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Mapping the Viability, Time, and Cost of Manual Borehole Drilling in Developing Regions

Pedro Martínez-Santos [1,*], Miguel Martín-Loeches [2], Daniel Solera [1], Beatriz Cano [1] and Silvia Díaz-Alcaide [1]

1 Departamento de Geodinámica, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid, C/José Antonio Novais 12, 28040 Madrid, Spain; d.solerajimenez@gmail.com (D.S.); beatrizcanoarnaiz@gmail.com (B.C.); sdalcaide@gmail.com (S.D.-A.)

2 Departamento de Geología, Geografía y Medio Ambiente, Facultad de Ciencias Ambientales, Universidad de Alcalá, Campus Universitario, Ctra. Madrid-Barcelona, Km 33,600, Alcalá de Henares, 28801 Madrid, Spain; miguel.martin@uah.es

* Correspondence: pemartin@ucm.es; Tel.: +34-91-394-4863

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Abstract: While access to water remains an issue in arid and semiarid regions across the world, aquifers have the potential to help millions of people out of poverty by providing a reliable source of drinking and irrigation water. Manual boreholes are increasingly advocated as a safe and cost-effective substitute to mechanized drilling, as well as to traditional excavation methods. This research banks on the assumption that field and remote sensing data can be integrated within a geospatial database in order to map the viability of manual boreholes based on factors such as rock type, water table depth, landforms, or water quality. The approach presents three main novelties in relation to methodological precedents: (1) outcomes are not only expressed in terms of technical feasibility, but also as a function of drilling time and cost; (2) maps refer to a specific drilling technique; and (3) results take into account borehole diameter, as this constrains both drilling time and cost. The method provides univocal outcomes that can be immediately useful for non-experts, donors, planners, or practitioners and that can be readily exported to other catchment-scale settings. Results were validated against geophysical data.

Keywords: manual boreholes; appropriate technologies; developing regions; water supply; geographic information systems; Mali

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1. Introduction

1.1. Background

Water is essential for human settlements. Since prehistoric times, water availability has played a key role in determining the origin and fate of entire civilizations [1]. In today's industrial societies, drinking and irrigation water supply is often taken for granted. This is because water infrastructures are solidly engineered and there are enough resources to build and maintain them. As a result, failures are rare and the population does not need to worry about taps running dry. However, access to water remains an issue in many regions across the world. In developing countries, where a productive well not only means hydration but also food security, hygiene, health, and, arguably, a better chance for education, a significant share of the population does not yet have access to improved water sources [2]. Millions of people live more than one kilometer away from the nearest faucet, and walk several hours each day to provide water for such ordinary needs as drinking or cooking [3]. More often than not, fetching water is a task for women and children—a task that is carried out at the expense of education and leisure, and often leads to chronic injuries and to missing out on opportunities for personal development [4].

In areas subject to the West African Monsoon, rainfall is erratic and concentrated almost exclusively in the wet season. People are often forced to rely on the unreliable to meet their domestic needs and grow low-value crops. Within this context, groundwater resources can play a key role in challenging poverty by providing a stable supply of water [5,6]. Aquifers allow users to deliver for themselves, their crops, and livestock during long dry spells. This is partly because of the large quantities of water that are naturally stored in aquifer systems and partly because groundwater can be accessed with relative ease. Nevertheless, improved water sources such as mechanized boreholes may be extremely expensive for rural communities. In the Sahel region, a mechanized borehole costs several thousand USD [7]. Bearing in mind that a large share of the population makes under 1 USD/day, this sum implies that drilling mechanized boreholes is beyond the means of most people. Devising cost-effective methods to access groundwater resources and build local infrastructures is thus crucial to ensure food security and protect human livelihood [8,9].

Manual drilling is a discipline in its own right [10]. It is conceptually different from digging and presents a series of specific features that set it apart from mechanized drilling. Hence, its potential and competitiveness need to be appraised in terms of relative strengths and weaknesses. For instance, a clear conceptual distinction exists between hand drilling and excavation (Table 1). Manually drilled boreholes are not made by means of pick and shovel, but by replicating mechanical drilling methods by hand. As a result, the holes are small in diameter (typically 2 to 4 inches) and can be cased and equipped with gravel packs, submersible pumps, and sanitary seals, much like mechanized boreholes. Moreover, manual boreholes are deeper on average than excavated wells. This presents several additional advantages. Perhaps the main one is that the technique is not limited to the point when the water accumulated at the bottom of the hole makes it too difficult to keep digging by hand. In consequence, manual boreholes often exceed 30 or 40 m, while dug wells rarely reach 20. The possibility of drilling several meters below the water table implies that users are unlikely to run out of water during the dry season. Furthermore, deeper ground waters are better protected from contamination. This poses an added benefit in relation to excavated wells, where pollution is generally an issue [11]. Finally, manual drilling is safer during the construction stage because the drilling crew works outside the hole and needs not worry about collapses.

Manual drilling is also different from mechanized drilling. For practical purposes, manual drilling is slower and more labor-intensive. In addition, its potential is limited by geological factors. However, when conditions allow, manual drilling provides a highly cost-effective alternative to access groundwater [12–16]. For instance, in the geographical context where this research was carried out, a fully equipped manual borehole, including the pumping device, may be up to 95% cheaper than a fully equipped mechanized borehole of the same depth.

Manual drilling falls under the umbrella of appropriate technologies. This means that materials can be obtained locally and users can be trained to drill and maintain their own boreholes. As a result, there is often no need to rely on external technical support or specific spare parts. These are some additional reasons why manual drilling was included within the Millennium Development Goal Good Practices by the United Nations Development Group. Efforts have subsequently been made to raise the profile of manual drilling among stakeholders [17]. Manual drilling also has the potential to contribute to several the Sustainable Development Goals, including Goal number 6, “ensure access to water and sanitation for all”.

Table 1. Terminologies used in the manuscript.

Category	Term	Definition
Wells and boreholes	Borehole	A narrow shaft bored in the ground for the purpose of extracting groundwater. Boreholes are cased, gravel packed and equipped with a pump and wellhead protection.
	Manual borehole	A borehole drilled by manual means, replicating the work of a mechanical rig by hand. Typically less than 50–60 m deep, with a casing diameter of two to four inches. Drilling methods include augering, percussion, sludging and jetting.
	Mechanized borehole	A borehole drilled by means of a mechanical rig, usually mounted on a truck. May be hundreds of meters deep. Casing diameter usually measured in inches. Mechanized boreholes are comparatively more expensive than manual boreholes.
	Excavated well, dug well, well	A large diameter (typically >0.5 m) hole in the ground used for the purpose of extracting groundwater. Typically dug using peaks and shovels. Generally less than 25 m deep.
Pumps	Standard pump	A commercially-available pump used to extract groundwater from within a borehole. Most standard pumps in the study area require four-inch casing diameters. Yields can be highly variable, depending on the type of pump.
	Hand pump	A sub-type of standard pump. Commercially-available and powered by hand. If the aquifer is sufficiently transmissive, yields are limited by the pumping capacity of a human being (which typically ranges between 0.5 and 1.5 m^3/h).
	Powered pump	The other sub-type of standard pump. Commercially-available pump powered by electricity or gasoil. If the aquifer is sufficiently transmissive, yields may greatly exceed those from hand and homemade pumps (typically several cubic meters per hour in the study area).
	Homemade pump, locally-made pump	A non-standard hand pump. Made with inexpensive local materials and powered by human action. Typically less durable than a standard pump, but also easier and cheaper to fix. Yields do not often exceed 1 m^3/h.

1.2. Methodological Precedents, Research Objectives, and Novelties

It is well known that geographic information systems (GIS) are designed to analyze the interrelation between different layers of spatially distributed data. GIS is the tool of choice when integrating information from various sources to tackle complex problems. Geospatial information has proven useful to explore the link between water and poverty [18,19]. In the case of groundwater resources, GIS has frequently been applied to delineate groundwater potential areas [20–24], study the spatial distribution of aquifer recharge [25–27], or assess the vulnerability of aquifer systems to pollution [28–30].

The literature on manual drilling potential is comparatively scarce, despite the fact that most hand drilling techniques have been known for a long time [31]. Sludging, for instance, is considered a traditional technique in countries like India or Bangladesh [12], while percussion was already being used by the Chinese several millennia ago [32]. Hand drilling is largely a forgotten art in the West, where it has been replaced by automated methods of all kinds. However, it is fair to say that manual drilling has experienced a revolution in the last two decades, partially fueled by international relief projects. Global estimates as to the total number of hand-drilled boreholes are hard to come by, but some telling figures exist. For instance, it is known that over 8 million hand boreholes have been drilled in Bangladesh, to go with several thousand in Nigeria, Niger, Madagascar, and Chad [12,17,33]. Moreover, manual drilling is more or less widespread in countries like Bolivia, Nicaragua, or Senegal, and has become a flourishing business in rural areas of Bangladesh, Niger, and Sudan [33].

Methodological precedents on mapping the feasibility of manual borehole drilling are limited. National-scale maps for drilling manual boreholes have been developed for different African countries in recent years [34–36]. Other authors narrow down the geographical focus, thus attaining a higher spatial resolution in the results [37,38]. Geographical and geological variables have been demonstrated to constrain the efficiency of manual drilling [39–41]. For instance, progress may be reasonably fast in softer formations such as clay or sand, where it is possible to drill several meters per hour. Conversely, drilling rates in hardened layers may slow to just a few centimeters per day. The hardness factor is closely linked to the depth to the water table, which in turn translates into time, cost, and the potential to encounter unexpected difficulties. This implies that lowlands tend to be more suitable for manual boreholes than highlands. Other aspects, including accessibility, water quality, slope, or the aquifer's hydrodynamic parameters also need to be taken into account, as they influence both the drilling process and the usability of the borehole [42].

The key hypothesis behind this paper is that the above factors can be combined meaningfully into a geographic database in order to decide which areas of a given region are suited to manual drilling. The method is illustrated through its application to a bedrock aquifer in southern Mali (Figure 1) and the outcomes are calibrated against geophysical data. Thus, the GIS database is best described as a decision support system that may allow us to make optimal decisions as to where to drill a manual borehole. By definition, a decision support system is a computer-based information system that can be used to underpin business or organizational decision-making [43]. Decision support systems have the ability to integrate diverse aspects of the planning process, and may take into account the spatial dimension. As such, they have been broadly used in the management of natural resources, including water [44,45], fire [46,47], or wind [48]. Decision support systems may be used to produce scenarios or forecasts [49] and may encompass a large number of qualitative or quantitative variables.

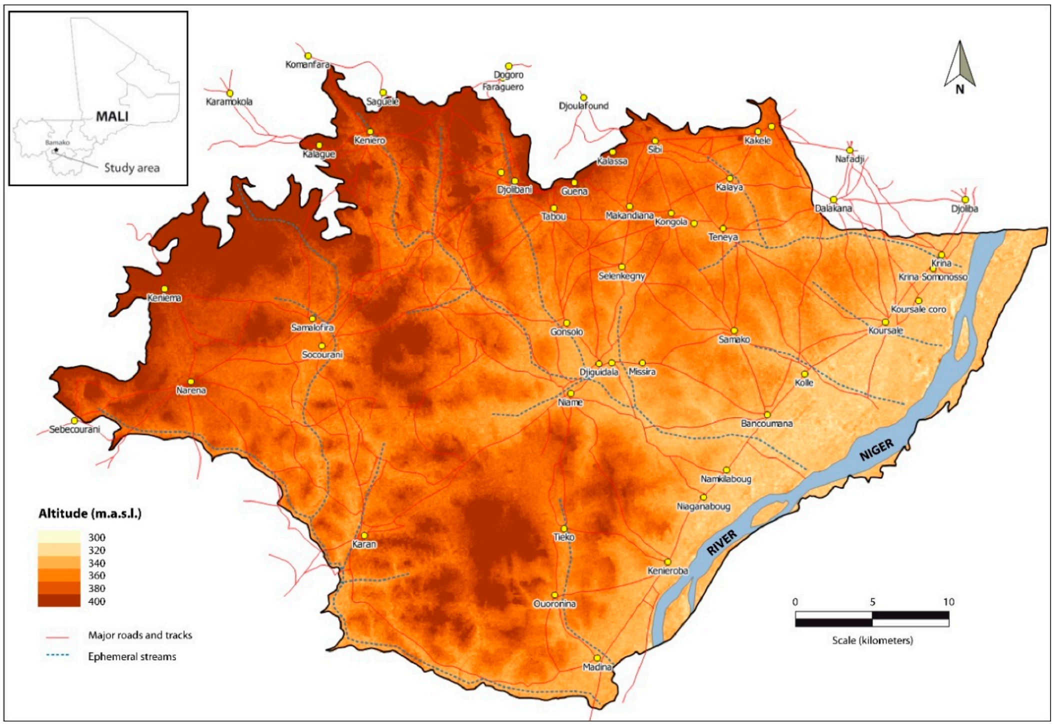

Figure 1. Geographical setting.

The novelty of this approach is three-fold. In the first place, it is argued that the traditional focus on drilling feasibility may be broadened as a means to enhance the practical value of the outcomes. Feasibility, or potential, provides a qualitative depiction of reality (i.e., "high", "medium", "low"). It is also a relative measure, for it depends of user-dependent factors such as experience. Hence, feasibility maps find their appropriate context in larger geographical scales. By narrowing down the geographical focus, we are able to express the outcomes in terms of drilling cost and time, thus providing univocal outputs for non-experts. The results are immediately useful for decision-makers such as cooperation entities, incipient drilling businesses, or donors.

Secondly, maps in this manuscript are referred to a specific percussion-based drilling technique [50]. Technique-specific maps are perceived to be a welcome methodological addition because each manual drilling type presents advantages and disadvantages of its own [12,51]. For instance, methods such as hand augering are largely inappropriate when drilling through consolidated rocks such as laterite or sandstone, whereas percussion-based techniques such as the one at hand may prove suitable. This means that drilling in the same geographical area can be unfeasible for a given technique but feasible using a different one. Since a general feasibility map is partially unable to capture this reality, it is contended that technique-specific approaches are likely to render more practical outcomes. The choice of drilling method is due to the fact that the authors have direct experience with it, having drilled about 20 manual boreholes in geologically similar areas of Mali over the last two years. This means that there is sufficient direct knowledge to estimate relevant parameters such as drilling rates, wages, or material costs.

Finally, for the purpose of expressing the results in terms of time and cost, mapping should take into account casing diameters. A four-inch diameter borehole takes significantly longer to drill than a two- or three-inch one. Furthermore, the casing diameter constrains the choice of pumps. Most standard hand pumps such as the India-Mark types are designed for four-inch boreholes (three-inch models also exist, but are difficult to find in some countries). Thus, a narrower diameter implies the need to fit a powered pump (three-inch powered pumps can also be difficult to find) or to manufacture homemade pumps with local materials. This in turn affects the durability and cost of equipping the borehole.

2. Study Area

This research focuses on the Kamalé-Narena-Madina sector of southeast Mali's basement aquifers. The region is bound by the Mandigue Plateau towards the north, by the River Niger to the east and the south, and by the Koba streambed to the west. It spans approximately 1650 km^2 (Figure 1).

The region presents a hot semi-arid climate. Temperatures are high throughout the year, with the average at 26 °C. Average rainfall exceeds 1000 mm/year, but takes place almost exclusively during a short and irregular wet season. In the dry months, lasting between October and June, there is barely any precipitation [42]. As a result, all surface water courses run dry throughout most of the year, except for the River Niger. The river is too far away from most villages to be used for domestic supply, so the bedrock aquifer provides a more reliable and accessible source [42].

Groundwater is widely used by the population. Most people access groundwater by means of shallow excavated wells, where water is extracted with buckets. Deep boreholes are found in some of the main villages. The majority are equipped with hand pumps and used for domestic purposes. The larger towns are equipped with water towers. These draw groundwater from deep boreholes and distribute it to several public faucets by means of pipelines.

Most of the agricultural production is rain-fed. The main crops are millet, rice, sorghum, and maize. Some irrigation takes place during the dry season, but is comparatively unimportant. The vast majority of irrigation schemes in the area are linked to groundwater, with the exception of those located near the River Niger. Most irrigated plots are small (typically less than 200 m^2) and are used to complement family needs. Much like domestic consumption, small-scale irrigation relies on shallow wells. Modern irrigation schemes, (i.e., land plots in excess of one hectare equipped with boreholes and irrigation networks), are slowly gaining presence, but are still rare.

The area features a predominantly flat landscape, sloping gently from the piedmont of the Mandingue Plateau (altitude ≈380 m a.s.l.) to the River Niger (≈320 m a.s.l.). From the geological standpoint, it presents a classic weathering pattern found in many sub-Saharan bedrock aquifers [52,53] (Figure 2). For drilling purposes, it is best defined as a three-layer system [54]. The bedrock is made up of massive granite and schists. In many parts of the world, crystalline rocks are considered impervious for practical purposes. The main reason is that these are highly anisotropic and that the matrix presents negligible porosity coefficients. Groundwater may be stored in the fractures, but these tend to yield only moderate amounts of water [22,55]. Weathering products overlie the bedrock. The thickness of the unconsolidated weathered pack in the study area typically ranges between 20 and 40 m. It is made up of sand and boulders at the bottom, while clay content increases towards the surface. This means that the bottom part is generally more favorable to groundwater flow. The clayey unit behaves as a leaky aquifer that may store modest amounts of groundwater. The third and uppermost layer of the system consists in a hard laterite crust. Laterite is thinner (typically less than 10 m), impervious and discontinuous in space [42,56]. Alluvial deposits are found along streambeds (Figure 3). These are relatively thin except in the case of the River Niger, whose sediment pack may exceed 20 meters [56].

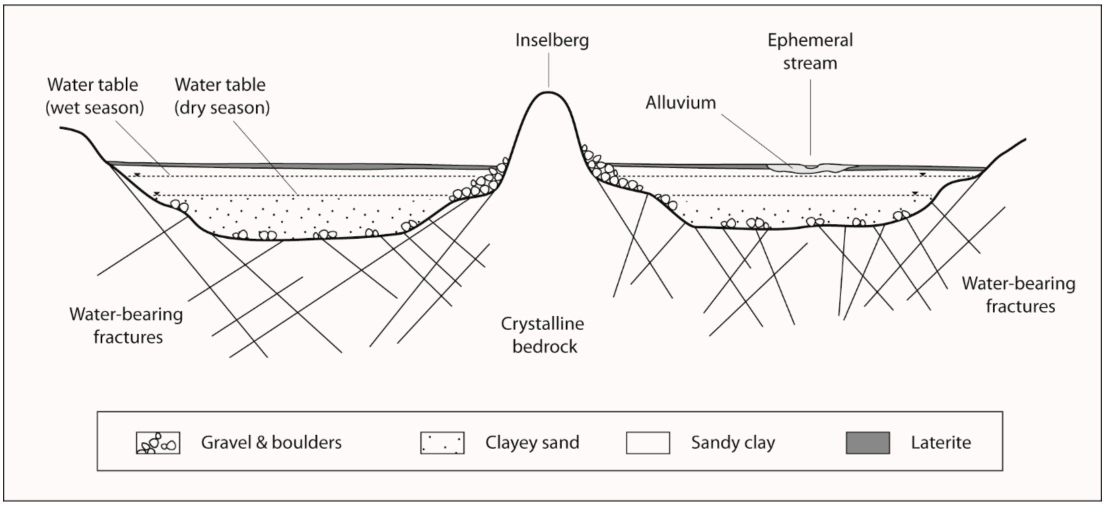

Figure 2. Schematic geological section of the study area.

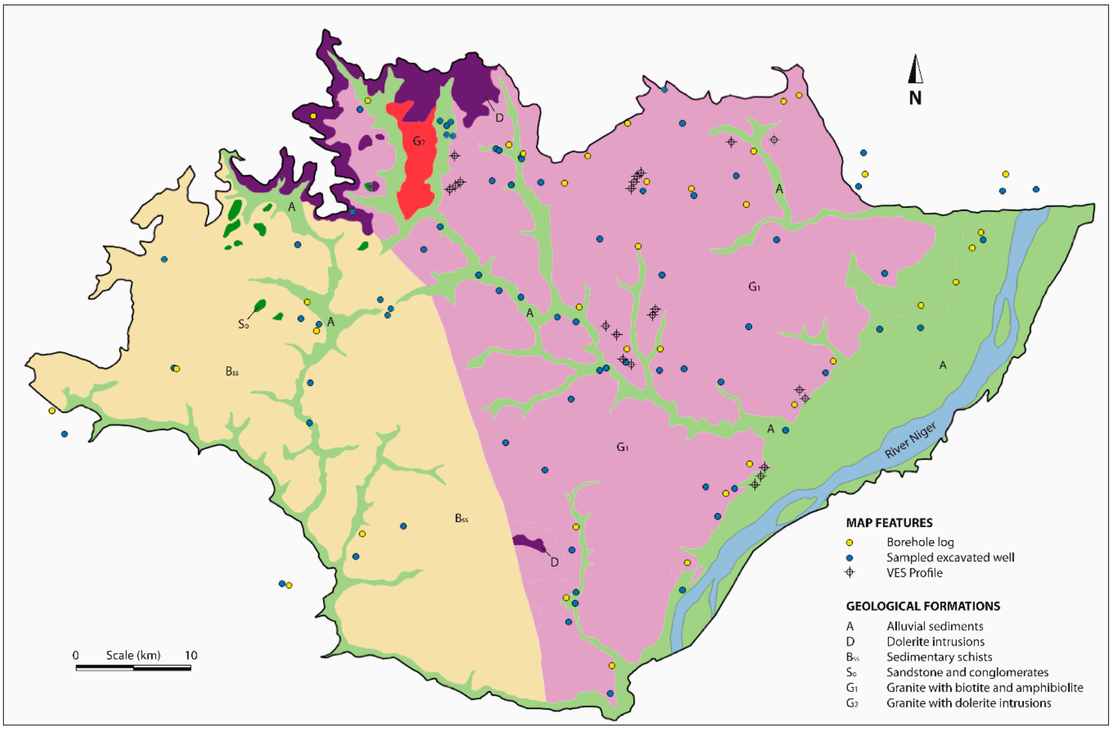

Figure 3. Geological map of the study area, including the presence of borehole logs, sampled wells, and vertical electrical sounding profiles.

Groundwater flow follows a northwest to southeast direction, from the Mandingue Plateau to the River Niger [57]. The water table typically fluctuates by several meters in a single year, causing shallow wells to dry up during the dry season. In most villages, water table depth ranges between about five and 15 meters at the end of the dry season and between one and five meters during the rainy months. According to [58], aquifer recharge can be estimated at around 180 mm/year.

3. Materials and Methods

3.1. Description of the Manual Drilling Technique

There are four mainstream methods to drill boreholes by hand, namely augering, sludging, jetting, and percussion [51]. Each of them presents a wide diversity of alternatives, which are frequently associated with specific hydrogeological contexts. As noted above, this research refers to a drilling method that combines percussion and reverse water circulation and whose use is relatively widespread in Africa and Latin America [59].

Percussion is used to break the rock, while circulation removes all loosened material from the hole (Figure 4). From the bottom to the top, a percussion tool comprises a heavy drilling bit, a series of hollow tubes, and an outlet. A valve is fitted either to the drill bit or to the outlet. The tool hangs from a rope, which in turn runs through a pulley attached to the top of a tripod. Prior to drilling, a shallow hole and a mud pit are dug by hand. Both are connected by a shallow channel and filled with water. The bit is lifted and allowed to fall repeatedly into the shallow hole by pulling the rope. The valve opens on the downstroke, allowing water and sediment from the bottom of the hole into the hollow inside of the percussion tool. Conversely, it closes on the upstroke, forcing the mix to move upwards. As the fluid reaches the outlet, it is released into the mud pit. The pit acts as a decanter from which water flows back into the hole. Tubes are added to the percussion tool as the hole gets deeper. A drilling crew is typically made up of six to 10 people, who take turns pulling the rope, resting, and operating the percussion tool.

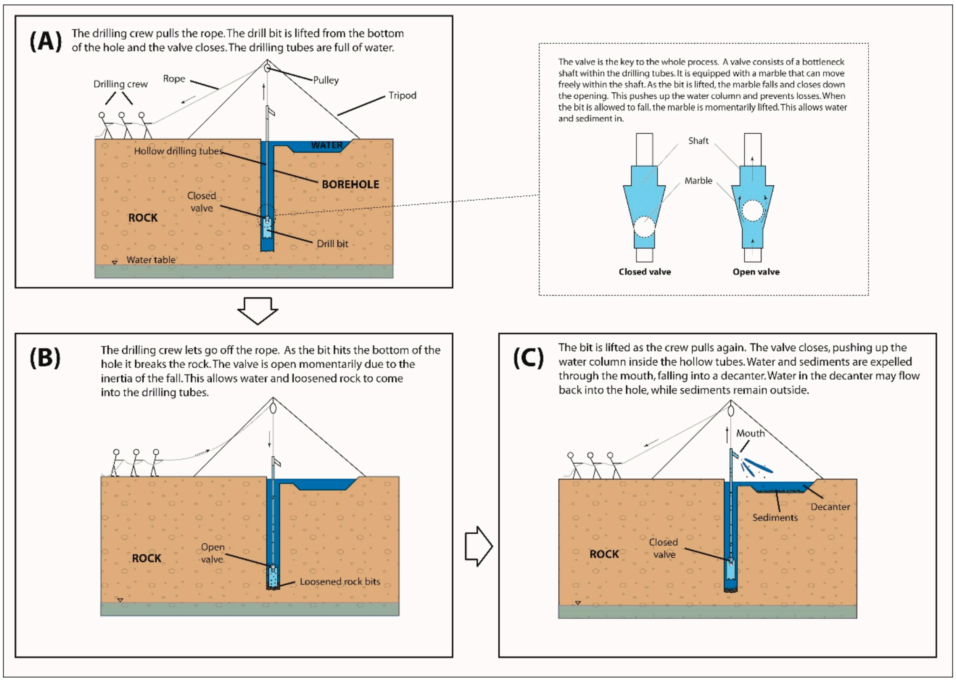

Figure 4. Overview of the drilling method.

Boreholes drilled by this method usually range between 25 and 50 m in depth. Drilling time normally fluctuates between two or three days and a few weeks, depending mostly on the geological context. The drilling technique is best suited to soft materials such as unconsolidated weathering products or alluvial sediments, but can break through relatively hard consolidated rocks like sandstone or laterite. Its applicability is limited in massive crystalline rocks.

3.2. Database Parameters and Field Survey

Drilling feasibility maps are a relatively new addition to the academic literature. However, these are closely related to traditional applications of spatial databases, which have been used in the past to map the groundwater potential of aquifer systems. Thomas et al. [38] provide a comprehensive summary of the literature, reviewing some widely used parameters that could be meaningful in the context of manual drilling. Some of these may be considered essential in all settings, while others need only be used on a case-by-case basis. The former include depth to the water table or surface and subsurface geology. These are crucial because they constrain the extent to which manual drilling is actually feasible. Moreover, they weigh heavily in terms of drilling time and cost. Examples of context-specific parameters include rainfall, accessibility, slope, geological lineaments, vegetation, ground temperature, soils, or landforms. Some of these were considered of little relevance in the case at hand. For instance, the geological nature of the aquifer (i.e., the thickness of the weathered pack), coupled with the limitations of manual drilling in terms of traversing granite, implies that lineaments are relatively unimportant for practical purposes.

As discussed later, fieldwork shows that the water table in the study area is best described as a continuum. Groundwater is likely to be found almost anywhere, provided that one drills deep enough. A working assumption for mapping purposes is that manual boreholes need to be drilled at least five meters below the dry-season water table in order to remain serviceable under unfavorable conditions. Within this context, typical markers of shallow groundwater presence such as vegetation or land temperature are only partially relevant.

Thus, the spatial database in the case at hand relies on topography, water table depth, surface and subsurface geology, and accessibility for the purpose of developing feasibility maps (Figure 5). In the case of time and cost maps, such parameters are complemented by drilling rates, wages, material costs, and other additional factors. These are all discussed later. Table 2 summarizes the data requirements and sources for the spatial database.

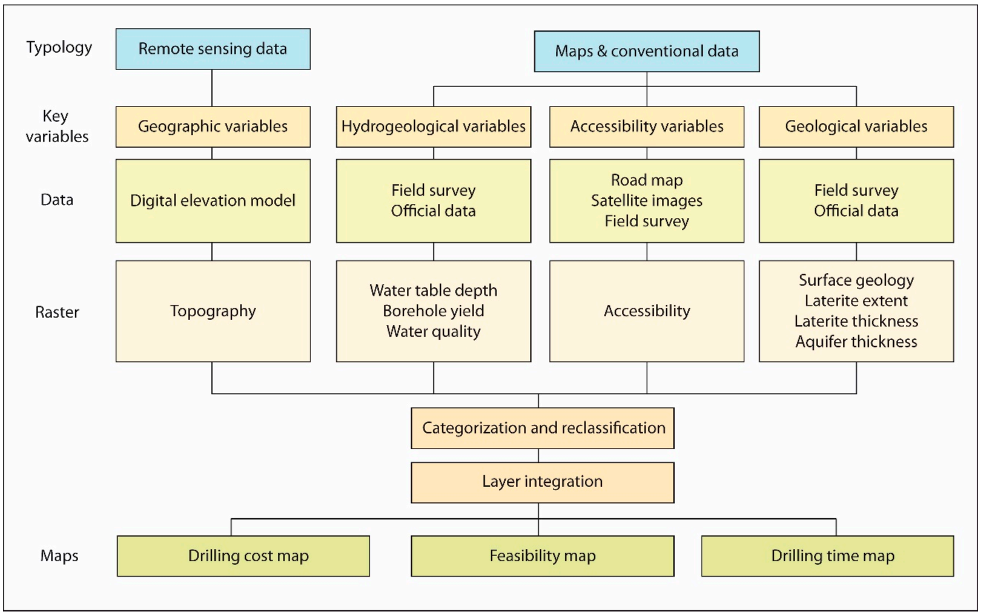

Figure 5. Structure of the GIS database, including data sources.

Table 2. Data requirements, resolution, reliability, and sources.

Category	Data	Description	Source	Year
Topography	Topography map	Map ND29-15. Series G504. Bamako. Scale 1:250,000	US Army Corps of Engineers	1955
	Digital Elevation Model	Obtained from the EarthExplorer website, pixel resolution 30 m × 30 m (www.earthexplorer.usgs.gov)	United States Geological Survey	2013
Surface geology	Spatial distribution of geological formations at the surface	Obtained from the "Carte photogéologique du Mali Occidental. Bamako-Ouest" Scale 1:200,000	Direction Nationale de la Géologie et des Mines, Mali	1986
Subsurface geology	Geological logs	Thirty-seven borehole logs were made available on demand by different sources. The thickness of the laterite layer was measured directly in 31 large diameter wells. Twenty-two geophysical profiles were gathered after fieldwork for the purpose of calibrating the results of the database.	Direction Nationale de l'Hydraulique, Mali. Private contractors. Geologists Without Borders. Fieldwork	Various
Groundwater	Water table depth	Water table depth sampled in 71 wells towards the end of the dry season (most unfavorable conditions).	Fieldwork	2015/2016
Surface water	Main, secondary rivers, and water bodies	Obtained from the Humanitarian Data Exchange website. Scale 1:1,000,000 (www.data.humdata.org)	Office for the Coordination of Humanitarian Affairs, Mali	2015
Accessibility	Road and trail network	Traced from satellite imaging and checked during field survey.	Google Earth	2016
Drilling cost	Wages, cost of drilling, and pumping equipment	Obtained from direct experience, drilling 20 manual boreholes in nearby geologically similar areas.	Fieldwork	2015/2016
Drilling time	Drilling times	Obtained from direct experience, drilling 20 manual boreholes in nearby geologically similar areas.	Fieldwork	2015/2016

A hydrogeological field survey was carried out towards the end of the dry season in 2015. Water points were geo-referenced doubly, first by means of a GPS and later by locating them by hand on a printed aerial photograph. The water table depth was measured at 71 excavated wells. Most correspond to major towns and villages, but some isolated ones located in unpopulated areas were also sampled so as to obtain a better spatial distribution. The elevation of the water table above the sea level was calculated by subtracting the depth from the elevation of the surface. Groundwater flow patterns were obtained as a result. Boreholes could not be sampled for water table depth due to the absence of piezometric tubes.

Water quality was sampled at all wells and boreholes. Water was tested on-site for electric conductivity, turbidity, total dissolved solids, temperature, and pH using a Hannah HI-98121 multiparametric device. Sixty-six water samples (including boreholes and wells) were taken to the laboratory to evaluate mineral content. Mineral water quality was found to be approximately uniform across the study region and appropriate for direct consumption and irrigation. Groundwater is of the calcium bicarbonate type, with low to moderate electric conductivity values (<0.5 mS/cm) and a slightly acidic pH (5.5 to 7). Iron concentrations sometimes exceed 5 mg/L. Arsenic is found on an isolated basis, but it is not a widespread health hazard. Its presence may be attributed to mineralized lateritic soils, whose shallower levels have been noted to contain accumulations of arsenic in other regions of Mali [60,61]. Despite being theoretically safe, deep boreholes are contaminated by fecal coliforms in some villages. Potential sources such as latrines or animal waste appear obvious in many cases. Most of these particularities are, however, lost at the regional scale. Hence water quality plays a minor role in the results, although it is recognized that this could be a key factor in other geographical settings where contaminant-removal solutions would need to be sought [62,63].

The thickness of the laterite crust was recorded at 31 excavated wells. Laterite depth was established by using the water level meter. In some large-diameter wells, the interface between laterite and the underlying clay formation was shallow enough to be observed directly. In 10 cases, where the interface was beyond sight, locals offered to climb down wells to identify the change. Finally, diggers at work were kind enough to provide accurate information at five different locations. The laterite thickness dataset, which is particularly important for the time and cost maps, was completed with data from 37 boreholes (Table 2). Additionally, the thickness of laterite outcrops could be sampled at several isolated points along the main streambeds.

There was little opportunity to evaluate the aquifer's hydrogeological parameters directly. Thus, these were obtained from the available data. According to official sources, the average transmissivity of the aquifer system is in the order of 50–100 m^2/d, whereas the storage coefficient is estimated at 10% [64]. No spatially distributed data were available in terms of transmissivity and storage coefficients, but official information was found in relation to borehole yields [65]. These range between 1 and 20 m^3/h, with the distribution being heavily skewed towards the lower part of the interval. The average stands around 2 m^3/h, while yields above 10 m^3/h are uncommon.

3.3. GIS Database Development

Figure 5 provides an overview of the modeling framework. The GIS database includes spatially distributed data for geographical parameters such as topography and road accessibility, as well as for geological, hydrogeological, and hydrochemical variables. All maps were compiled into a single database with QGIS 2.12.2-Lyon and geo-referenced as per UTM Zone 29N, Datum IGN Astro 1960. Pixel resolution is 30 m $\times$ 30 m. Geostatistical interpolations were developed with Surfer 11 (Golden Software, Golden, CO, USA) and exported into QGIS.

3.3.1. Feasibility Map

The feasibility map is a combination of all thematic layers, including topography, landforms, geology, accessibility, and well yield. Topography is relevant because it can be coupled with groundwater levels to establish the depth to the water table. The combination of both elements is perhaps the single most important component of the database, as the water table depth largely determines the amount of time, work, and money that needs to be put into the drilling process. Land elevation data was obtained from the EarthExplorer website [66]. In turn, the water table map was developed using field survey data and corresponds to the later stages of the dry season.

The database includes several geological parameters. The first represents the geological layout of the region based on the 1:200,000 national map, Bamako Ouest [67]. This depicts the Quaternary deposits and the other formations overlying the impervious bedrock. Official cartography is useful inasmuch as it provides spatially-distributed regional-scale data. More specifically, it can be used to delineate those areas where hardened materials such as laterite are not to be found, i.e., the alluvial deposits. However, its resolution is insufficient to determine where the laterite patches lie for the remainder of the study area. Moreover, it fails to account for the thickness of the main geological units.

These variables—i.e., the extent and thickness of the laterite layer—are relevant because both affect drilling time. A borehole drilled partially through laterite and partially through clay will take longer to make than one that only traverses clay, provided that both are of the same depth. This is because laterite is harder and therefore more difficult to break. The thickness and extent of the laterite layer were determined as explained in the previous section. Official borehole data were used to establish the depth of the impervious basement [65].

Proximity to landforms is closely related to topography and geology. Landforms are important because these generally correspond to outcrops of the crystalline basement. In the case at hand, landforms are almost exclusively associated to inselberg formations. Inselbergs outcrop towards the north, east, and southwest of the aquifer and can be considered both impervious and unsuitable for manual drilling. A buffer area was developed around them. The buffer was used to ensure that the saturated zone during the dry-season was at least five meters deep.

In the absence of detailed pumping-test data, well yield is assumed to provide an acceptable indicator of aquifer potential. Official statistics provide the total number of mechanized boreholes per village, their success rate (ratio between the number of drilled and successful wells), the average yield per borehole, and the flow rate distribution (number of wells per village yielding less than 5 m^3/h, between 5 and 10, and over 10 m^3/h) [65]. Bearing in mind the regional scale of the map, a weighted average of borehole yields for each village was found to be the only suitable proxy for the aquifer hydrodynamic properties (Figure 6).

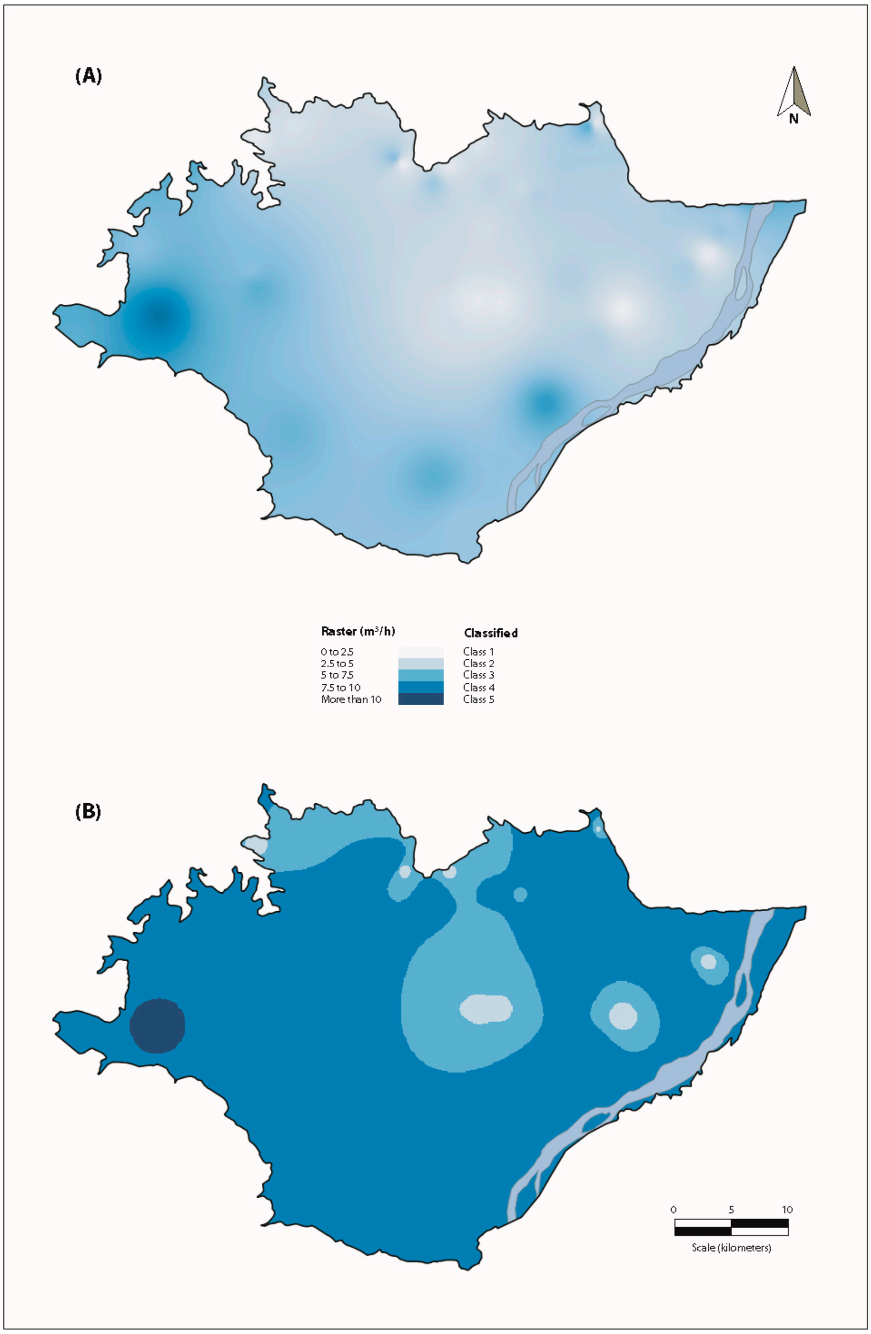

Figure 6. (**A**) Raster and (**B**) classified outcome for mechanized borehole yield. Estimates based on official data [65].

Finally, the accessibility layer compiles all major and secondary roads, as well as those tracks and trails that are large enough to allow motorized vehicles or donkey carts. In a certain sense, it is debatable whether access should be considered a feasibility constrain. This is because, in theory, one of the main advantages of manual drilling in relation to mechanized drilling is that materials can be obtained locally and there is no need to mount them on a large truck. However, it is also true that the equipment can be heavy to carry. Moreover, there are some key drilling inputs such as water that may be problematic to obtain if the site is far away from a major trail. While the end goal can still be accomplished under such conditions, it is also true that these detract from the effectiveness of the process. Hence, accessibility is considered a sufficiently important parameter to feature in the database.

In this case, accessibility is established in terms of distance to roads, and is computed by buffering the road network by 100, 500, and 1000 m. The road layout was obtained from a combination of sources, including topographic maps, satellite pictures, and field exploration.

Table 3 summarizes the classification of each of the basic layers. Drilling feasibility, F, at each pixel, i, was calculated as per Equation (1):

$$F_i = L_i \cdot \sum (G_i + P_i + A_i + Y_i) \quad (1)$$

where L is a Boolean factor that refers to the proximity of landforms, G corresponds to the geological grading, P is the grading associated to water table depth, A is the accessibility grading, and Y refers to aquifer potential. Outcomes are expressed on a scale of 0 (low feasibility) to 20 (high feasibility).

Table 3. Main features of the spatial database, including classification values for feasibility mapping.

Layer	Range	Unit	Class	Obtained from
Landforms (proximity), L	Absent Present	(.)	1 0	Topography, geology, water table depth
Geology (laterite thickness), G	0 to 2 2 to 4 4 to 6 6 to 8 8 to 50 >50	m	5 4 3 2 1 0	Field survey, geological map, topography
Water table depth, P	<5 5 to 10 10 to 15 15 to 20 20 to 25 >25	m	5 4 3 2 1 0	Topography, field survey
Accessibility, A	0 to 500 500 to 1000 >1000	m	3 2 1	Road network, satellite imaging, field survey
Well yield, Y	>7 3 to 7 2 to 3 1 to 2 <1	m^3/d	5 4 3 2 1	Official data
Water quality, Q	<1000 1000 to 2000 >2000	μS/cm	2 1 0	Official data, field survey

3.3.2. Time and Cost Maps

Time and cost maps are referred to a drilling diameter because drilling larger-diameter boreholes implies longer working times and higher costs, particularly in the case of harder formations. Borehole diameters also present practical implications in terms of yield. For instance, two-inch casing is sufficient to accommodate locally made hand pumps (Table 1). These provide yields in the order of one-half to one cubic meter per hour, which is good enough for domestic use or to irrigate a small plot. Three or four-inch casing is, however, needed for standard pumps. The yield of a standard pump depends on a variety of factors, including pump type (manual or powered), pump diameter, or water table depth, among others, but will exceed the yield by homemade pumps in most cases. Fitting a standard pump opens the field to public supply. This is because national legislation establishes four inches as the minimum casing diameter for public-supply boreholes. Standard pumps are also used for commercial-scale irrigation schemes.

Hands-on experience suggests that the fastest way to drill a four-inch borehole is to drill a two-inch one first and then widen it with a larger bit. The widening process may be relatively quick, even in the case of hard formations. This is because the falling bit no longer needs to hit solid rock, which is slow to break. Instead, it chips away at weakened edges, which tend to come off more easily.

Diameter aside, time and cost maps essentially rely on depth to the water table, subsurface geology, and laterite thickness. Time is computed differently depending on the geological formation where the well is to be drilled. Wherever the geological map shows alluvial formations, boreholes will traverse the alluvial formation first and then sand and clay all the way down to the granitic basement. In all other areas, wells may traverse laterite and then sand and clay, or just sand and clay. In the case of two-inch boreholes, this can be expressed as per Equations (2) and (3):

$$T_a = (D + E)/R_a \tag{2}$$

$$T_o = A/R_l + (D - A + E)/R_c \tag{3}$$

where T_a and T_o are the number of days needed to drill through alluvial and the non-alluvial areas, respectively; D is the depth to the water table in meters; A is the topographic elevation, also in meters; R_a, R_l, and R_c, are the expected drilling rates in meters per day for alluvial, laterite, and the sand and clay formations, respectively; while E is the depth below the water table that wells need to reach to remain usable during the dry season, also in meters. In the case of four-inch boreholes, the expressions will be similar, except that an additional term is added to take into account the time needed for the widening process. In this case, W represents the rate at which the borehole can be widened in meters per day (Equations (4) and (5)):

$$T_a = [D + E]/R_a + [D + E]/W \tag{4}$$

$$T_o = A/R_l + \frac{[D - A + E]}{R_c} + [D + E]/W \tag{5}$$

The total cost, C, is expressed as the joint cost of supplies and materials, C_s, plus the operators' wages, C_w, all of them in dollars (USD). It is computed as per Equations (6) and (7):

$$C = 1.2 \cdot C_s + C_w \tag{6}$$

$$C_s = [D + E] \cdot [C_c + C_p] + C_m \tag{7}$$

where C_c is the cost of the pump, C_p is the cost of the well casing, and C_m is the cost of the outer structure. The cost of the outer structure is largely fixed, while the [D + E] factor reflects the fact that the cost of a homemade pump increases proportionally with depth (more tubes are needed to reach below the water table).

Operator wages are computed differently for alluvial and non-alluvial materials. Wages are paid on a per-day basis and are dependent on borehole depth and drilling speed. In the case of two-inch boreholes in alluvial materials, operator wages are calculated using the following formula, where C_d is the total wage of the entire drilling crew in USD per day (Equation (8)):

$$C_w = [D + E] \cdot C_d/R_a \tag{8}$$

In non-alluvial materials, the daily wage is computed as per Equation (9), where T_l is the thickness of the laterite layer in meters (the thickness of the laterite layer comes into this equation because it is related to drilling time, and therefore, to drilling cost):

$$C_w = \left[\frac{T_l \cdot C_d}{R_l}\right] + [D - T_l + E] \cdot C_d / R_c \tag{9}$$

Four-inch boreholes need to incorporate the wages associated to the extra days required to widen the borehole. Therefore, the following term (Equation (10)) is added to the right-hand side of each of the C_w expressions shown above:

$$[D + E]/W \tag{10}$$

Time and cost estimates are based on the authors' direct experience [68]. For two-inch drill-bits, R_a is typically 8 m/d, R_l is 1 m/d, and R_c is 5 m/d; whereas C_c and C_p amount to 1.2 USD/m. Pump costs are variable. The fixed cost of the outer structure is on the order of USD20 for a homemade pump but the cost of the rising main depends on the depth at which the pump is installed. In the case of four-inch boreholes, where other pumping alternatives exist, costs can be much more variable. A standard India-type hand-pump ranges between about USD500 and USD1000, depending on the depth of the well, while a standard solar pump equipped with panels costs around USD1300. In turn, the cost of a six-people drilling crew is approximately 25 USD/day. E is established at five meters below the water table throughout, while 10 is considered a reasonable estimate of W. Depths to the water table in excess of 25 m were assigned a zero classification for demonstration purposes (Table 3), although the technique is not necessarily limited to that depth. All other parameters are obtained directly from the thematic layers.

3.4. Data Interpolation Methods and Calibration Procedure

Information on variables such as topography, surface geology, or accessibility is spatially distributed and considered sufficiently precise for practical purposes. Other important elements such as the depth to the water table, borehole yield, or subsurface geology rely on point data. Different geostatistical techniques were used to estimate the spatial distribution of these layers. Golden Software Surfer 11 was used to this effect. This software was preferred over QGIS' in-built functions because it offers a wider variety of interpolation alternatives. Twelve different methods were tested, six of which rendered outright unrealistic outcomes. These were discarded. The better suited methods included ordinary kriging, minimum curvature, polynomial regression, the modified Shephard method, inverse distance to a power, and the radial basis function.

The most adequate way to appraise the accuracy of the spatial database is to check its outcomes against field data, i.e., against the results of actual drilling experiences. Unfortunately, to the authors' knowledge no manual wells have been drilled in this area. This means that actual information on hand drilling feasibility, time, or cost is unavailable. The next-best alternative is to narrow down the uncertainties by providing independent estimates of the more tentative elements of the spatial database.

Subsurface geology is considered to be the most uncertain parameter. An indirect calibration method was devised based on the fact that subsurface geology ultimately constrains drilling speed and, therefore, drilling time and cost. Within this context, it is well known that geophysical methods can render an independent picture of subsurface conditions. This means that they can also provide a separate approximation of drilling time. Point-estimates obtained from geophysical records can then be compared to the outcomes of the spatial database. Provided that the estimates of drilling rates per rock type are sufficiently accurate, a good agreement between them would suggest that the database adequately portrays the field conditions.

Vertical electrical sounding (VES) is a standard geophysical technique. It is used to provide an idea of subsurface conditions based on the estimation of the electrical conductivity or the resistivity of the rock. This is done by measuring the voltage of the electrical field induced by several grounded electrodes. Results are generally checked against borehole logs for optimal results. While other geophysical techniques are more sophisticated, VES offer the advantages of its relative simplicity and cost-effectiveness. Thus, it is still used widely in developing regions. In the case at hand, 22 vertical profiles were obtained by private contractors, non-profit organizations, and other sources. These were used to obtain independent estimates as to the spatial distribution of subsurface geology, and, therefore, to calibrate the model.

Several layers of the spatial database rely on point information. Geostatistical techniques are needed to estimate field conditions in between. The rationale for selecting an optimal interpolation method is different in each case. In terms of the water table, the more accurate outcome can be determined based on a combination of hydrogeological and mathematical criteria. A priori analysis of field data shows a clearly defined NW-SE pattern of groundwater flow, implying that the regional aquifer discharges into the River Niger. This is consistent with the conceptual model of the study area, as no other major discharge mechanisms have been identified (extractions are still relatively minor in relation to renewable resources and no major pumping cones are observed). Furthermore, the study area is predominantly flat, relatively small in size and circumscribed to a specific sector of a well-defined bedrock aquifer. Hence, except in the proximity of inselbergs, the water table can be assumed to be a spatial continuum with an uninterrupted gradient [57]. Within this context, only the kriging and minimum curvature methods provide a sufficiently realistic depiction of the field conditions (Figure 7). Kriging is the favored method between the two due to a slightly more convincing portrayal of the hydrogeological conditions and better cross-validation statistics (Table 4). Thus, the most likely outcome corresponds to the water table depth presented in Figure 8.

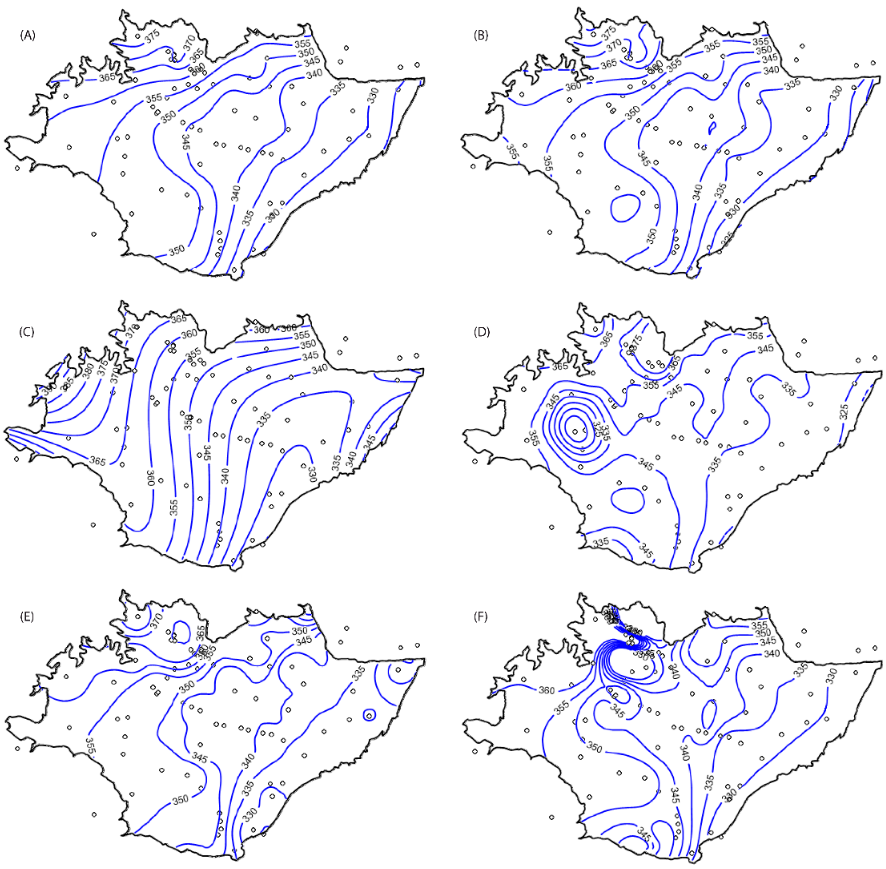

Figure 7. Spatial distribution of the water table elevation as per different geostatistical interpolation methods (field data collected over four consecutive days in February 2015): (**A**) Ordinary kriging; (**B**) minimum curvature; (**C**) polynomial regression; (**D**) modified Shepard's method; (**E**) inverse distance to power; (**F**) radial basis function.

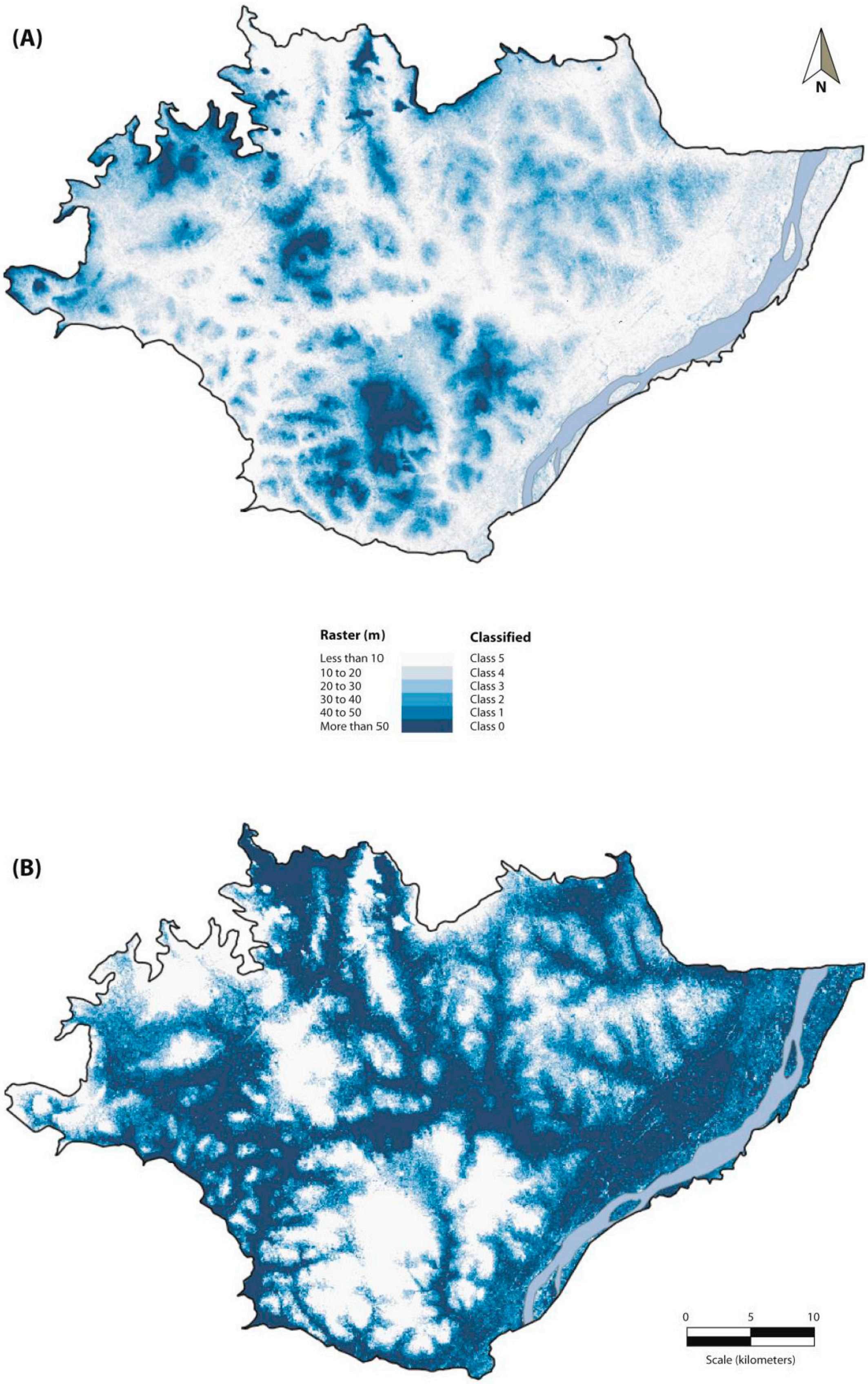

Figure 8. (**A**) Raster and (**B**) classified outcome for the water table depth.

Table 4. Univariate cross-validation statistics for spatially interpolated data (water table level).

Variable	Method	Mean Residual	Standard Deviation	Standard Error	RMS
Water table level (m a.s.l)	Kriging	0.04	3.25	0.43	3.24
	Minimum Curvature	−0.34	4.24	0.56	4.21
	Radial Basis Function	−0.36	6.74	0.89	6.69
	Inverse Distance to Power	−0.62	6.67	0.88	6.65
	Modified Shephard	0.09	4.81	0.63	4.78
	Polynomial Regression	7.26	7.78	1.02	7.71

Note: RMS: Root mean square.

A similar approach was used for subsurface geology, more specifically, for the thickness of the laterite layer. Depth to the crystalline bedrock was found to be comparatively less important, as it only constrains the potential for drilling around major landforms. In both cases there is a randomness component. This is because the thickness of a geological formation is constrained by many different factors. As a result there is relatively little room for interpretation. Geostatistical interpolation outcomes are calibrated against vertical electrical sounding data (Figure 9). Geophysical profiles are useful for this purpose because they present a sufficiently marked contrast between the different geological formations (Figure 10). Laterite resistivity ranges between 3000 and 18000 Ω·m across all sections, while the sand and clay layer presents values in the order of 30 to 700 Ω·m and fresh granite between 1000 and 4500 Ω·m. In turn, the resistivity of alluvial sediments ranges between 10 and 200 Ω·m.

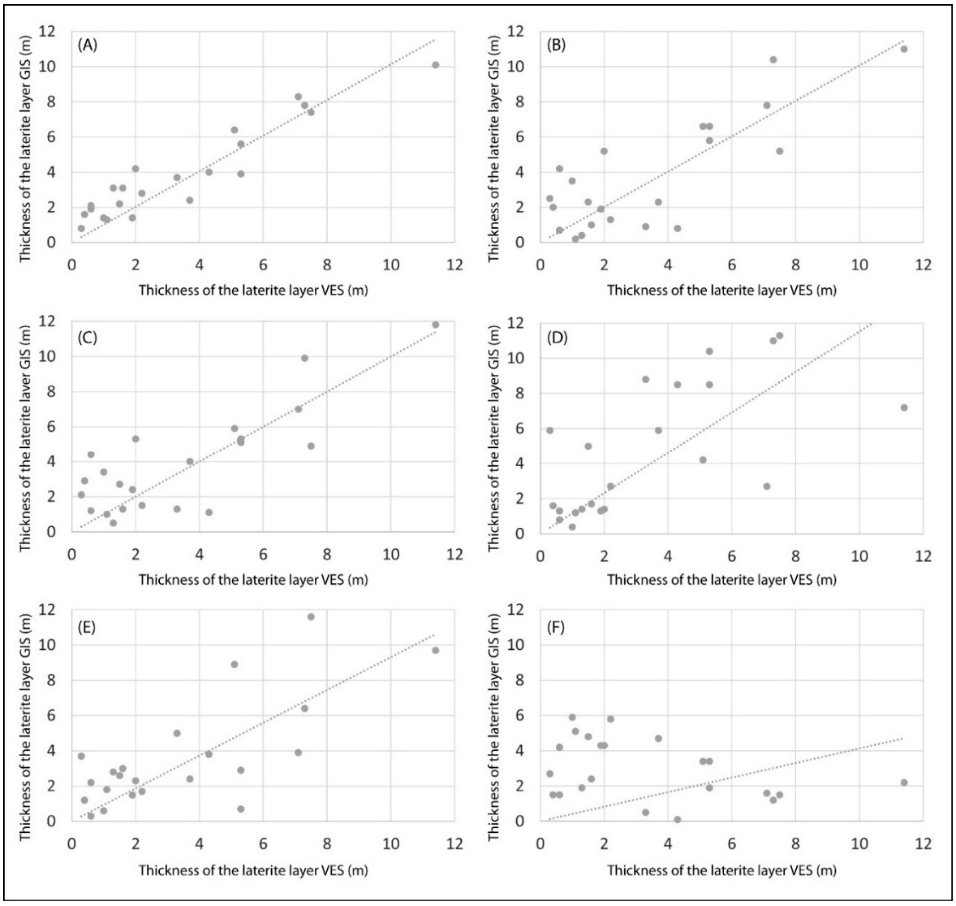

Figure 9. Calibration of the spatial distribution of subsurface geology: spatial database outcomes versus geophysical survey results. (**A**) Ordinary kriging; (**B**) minimum curvature; (**C**) radial basis function; (**D**) modified Shepard's method; (**E**) inverse distance to power; (**F**) polynomial regression. VES: Vertical electrical sounding.

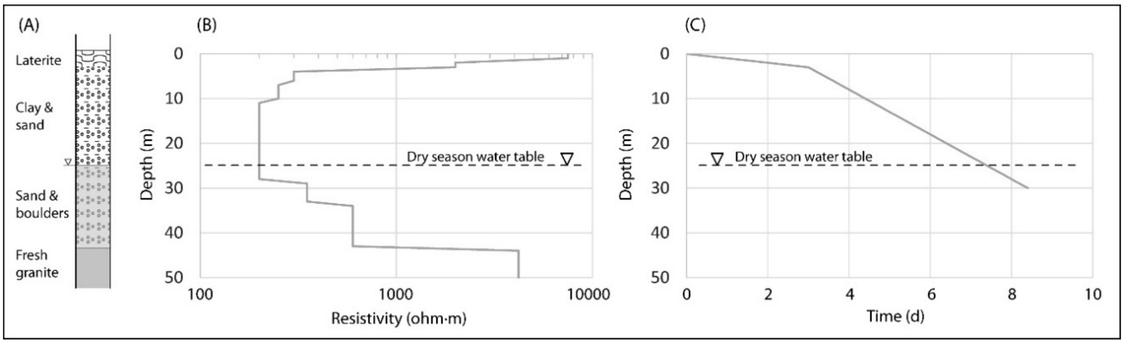

Figure 10. (**A**) Geological section; (**B**) resistivity curve obtained by vertical electrical sounding; (**C**) drilling time in days.

4. Results and Discussion

4.1. Drilling Feasibility, Time, and Cost Mapping

Figure 11 presents the feasibility map. In general terms, the most favorable areas for drilling correspond to lowlands with adequate accessibility, i.e., the alluvial valleys. Some weathered bedrock areas are also favorable for practical purposes, although most showcase medium feasibility. Within this context, depth to groundwater plays a defining role on the final score. Most of the area seems flat upon visual inspection, but gentle topographic gradients over several kilometers translate into differences of several meters in terms of the depth to the water table. As a result, watershed divides showcase lower feasibility values. Zero-multipliers associated to the presence of inselbergs are only slightly relevant to the final outcome.

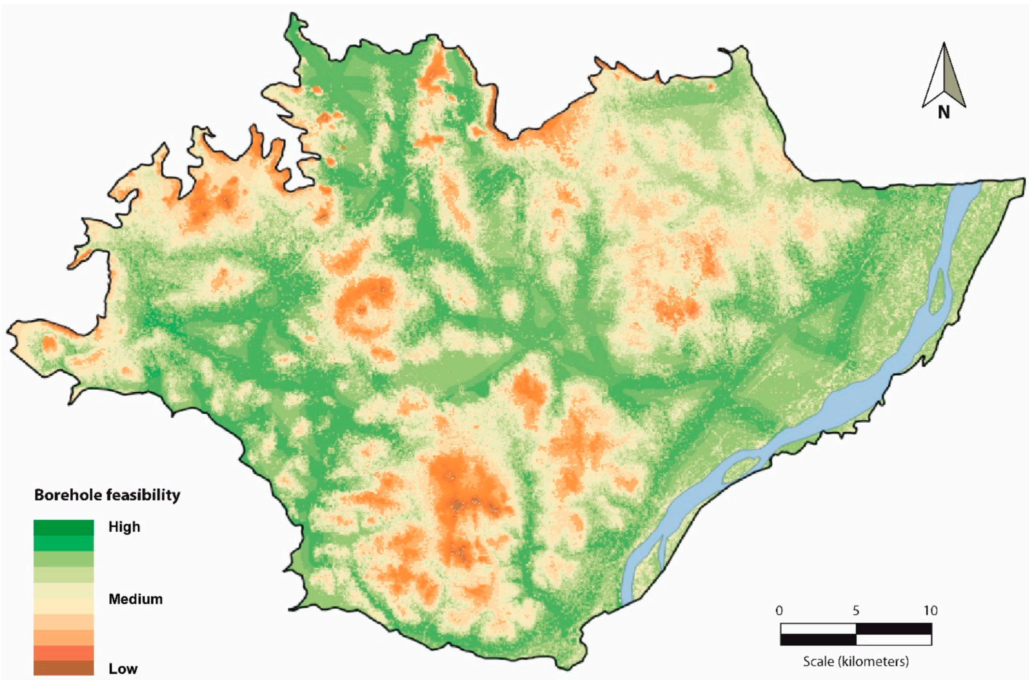

Figure 11. Drilling feasibility map.

From the quantitative standpoint, approximately 11% of the land obtains a high feasibility score, while 44% gets medium to high. About 30% of the surface area qualifies as medium feasibility and 14% as low to medium. In contrast, less than 1% presents a low feasibility score. These results suggest that the area is generally appropriate for manual drilling.

Feasibility maps provide added value by enhancing our hydrogeological knowledge of regions that have seldom been studied. However, their outcomes are merely qualitative and therefore open to interpretation. A clearer meaning was attained by translating combinations of the basic layers into time and cost estimates. Figures 12 and 13 show that favorable locations (in terms of time and cost) account for approximately half of the study region. Areas with very low cost or drilling times generally correspond to alluvial lowlands with shallow water tables. Although these conditions are theoretically optimal, some practical precautions are in order. For instance, lowlands can be subject to flooding during the wet season. This is problematic in the case of drinking supply boreholes because these need to be accessible all year round and because contaminated surface water may infiltrate into the borehole if the seal leaks. Flooding is not so much of a limiting factor if the borehole is only meant to supply water for irrigation, as there is generally no need to irrigate the crops during the rainy months.

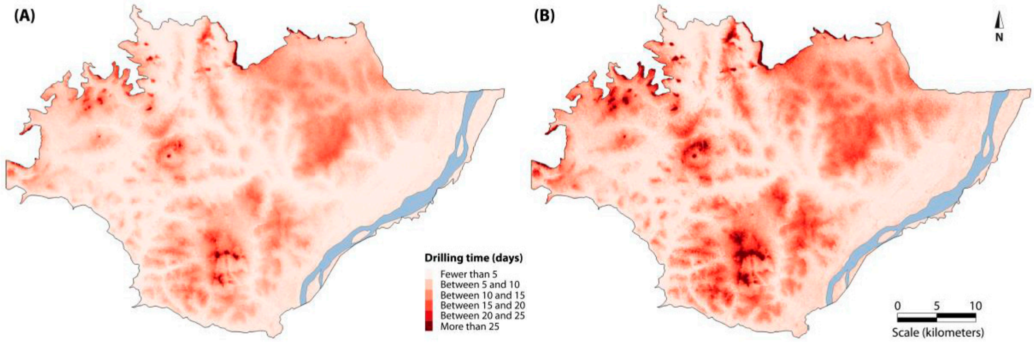

Figure 12. Approximate drilling time maps for (**A**) two-inch diameter boreholes, and (**B**) four-inch diameter boreholes.

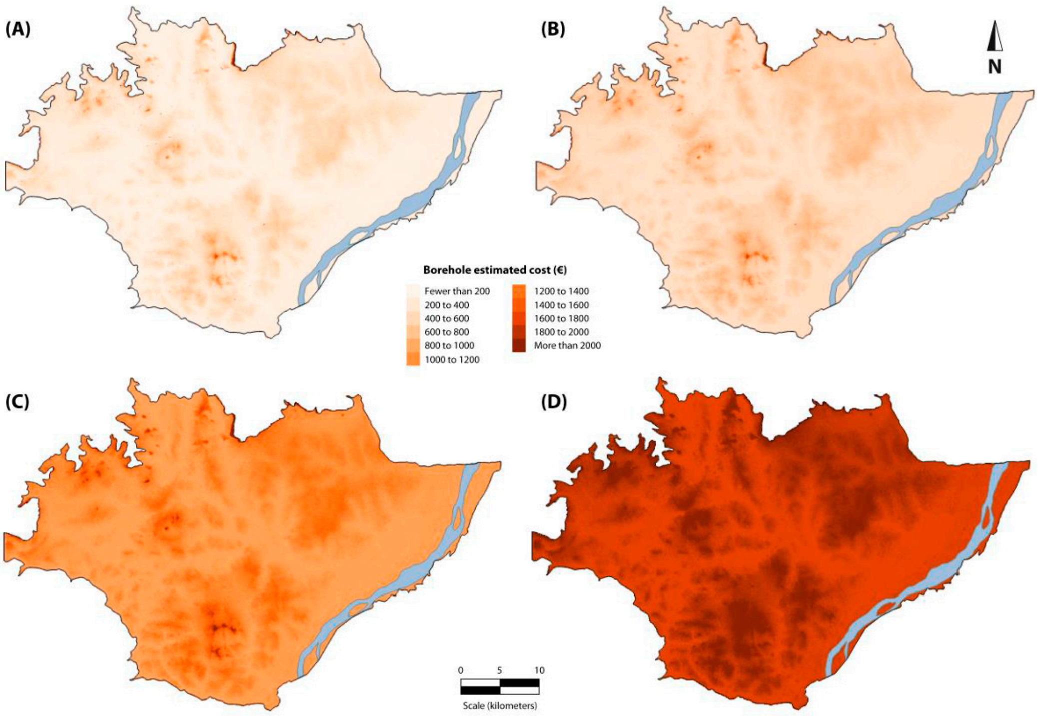

Figure 13. Approximate cost of a fully equipped borehole. Results include salaries, materials, casing, development, and pump cost and installation, but do not consider amortization. (**A**) Two-inch diameter, homemade pump; (**B**) four-inch diameter, homemade pump; (**C**) four-inch diameter, standard hand-pump; (**D**) four-inch diameter, standard solar pump with panels.

Time and cost produce analogous images, owing to the fact that both variables are strongly interrelated. Both also bear a strong resemblance to the feasibility maps. While useful for practical purposes, time and cost maps fail to take into account the accessibility factor. As a result, areas whose estimated time and cost is reasonable may not be fully appropriate for drilling. This means that all three maps—feasibility, time, and cost—must be read together in order to gain an accurate estimate of the field conditions.

Time and cost are constrained by two main factors, namely borehole diameter and pump type. Two-inch diameter boreholes take less time to drill than three- or four-inch boreholes. Typically, a two-inch borehole is drilled first and then widened to three or four inches. This necessarily translates into increased costs. Larger-diameter boreholes are sometimes desirable because they allow for different pumping options: while two-inch boreholes can only be equipped with homemade pumps, four-inch boreholes allow for the installation of standard pumps (Table 1). The latter are significantly more efficient and durable, but also considerably more expensive (Figure 12)

According to the results, the cost of a fully-equipped two-inch borehole in most of the region ranges between USD100 and 600. This is consistent with our experience in similar geological environments. Time outcomes are also coherent, as boreholes in these environments typically take between three and 10 days to execute. Most areas of the map exceeding these values are either poorly suited or largely unpopulated. In contrast, the final cost of a four-inch borehole can be highly variable. This is largely due to a broader choice of pumps. Consider the case of a favorable drilling location. All other factors remaining equal, a four-inch borehole equipped with a homemade pump will cost on the order of USD400. In contrast, the cost will be around USD1000 if equipped with a standard hand-pump and up to USD1800 for a standard solar-powered pump.

In order to check the accuracy of the results, two independent estimates of drilling time were obtained by combining geological factors (as obtained from VES profiles) with the depth to the water table (Figure 14). Some descriptive statistics for each method are presented in Table 5. As shown, interpolating laterite thickness by means of ordinary kriging provides a better adjustment between the spatial database and geophysical information. A Pearson correlation coefficient of 0.89 is obtained, with a mean absolute error of less than one day. In contrast, polynomial regression yields an R^2 of 0.41 with an average error in excess of three days.

The outcomes of the database present a series of broader implications. The fact that manual boreholes can reach the bedrock and that they can be equipped with standard pumps means that, in many cases, their level of service is similar to that of a mechanized borehole. Consider this: mechanized boreholes in the study area seldom reach below the weathered bedrock (i.e., their depth does not usually exceed 40 or 50 m), and they invariably cost several thousand USD once equipped with wellhead protection and a standard India-Mark type pump for domestic supply [7,68]. Manual boreholes reach similar depths and can be equipped with the same type of pump and protection elements, but at a much lower cost. This suggests that manual boreholes are not only practical from the technical standpoint, but also highly competitive in terms of cost.

Manual drilling presents an enormous potential to facilitate access to groundwater in developing contexts, particularly in regions where sediments are soft to moderately hard and where water tables are relatively shallow. This is the case with many bedrock and unconsolidated sediment aquifers in developing regions across the world. In sub Saharan Africa alone, it is estimated that bedrock aquifers account for 40% of the total surface area, while aquifers made up of unconsolidated sediments amount to 22%. Together, both types of aquifer systems sustain a rural population of nearly 300 million [69]. This means that nearly every country has an area that could be well suited for manual drilling. The same reasoning could be extended to other parts of the planet, including large portions of Asia and Latin America.

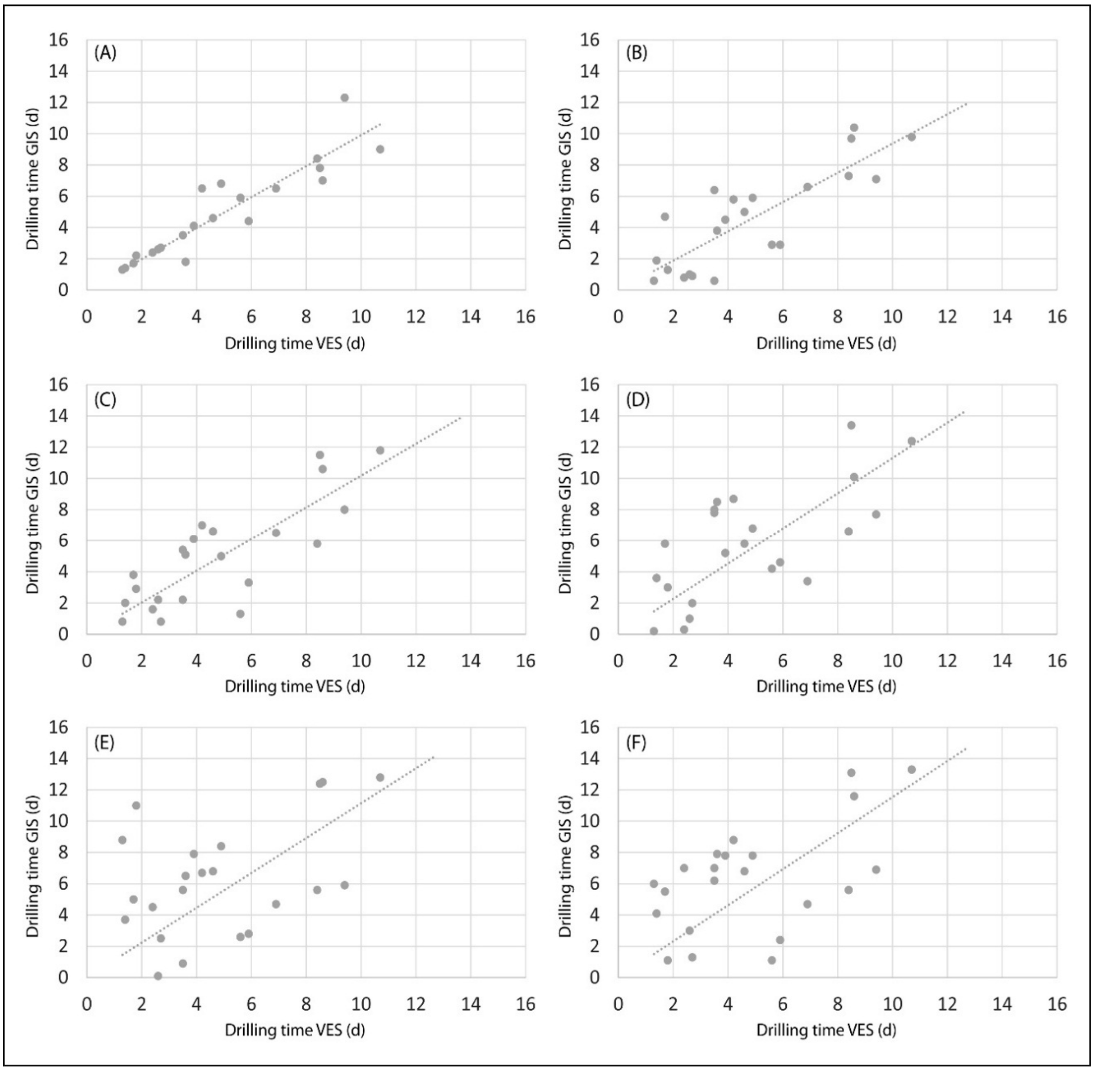

Figure 14. Drilling time estimates obtained by two independent methods (vertical electrical sounding and the GIS database). Times are referred to three-inch diameter boreholes. (**A**) Ordinary kriging; (**B**) minimum curvature; (**C**) polynomial regression; (**D**) modified Shepard's method; (**E**) inverse distance to power; (**F**) radial basis function.

Table 5. Descriptive statistics for the correlation between drilling time as obtained by means of vertical electrical sounding and through the GIS database (OK: ordinary kriging; MC: minimum curvature; RBF: radial basis function; MSM: modified Shepard's method; IDP: inverse distance to power; PR: polynomial regression).

Statistic	OK	MC	RBF	MSM	IDP	PR
Pearson R^2	0.89	0.83	0.80	0.67	0.53	0.41
Mean absolute error (d)	0.76	1.45	1.71	2.47	3.14	3.29
Mean StDev (d)	1.01	1.06	1.03	2.42	1.25	1.85
Max Error (d)	2.96	3.30	4.81	5.99	4.74	9.01
Min Error (d)	0.03	0.15	0.36	0.70	0.40	0.29

4.2. Map Resolution and Discussion in the Context of Methodological Precedents

The spatial scale of the database plays an important role in the results. For the purpose of the ensuing discussion, local, regional, and country scales are defined loosely according to the Mali context and as per the feasibility of gathering the necessary data. Hence, the local scale can be assumed to span a few square kilometers, the regional scale ranges between a few hundred and a few thousand, and the country scale refers to hundreds of thousands to millions of square kilometers.

To the authors' knowledge, methodological precedents in the study area are limited to the national-scale feasibility map of Mali [34]. Country-scale approaches provide a satisfactory overview for informative purposes. In particular, these have proven useful to underpin large-scale schemes, as well as to target the most favorable areas within a large geographical domain. This research shows that a narrower geographical focus can be used to obtain higher-resolution outcomes. Relevant variables such as groundwater depth, the thickness of hardened layers, or accessibility constrains are more easily captured at smaller scales. Thus, these are able to render meaningful outcomes in terms of potentially important parameters such as time or cost, especially when the outcomes are referred to specific casing diameters. Such accuracy is largely unfeasible if maps are supposed to span millions of square kilometers, but is desirable when working in catchment-scale contexts such as the one at hand.

Referring the maps to a specific drilling technique is a methodological novelty. In this case it is possible to find some contrast between the outcomes of national and regional approaches. The national-scale map [34] deals with the feasibility of implementing manual drilling techniques as a whole, banking on the evidence that softer materials are generally better suited. As a result, it divides the study area into two different feasibility scores, namely, a high feasibility zone along the River Niger and a medium feasibility area associated with the presence of alluvial sediments throughout the remainder of the system. Both favorable units amount to approximately 25% of the study area. In contrast, the regional-scale map identifies many additional areas where manual drilling can be successfully carried out: about 85% of the region presents at least a medium feasibility score. This is largely because our approach is technique-specific, i.e., it is concerned with a percussion method that can get through relatively hard materials such as laterite.

The geographical focus could be narrowed even further. A local-scale approach would be expected to provide a highly detailed portrayal of the field conditions. This could be useful to take into account potentially relevant information such as localized contamination sources, which is largely lost at the catchment scale. However, it would not substantially improve the regional-scale information in relation to key variables such as the water table depth. This is because variables such as water table elevation rely on the extrapolation of point-source information and require the regional context to be meaningful. Moreover, working at a local scale will not significantly enhance the accessibility or land elevation information, since the available regional data already provides a reasonably accurate representation. Thus, the added value of a local-scale map may be marginal for the amount of work it entails.

5. Conclusions

Manual borehole drilling is increasingly advocated as an affordable means to obtain year-round access to water in developing regions. Multi-million dollar projects currently foster manual drilling technologies around the world, particularly in sub-Saharan Africa. Within this context, the need to prioritize funding and to direct actions on the ground calls for cost-effective approaches to inform decision-making. Geospatial databases have to potential to efficiently underpin regional-scale initiatives, providing a means to identify the better opportunities and profit from them.

This paper has presented an approach to map the feasibility of manual borehole-drilling based on water table depth, accessibility, geology, water quality and aquifer potential. A geospatial database was compiled by integrating remote sensing information, traditional cartography, and data from field surveys so as to identify favorable lands for drilling in a rural region of Mali. Care was taken to express the outcomes not only in terms of technical feasibility, but also of time and cost. This constitutes one of the main methodological novelties of the paper. The results show that most of the study area presents medium to high feasibility for manual drilling. Costs range widely. A fully-equipped two-inch diameter borehole costs between USD200 and 600, while drilling times range between three and 10 days throughout most of the region. Four-inch boreholes are more expensive due to increased labor costs and a wider choice of pumping systems. The overall cost of drilling and equipping a larger-diameter borehole is highly variable because it largely depends on pump type. The results are consistent with hands-on experience and present a reasonable agreement with an independent estimate of drilling time based on geophysical methods. This suggests that the GIS database produces an adequate portrayal of the field conditions.

From the methodological standpoint, it is recognized that the key constrains for manual drilling may vary from one region to another. While parameters such as depth to the water table or rock type will nearly always be important, issues such as land use, rainfall patterns, slope, thickness of the saturated and unsaturated zones, or inadequate water quality can also play a relevant role in different geographical contexts. Moreover, operating costs—and even drilling times—can be expected to vary significantly. These factors imply that there is room to further develop this approach based on site-specific considerations.

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