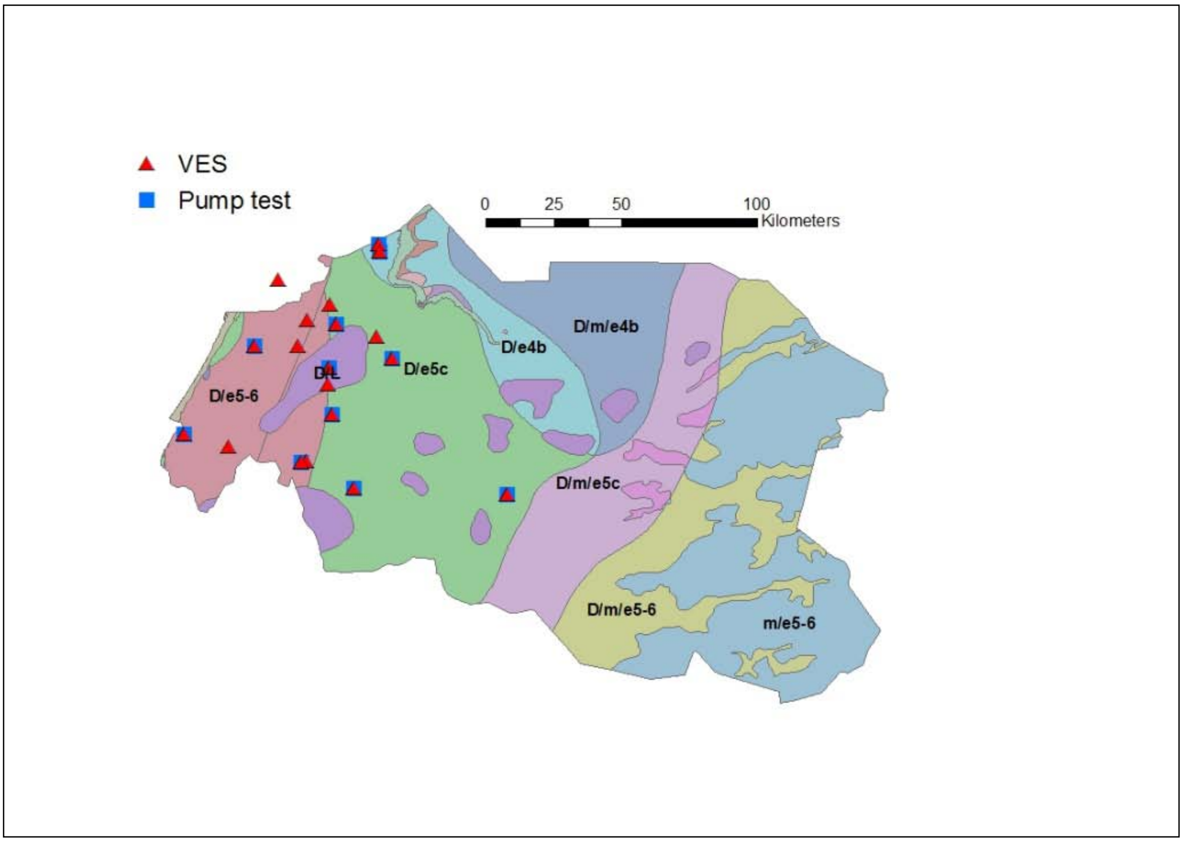


Figure 35 ***distribution of field measurements in Senegal overlaid on geological map***

Pump and recovery test in large diameter wells:

Their main purpose was to obtain direct measurements of hydraulic parameters for shallow aquifer (the expected target for manual drilling). These values were later compared to the estimated values obtained though borehole logs data processing in order to check the parameters used in the conversion from texture composition to hydraulic conductivity.

The main criteria considered in the selection of the wells for pump tests are:

- they must be distributed in the whole study area (where possible);
- they must cover all the main geological units;
- water column in the well must be high (possibly more than 1.5 m);
- water level in the well must not be deeper than 40 m.

The equipment used for pump tests are:

- a transportable submersible pump installed close to the bottom of the well and connected with a electrical generator (Figure 36);
- a pressure probe, installed at the bottom of the well and connected to a laptop computer; in this way it was possible to monitor continuously the variation in pressure during the test and have detailed record of drawdown and recovery (Figure 37);
- a deep meter and chronometer, in order to check manually the modification of water level, avoiding the risk of loss of data in case of failure of the pressure probe;

a gauging valve and flow meter at the end of discharge pipe, in order to monitor the yield during the pumping phase of the test.

Figure 36 ***Installation of pump and generator in a large diameter well***

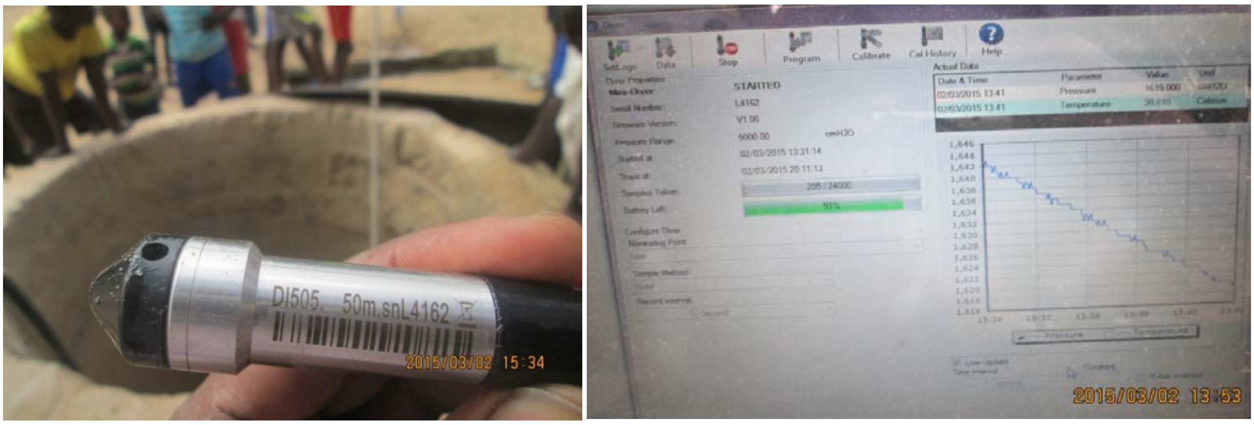


Figure 37 ***Pressure probe installed in the well (left) and automatic monitoring of change in water column (right) during the pump test***

Considering that both field campaigns occurred in the late dry season, it was difficult to find wells with adequate water column to carry out pumping for an extended period; this fact obliged to carry out pump tests in wells with limited water.

Pumping phase was ideally extended for one hour, but in several cases it was interrupted after a shorter period because water column was too small to run the pump in safe condition. Recovery phase was monitored for 1-1.5 hours; this part of the test provided the most relevant information for the estimation of hydraulic parameters.

Interpretation of pump test

Most of the methods to calculate hydraulic parameters from pump tests assume that storage capacity of the wells is negligible; in this case all the water extracted comes from the aquifer and there is no contribution of the water stored in the well. But this assumption is not possible in a large diameter well, with an elevated storage capacity. The modification of water level in the well is little influenced by flow from the aquifer for a significant period after start of abstraction, while it is more affected by the extraction of the water already stored in the well.

During the recovery phase, however, the head variations in the well depend only on the rate at which water flows from the aquifer; recovery data are more diagnostic of aquifer parameters than drawdown, particularly for short periods of pumping (Barker and Herbert, 1989).

The interpretation of recovery after pumping in large diameter well can be done with two different approaches:

- pumping has been sufficiently slow in order to reach the equilibrium between drawdown in the well and depression in the water table. Water extracted comes from the inflow from the aquifer to the well (like in traditional pump test in boreholes), plus the storage of the well. Different methods have been proposed for their interpretation: the numerical solution for the determination of aquifer properties from recovery data in fully penetrating large diameter wells was proposed by Papadopoulos and Cooper (1967); empirical equations (Herbert and Kitchen, 1981) and nomograms (Barker and Herbert, 1989) were presented for the application of this numerical solution. A review of different methods of interpretation based on empirical solutions and numerical models is presented by Herbert et al. (1992);
- the situation is similar to a slug test, where withdrawals of water is quick and water level (hydraulic head) in the well is lowered instantaneously. Water extracted comes from the storage of the well and there is no contribution of the inflow from the aquifer. Slug tests are good to for the estimation of aquifer properties in hand dug well because they are commonly used in low-permeability environments, take into consideration the storage of water in the well, are easy to conduct in the field and versatile (Mace, 1999). Different methods have been proposed for their interpretation (e.g. Hvorslev, 1951; Cooper et al., 1967; Bouwer and Rice, 1976; Rupp et al., 2001; Uribe et al, 2014).

Bouwer and Rice's model (1976) was originally designed for fully or partially penetrating wells tapping unconfined aquifers. The application of Bouwer and Rice model in different conditions from the original formulation was discussed by Bouwer (1989) who analysed different specific aspects of the interpretation (influence of well geometry, presence of confined aquifers, etc). Modifications of Bouwer and Rice's model were later proposed by different authors: Rupp et al. (2001) considered the influence of unsaturated hydraulic conductivity and introduced a coefficient depending on soil texture. Shaw-Yang and Yeh (2004) proposed polynomial equations to describe the curves for three coefficients as presented in the original Bouwer and Rice's model.

For the selection of the interpretation method, the first step was defining which of these two approaches was more similar to the dynamics of pumping phase. Two parameters were observed: the dewatering rate and the shape of drawdown curve.

The dewatering rate (DR) corresponds to the ratio between the volume of the well that was emptied during pumping and total volume of water extracted;

$$\text{DR} = \frac{\text{Volume of the well between starting and ending water level}}{\text{Total volume of water extracted during pumping phase}}$$

[eq. 5.3]

In case of slow and extended pumping (in equilibrium with modified shape of water table in the aquifer), all the water extracted comes from the flow from the aquifer to the well, while well storage is negligible. This is the situation in small diameter wells or pumping phase over a long duration; DR is close to 0.

On the contrary, in case of quick pumping and instantaneous drawdown of water level in large wells, all the water extracted comes from storage of the well and no inflow from the aquifer occurs (with no modification of the shape of water table). In this case DR = 1 and the tests is similar to a slug test.

The 11 pump tests carried out in Senegal shows DR close to 1 (Figure 38), with the exception of Ndimb Wolof (but this pump test faced many problems during its execution and was stopped after a very small drawdown). Therefore they can be considered similar to slug tests and their interpretation is based on those methods proposed for this type of tests.

Village	Yield (l/s)	well diameter (m)	water static level (m)	Drawdown (cm)	Pumping time (min)	DR (Dewatering Rate)
DARAL (THIAMBENE)	2	1.45	10.6	34	5	0.9
KEUR MATTAR GUEY	1.67	1.50	35.27	54.5	10	1.0
KEUR NDAY SAR	1.83	1.90	14.9	161	45	0.9
NDIM PEULH	1.67	1.85	24.8	159	50	0.9
NDIM WOLOF	1.67	2.06	17.8	31	30	0.3
NDOYENE	1.25	1.67	40.38	44.7	16	0.8
NGUEYE DAIDJE	1.33	1.50	36.02	63	14	1.0
NYAMBOU FALL	2	1.80	27.69	104	22	1.0
ROY DEYE	1.4	1.40	28.5	198	50	0.7
SAGATTA DIOLOF	1.862	1.60	18.8	68	15	0.8
TOUBA MATALBAN	1.33	1.70	40.5	78	22	1.0

Figure 38 ***Characteristic of pump test completed in Senegal***

A second method to analyse the dynamics of pumping phase is by observing the shape of drawdown curve: if pumping rate and well radius are constant, a linear drawdown curve (as we can observe in Figure 39) suggests that all the water removed from the well is from well-bore storage and the withdrawal period can be considered “instantaneous” (Mace, 1999).

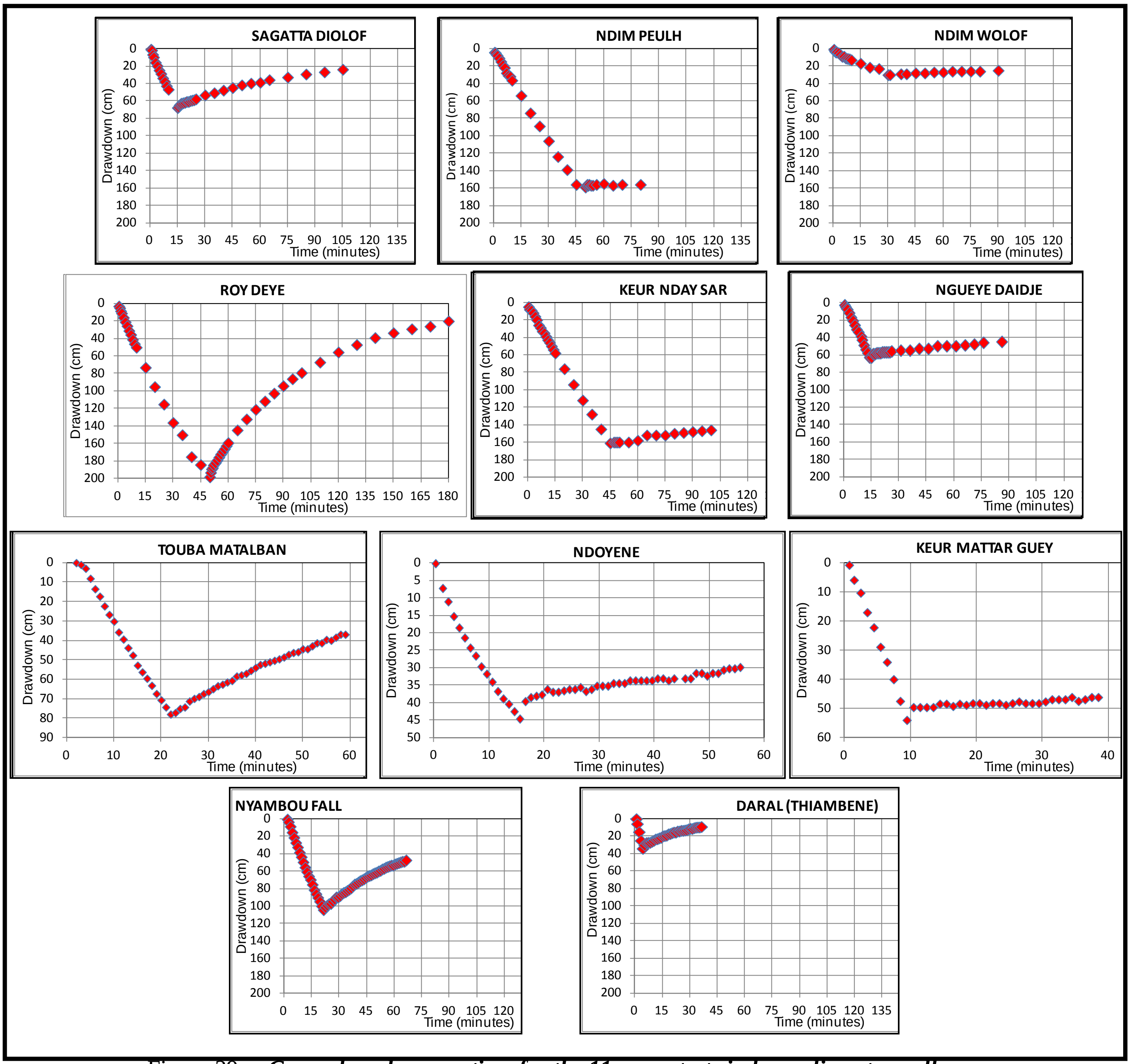


Figure 39 ***Curve drawdown vs. time for the 11 pump tests in large diameter wells***

Bouwer and Rice's methods (and modifications) seemed the most suitable for the interpretation, given the geometry of the system and the development of the test. In fact this method was designed for the interpretation of slug tests in fully or partially penetrating wells, tapping unconfined aquifers. Therefore it is more versatile than other methods (e.g. Hvorslev, 1951; Cooper et al., 1967) originally designed for confined aquifers (Mace, 1999). The hydrogeological condition of the wells in our research are unconfined and it was not possible to approximate confined conditions keeping small the drawdown , since the water column in the wells is too limited to adopt this solution.

Bouwer and Rice's method (1976) makes the following assumptions:

- drawdown of the water table around the well is negligible;
- flow above the water table (in the capillary fringe) can be ignored;
- head losses as water enters the well (well losses) are negligible;
- aquifer is homogeneous and isotropic.

According to Bouwer and Rice's method, K can be calculates as:

$$K = \frac{{r_c}^2 \ln{(R_e/R_w)}}{2L} \frac{1}{T} ln \frac{\gamma_0}{\gamma_t}$$

[eq. 5.4]

Where:

- r_c is the radius of the well;
- R_w is the radial distance between the undisturbed aquifer and the centre of the well;
- L is the height of the portion of well through which water enters;
- $\gamma_0$is the vertical distance between water level in the well and equilibrium water table at t=0;
- γ_t is the vertical distance between water level in the well and equilibrium water table at t
- R_e is the effective radius over which γ is dissipated.

A schematic representation of the geometry of the model is presented in Figure 40

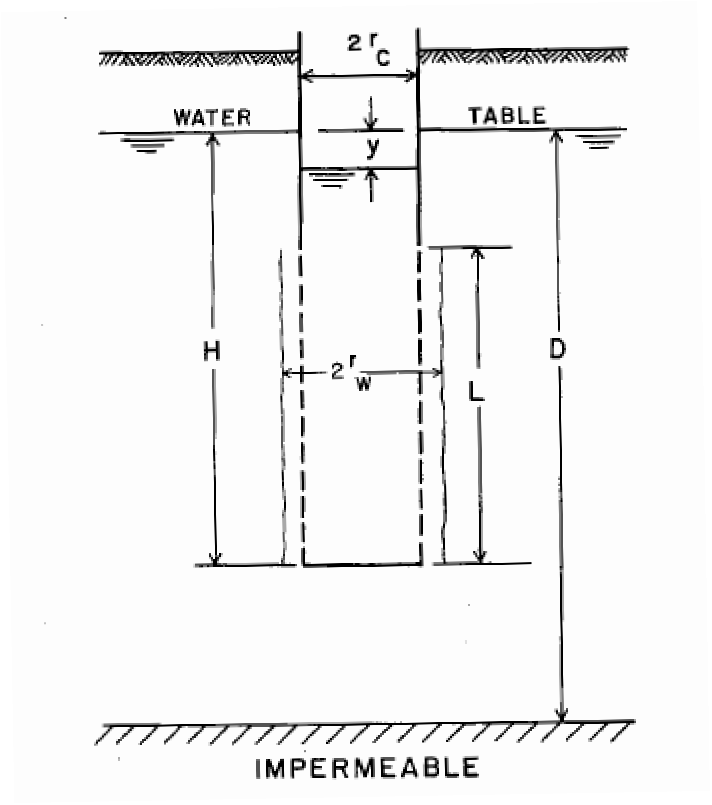


Figure 40 ***Geometry of a large diameter well in unconfined aquifer (from Bouwer and Rice, 1976)***

To determine R_e, Bouwer and Rice used and electrical analogue model for different combination of L, Rw and Rc; they proposed two equations depending from the geometry of the well. For partially penetrating wells:

$$ln\frac{R_e}{R_w} = \left[\frac{1.1}{\ln\left(H/R_w\right)} + \frac{A + B\ln\ |(D - \ H/r_w|}{L/r_w}\right]^{-1}$$

[eq. 5.5]

where:

- H is the vertical distance between water table and bottom of the well;
- D is the vertical distance between water table and bottom of the aquifer;
- A and B are dimensionless coefficient that are functions of L/r_w. If D >> H, an increase in D has no measurable effect on $ln\frac{R_e}{R_w}$.

Or for fully penetrating well:

$$ln\frac{R_e}{R_w} = \left\lfloor\frac{1.1}{\ln\left(Lw/R_w\right)} + \frac{C}{L/r_w}\right\rfloor^{-}$$

[eq. 5.6]

The coefficients A, B and C are function of the ratio L/r and are taken from curves published by Bouwer (1976). Shaw-Yang and Yeh (2004) presented polynomial equations describing these cures and allowing the calculation of the 3 parameters.

Rupp (2001) showed that Bouwer and Rice method underestimate K, producing large errors especially for broad and shallow wells (the performance of Bouwer and Rice's method was better for increasing L/r values). Rupp compared the estimation of K using Bouwer and Rice's method with the results of simulated slug tests using the Hydrus-2D model (Simunek et al., 1999) that considered the influence of unsaturated hydraulic conductivity.

Rupp proposed a modified equation for the estimation of $\ln\frac{R_e}{r}$:

$$\ln\frac{R_e}{r} = \frac{C_0 + C_1\ \ln[\Lambda(L/r)^2]}{1 +\ C_2[(D-L)/D]^{1/2}\,(L/r)^{-5/8}}$$

[eq. 5.7]

Where:

Λ is parameter (m) characterizing the soil capillarity. Its value depends on the texture class of soil (Table 10);

C_0, C_1 and C_2 are three coefficients whose proposed values by Rupp are:

C_0 = 1.839

C_1 = 0.209

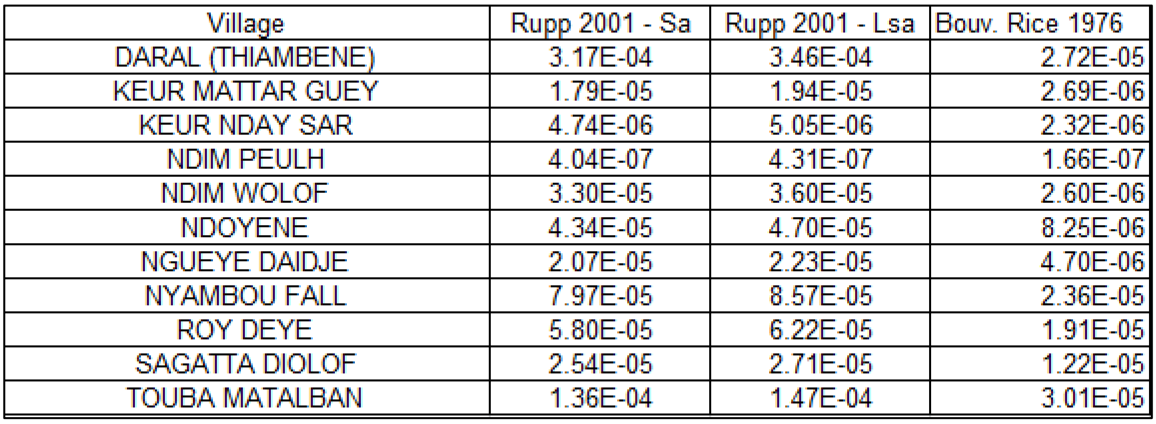
C_2 = 1.614

Soil	Texture Class	% Sand	% Silt	% Clay	Λ (m)
Sa1	Sand	97	3	0	0.41
LSa1	Loamy Sand	80	15	5	0.88
SiCL1	Silty clay loam	10	61	29	9.53
SiC1	Silty clay	5	50	45	39.19

Table 10 ***Values of Λ depending by soil class (from Rupp, 2001, modified)***

We assumed that the well is fully screened, therefore filtration occurs along the whole well surface between water table and bottom of the well (H = L). Although the screened section of the well (perforated concrete rings) is smaller, the presence of gravel packing up to water table facilitate filtration event from shallower part of the aquifer.

K was estimated using the original Bouwer and Rice's method (1976) as well as the modified equation for ln (Re/R) proposed by Rupp (2001) for soil classes Sa1 (Sand) and Lsa1 (Loamy sand). K was estimated for fully penetrating wells (D = L), considering that there is a concrete slab at the bottom of large diameter in Senegal constructed or improved by the national water authority; therefore water flow is only lateral and the base of the well can be considered an impermeable layer.



Village	Rupp 2001 - Sa	Rupp 2001 - Lsa	Bouv. Rice 1976
DARAL (THIAMBENE)	3.17E-04	3.46E-04	2.72E-05
KEUR MATTAR GUEY	1.79E-05	1.94E-05	2.69E-06
KEUR NDAY SAR	4.74E-06	5.05E-06	2.32E-06
NDIM PEULH	4.04E-07	4.31E-07	1.66E-07
NDIM WOLOF	3.30E-05	3.60E-05	2.60E-06
NDOYENE	4.34E-05	4.70E-05	8.25E-06
NGUEYE DAIDJE	2.07E-05	2.23E-05	4.70E-06
NYAMBOU FALL	7.97E-05	8.57E-05	2.36E-05
ROY DEYE	5.80E-05	6.22E-05	1.91E-05
SAGATTA DIOLOF	2.54E-05	2.71E-05	1.22E-05
TOUBA MATALBAN	1.36E-04	1.47E-04	3.01E-05

Table 11 ***Estimated K(m/s) from interpretation of recovery curve. Calculated with Rupp's method (2001) for sand (Sa), loamy sand(Lsa) and calculated by using the original Bouver and Rice's method (1976). Condition of fully penetrating wells or infinite aquifer (D=L)***

These K values were compared with the estimation obtained with TANGAFRIC as follows:

- For each pump test we extracted all the borehole logs closer than 7 km. Each log was associated to the closest pump test.
- In each log the series of stratigraphic intervals of 2 m (as obtained after processing with TANGAFRIC) located in a similar depth as the corresponding static water level of the associated pump test were selected (it means those intervals placed in the range of depth from 4 m above the static water level of the associated large well to 6 meter below);
- The average value of K and % of coarse fraction in the selected interval was calculated for each log. Finally we calculated the mean K value and % of coarse fraction among the set of borehole logs located in the proximity of each pump test. This value was compared

with the results of interpretation of recovery curve using Bouwer and Rice's and its modification. For some pump test it was not possible to find boreholes logs close, or the test was considered not properly done (e.g. Ndim Wolof, Ndim Peulh).

To give an example of the procedure, if we carry out a pump test in a large diameter well having depth of water level at 30 m located in a specific village, we will select all the boreholes closer than 7 km from that large well and we will extract the percentage of coarse fraction and K considering the interval between 26 and 36 m; then we will make the average of K values extracted and we will compare with the K values resulting from the interpretation of the pump test with three different equations (Rupp for Sa soil class, Rupp for Lsa soil class, original Bouwer and Rice)

Village	Average % of coarse fraction	Average K(m/s)
Keur Mattar Guey	51.39	1.33E-05
Keur Nday Sarr	0.00	2.55E-05
Ndoyene	0.00	5.01E-06
Ngueye Daidje	70.00	2.51E-05
Roy Deye	70.00	2.51E-05
Sagatta Diolof	49.58	9.81E-06
Touba Matalban	53.13	1.15E-05

Table 12 ***Estimated K(m/s) and average % of coarse fraction in borehole logs located within 7 km from each pump test, considering the range of depth from4 m above to 6 m below static water level***

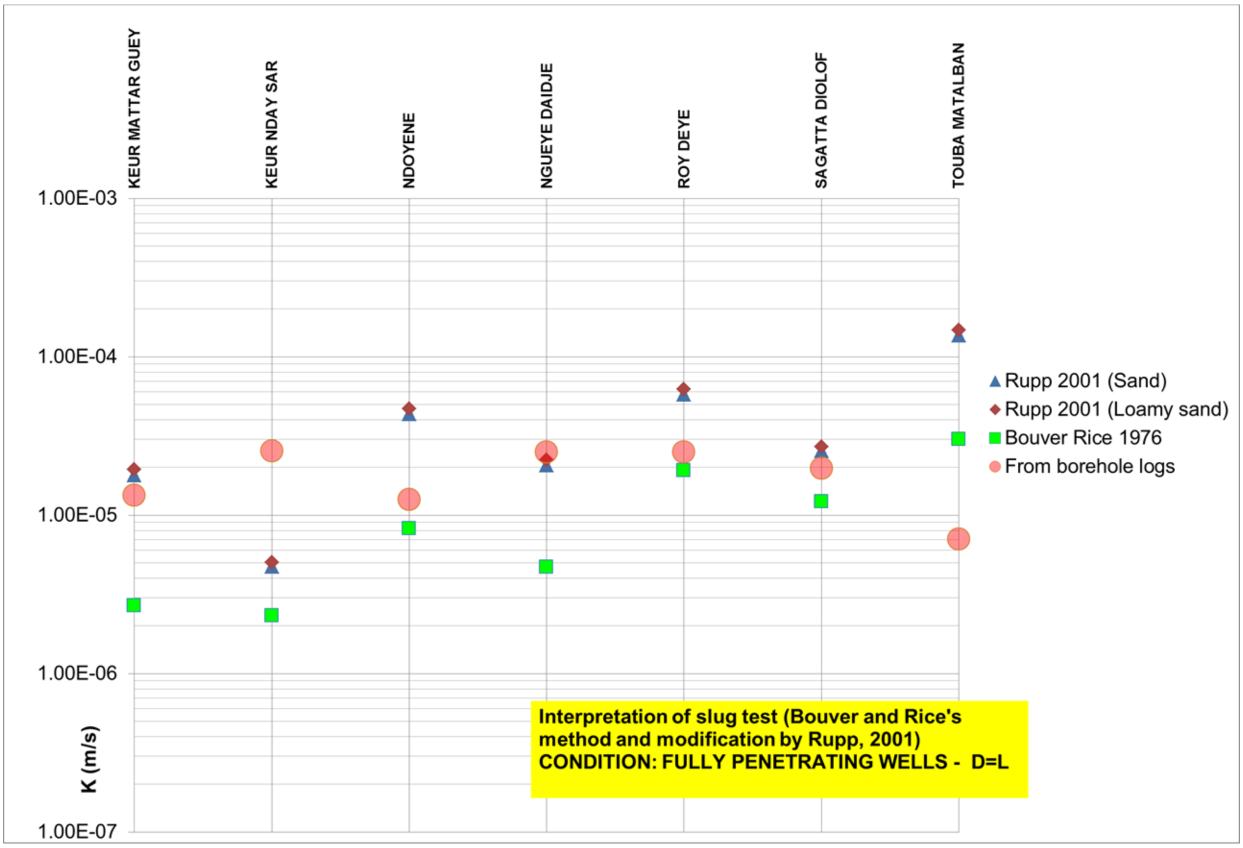


Figure 41 ***Estimated values of K(m/s) with different methods of interpretation of pump tests and extracted from borehole logs close to large wells position***

	Rupp(Sa)	Rupp(Lsa)	BW
MEAN	0.42	0.44	1.22
MEDIAN	0.25	0.28	0.48

Table 13 ***Estimation of mean and median of the difference between LogK obtained through interpretation of from pump tests and borehole logs (7 samples)***

As we can observe (Table 13) the mean and median of the difference in the estimation of K obtained through interpretation of pump tests (direct measurement in the field) and processing of borehole logs results of pump (transformation of stratigraphic description to texture composition of layers and then conversion to estimated K) is limited, especially using Rupp's method and considering sandy soil. In 5 out of 7 samples Rupp's method gives an estimated K higher than the value obtained from stratigraphic logs.

Therefore we can consider that the K estimated during the analysis of stratigraphic logs by using TANGAFRIC is reasonably consistent with the results of pump tests, possibly slightly underestimated. We have also to consider this method of comparing K values from pump test with the surrounding borehole logs at the same depth as the static water level of the well is based on the assumption that there is no lateral modification of texture and K (only vertical modification) in the area and that topography is flat; if these conditions are not confirmed they can introduce relevant factors that makes this comparison less correct.

Electrical Vertical Soundings (Schlumberger):

The method of geophysical investigation consisted in implementing the DC electrical prospecting (Figure 42) using a vertical electrical sounding device (VES). When electrical contrasts are quite pronounced along the profile, superficial indurations (laterite and lateritic crust) and the presence of the aquifer can be highlighted.

The implementation of an electrical survey consists in determining the variation curve of the apparent subsoil resistivity according to the distance of line current AB, through the surface quadrupole device NBMA.

The depth of investigation is proportional to the distance between current electrodes injection A and B; it is statistically comprised between AB/12 and AB/4 according to the average values ofresistivity of the medium. The measuring device is of Schlumberger type; that is to say AB/MN ratio remains high (4 <AB/MN <20). In this case, ρ is the apparent resistivity expressed by the formula:

$$\rho = \frac{KV}{I}$$

[eq. 5.8]

Where:

ρ = Apparent resistivity (ohm.m)

V: potential difference between M and N (in mV);

I: intensity of the injected current between A and B (in mA);

K: coefficient depending to the geometric dimensions of the measuring device;

their main purpose is the estimation of stratigraphic model in the position of large diameter wells and compare with the geological layers described in borehole logs located at short distance.

VES survey were carried out by a team of UCAD from Dakar, using a resistivimeter model Terrrameter ABEM SAS4000 (Figure 43). Quadripole arrays were designed for a target depth of 50 m.

*

Figure 42 ***Electrical prospecting in Schlumberger configuration***

Figure 43 ***Resistivimeter used in VES survey***

Data obtained from VES were processed with the inversion IX1D software that provides geo-electric log at each of the VES profile. These geoelectrical logs were compared with the direct measurements of water table (carried out in the large wells) and the geological layers recorded in the borehole logs located close to the VES position. A synthesis of the correlation between static water level and geoelectrical model is given in Table 14

Nr	Village	Depth of water	Correlation
1	Keur Ibra Niang	19,7m	at 19.6 m depth, resistivity increases from 11.0 to 11.9 Ωm on the smooth model (resistivity of sands with brackish water)
2	Keur Ndiouga Sarr	14,9m	at 14.4m depth, resistivity drops from 13.6 to 7.2 Ωm on the smoothed model and 14.2 to 2.5 Ωm on the unsmoothed model
3	Ndimb Peulh	23,9m	data are quite dispersed ; however at 22,6m depth, resistivity increases from 3,4 to 3.8 Ωm (brackish aquifer)
4	Ndimb Wolof	16,5m	at 14.4m depth , resistivity varies from 42.8 to 29.3 Ωm on the smoothed model (offset of 2m between measured and model values)
5	Nguèye Diadje	36,02m	at 36,6m depth, the resistivity increases from 49.7 to 86.7 Ωm on the smoothed model
6	Roye Dièye	27,5m	At 26.8 m depth, the resistivity increases from 20.2 to 47.3 Ωm on the smoothed model (slight difference between the static (NS) and dynamic (ND) levels
7	Sagatta Djolof	16,18m	at 14.4m depth, resistivity varies from 35.9 Ωm to 14.2 Ωm on the smoothed model

Table 14 ***Correlation between depth of water in the wells and geoelectrical model obtained from processing of VES data***

Comments about the relation between direct field test and data from borehole logs

The general procedure to process and compare field measurements and stratigraphic logs is shown in Figure 44.

Pump tests were interpreted and an estimated value of K was obtained. This was compared with the K value obtained from codification and processing of stratigraphic layers, selecting borehole logs located closer than 7 km from the wells and those layers at a similar depth of water level measured in the well.

VES data were processed, thus obtaining a geoelectrical model where a sequence of different layers (discriminated on the basis of their estimated resistivity) is indicated. This model is compared with the sequence of geological layers indicated in borehole logs and with the depth of water measured in the well

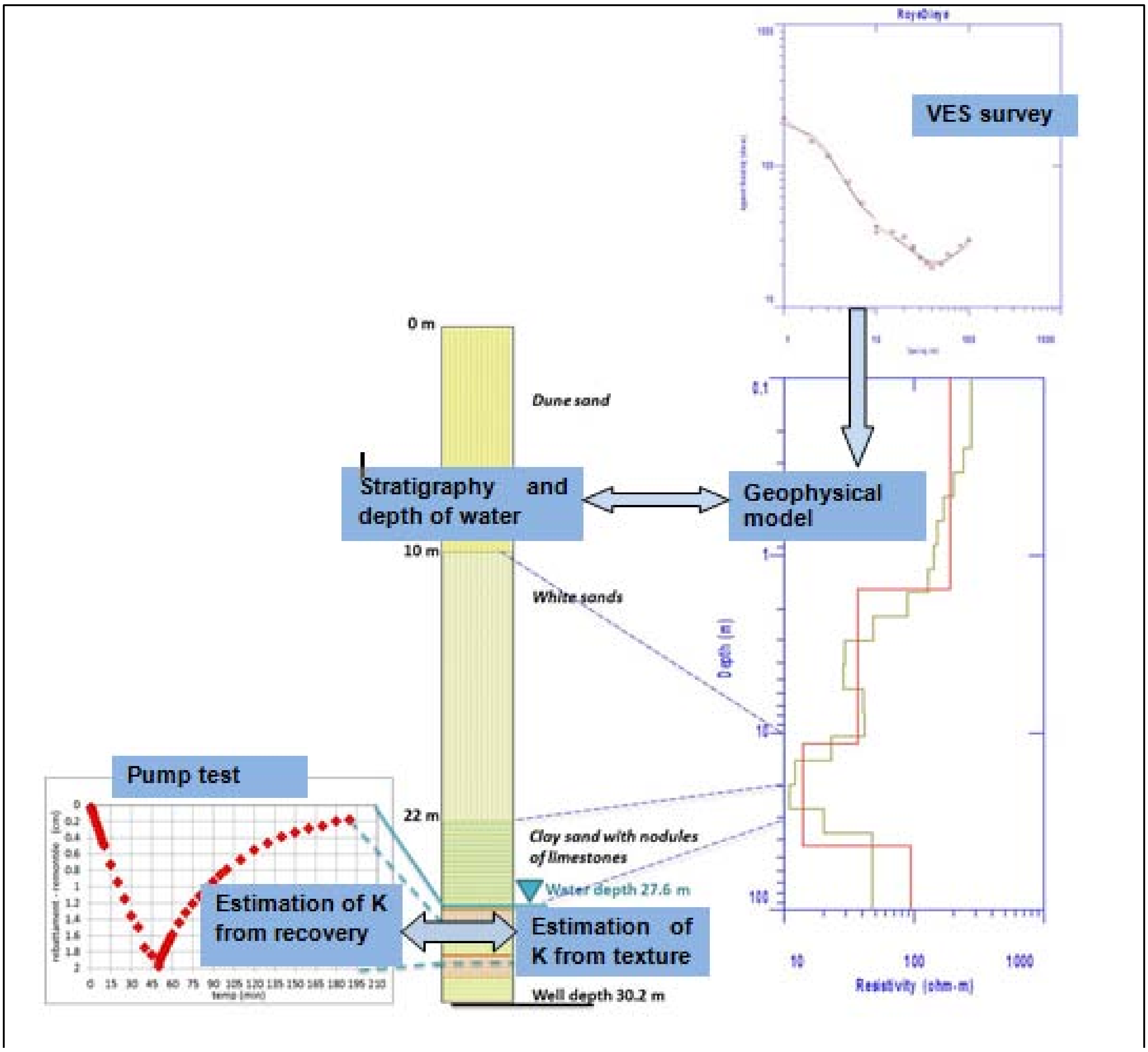


Figure 44 ***Schematic procedure for the comparison of field measurements and stratigraphic logs***

We can observe that in most cases the K values obtained from pump test and processing of stratigraphic logs were similar (with slightly higher values from the pump test). In this sense, we can consider that the conversion from texture to K used in the processing of stratigraphic provided estimated K values confirmed by field results. Furthermore pump test in large diameter wells are a valid method to obtain hydraulic parameters from shallow aquifer, therefore they can provide a method to explore the characteristics of shallow aquifer and estimate the suitability for manual drilling even in those areas where borehole logs are not available.

The results of geoelectrical surveys show that the difference in texture and lithology of unconsolidated aquifer were not identified; the main reason is that the porous aquifer in the study area of Senegal is characterized by a gradual shift from sandy to sandy clay layers, without sharp discontinuities (that can be identified and modeled as different geoelectrical layers). Hard lateritic layers were not present and the contact with rocky basement was below the depth of exploration during VES surveys. On the other hand in some cases geoelectrical survey was able to identify the depth of water table. In these cases the resistivity of the saturated layer can provide relevant indication about the quality of ground water, in particular the presence of brackish or salty water.

Chapter 6. Remote Sensing Indicators and morphometric parameters related to subsurface geology

Remote Sensing is an important tool for hydrogeological interpretation. It offers the chance of synoptic views and time series; these characteristics results highly relevant for regional and sub-regional analysis of different aspects related to groundwater exploration and groundwater management.

The analysis of data obtained from remote sensing can be done with a qualitative approach (for example in the traditional visual interpretation of aerial picture or satellite images) or with numerical analysis of quantitative parameters recorded by a large variety of sensors.

For a long period the use of remotely sensed data were basically limited to aerial photo-interpretation. They have high spatial resolution (therefore they can be used for detailed mapping), stereovision (enhancing the perception of morphology in 3d views), availability in most of the countries at low cost.

For hydrogeological purposes, optical remote sensing data from visible or near infrared bands are widely used for different applications (Mejierink, 2007). For example:

- Interpretation of geology, geomorphology and land cover to evaluate recharge and groundwater flow system;
- Detection in crystalline basement, karst and other terrain of lineaments, with which groundwater occurrence is associated;
- Estimation of net groundwater drafts for irrigation and other groundwater management aspects.

Thermal infrared data can instead provide relevant information about the energy balance of the surface (therefore in the estimation of evapotranspiration and water budget) and identify anomalies in thermal response related to presence of water at shallow depth or difference in water quality

Radar images can provide information in those regions with intense cloud or vegetation cover (where optical remote sensing has limited capacity of penetration) and they are the most important type of data from remote sensing for the analysis of soil moisture.

Furthermore the use of radar data has allowed elaborating worldwide digital elevation model of the earth that facilitates the analysis of morphological features of the surface.

In the last years the availability of free satellite images has largely increased, as well as their quality and diversification of products. This aspect, together with the increase of free software for image processing and GIS, has contributed to geological and hydrogeological interpretation in those regions of the world with limited field data and not detailed maps available.

In this research three potential indicators of shallow hydrogeology, especially in tropical regions, have been selected: vegetation persistence, soil moisture, and thermal inertia. They have been investigated using multitemporal series of optical and radar images at different spatial resolutions. This analysis has permitted to extract a quantitative parameters in order to explore their relation with hydrogeological features considered relevant for the assessment of suitability for manual drilling.

Vegetation dynamics

The characteristics of vegetation (like abundance, type and yearly dynamics) depend on the availability of water and nutrients. For this reason vegetation can provide relevant information about the presence of subsurface groundwater, lithology of shallow geological layers, presence of hard lateritic layers.

In arid zones, the persistence of vegetation in dry season can indicate shallow water table or the presence of porous materials with capacity of retention. Furthermore the presence of shallow water table can be indicated by the distribution of specific types of phreatophyte plants (Ahring and Steward, 2012).

Source of data

Multitemporal series of public MODIS (Moderate Resolution Imaging Spectroradiometer) satellite images were used in this research.

MODIS data are free, they cover the whole Earth surface and are available from 1999 till now.

MODIS instrument has a viewing swath width of 2,330 km and views the entire surface of the Earth every one to two days. Its detectors measure 36 spectral bands and it acquires data at three spatial resolutions: 250-m, 500-m, and 1,000-m

In this research we used the MODIS product MOD13Q1 to analyse the dynamics of vegetation. This product provides information about NDVI and EVI vegetation indices, with a temporal resolution of 16 days and spatial resolution of 250 m.

Normalized Difference Vegetation Index (NDVI) (Rouse et al. 1973) is the most common index in remote sensing to study the vegetation. Its formula is:

$$\text{biag}NDVI = \frac{\text{NIR}-\text{VIS}}{\text{NIR}+\text{VIS}}$$

[eq. 6.1]

Where:

NIR = spectral reflectance in the infra-red region

VIS = spectral reflectance in the red (visible) region

A temporal series of images covering the period 2008 to 2012 (23 images per year) was used for Senegal and Guinea.

Methods

Data processing was implemented as follows:

1. The set of images for the relevant period have been downloaded and a multiband image has been created, containing the whole time series.
2. The temporal series has been filtered and smoothed applying a specific algorithm derived from Chen et al. (2004) to generate high quality NDVI series. The complete procedure (Fava et al., 2012) is based on the iterative application of Savitzky and Golay filter, decreasing the weight of low quality data (as detected from the index QA and UI included in the MODIS image) and retrieving a smoothed NDVI time series well adapted to the upper envelope of original data.
3. The smoothed NDVI series has been used as input to retrieve vegetation phenological metrics In particular the following parameters have been obtained:

- minimum yearly NDVI
- maximum yearly NDVI
- length of the dry season (period when NDVI<0.5NDVImax, therefore corresponding to the period of reduced vegetation cover)
- average NDVI during the dry season

Each of these parameters has been calculated as average value over 5 years (2008-2012). A specific raster map covering the whole study area has been produced for each parameter.

Results

In Guinea vegetation cover during dry season has a general decreasing trend moving north-eastward (Figure 45), partially in concordance with rainfall distribution (Figure 46), although various anomalies can be evidentiated (Figure 45).

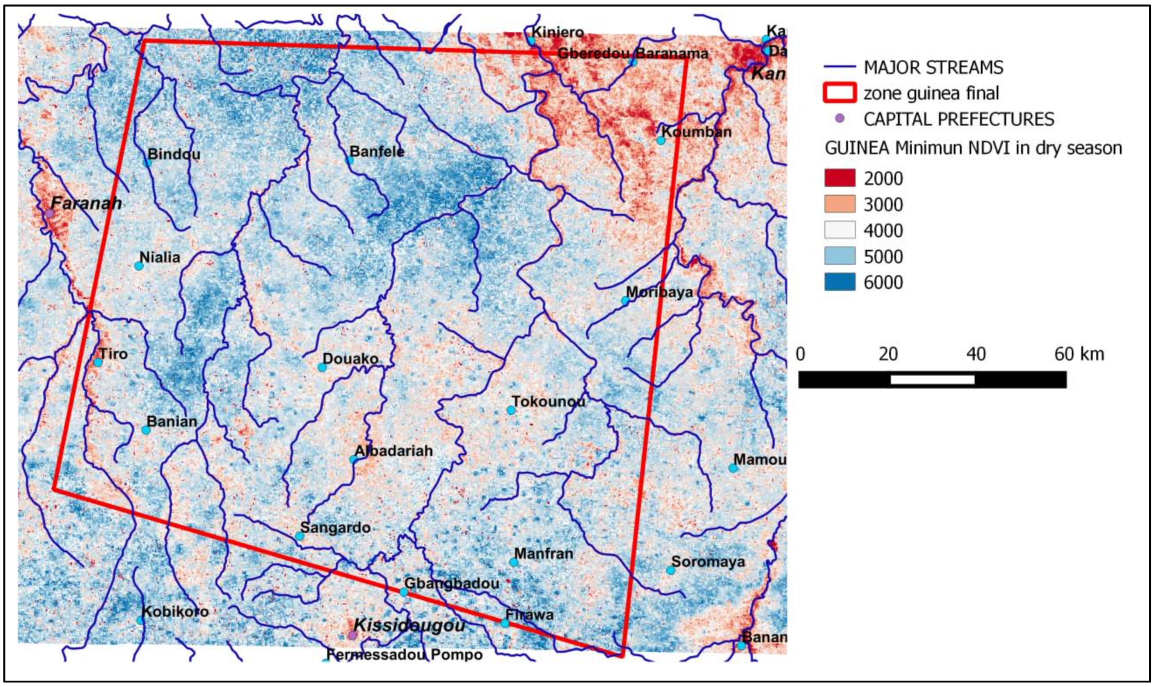


Figure 45 ***GUINEA – minimum yearly NDVI in dry season (average 2008-2012)***

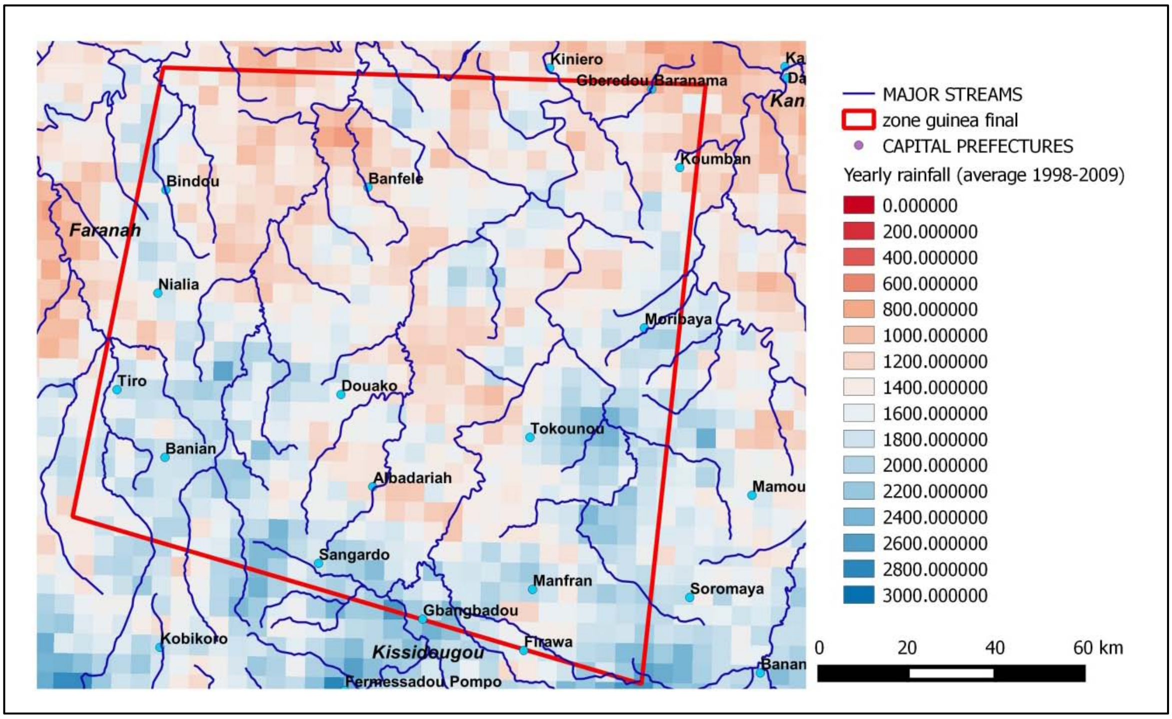
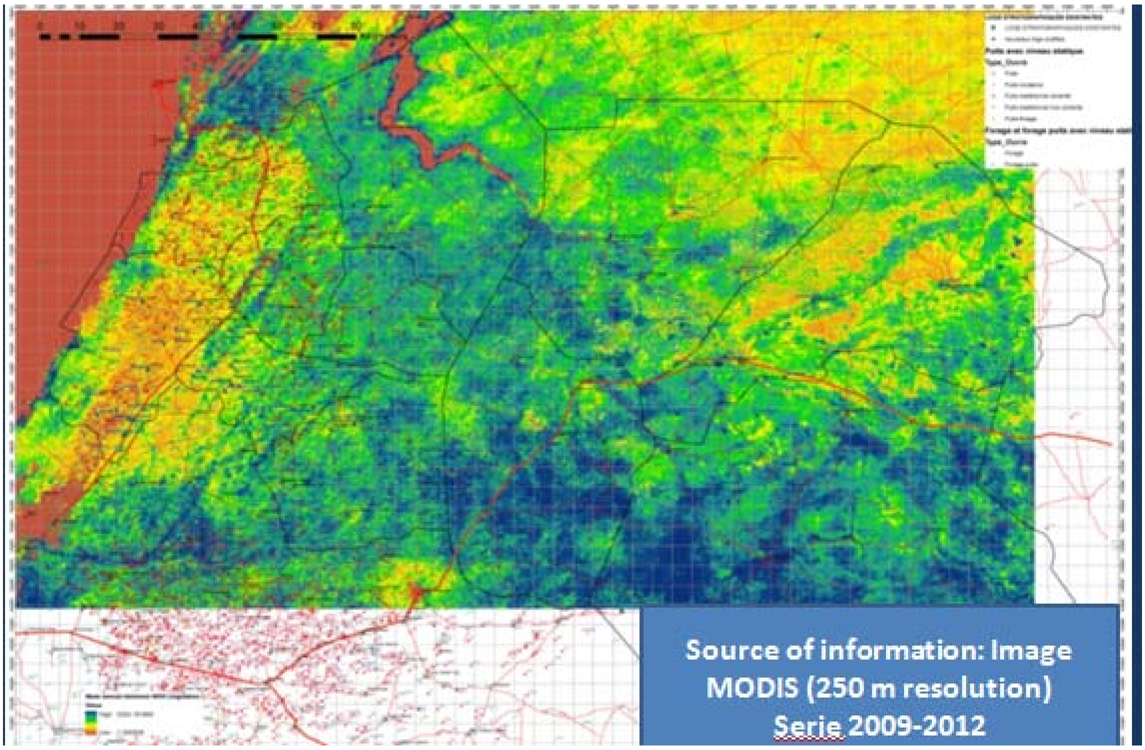


Figure 46 ***GUINEA – yearly rainfall (average 1998-2009)***

In Senegal the persistence of vegetation in dry season (Figure 47) seems not depending by the annual rainfall, but is more related to difference in texture of soil. In fact we can observe that NDVI is higher in the central and eastern part of the study area (with loam and clay soils) while it is extremely low the persistence of vegetation in the western part (with the exception of the coastal strip, where it is also influenced by the practice of irrigation).



Source of information: Image MODIS (250 m resolution) Serie 2009-2012

Figure 47 ***SENEGAL – minimum yearly NDVI in dry season (average 2009-2012)***

Apparent Thermal Inertia

The thermal inertia (TI, [J m^{-1} K^{-1} $m^{-1/2}$]) of a substance, a material or a surface determines its resistance to temperature variations and is function of the bulk density (ρ, [kg m-2]), the specific heat capacity (c, [J kg-1 K-1]) and the thermal conductivity (K, [W m-1 K-1]).

$$TI = \sqrt{\rho c K} \qquad \text{[eq. 6.2]}$$

As thermal inertia depends on the type of materials and also is affected by the presence of water, different applications have been proposed for the application of this parameter for geological mapping (e.g. Cracknell et Xue, 1996; Mitra and Majumdar, 2004), estimation of soil moisture and groundwater depth (e.g. Minacapilli et al., 2009; Alkhaier et al., 2012).

Various models for thermal inertia estimation using remote sensing data have been proposed (Pratt and Ellyet, 1979: Kahle, 1977, Sobrino and El Kharraz, 1999). However, these approaches require field data to retrieve different physical parameters that cannot be estimated from remote sensing, limiting their potential for operational applications.

Fairly recently, Van Doninck et al. (2011) proposed a methodology to retrieve a proxy of thermal inertia, the Apparent Thermal Inertia (ATI), using exclusively day time and night time thermal remote sensing data and albedo, without need for field information. This approach has been selected in this research given its relevant potential for regional studies in Africa.

ATI [K-1] is estimated as:

$$ATI = C\,\frac{1-\alpha_0}{A} \qquad \text{[eq.6.3]}$$

Where C is the solar correction factor [-], α0 is the surface albedo [-], and A is the amplitude of the diurnal LST (land surface temperature) cycle [K]

Source of data

The dataset of remote sensing images was acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor. It consists of two multi-temporal series for a period of 5 years (2008-2012) in Senegal and 3 years (2010-2012) in Guinea.

1) Land Surface Temperature (LST), with a spatial resolution of 1 km and a sub-daily temporal resolution of 4 images per day.

Products:

- MODIS/Terra Land Surface Temperature/Emissivity Daily 13 Global 1Km SIN Grid V005 (MOD11A1)
- MODIS/Aqua Land Surface Temperature/Emissivity Daily 13 Global 1Km SIN Grid V005 (MYD11A1]

2) Surface Albedo, with spatial resolution of 1 km and a temporal resolution equal to 16 days.

Product:

- MODIS/Terra + Aqua Albedo 16-Day L3 Global 1Km SIN Grid V005 (MCD43B3

Method

Thanks to MODIS AQUA/TERRA overpass frequency, two to four daily observations of LST are available. By using these data it is possible to model, by means of specifically designed codes in IDL and Matlab, the daily fluctuation of temperature with a a sinusoidal approximation of the diurnal surface temperature curve and obtain the amplitude of the daily LST cycle (A in eq.6.3) and then interpolate this parameter for the whole year. With this method it is possible to obtain a daily value of ATI and the final output of a multitemporal series of monthly average ATI.

- Download daily TS of LST (TERRA and AQUA) and 8 day albedo images in .hdf format for the period of analysis (e.g. 1 year).
- Run the IDL code PhaseCalculation.pro. The code calculate ψ time series only when four observations are availables.
- Run the Matlab code input_hants.m to interpolate ψ and generate daily time series images. The code ouput is a multitemporal image in ENVI/IDL format.

- Run the IDL code Multitemporal_Inertia.pro. Input for the code are daily LST observations (TERRA+AQUA), ψ time series image generated from input_hants.m, and Albedo images.

The code output are: ATI time series and number of observations time series in ENVI/IDL format.

The distribution of ATI in selected months (especially in the dry season, when this value is not affected by rainfall) was analysed in relation to geological and hydrogeological features.

Soil moisture dynamics

The dynamics of surface moisture is related to climate, characteristics of soil, vegetation, topography, interaction between surface and water table. Although remote sensing can detect soil moisture for a thickness of few cm, in some context it can provide information concerning subsurface geology, potential of recharge of aquifers and depth of water table.

Radar data, with their high sensitivity to the soil dielectric constant is a good tool to estimate soil moisture. The works carried out in recent years in the Sahel, showed good sensitivity of radar data (in C-band and Ku-band), on dynamics of vegetation, soil roughness and soil water content (Ulaby et al, 1978; Bradley and Ulaby, 1981; Le Toan et al, 1981; Jackson and O'Neil, 1985; Dobson and Ulaby 1986; Bruckler et al, 1988; Kennett and Li, 1989a; Oh et al, 1992 ; Dubois et al., 1995; Frison and Mougin, 1996a; Frison et al, 1998; Quesney et al., 2000; Le Hégarat et al., 2002; Zribi and al., 2002;, Faye et al, 2011, Wagner et al., 2000).

Radar response consists of a contribution of vegetation cover, roughness and soil moisture.

In past years the available data about soil moisture retrieved from radar data were at broad scale (spatial resolution 25 km or less). A soil moisture index derived from ASAR data and downscaled at 1 km was proposed by the Technical University in Wien (Pathe et al., 2009; Doubkova et al., 2012; Doubkova et al., 2014). Although this 1 km soil moisture index is available for the whole African continents and other areas (therefore facilitating the application of this approach in other countries), it results not effective to separate the contribution of soil moisture from the other components of the radar signal. For this reason a different approach was adopted in this research.

Source of data

Two types of satellite data were used.

- ASAR radar data from Envisat (C-band data -VV polarization- with a spatial resolution of 1 km and a temporal repeatability of on average 2 to 3 images per month). These data are not directly downloadable but they were obtained from ESA (European Space Agency) after acceptance of a research project submitted;
- Optical data from SPOT – VEGETATION (1 km spatial resolution, 10 days temporal resolution) obtained from the website of VITO (ftp.www.vito-eodata.be/). NDVI (Normalized Difference Vegetation Index) data and DMP (Dry Mater Product) data were used.

These data were collected for the years 2008 to 2011. It was not possible to extend the period till 2012 (in this case covering all the period considered for Apparent Thermal Inertia and Vegetation) since Envisat interrupted its data collection in March 2012.

Methods

Pre-processing of radar data

Radar data were pre-processed with the software BEST (BEST, 2005) that allows:

- To correct the geometry of the image (distorted depending from the trajectory of satellite when the image was recorded);
- To calculate the backscatter coefficient using as input the DN (digital numbers) of the , the angle of incidence and the calibration constant.

Selection of optimal period for the estimation of soil moisture

Several authors, including Wang et al., 2004, demonstrated that for very large plant hedges (NDVI> 0.5 or more, as the case often in the area of Guinea) Soil contribution to radar signal is very low or zero. This results in a misinterpretation of soil moisture by the model used. Moreover, during very wet periods (more than 10 days of rain per month), the ground is permanently saturated with water, it could also disrupt the interpretation of soil moisture by the model from radar signal.

For the area of Senegal, neither of these constraints arises. Indeed, in Senegal, the number of monthly rainfall event is always less than 10 days on the one hand, and on the other biomass production remains low to impact the interpretation of soil moisture. The period from May to November (corresponding to the rainy season and three following months) in this area was considered for this study.

Unlike Senegal, the study area of Guinea is characterized by high rainfall and NDVI can easily exceed 0.5. For this reason, we sought to identify favourable periods (less than 10 days of rain per month and NDVI <0.5).

The analysis of temporal series of NDVI shows that during the period between the 8th decade (10 March) and the decade of the 19th (July 10th) there are NDVI condition most suitable for the detection of soil moisture. In the meantime that during the months of June and July there are often more than 10 days of rain per month. This could result in permanent soil saturation and therefore a misinterpretation of soil moisture by the model. Given these two constraints related to NDVI and rainfall, we see that the best period to estimate soil moisture from radar data in the Guinea area falls in the months from March to May. During these months the NVDI is quite low, which allows a small contribution of vegetation to the radar signal. Secondly rainfall is not important, so to detect changes in soil moisture.

Estimation of biomass

The available biomass is used by the radiative transfer model to extract the contribution of soil moisture on radar signal and thus estimate the latter.

DMP, or Dry Matter Productivity, represents the overall growth rate or dry biomass increase of the vegetation, expressed in kilograms of dry matter per hectare per day (kgDM/ha/day). During the growing season (starting with the beginning of rainfall) the biomass available at a specific day is the sum of the daily productivity of every day of the season before that date.

In Senegal (where the selected period for the study starts with the rainy season) this methods was used to calculate the biomass on a decadal basis.

In Guinea the selected period does not coincide with the growing season. For this reason the approach was different, the relation between DMP and NDVI in the same day was estimated during the growing season, after that this relation was used to calculate DMP from NDVI data for the other months of the year (Santin-Janin et al., 2009).

Soil moisture estimation

Soil moisture was estimated using a radiative transfer model (Karam et al., 1992). It allows to simulate the radar signal from the knowledge of surface parameters (vegetation, roughness, dielectric constant that depends strongly on soil moisture). The input data of this model are:

- Biomass production;
- Surface roughness;
- Soil moisture.

The results of these simulations are then compared with the data measured by the radar to calibrate the model.

The model was then inverted to estimate the input data, starting from the radar signal. For this scope a back-propagation algorithm was associated with the model; this algorithm searches the combination of values of the three parameters which have obtained the same value as the radar coefficient. Then, if we know surface roughness and biomass production, we can obtain soil moisture.

In the late months of the dry season, when the ground is dry and the biomass production is almost zero, only the roughness influences the radar response. Therefore we used the data in this period to obtain surface roughness (constant throughout the year).

Biomass production was estimated from DMP data, as explained above.

Knowing these two parameters, the back-propagation algorithm seeks soil moisture allowing the radiative transfer model to return the same value as the radar coefficient.

In this way we obtained the estimation of soil moisture for those days when radar data were available and we extracted the following parameters (for the period under consideration):

- Minimum soil moisture
- Maximum Soil Moisture
- Mean soil moisture
- Coefficient of variation of soil moisture

These parameters were extracted for each year of the period 2008-2011 and then the average value over the four year was calculated

Results

In both countries minimum soil moisture resulted the most significant parameter showing a relation with hydrogeological characteristics. In fact during wet season, there is a strong influence of rainfall on soil moisture pattern, with an evident South-North gradient.

In Senegal of soil moisture in the driest period (Figure 48) shows a distribution pattern reflecting the different geological units, while the influence of yearly rainfall is less evident. Highest values are observed close to the coastline and in the SE part of the study area, as shown in the transect of Figure 50 (the soil moisture profile has been smoothed with a moving average filter with a window of 10 km. Louga town produce an anomaly in soil moisture natural trend).

In Guinea the minimum soil moisture has a decreasing trend from SW to NE, in concordance with rainfall trend; here the higher yearly rainfall and vegetation cover makes the analysis of soil moisture less significant for the interpretation of shallow hydrogeology. Low values exists in the NE part of the study area, especially in small reliefs and along the valley; in this last case this is the results of the low reflectivity of water, resulting in a misinterpretation of the signal by the model

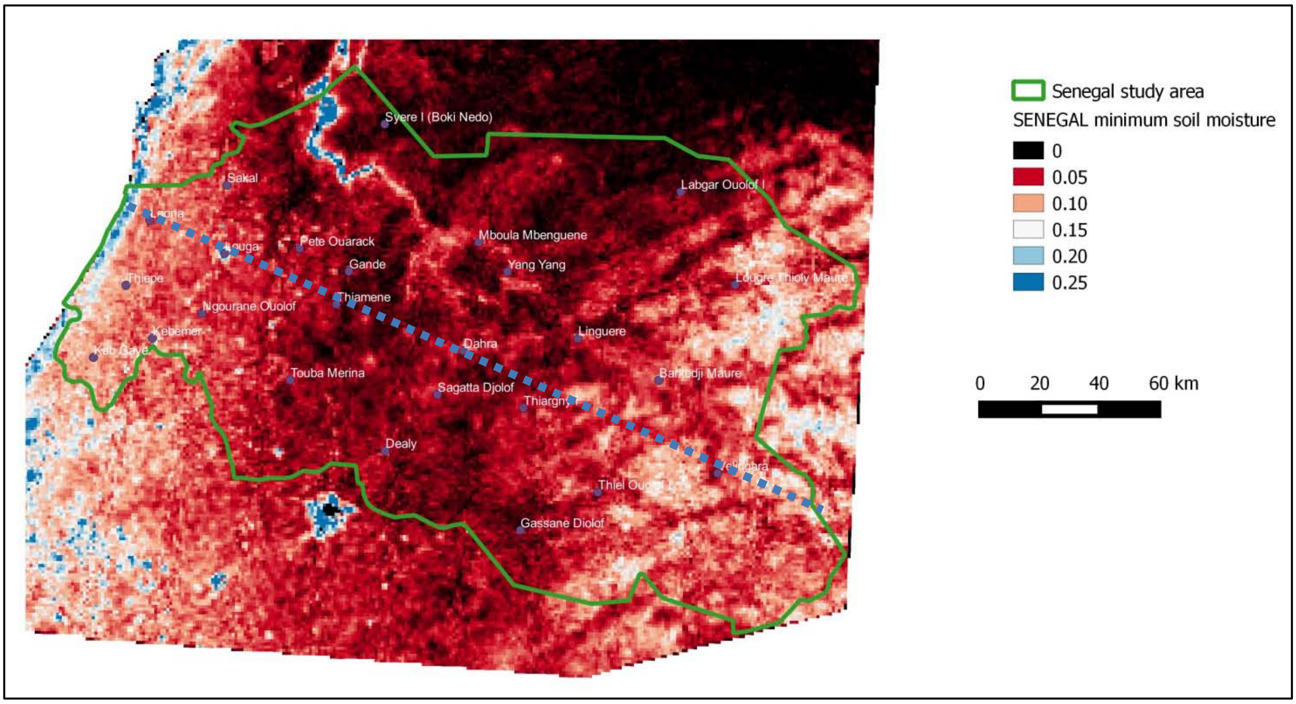


Figure 48 ***SENEGAL – minimum soil moisture in dry season (average 2008-2011)***

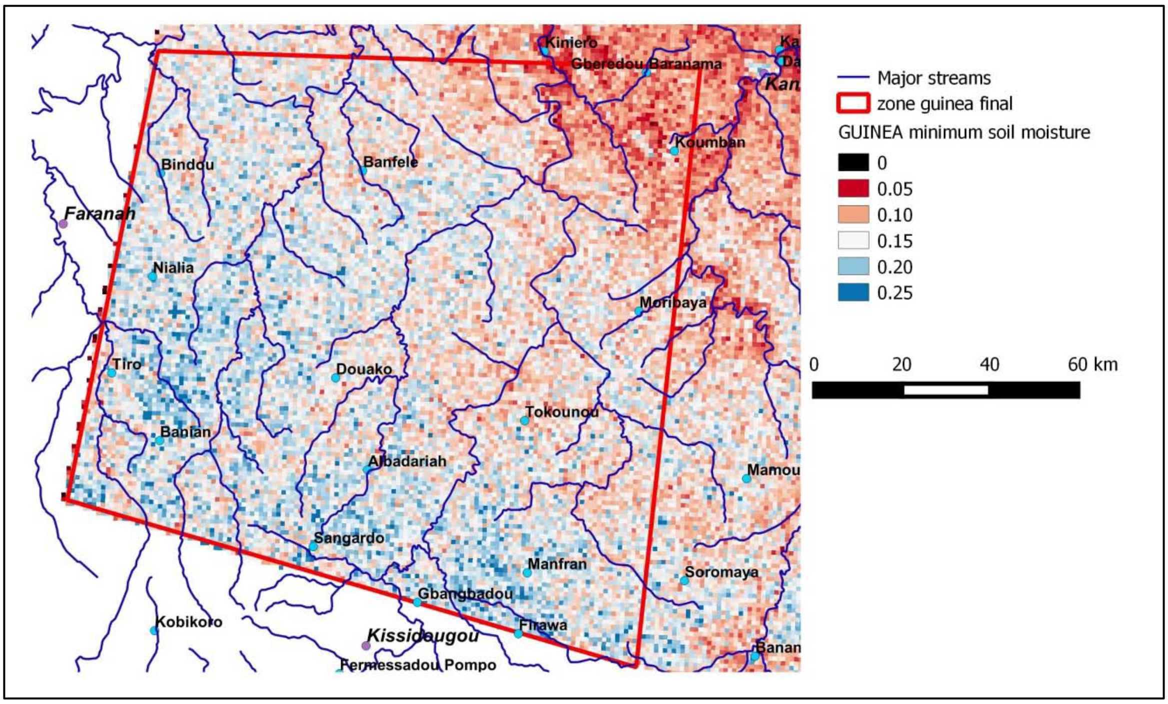


Figure 49 ***GUINEA – minimum soil moisture (average 2008-2011)***

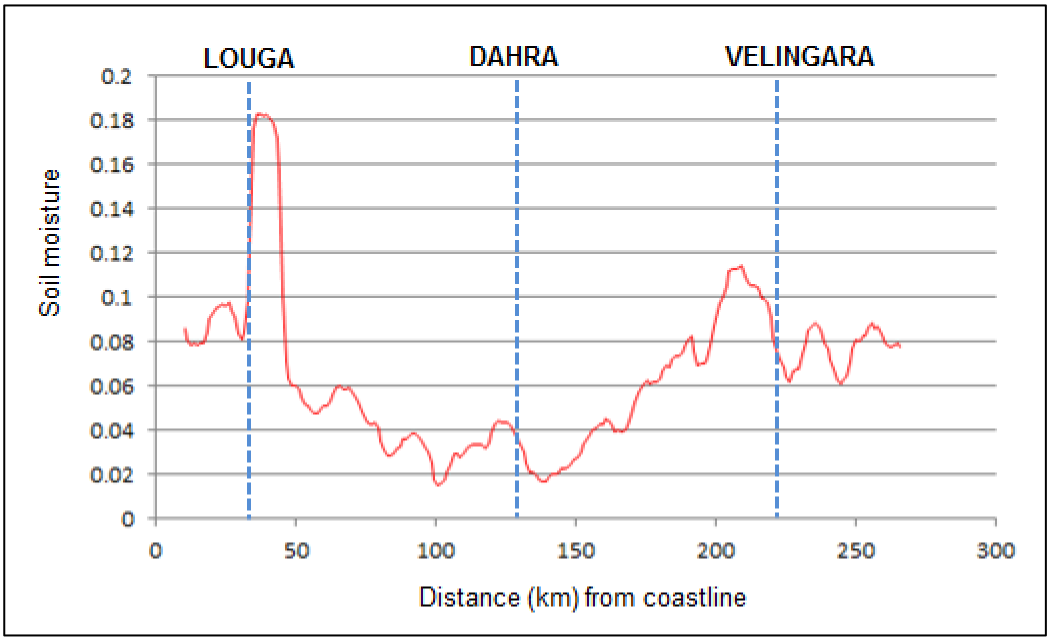


Figure 50 ***Soil moisture transect in Senegal (dotted line, from Leona to Velingara)***

Morphometric parameters

The characteristics of shallow geological layers are strongly dependent from geomorphological processes and are usually reflected in the morphological characteristics of landform. For this reason the methods of investigation used in geomorphometry can provide relevant information for the characterization of shallow unconsolidated deposits. Furthermore the shape of shallow unconfined water table and consequently groundwater depth are generally dependent from surface morphology.

The fundamental operation in geomorphometry is extraction of land surface parameters and objects from Digital Elevation Models

Different categories of land surface parameters can be extracted (Hengl & Reuter, 2004):

- Basic parameters and objects describe local morphology of the land surface (e.g. slope gradient, aspect and curvature)
- Hydrological or flow-accumulation parameters and objects reflect potential movement of material over the land surface (e.g. indices of erosion or mass movement
- Parameters and objects calculated by adjusting climatic or meteorological quantities to the influence of surface relief.

A special group of land-surface objects are geomorphological units, land elements and landforms. A landform is a discrete morphologic feature — such as a watershed, sand dune, or drumlin — that is a functionally interrelated part of the land surface formed by a specific geomorphological process or group of processes.

Source of data

The public digital elevation model ASTER GDEM 2 represented the main sources of information (http://www.jspacesystems.or.jp/ersdac/GDEM/E/4.html). This digital elevation model is available for the whole earth surface between latidute 83°S and 83°N.

The ASTER Global Digital Elevation Model (ASTER GDEM) is a joint product developed and made available to the public by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). It is generated from data collected from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), a spaceborne earth observing optical instrument.

The first version of ASTER GDEM was released in 2009. Version 2 of the ASTER GDEM was delivered in 2001, employing an advanced algorithm to improve GDEM resolution and elevation accuracy.

ASTER GDEM has a posting interval of 1 arc-second, corresponding to a spatial resolution of 30m, Vertical accuracy is estimated between 7 and 14 m.

The use of SRTM (Shuttle Radar topographic mission) digital elevation model was also evaluated.

SRTM 3 arc-second (90 m spatial resolution) was considered less suitable to describe landscape variability in certain sectors of study areas (for example the western part of the area in Senegal, dominated by recent sand dunes)

In 2014 SRTM started to release a new 1 arc-second digital elevation model (30 m spatial resolution). This dataset is still not available for the whole earth; furthermore it was compared to ASTER GDEM for the study area in Senegal, resulting with a higher level of errors.

Methods

The extraction of a set of morphometric parameters frequently used to characterize geomorphological and hydrological process has been carried out using the free and open Source Software GRASS GIS (Chemin et al., 2015; Neteler et al., 2012).

Parameter	**Description**
Elevation	Elevation obtained from ASTER GDEM [2]
Flow accumulation	GRASS module r.watershed (Metz et al., 2011)
Slope	Algorythm: GRASS module r.slope.aspect (Hofierka et al., 2009)
Topographic Wetness Index (TWI)	The topographic wetness index (TWI) is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction (Beven& Kirby, 1979). It is commonly used to quantify topographic control on hydrological processes. Algorythm: GRASS module r.watershed (Metz et al., 2011)
Forms (Geomorphon)	Geomorphon is a tool for representation and analysis of terrain forms, that utilises 8-tuple pattern of the visibility hood. The pattern arises from a comparison of a focus pixel with its eight neighbors starting from the one located to the east and continuing counterclockwise producing ternary operator. Algorythm: GRASS module r.geomorphon (Jasiewicz & Stepinsky, 2013)
Convergence Index	Convergence index is a terrain parameter that shows the structure of the relief as a set of convergent areas (channels) and divergent areas (ridges). It represents the agreement of aspect direction of surrounding cells with the theoretical matrix direction. Algorythm: GRASS module r.convergence

Topographic Position Index (TPI)	Relative topographic position (also called the Topographic Position Index) is a terrain ruggedness metric and a local elevation index (Jennessen, 2004). Topographic position of each pixel is identified with respect to its local hood, thus its relative position. The index is useful for identifying landscape patterns and boundaries that may correspond with rock type, dominant geomorphic process, soil characteristics, vegetation, or air drainage.
Standard Deviation of Elevation (SDE)	Standard deviation of elevation is a measure of topographic roughness (Ascione et al., 2008)
Slope Variability (SV)	Slope Variability (SV = Smax – Smin) is a measure of the “relief of slope” of a landscape (Ruszkiczay-Rüdiger et al. 2009).
Curvatures (Profile / Transversal)	GRASS module r.slope.aspect (Hofierka et al., 2009)
Terrain Ruggedness Index (TRI)	Terrain Ruggedness Index (TRI) is the difference between the value of a cell and the mean of an 8-cell hood of surrounding cells. Ruggedness index values are then classified according to the 7 categories, as defined by Riley (1999).
Distance from stream and Elevation from stream	Since in Senegal there is no surface water, These parameters were calculated only for the study area of Guinea using a threshold of 1500 pixels

Table 15 ***Morphometric parameters extracted for Senegal and Guinea study areas***

Chapter 7. Spatialisation of hydrogeological parameters

Introduction

In previous chapter we have described the process to extract relevant hydrogeological parameter for the estimation of suitability to manual drilling from water point data of the national database in Senegal and Guinea. The basic hydrogeological parameters are (Table 16):

1 - Depth of groundwater
2 - Depth of rock
3 - Texture and hydraulic conductivity of shallow exploitable aquifer (as a maximum depth of 50 m)
4 - Presence and thickness of intercalated hard lateritic layers

Table 16 ***Basic hydrogeological parameterers used in the estimation of suitability***

Combining this parameters it is possible to obtain the feasibility (Figure 16) and the potential (Table 4) for manual drilling, arriving to the final assessment of suitability (Table 5) for it. With this procedure a map of suitability at borehole logs position have been constructed (Figure 31 for Senegal)

Source of data

Direct data about water points were obtained from the national database of Senegal and Guinea. Different datasets were created, extracting subsamples of water points from the national database.

In Senegal We used two different datasets:

- The first dataset consists of 161 borehole logs codified and processed by means of TANGAFRIC. Parameters 3,4 and 5 (Table 16) are obtained from TANGAFRIC data processing (see chapter 6). The real depth of groundwater is not registered, but we use the information about static water level for its estimation. This assumption can be done when there are no stacked water tables with confined conditions (therefore when the static water level can be shallower than the real depth where water strikes into the well)
- The second dataset contains data from 585 open hand dug well (no deep borehole is included); we used only the information about static water level, because the other hydrogeological parameters are not available for open wells. Since open well exploit the shallow unconfined water table, their water level can be considered the reald depth where a manual drilled wells would find exploitable groundwater

In Guinea there is no information about open wells in the national database. We used the following datasets:

- A dataset of 90 codified borehole logs, with the relevant hydrogeological parameters and static water level (Figure 20);
- A dataset of 459 boreholes (without stratigraphic log); the only information used in our study was the depth of static water level, since there was not any geological description that could be used to extract the other hydrogeological parameters.

The geoenvironmental indicators used in the spatialisation process were extracted from thematic maps, satellite images and digital elevation models, as explained in chapter 7

Methods

Different methods to extrapolate the different parameters from borehole logs position to the whole study area are applied. The combination of a series of maps with the different parameters using GIS raster algebra functionality gives the final map of suitability, identifying those zones with favourable conditions.

Two different approaches are applied:

- **Interpolation from direct data**: Spatialisation based on geostatistical analysis of distribution of target parameters and interpolation through the whole study area;
- **Multivariate regression from geoenvironmental indicators**: spatialisation based on multivariate statistical analysis aiming to identify relations between target hydrogeological features (available only at borehole logs position) and indirect geo-environmental indicators obtained from various data source (thematic maps, remote sensing, digital elevation models) available in the whole area, definition of a geostatistical model and extrapolation of target parameters (Figure 51).

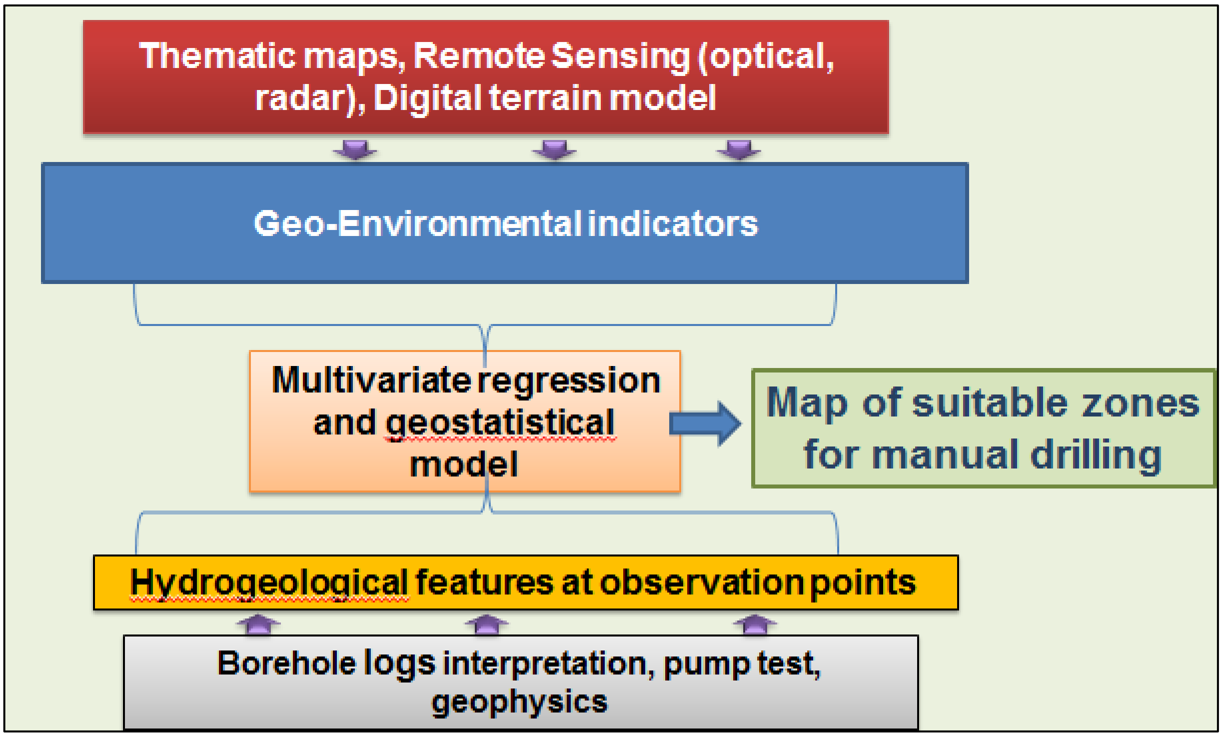


Figure 51 ***Spatialisation based on multivariate regression of geoenvironmental indicators***

A similar approach was applied in Niger to estimate groundwater depth as a support for the implementation of manual drilling (Thomas et al., 2012). In this research we try to estimate both groundwater depth and geological characteristics of shallow layers that can be relevant to identify suitable zones.

Interpolation from direct data

Interpolation predicts values for cells in a raster from a limited number of sample data points. It can be used to predict unknown values for any geographic point data, such as elevation, rainfall, chemical concentrations, noise levels, and so on.

There are two main groupings of interpolation techniques: deterministic and geostatistical.

Deterministic interpolation techniques use mathematical functions for the interpolation and create surfaces from measured points, based on either the extent of similarity (Inverse Distance Weighted) or the degree of smoothing (Radial Basis Functions).

Deterministic interpolation techniques can be divided into two groups, global (if they calculate predictions using the entire dataset) or local (calculate predictions from the measured points within neighborhoods, which are smaller spatial areas within the larger study area. They can also be divided into “exact” (if the interpolated surface is forced to pass through the original data, therefore it predicts a value that is identical to the measured value at a sampled location) or “inexact” (if they predict a value that can be different from the measured value).

Geostatistical interpolation techniques (kriging) utilize the statistical properties of the measured points. Geostatistical techniques quantify the spatial autocorrelation among measured points and account for the spatial configuration of the sample points around the prediction location. Geostatistical techniques rely on both statistical and mathematical methods that can be used to create surfaces and assess the uncertainty of the predictions.

Kriging is based on the regionalized variable theory that assumes that the spatial variation in the phenomenon represented by the z-values is statistically homogeneous throughout the surface. Geostatistical interpolation is suitable when the analysis of spatial variance of the data (through the observation of the semivariogram) shows that there is a relation between distance and variance that can be described with a mathematical model of the variogram.

Point sets that are known to have anomalous pits or spikes, or abrupt changes, they are not appropriate for the kriging technique. In some cases, the data can be pre-stratified into regions of uniform surface behaviour for separate analysis.

As a general rule, interpolations can give accurate results if the original dataset cover the whole study area and it is homogeneously distributed. On the other hand they give bad results in case of data concentrated only in few zones and the existence of void spaces, without any measured data

Multivariate regression from geoenvironmental indicators

The statistical analysis applied here comprehends methodologies aimed at searching simple and interpretable linear multivariate models for the estimation of relevant hydrogeological parameters using a set of variables derived from existing thematic maps, digital elevation models, optical and radar remote sensing (0).

For geology, morphopedology, landcover and soil, the existing thematic map was simplified; he original units were aggregated (according to expected similar characteristics) and transformed in a reduced number of groups for each thematic layer.

FROM EXISTING THEMATIC MAPS (after aggregation and simplification)
GEOGR = Geological group from simplified geological map
MPGR = Morphopedological group from simplified morphopedological map
OCSGR = Landcover group from simplified landcover map
SOILGR = Soil group from simplified soil map
FROM DIGITAL TERRAIN MODEL
Elevation
Slope
Topographic Wetness Index (WET_IND)
Flow accumulation (ACCUM)
Forms (Geomorphon)
Convergence Index (CONV)
Topographic Position Index (TPI)
Standard Deviation of Elevation (SDE)
Slope Variability (SV)
Curvatures (Profile / Transversal)
Terrain Ruggedness Index (TRI) and TRI categories (TRIcat)
Distance from stream (dist_stream). Only in Guinea
Elevation over stream (Elev_stream). Only in Guinea
FROM OPTICAL REMOTE SENSING
Vegetation - Minimum yearly NDVI (NDVI_min)
Vegetation – Length of dry season (Dslenght)
Average monthly ATI (Apparent Thermal Inertia) for each month
FROM RADAR DATA
Minimum soil moisture (Moist_min)

Table 17 ***Geoenvironmental indicators considered in the multivariate analysis***

Different techniques of multivariate analysis were considered, like regression and classification tree (already used in a similar study in Niger, see Thomas, 2012). Finally we choose to apply a Multivariate Ordinary Least Squares (OLS) regression. This methodology has the strength of being always interpretable and produces a model that is easily applicable in a GIS environment.

Different procedures were tested for the selection of variable to use in the predictive model:

- The first variable selection methodology is the Step Wise Regression (SWR): all possible regression models are created and a specific variable is included only if it increases the goodness of fit (i.e. coefficient of determination R2) of the multivariate regression. Among all models, we selected those with the highest prediction capability, ordering them according to the Akaike Information Criterion (AIC) (Venables and Ripley, 2002). The second variable selection method is based on a Genetic Algorithm (GA) optimization

(Leardi and Gonzales, 1998). In this case, all possible linear models are created according a series of rules based on the evolution theory. Increasing model complexity is limited by cross-validation in order to limit data overfitting. The model with the highest prediction capability is then chosen for ground water properties estimation

In both cases the categorical variables (geogroup, morphopedol. group, landcover group, soil group, TRI category) were transformed in a set of Boolean (0/1) single group variables, one for each group; the value 1 was assigned to the group associated to each pixel. For example, after transforming the possible geogroups (from 1 to 8) to 8 single Boolean variable, one pixel falling in GEOGR = 5 will have the following values (Table 18):

	Transformed boolean variables							
ORIGINAL GEOGROUP	GEOGR1	GEOGR2	GEOGR3	GEOGR4	GEOGR5	GEOGR6	GEOGR7	GEOGR8
5	0	0	0	0	1	0	0	0

Table 18 ***Transformation of categories into boolean variables for the selection***

.

The multivariate models found with these methods can be expressed as a linear combination of coefficient and variables (eq. 7.1). These models were applied in a GIS environment, with map algebra functionality:

$$Y = b_0 + b_1X_1 + b_2X_2 + \ldots\ldots b_nX_n$$

[eq. 7.1]

Where Y is the raster map of the hydrogeological parameter to estimate (depth of water, depth of rock, texture or hydraulic conductivity of porous aquifer) and $X_1, X_2 \ldots X_n$ are a series of raster maps, each one with a specific variable considered in the selected statistical model.

Results

SENEGAL

Depth of groundwater

The estimation of depth of groundwater was carried out using three methods: two of them used the dataset of borehole logs and different algorithms (GA and SWR) for the selection of the variables to include in the MOLS regression model. The third method uses another data set (large diameter wells) and a SWR algorithm for the selection of variables.

Method 1.

Based on static water level of a datasets of 161 boreholes scattered across the whole study area, the best results (R^2=0.73) were obtained with a MOLS regression model and selection of the variables with GA optimization method (Figure 52).

	Variables	Coefficient (b)
b_0		-119.4
X_1	ELEVATION	0.68
X_2	X-COORD	-8.18
X_3	WET_IND	0.28
X_4	MPGR-6	2.22
X_5	GEOGR-1	-4.64

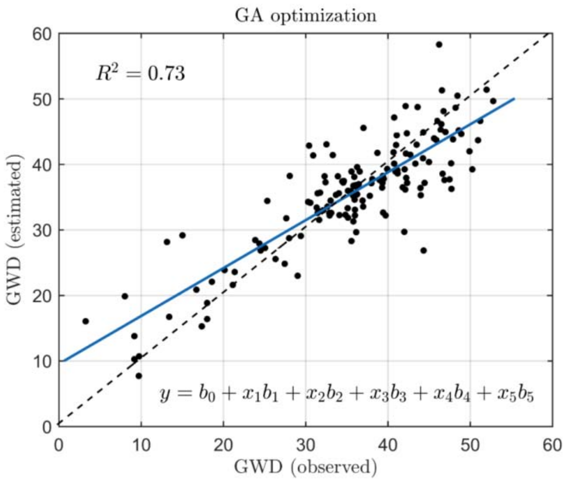


Figure 52 ***Estimated depth of groundwater. Selected variables using GA optimization algorithm and results on 161 borehole data in Senegal***

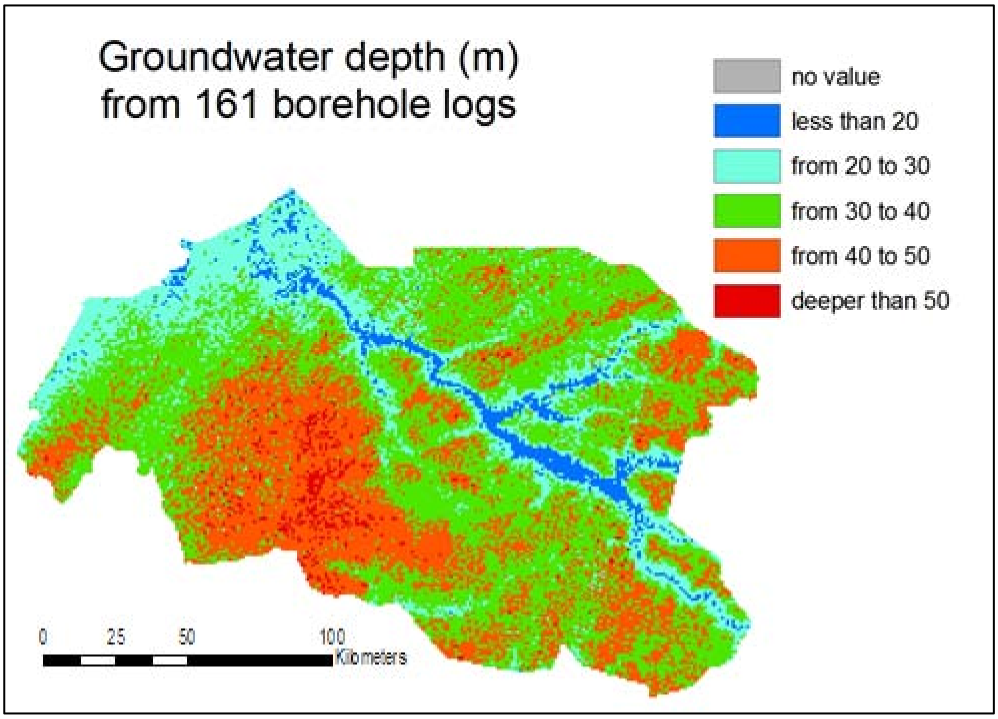


Figure 53 ***Map of estimated groundwater depth obtained from GA optimization (see Figure 52)***

Method 2.

With the same dataset of 161 boreholes it was tested MOLS regression using SWR method for the selection of variables. In this case the resulting model is more complex (18 variables selected by the algorithm, although only 9 are considered more relevant) and the final result is worse than before (R^2=0.64).

		Coefficients	Std.	Error	t value	Pr(>|t|)
b_0	(Intercept)	-110.77661	39.04338	-2.837	0.005298	**
X_1	GEOGR-02	4.96126	3.38433	1.466	0.145134	
X_2	GEOGR-03	-0.26827	5.05503	-0.053	0.957759	
X_3	GEOGR-04	4.09483	1.70254	2.405	0.017609	*
X_4	GEOGR-05	-1.19213	3.30526	-0.361	0.71894	
X_5	GEOGR-06	6.19808	1.77296	3.496	0.000651	***
X_6	GEOGR-07	-7.28279	5.94773	-1.224	0.223043	
X_7	SOILGR_IDRB	-3.9042	3.6602	-1.067	0.288147	
X_8	SOILGR_IDRS	-16.11964	6.34961	-2.539	0.012335	*
X_9	SOILGR_IDTS	-1.463	2.49942	-0.585	0.55936	
X_{10}	OCSGR-04	0.80658	1.29718	0.622	0.535189	
X_{11}	OCSGR-05	4.51996	1.61767	2.794	0.006011	**
X_{12}	OCSGR -06	5.40177	2.28746	2.361	0.019723	*
X_{13}	OCSGR-07	-1.51672	3.93466	-0.385	0.700529	
X_{14}	Slope	0.19963	0.22688	0.88	0.380581	
X_{16}	TRI	-0.24244	0.12882	-1.882	0.06212	.
X_{17}	xCoord	-7.88824	2.36448	-3.336	0.001114	**
X_{18}	Elevation	0.66371	0.06752	9.829	<0.0000000000000002	***

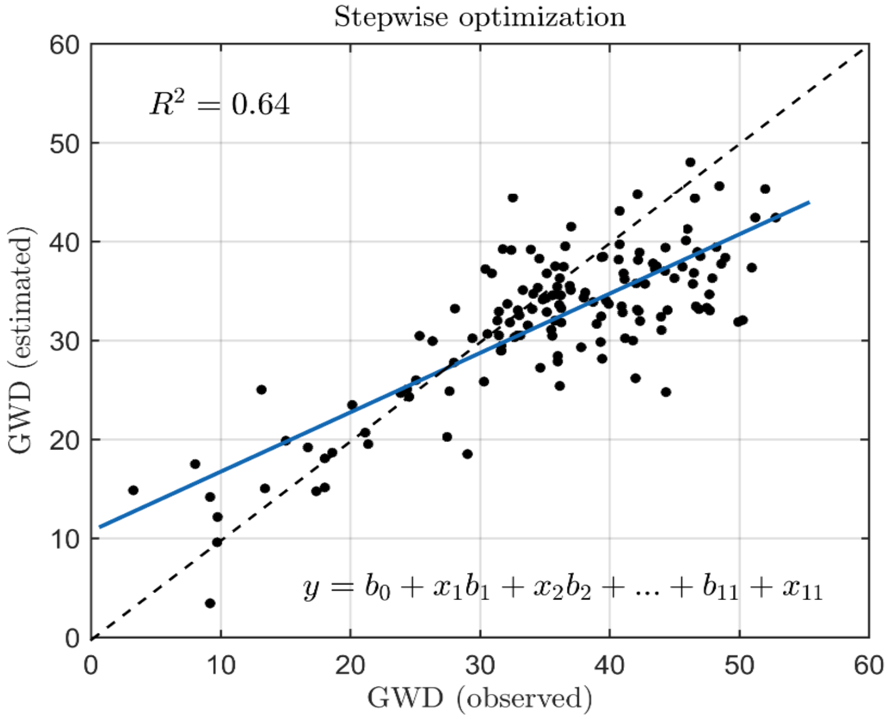


Figure 54 ***Estimated depth of groundwater. Selected variables using SWR algorythm and results on 161 borehole data in Senegal***

Method 3

Estimation of depth of groundwater was carried out also using 585 data of static water level from open hand dug wells. In this case the best results were obtained using SWR method for variable selection.

		Coefficients	Std.	Error	t value	Pr(>|t|)
b0	(Intercept)	285	54.9	5.188	2.93E-07	***
X_1	xCoord	8.75	1.51	5.782	1.2E-08	***
X_2	yCoord	-8.62	3.14	-2.746	0.00621	**
X_3	ELEVATION	0.602	0.0554	10.881	<0.0000000000000002	***
X_4	wet_idx	0.213	0.0726	2.937	0.00344	**
X_5	slope	-0.337	0.178	-1.891	0.05905	.
X_6	ACCUM	-0.0000192	0.0000356	-0.54	0.58957	
X_7	CONV	0.025	0.0117	2.14	0.03274	*
X_8	SOILGR_IDHY	11.2	4.3	2.594	0.00973	**
X_9	SOILGR_IDRB	10.8	4.32	2.5	0.01268	*
X_{10}	SOILGR_IDTS	5.4	4.99	1.082	0.27965	

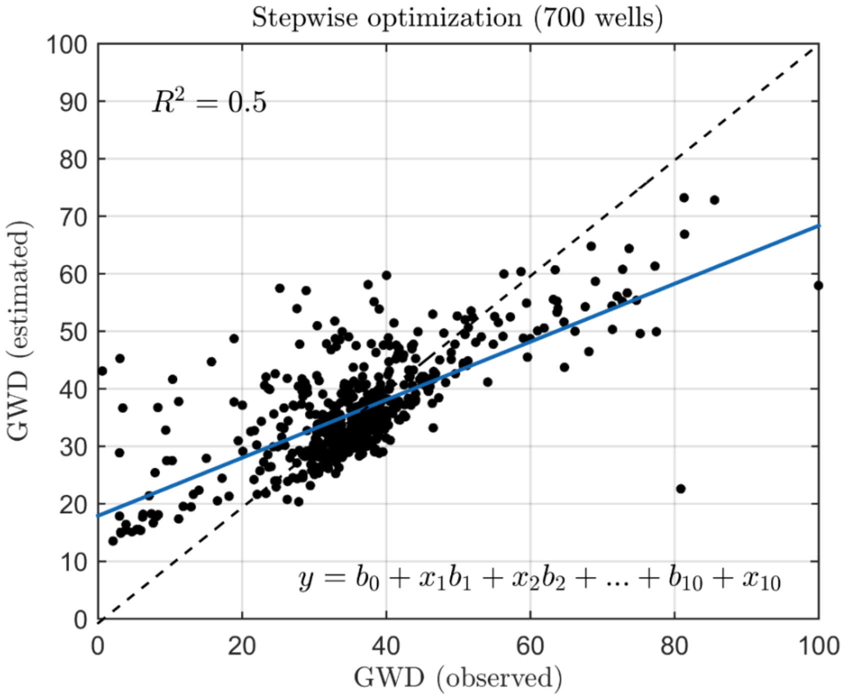


Figure 55 ***Estimated depth of groundwater. Selected variables using SWR algorythm and results on 585 open well data in Senegal***

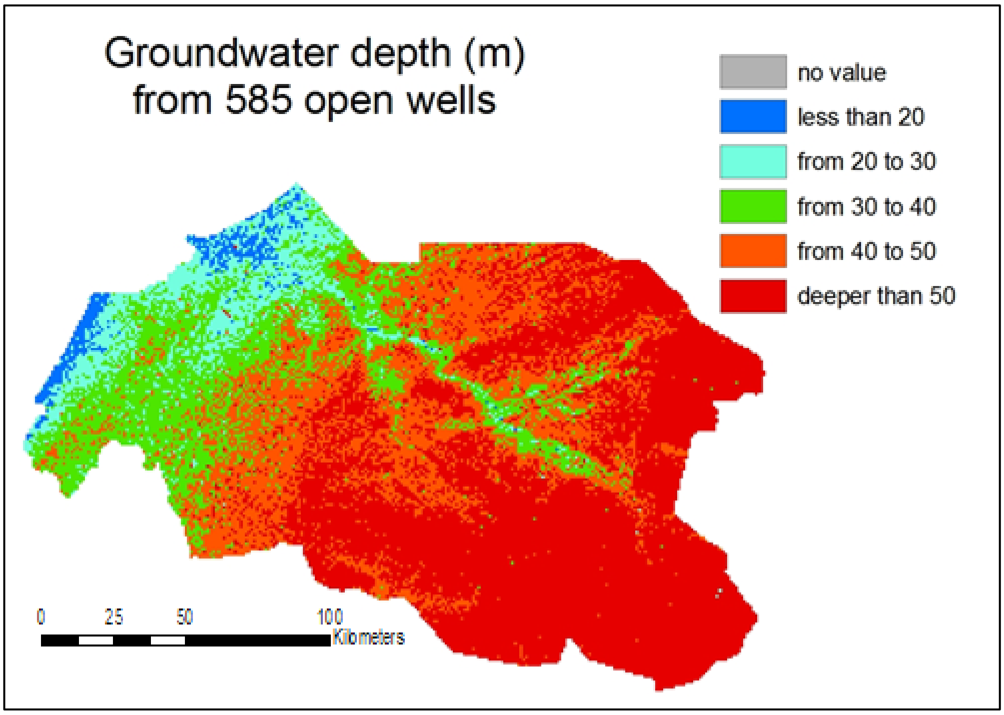


Figure 56 ***Map of estimated groundwater depth obtained from SWR selection on 585 open well data (see Figure 55)***

The first estimation (based on 161 boreholes distributed in the whole study area and GA optimization) obtained the best statistical result (R^2=0.73). However this estimation cannot be considered representative of the depth of exploitable water, since the static water level of several boreholes (especially in the eastern sector) is referred to a deep confined aquifer, while the first water table (potentially exploitable by manual drilled wells) is much deeper.

At the contrary, static water levels in open hand dug wells are representative of the first and shallow water table. The third estimation (R^2=0.5) is more relevant for the suitability of manual drilling, although the dataset is concentrated in the western part of the study area. Furthermore, the estimated depth of water has a good result between 20 and 40 m, while there is an increasing error for deeper values, out of the range of feasibility for manual drilling.

Depth of rock

Depth of rock was estimated with two methods, using the same data sets of 161 borehole logs (distributed as shown in Figure 23).

The first approach uses a MOLS regression on geoenvironmental indicators, using SWR algorithm for the selection of the variables (Figure 57).

		Coefficients	Std.	Error	t value	Pr(>|t|)
	(Intercept)	-5.1974	79.388	-0.065	0.94792	
X_1	GEOGR_ 02	-29.3879	18.1397	-1.62	0.108077	
X_2	GEOGR_ 03	-32.5405	30.6615	-1.061	0.290885	
X_3	GEOGR_-04	-3.3748	16.4038	-0.206	0.83738	
X_4	GEOGR_ 05	-28.0243	25.7702	-1.087	0.279206	
X_5	GEOGR_ 06	31.0312	14.7283	2.107	0.037398	*
X_6	GEOGR_ 07	30.8982	55.0091	0.562	0.575468	
X_7	ATI(feb)	-3835.81	2419.158	-1.586	0.115701	
X_8	ATI(mar)	5673.072	1414.212	4.011	0.00011	***
X_9	slope	2.367	1.678	1.411	0.161184	
X_{10}	TPI	140.974	54.8677	2.569	0.011528	*
X_{11}	CONV	-0.2736	0.1335	-2.049	0.042849	*
X_{12}	Dslenght	-0.4047	0.1022	-3.961	0.000133	***
X_{14}	Elevation	0.9287	0.4608	2.015	0.046311	*

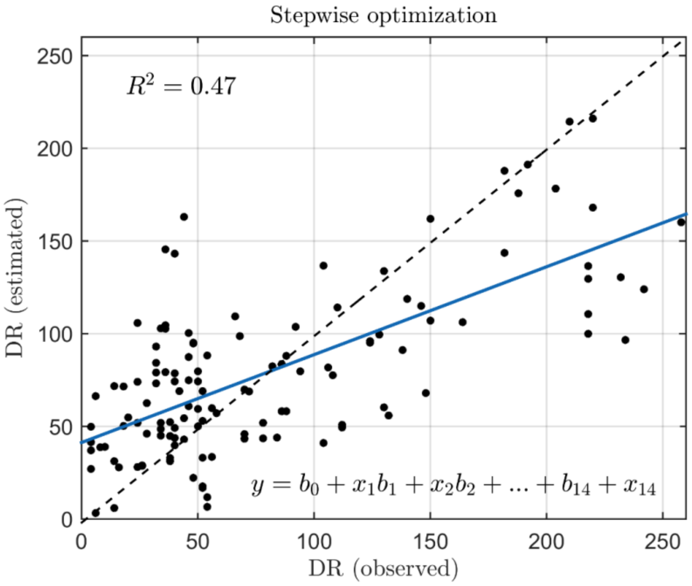


Figure 57 ***Estimation of depth of rock. Selected variables using SWR algorythm and results on 161 borehole data in Senegal***

The second method is based on spatial interpolation of the original data of depth of rock obtained from 110 borehole logs (51 borehole logs were not considered in the interpolation since they have no hard rock in their stratigraphic profile).

The analysis of semivariogram showed that there was no spatial structure in the data of depth of rock and that was not possible to find a model of variogram with good fitting of the data; therefore it was considered not adequate to use kriging method for the interpolation. Furthermore, it is likely that the depth hard rock cannot be considered a parameter varying with a continuous gradient, since boundaries of geological units can be considered breaklines.

After testing different methods it was decided to use a simple deterministic IDW (Inverse Distance Weight) method, with the following parameters, selected after testing different combinations and choosing the best results (lowest RMS):

- Nr of points to consider: 20
- Smoothing factor 0.8
- Anisotropy factor: 1
- RMS in crossvalidation = 74.5

The results is the map of estimated depth of hard rock in the study area

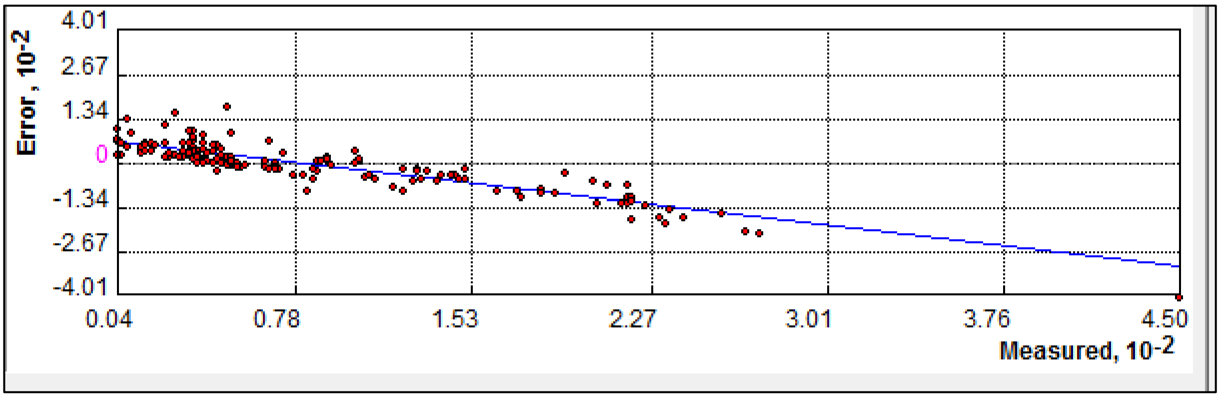


Figure 58 ***Distribution of errors in prediction of depth of hard rock***

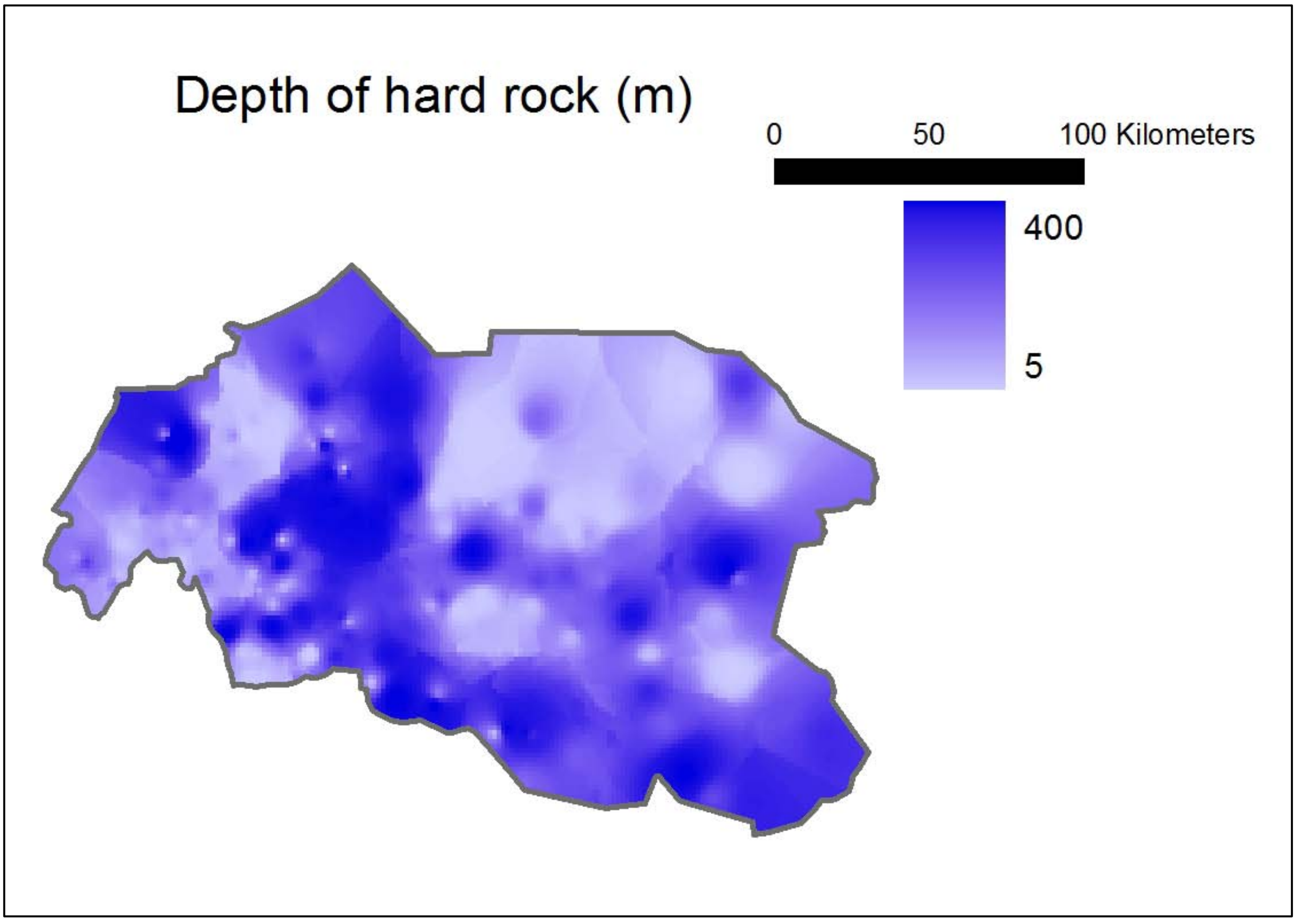


Figure 59 ***Map of estimated depth of hard rock, obtained from 110 borehole logs and interpolation using IDW (inverse distance weight) algorithm***

Classification of feasibility

Since in the whole study area there is limited presence of hard lateritic layers, we can consider that nowhere in the study area is required special drilling techniques to break hard intercalation. Therefore, with the estimation of depth of water and depth of rock we have at this stage all the parameters required to determine the feasibility for manual drilling, according to Figure 16.

Depth of rock resulted always compatible with the implementation of manual drilling. The only limiting factor in the feasibility for manual drilling is the depth of water; in this case hydrogeological conditions must be considered not feasible in the central-eastern part of the study area, it means where water level is deeper than 40 m.

Hydraulic conductivity (K) of saturated layer up to 50 m

This parameter is crucial to define transmissivity of unconsolidated exploitable aquifer and assign the class of potential.

It was not possible to find any MOLS regression model with an adequate fitting to the data obtained from 161 borehole logs.

In terms of methods of prediction based on spatial interpolation, it seemed not adequate to adopt exact method of interpolation (like IDW) as the level of errors in the original data of estimated K from borehole can be important. Therefore we tested different type of inexact interpolators (it means that the interpolated surface must not necessarily pass through the original data).

The use of kriging interpolators for the estimation of K can produce unreliable results; for regional scale results can be improved introducing secondary variables to carry out co-kriging or kriging with external drift techniques. (Patriarche et al., 2005).

In this research, a preliminary exploration of data evidentiated that the semivariogram was difficult to fit with a reliable model (Figure 60); for this reason kriging was not recommended and other methods of interpolations were tested.

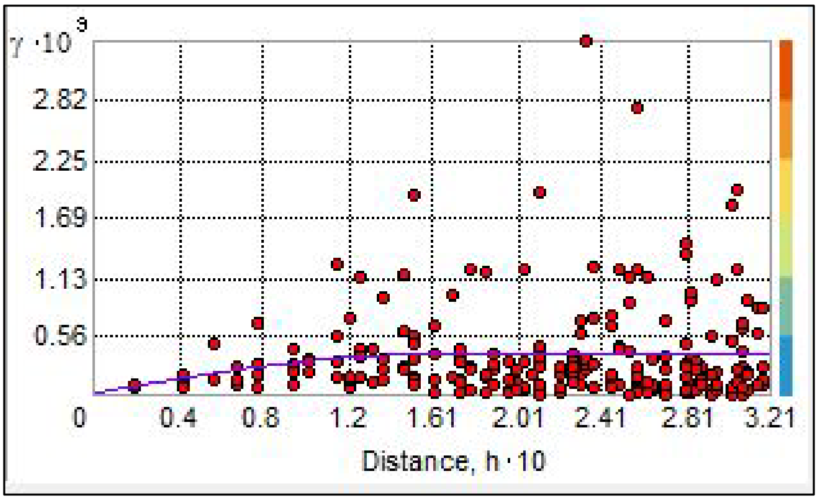


Figure 60 ***Semivariogram of Average K in the saturated layer up to 50 m deep. Dataset of 161 borehole logs in Senegal***

Finally we applied a spline with tension interpolator, using a smoothing factor of 0.5 and a resulting RMS = 0.0000203 (Figure 61).

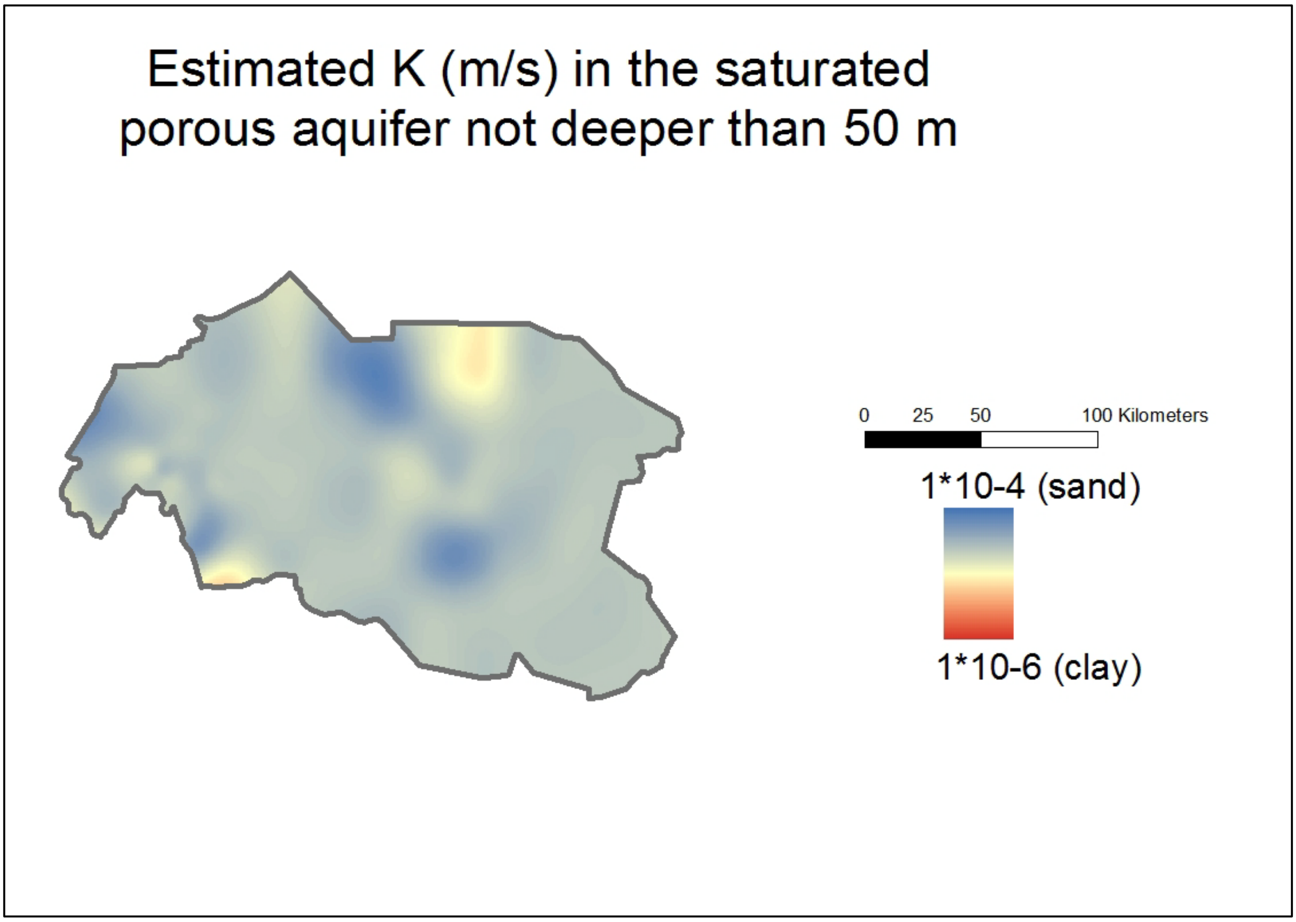


Figure 61 ***Map of estimated K in the saturated layer up to 50 m using spline interpolation in Senegal***

Estimation of transmissivity and potential for manual drilling

At this point we used map overlay function in GIS and we obtain:

- The exploitable saturated porous thickness, from the combination of depth of water and modified depth of rock (assigning the value of 50 m to all that zones where depth of rock is deeper than that);
- The map of exploitable transmissivity, applying eq. 5.1 and combining the map of exploitable saturated porous thickness and average K50;
- The map of class of potential, classifying the map of transmissivity according to Table 9 (Figure 62).

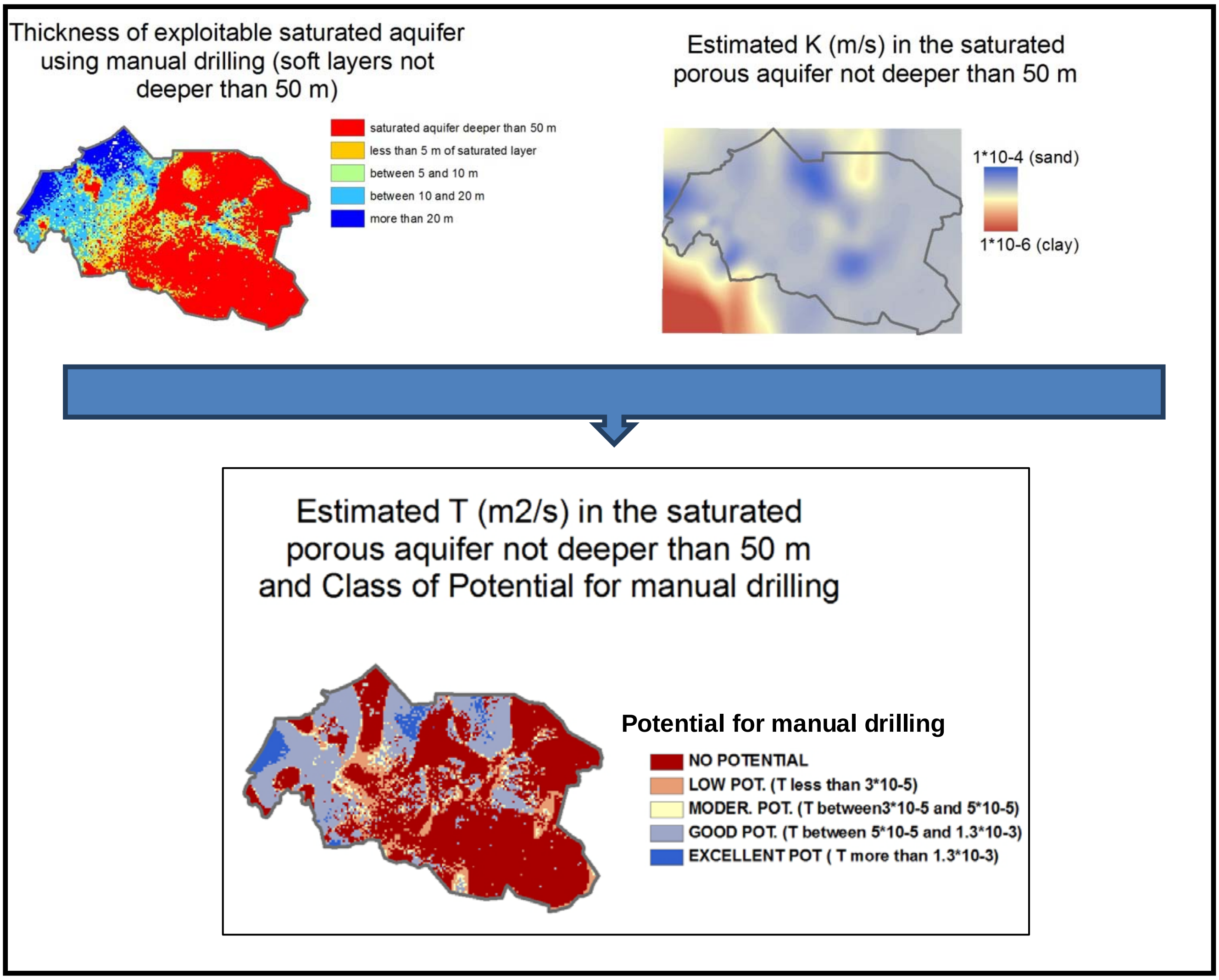


Figure 62 ***Map overlay process and creation of map of class of potential for manual drilling***

The final step of the process is the elaboration of the map of overall group of suitability (Figure 63). This map is created from the feasibility (in this case obtained directly from the map of depth of water, as this is the only limiting factor in this area) and the class of potential.

A schematic representation of the complete process of elaboration of the map of overall group of suitability for manual drilling in Senegal is shown in Figure 64.

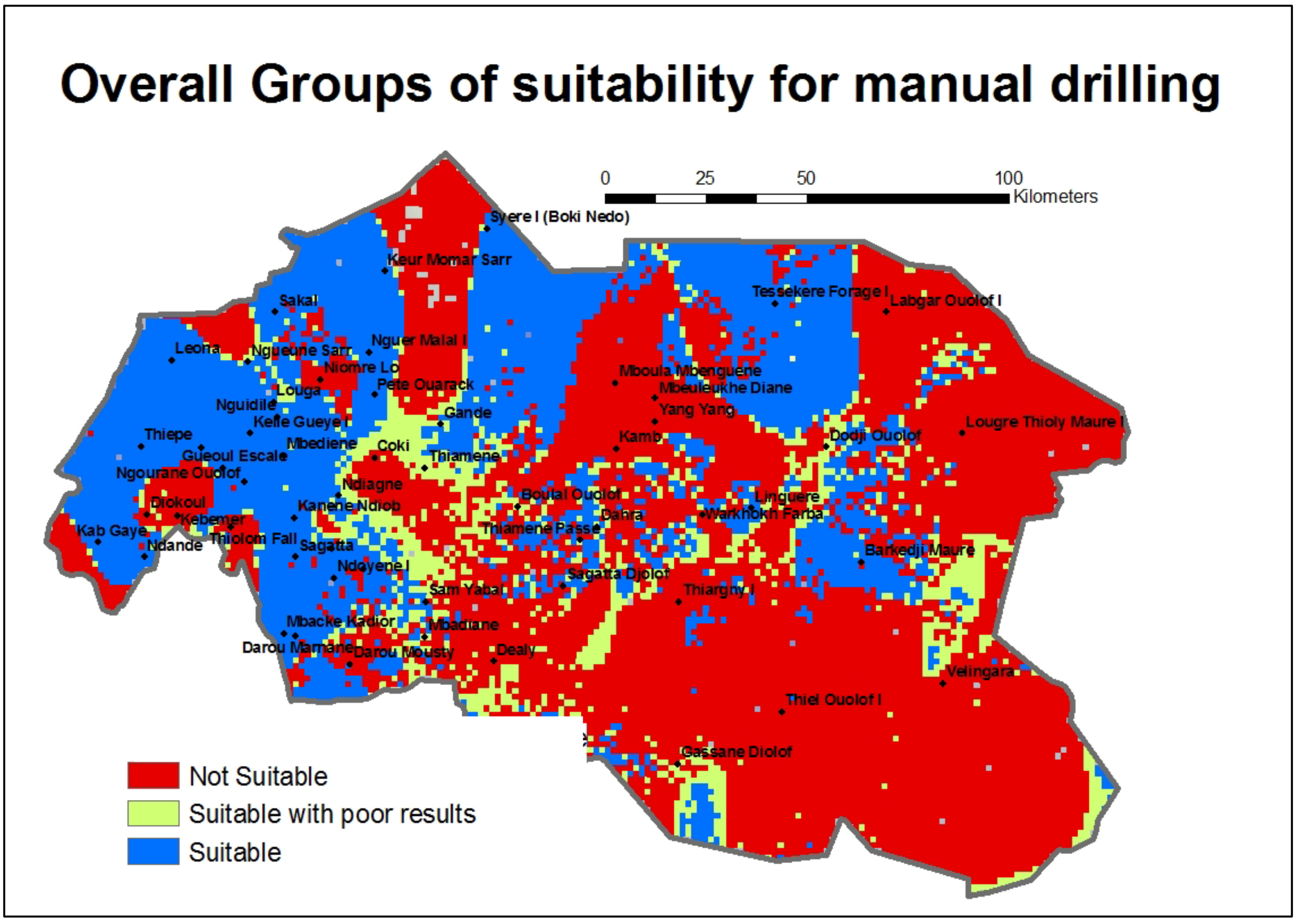


Figure 63 ***Map of overall group of suitability in Senegal study area***

Comparing this map of overall group of suitability (Figure 63) with the UNICEF map published in 2010 (Figure 14) some modifications result evident:

- the extent of zones considered suitable are much larger; this is mainly due to the increase of the limit of groundwater depth to define the feasibility (25 m in UNICEF study while 40 m in this research);
- a more detailed and semiautomatic processing of borehole logs allowed to decrease the estimated risk of hard laterite (that was considered a major problem in UNICEF study for this region);
- the discrimination of subzones in the central and western study area with higher or lower potential (previously considered in the same class of suitability as the method was based on a simple reclassification of a geological map with low level of detailed).

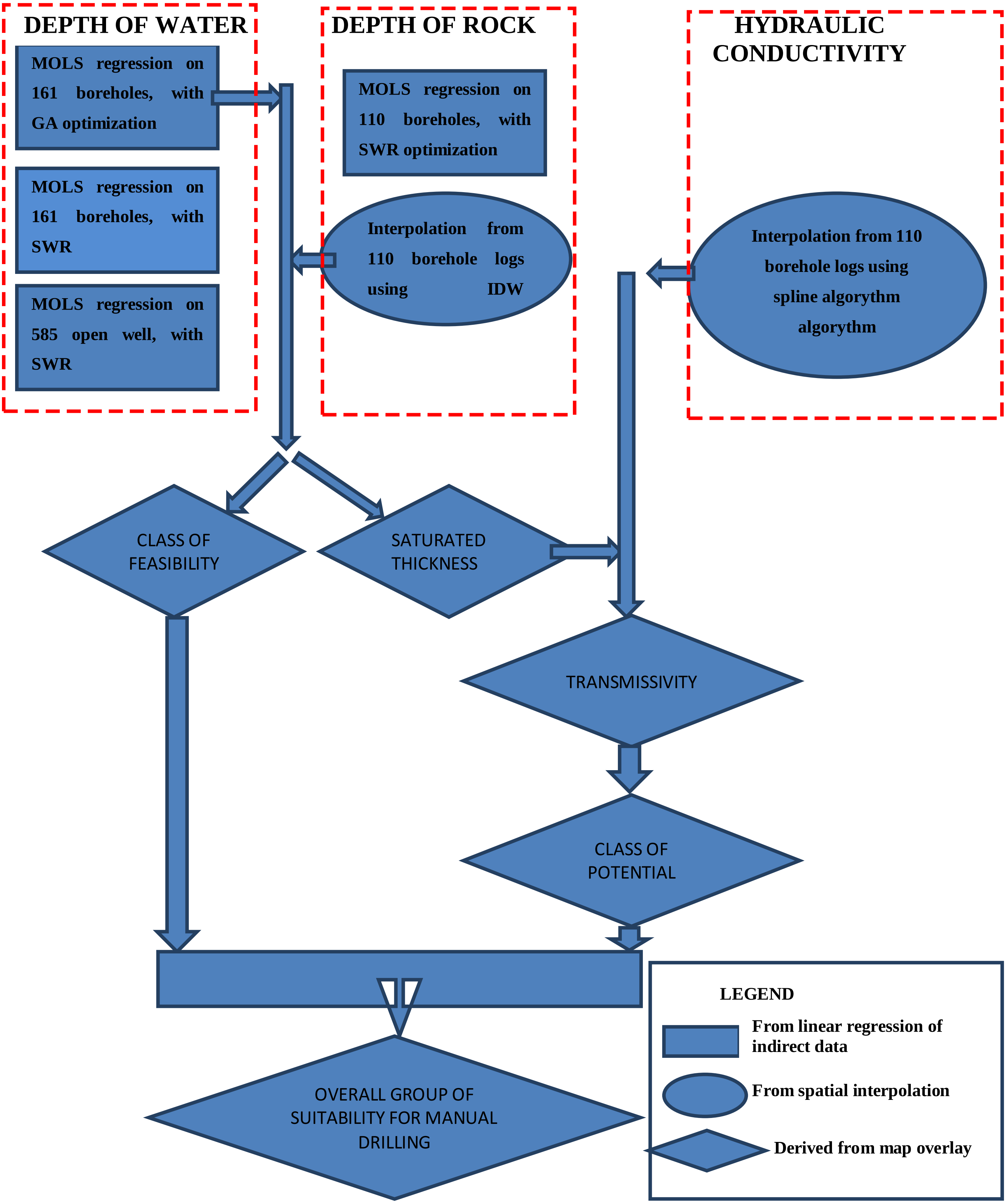


Figure 64 *Process to obtain map of overall suitability in Senegal*

GUINEA

In Guinea the limited number of borehole logs available made difficult the application of spatialisation techniques for the whole set of hydrogeological parameters required to estimate the suitability for manual drilling. On the other hand it was possible to apply multivariate regression on the dataset available for the estimation of ground water depth.

Depth of groundwater

Depth of groundwater was estimated with MOLS regression and SWR algorithm for variable selection. A database of 485 deep boreholes with the information of static water level (Figure 65) was used. Since in Guinea there is no systematized information from large hand dug well and no piezometer exists in the area, we could not obtain any evidence of stacked water table and confined aquifers exploited by deep boreholes (for example difference in static water level between deep boreholes and hand dug wells in the same location).

The direct measurements of water level in open well (extremely frequents in this area) was one of the main objectives of field survey, unfortunately this activity was cancelled because of ebola. Nevertheless, observations of few hand dug wells carried out during a field survey in 2011 in the framework of a study for UNICEF (GRAIA, 2012) showed that deep boreholes and shallow open well have similar water level. This corresponds also at the perception of local hydrogeologists

		Coefficients	std error	t value	Pr(>|t|)	
	intercept	2.69E+00	3.51E+00	0.768	0.444078	
	MPGROUP2	3.19E+00	1.39E+00	2.289	0.023601	*
	MPGROUP3	1.87E+00	8.25E-01	2.271	0.02468	*
	MPGROUP4	8.15E-01	1.13E+00	0.719	0.473185	
	MPGROUP5	7.56E-01	1.31E+00	0.579	0.563724	
	MPGROUP6	1.80E+00	1.21E+00	1.492	0.137993	
	MPGROUP7	4.10E+00	1.36E+00	3.012	0.003083	**
	MPGROUP8	-5.71E+00	2.00E+00	-2.86	0.004883	**
	MPGROUP9	3.18E+00	1.87E+00	1.702	0.090946	
	Moist_min	-1.14E+01	6.32E+00	-1.802	0.073643	
	DSlen	-3.01E-02	1.68E-02	-1.794	0.07494	
	NDVI_min	5.24E-04	2.25E-04	2.329	0.021315	*
	ATI (feb)	1.15E+02	4.15E+01	2.773	0.006316	**
	slope	2.15E-01	1.14E-01	1.888	0.06113	
	pcurv	-1.58E+02	6.94E+01	-2.279	0.024192	*
	Dist_stream	1.28E-03	4.73E-04	2.706	0.007673	**
	G_tricat2	5.19E-01	7.52E-01	0.69	0.491518	
	G_tricat3	-1.18E+00	1.38E+00	-0.857	0.393094	
	G_tricat4	-1.55E+01	4.06E+00	-3.822	0.000199	***

Figure 65 ***Estimated depth of groundwater. Selected variables using SWR algorythm and results on 485 boreholes data in Guinea***

General observation about the results of spatialisation by statistical models

The results of spatialisation of hydrogeological parameters using different statistical models based on geoenviromental indicators can be considered partially satisfactory for the prediction of ground water depth, while it proved not possible to obtain satisfactory models for the depth of rock and hydraulic conductivity.

The automatic procedure of selection of variables for the prediction of groundwater depth highlighted the importance of its relation with the absolute elevation. This was an expected result, since shallow water table is clearly dependent from topography and relative position to drainage (Haitjema and Michell-Burker, 2005).

In the case of Senegal, the other relevant variables selected by the algorithm are mainly the geographic coordinates (indicating the importance of the distance from the coastline), geology and some indicators obtained from the analysis of vegetation dynamics and ATI. On the contrary, in Guinea, the most important relation proved to be that with morphometric parameters and morphopedological units.

It can be inferred that vegetation dynamics and thermal inertia can provide relevant information for the prediction of ground water depth (and partially for depth of hard rock) in Senegal, where the limited vegetation cover and rainfall make remote sensing data more diagnostic of shallow hydrogeological features. On the other hand, temporal dynamics of remote sensing parameters seem not to be effective in providing information about shallow hydrogeology in Guinea, probably due to the masking effect of intense vegetation cover; while morphometric parameters assume a higher relevance.

Spatialisation of depth of rock and hydraulic conductivity is difficult to carry out at regional scale using geostatistical interpolation, as the distribution of these parameters has a discontinuous pattern related to the sharp difference between geological units. This was much more evident in Guinea (where geological variability is higher) and made it extremely difficult to find satisfactory predictive models.

Chapter 8. Conclusions

Ndian bhuubhudhan warata karan
(Fresh water cannot kill the insects)

Since 2006, UNICEF has been leading the activity of identification of suitable zones for manual drilling as part of its programme to promote low cost techniques for water supply in Africa. 15 national maps have been completed and they have been used, in many countries, as a planning tool for the definition of the national strategy to support manual drilling. At that stage, national maps proved generally effective for their scope; however, it was clear that they were (i) not sufficient to support directly the implementation in the field, (ii) based on unreliable interpretation where no previous data exist and, finally (iii) qualitative and not systematic. These aspects were considered in the formulation of the research project, which results are presented in this study.

The aim of this research is the definition of a methodology to improve the interpretation of shallow hydrogeology and the identification of suitable zones for manual drilling by the integration of different data and methods of analysis of the information.

The main results are exposed in the different chapters of this report:

- the definition of a structured and semi-quantitative procedure for the estimation of suitability for manual drilling (chapter 4);
- the elaboration of a systematic and semi-quantitative method for the interpretation of existing water points data (and a specific software to implement it), supported by direct field measurements for validation of the analysis (chapter 5);
- the definition of a series of geoenviromental indicators related to the shallow hydrogeological conditions and the elaboration of procedures to extract them from public remote sensing data and thematic maps (chapter 6);
- the identification of possible statistical procedures to predict hydrogeological parameters from geoenviromental indicators, providing a possible approach for the estimation of suitability for manual drilling in those areas where no direct hydrogeological information is available (chapter 7).

The proposed methodology for the estimation of suitability is systematic and semi-quantitative, therefore it is considered an improvement from the previous experiences (in particular the procedure adopted in the national maps of UNICEF). This method is simple and can be easily replicated in other zones. However, the values of the different input parameters of the model of suitability (depth of water, depth of rock, transmissivity in the exploitable aquifer and thickness of hard laterite) must be adapted to the local hydrogeological context as well as the local experience and skill in manual drilling techniques and available pumping equipment. For example, local drillers in Senegal have greater ability than Guinean drillers in the application of percussion techniques; therefore, they can perforate hard lateritic layers that are considered not drillable in Guinea. Furthermore, the estimation of suitability in certain zones must take into consideration the seasonal fluctuation in water table (sometimes affecting the efficiency of those wells with limited saturated thickness) and the aspects of water quality.

The support of dedicated technical staff in Senegal and Guinea, as well as the elaboration of a specific software for the codification and processing of water point data, proved to be key factors for an analysis of stratigraphic data that is much more detailed than in the previous study carried out by UNICEF and has a quantitative approach in the estimation of suitability from the interpretation of geometry and hydraulic parameters of shallow aquifer. Unfortunately, the small number of pump tests in large diameter wells and geophysics soundings we carried out made the process of calibration of the estimated hydrogeological parameters quite limited, although the preliminary results seem to indicate that this method can indeed be effective. It is also important to extend the use of TANGAFRIC to other geological situations and improve this valid tool, which was presented to the national water authorities in both countries and raised their interest.

Obtaining hydrogeological information from surface environmental parameters estimated from remote sensing has often been a difficult aspect. In Guinea the presence of high rainfall and intense vegetation produce a masking effect, while in Senegal the limited variability in shallow geology made it difficult to define subzones with different characteristics. However, the integration of remote sensing data and digital terrain models made it possible to identify anomalies in the distribution of geoenvironmental indicators that can facilitate the interpretation of shallow geology, in particular where vegetation cover is low and water table is shallow. The support that remote sensing can give is considered relevant where direct hydrogeological information is limited; satellite data have the advantage of being largely available free of cost in each part of the world, at a spatial resolution that makes it possible to reach a more detailed interpretation than thematic maps in some country.

The use of a statistical approach in the spatialisation of hydrogeological parameters couldn't provide reliable methods for their prediction by using multivariate analysis of geoenvironmental indicators; especially for the estimation of the depth of hard rock and hydraulic conductivity. This aspect of the research could reach better results in the future, although it would be advisable to improve the quality of the hydrogeological data set (for example with a direct verification in the field of static water level in the wells and the collection of a larger number of stratigraphic logs).

This research clearly shows the relevance of existing databases of water points in most African countries for hydrogeological interpretation. Both in Senegal and Guinea there is a huge amount of data from boreholes and wells; but they are poorly organized and centralized, not updated, and full of mistakes of incompleteness. It is also important to highlight the relevant information obtained from the observation of large diameter wells and the implementation of pump tests. The information of large hand dug well is generally not recorded in the database. However, they can provide essential elements for the interpretation of shallow aquifers and they are often used to carry out simple tests to estimate the potential yield (e.g. MacDonald et al., 2008) or monitor the modification in the water level. Large diameter wells are present even in those areas where the access to safe water from deep and protected boreholes is low, therefore those areas where manual drilling can have a relevant impact on living condition of the population.

The results of this research could contribute to improve the effectiveness of the various attempts to promote small-scale water supply and low cost technologies (including manual drilling). This strategy is receiving increasing interest by local institutions, international agencies and donors; a clear example is the recent extensive programme to support the manual drilling sector in West Africa, which is financed by the Dutch Cooperation and coordinated by UNICEF, in partnership with various national institutions.

A key factor to exploit the results of scientific research in the implementation of water supply programs is the close coordination and collaboration between academies, institutional decision makers and drilling groups in the field. This was the situation in Guinea after 2011 and one of the elements that contributed to the positive results that this country obtained in this sector in a few years. Unluckily, the outbreak of Ebola disease disrupted all the programs.

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