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A Commune-Level Groundwater Potential Map for the Republic of Mali

Silvia Díaz-Alcaide, Pedro Martínez-Santos * and Fermín Villarroya

Departamento de Geodinámica, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid, C/José Antonio Novais 12, 28040 Madrid, Spain; sdalcaide@gmail.com (S.D.-A.); ferminv@geo.ucm.es (F.V.)

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

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Abstract: Groundwater represents an essential resource in sub-Saharan Africa, where several hundred million people rely on aquifers for domestic supply. This paper presents a method to map groundwater potential in the Republic of Mali based on a spatially-distributed database of 26,040 boreholes. The database includes exhaustive information on key parameters such as borehole location, success rate of borehole production, depth, yield, static groundwater level or water quality. Representative variables were classified and interpreted jointly to develop a groundwater potential index for each of the 703 communes in Mali. This provides a methodological novelty because groundwater potential studies typically rely on indirect indicators such as lineaments, slope, soil moisture and landforms. Also, such large borehole databases have seldom been used to estimate groundwater potential. The highest indexes were obtained for the areas in and around the River Niger's Inner Delta, including southern Tombouctou and the central parts of the Ségou and Mopti Regions. The lower Precambrian formations, which include the country's thoroughly populated southern plateau, had moderate scores. The lowest groundwater potential was found in the northern part of the Kayes and Koulikoro Regions, as well as in the entire region of Kidal. By providing results at the commune scale, these outcomes show that groundwater potential across the country's geological and hydrogeological units can be highly variable, and that local and regional-scale information may be useful for groundwater management purposes. These results are policy-relevant in a context of rapid change and population growth, where groundwater resources can be expected to be increasingly relied upon in the coming years.

Keywords: groundwater potential; human rights; water access; water supply; geographic information systems; borehole; Mali

1. Introduction

Groundwater resources underpin the daily existence of 300 million people in sub-Saharan Africa [1]. Generally speaking, groundwater is widely present, of good quality, sufficient in quantity and affordable [2]. Furthermore, aquifers provide a reliable source of freshwater during dry spells, particularly in regions subject to monsoon-like climates, where rainfall and surface water may be absent for several months at a time. This is the case in the Republic of Mali, where groundwater is by far the main source of drinking water supply. Over 800,000 traditional wells and 25,000 boreholes currently exist [3,4].

Forecasts suggest that rainfall may become less reliable in the region in the coming years due to climate change [5]. This, coupled with population growth and irrigation development, suggests that further pressure will be placed on aquifer systems across the country. In this context, approaches that add to the existing knowledge about groundwater reserves are necessary.

Groundwater occurrence depends on spatially-distributed variables such as transmissivity, porosity, thickness and stratigraphy, and recharge rates. Thus, groundwater mapping techniques have been developed to deal with issues such as groundwater potential [6–9], vulnerability [10–12] and depletion [13,14]. The purpose of this paper is to explore a method to map groundwater potential based on a large country-wide database of 26,040 boreholes. The database includes extensive information on features such as borehole yield, average depth, success rate, static groundwater level and electrical conductivity [3]. Although the value of this kind of information has been referred to in the past [6], our approach represents a methodological novelty in groundwater mapping because (1) borehole data has seldom (if ever) been used in practice with the degree of detail presented in this research; and (2) most of the existing literature relies on the inference of groundwater potential from indirect parameters such as lineament density, slope, geomorphological features, rainfall distribution, soil moisture and lithology [15–18]. Also, outcomes are presented at the commune scale, thus providing an overview of groundwater potential that is relevant at both national and local scales.

2. Materials and Methods

2.1. Study Area

This work refers to the entire Republic of Mali, a land-locked country in West Africa (Figure 1). In terms of size, Mali ranks 8th among African countries and 23rd in the world, spanning a total surface on the order of 1,200,000 km^2. The landscape is dominated by vast flatlands, plateaus and plains. The country's lowest point is on the Senegal River, about 20 m a.s.l., while the highest elevation is 1155 m a.s.l. The surface drainage network is controlled by the Niger and Senegal Rivers. Approximately two-thirds of the surface area is classified as desert or semi-desert. Just 5% of the territory is considered arable.

Mali has three distinct climate zones [19]. From north to south, these correspond to Tropical wet climate (Aw), hot semi-arid climate (BSh) and hot desert climate (BWh), as per the classic Koppen classification. The northernmost part of the country, from the latitudes of Tombouctou and Gao to the Algerian border, is desertic. Sahelian conditions predominate immediately to the south, between the Gao-Tombouctou axis and the Bamako-Koutiala axis. Finally, the southernmost part of the country is characterized by a Sudanese-Guinean tropical climate. In terms of rainfall, Mali presents a clear north-south gradient. The mean annual precipitation is less than 50 mm in the drier Saharan zones, increasing gradually to 600 mm in the Sahelian region and to over 1200 mm in the tropical south (Figure 2). The country is subject to the West African monsoon, in which over 90% of the precipitation takes place between June and November.

From the geological standpoint, Mali extends over two main structures, the West African craton in the west and the Tuareg shield in the southeast [20]. As shown in Figure 2, the main geological units include the Precambrian crystalline basement, Lower Cambrian to Paleozoic indurated sandstones and metamorphic schists, Permian dolerite intrusions, mixed continental sediments of the Continental Intercalaire Formation, Upper Cretaceous to Eocene marine sediments, the Pliocene Continental Terminal sedimentary formation and Quaternary deposits [21,22].

Hydrogeological information at the national scale is scarce and unevenly distributed. The most comprehensive studies are several decades old [23–25] with the exception of a recent synthesis report published by the British Geological Survey [26]. Regional-scale works are typically isolated in geographical scope and developed ad hoc [27,28].

The *Département de la Coopération Technique pour le Développement* provides the most extensive description available of the aquifers of Mali [25]. Nine major systems have been defined, encompassing the whole country (Figure 3). These are classified as fissured (discontinuous) or intergranular (continuous) systems, each type covering approximately half of the total land surface. In some cases these may be superimposed. Superficial Quaternary aquifers are usually considered part of the underlying systems, even if they sometimes behave as perched units. The denomination of fractured aquifers typically refers to the crystalline and sedimentary formations of Precambrian and Paleozoic age. This includes igneous rocks, such as dolerites, that may form aquifers of local importance. The hydrogeological properties of fissured aquifers are highly dependent on fracture density, size and degree of interconnection, and the thickness and permeability of the overlying weathered layer. Intergranular aquifers, on the other hand, are generally associated with the accumulation of unconsolidated deposits in large sedimentary basins. These typically range in age from the lower Cretaceous to the Quaternary (Table 1).

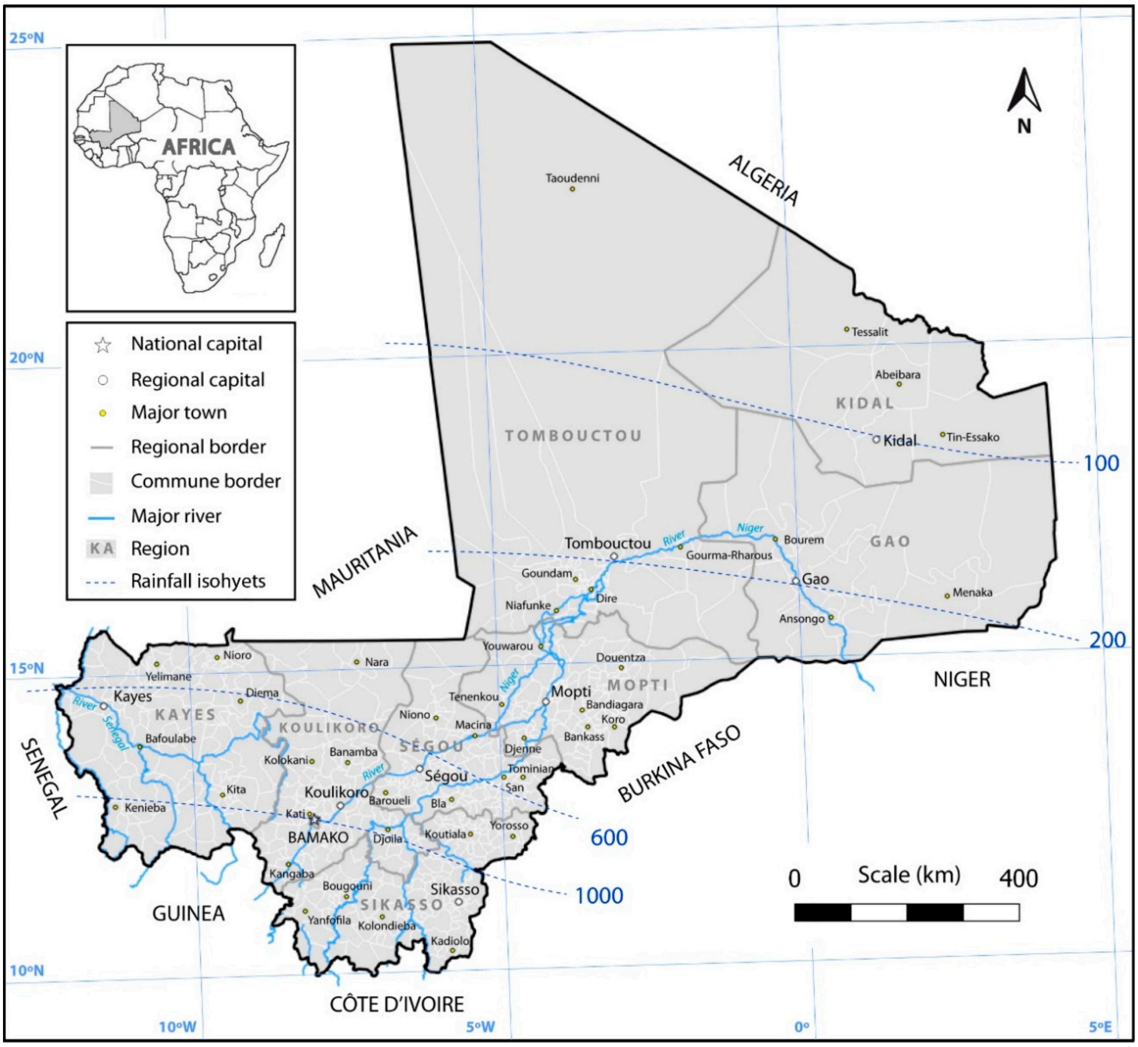

Figure 1. Geographical setting. The Republic of Mali showing regional and communal divisions, major towns and the main fluvial network.

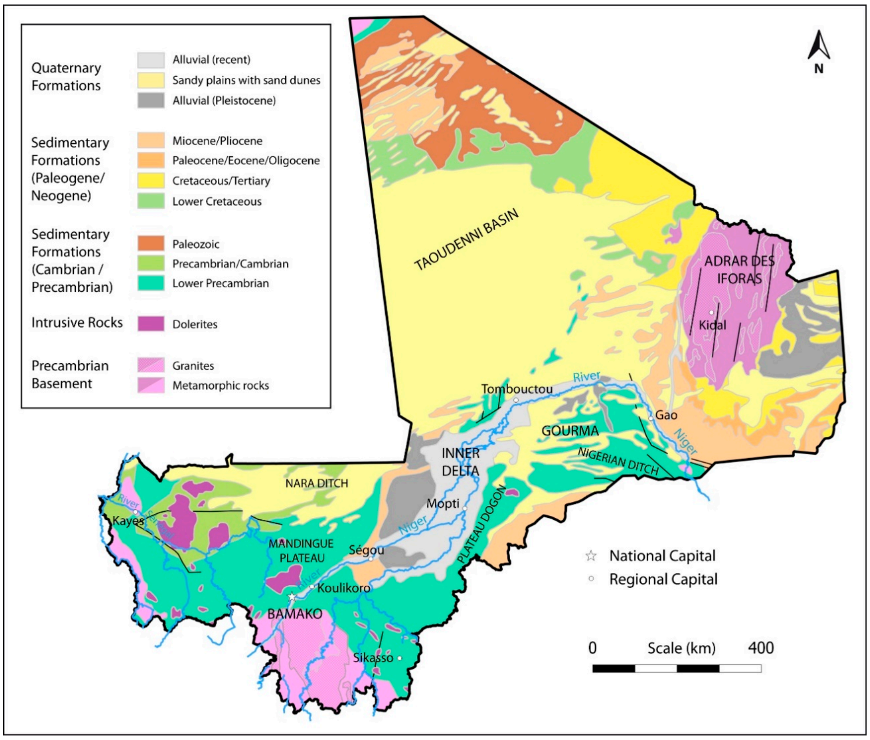

Figure 2. Main geological units of Mali (modified from Raase 2010 [29]).

Table 1. Groundwater units of Mali (after Département de la Coopération Technique pour le Développement du Mali [26]). See Figure 3 for the spatial location of groundwater units.

Aquifer Type	Groundwater Unit	Lithology	Area (km^2)	Area (% Mali)	Code/Sector
Intergranular	Continental Terminal and Quaternary	Clay, sandy clay, sand, laterites	202,830	16	*12 Fossé de Gao* *13 Azaouad Sud* *14 Gourma Nord Ouest* *15 Delta Intérieur*
	Upper Cretaceous and Lower Eocene	Limestone, marl	138,910	11	*21 Bordure Adrar*
	Continental Terminal and Continental Intercalaire	Sand, sandy clay, clay	208,870	17	*31 Azaouad Nord* *32 Fossé de Nara*
	Continental Intercalaire	Sand, sandstone, conglomerate	82,320	7	*41 Tamesna* *42 Khenachich*
Fissured	Paleozoic Taoudenni	Limestone, sandstone	112,700	9	*51 Primaire Taoudenni*
	Cambrian	Schist, shale, limestone, sandstone	66,060	5	*61 Ouagadou* *62 Kaarta*
	Infracambrian Tabular	Sandstone, schist	174,810	14	*71 Plateau Dogon* *72 San-Koutiala* *73 Bani Moyen* *74 Est Plat. Mandingues* *75 Baoulé* *76 Bakoye* *77 Bafing*
	Infracambrian Metamorphic	Schist, limestone, quartzite	97,420	8	*81 Nord Delta* *82 Gourma* *83 Gondo*
	Basement (granitic and metamorphic)	Laterite, clay, sand, gravel	156,080	13	*91 Adrar des Iforas* *92 Bagoe* *93 Baoulé* *94 Sankarani* *95 Kéniéba* *96 Kayes*

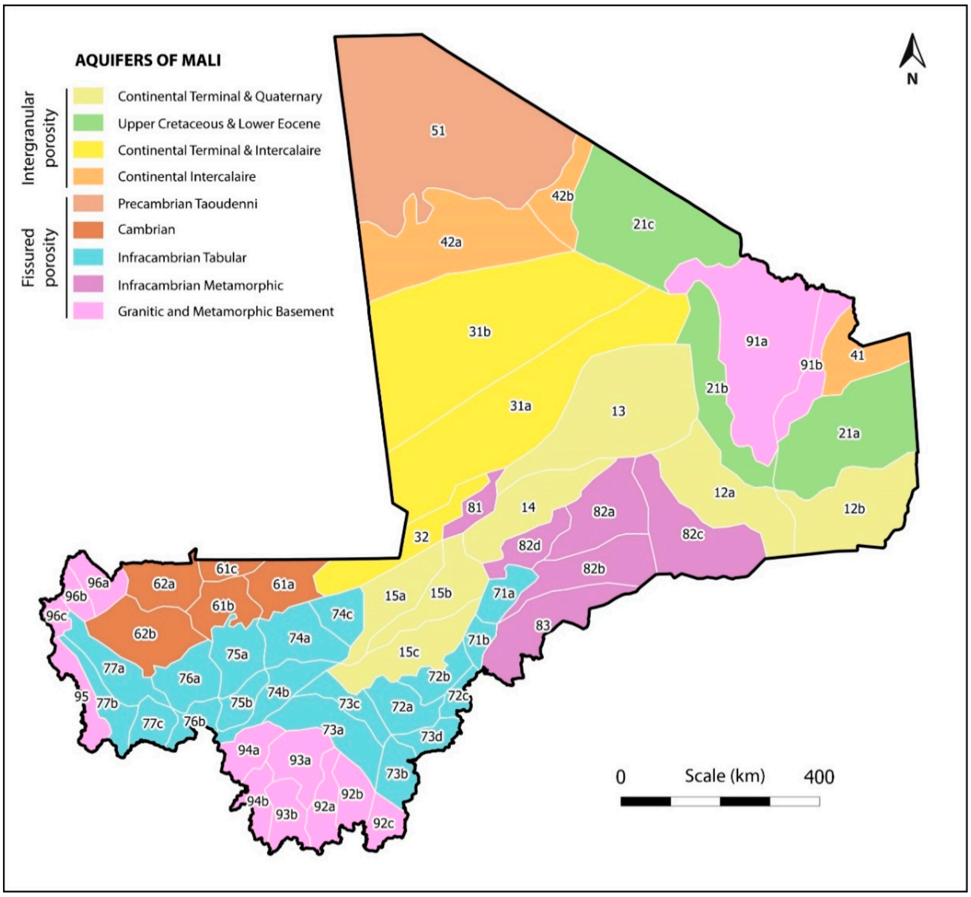

Figure 3. Main hydrogeological units of Mali (adapted from the map by the Département de la Coopération Technique pour le Développement du Mali [26]). Numbers represent the official code of each aquifer sector as outlined in Table 1.

2.2. Borehole Database

This research relies on a database [3] of 26,040 boreholes, of which 19,803 (76%) were successful and 6237 (24%) were not. For practical purposes, a successful borehole is that which finds groundwater in sufficient quantity to fulfil a specific need, typically irrigation or domestic consumption. An unsuccessful (or negative) borehole is one that finds no water, or not enough. Table 2 summarizes the borehole numbers per region, while Figure 4A provides an overview of the spatial distribution of borehole data. The dark dots represent human settlements (capitals, towns, villages) where boreholes have been reported. As shown, the number of population centers is heavily skewed towards the south of the country, where over 75% of the people live.

Data were aggregated at the commune scale, that is, the third-level administrative division of the country. Generally speaking, a commune can be assimilated to the concept of municipality, as most communes comprise one main town together with a number of small villages. Mali comprises 703 communes, grouped in eight regions (Kayes, Sikasso, Segou, Mopti, Tombouctou, Gao, Koulikoro and Kidal) and one capital district (Bamako). Just 12 communes, most of which are located in the southern half of the country, account for over 20% of the population. The six urban communes that comprise the Bamako District alone add up to 12.5%. The mean size of a commune is 1789 km^2, although they range from 5 km^2 (Somankidy Commune, Kayes Region) to 292,582 km^2 (Salam Commune, Tombouctou Region). The size range is heavily skewed towards the smaller end, 610 of the 703 communes (87%) being smaller than the arithmetic mean.

Table 2. Communes, surface area, population and basic borehole data in Mali, by region [3].

Region	Surface (1000 km^2)	Communes	Population (Thousands)	Boreholes (Successful)	Boreholes (Unsuccessful)	Borehole Success (%)	Successful Boreholes per km^2	Successful Boreholes per 1000 People
Bamako	0.25	6	2352	304	48	86	1206	0.1
Gao	89.53	24	701	653	136	83	7	0.9
Kayes	119.74	129	2590	3762	1968	66	31	1.5
Kidal	151.43	11	81	181	226	44	1	2.2
Koulikoro	95.85	108	3147	3560	1581	69	37	1.1
Mopti	79.02	108	2645	2004	527	79	25	0.8
Segou	64.82	118	3038	3384	574	85	52	1.1
Sikasso	70.28	147	3434	4985	1041	83	71	1.5
Tombouctou	496.61	52	877	970	136	88	2	1.1
Total/Avg		703	18,865	19,803	6237	76	17	1.0

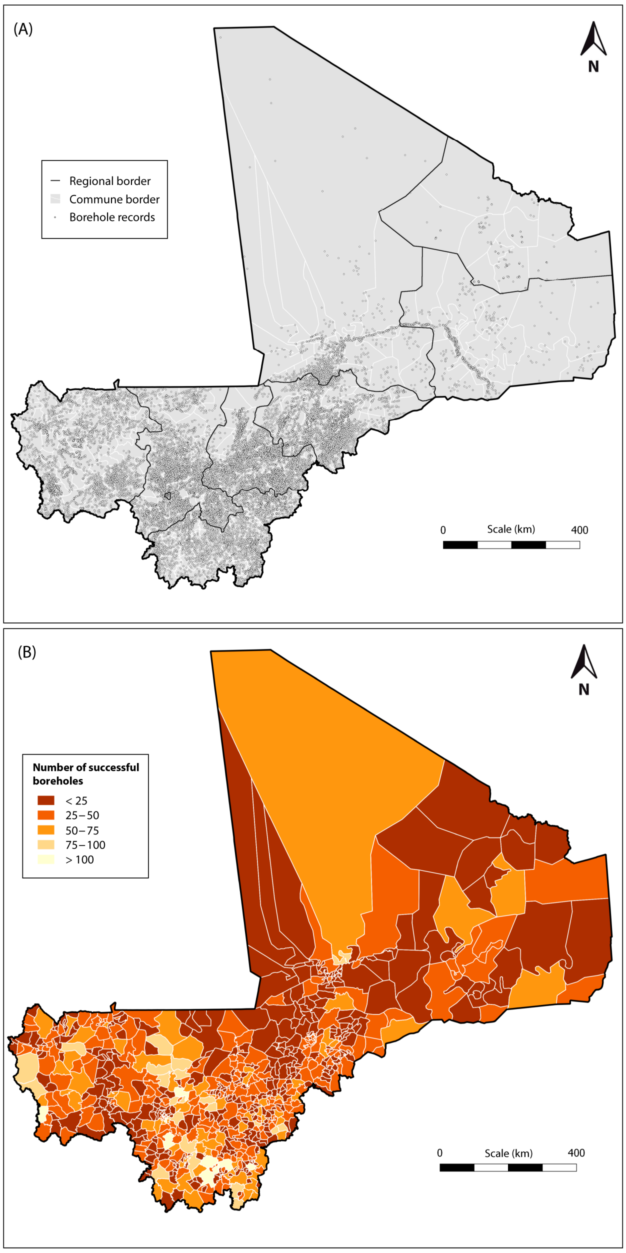

Figure 4. (**A**) Human settlements where borehole data are available (dark dots represent human settlements where boreholes have been reported); (**B**) Number of successful boreholes per commune.

2.3. GIS Analysis

All borehole information was compiled into a spatial database, together with a national-scale geological map. QGIS 2.12.2-Lyon (http://www.qgis.org/en/site/) was used to integrate all the data. QGIS is a cross-platform free and open-source desktop geographic information system that supports viewing, editing and analysis of geospatial information. A thematic map was developed for each of the variables in the spatial database. Five categories were defined for each of the six key variables, from "very high" (5) to "very low" (1), to provide a common ground for interpretation (Table 3). Breaks between categories were based on different criteria for each variable, to make the scores as meaningful and comparable as possible (Figure 5). For instance, electrical conductivity data were classified based on commonly accepted drinking water standards. On the other hand, borehole yield and depth, and aquifer recharge [30] and thickness, were classified based on Jenks' frequency analysis method for natural breaks [31]. Extreme outliers were ignored in the classification, which is the main reason why some categories differ in the magnitude of the ranges. Uniform breaks were considered meaningful in the case of borehole success rate.

A groundwater potential score (1 to 5) was then calculated for each commune as the arithmetical mean of each of the six thematic scores (Table 3). No index was computed for a small number of communes (fewer than 10), for which information on at least one of the four borehole-related parameters is not available.

Table 3. Groundwater potential scores for each of the six key variables and basic descriptive statistics of the available data.

Item	Borehole Success Rate (%)	Borehole Yield (m^3/h)	Electrical Conductivity (µS/cm)	Drilling Depth (m)	Annual Recharge (mm)	Aquifer Thickness (m)	Groundwater Potential
Very High	>80	>20	<250	<25	>150	>125	5
High	60–80	15–20	250–500	25–50	100–150	100–125	4
Medium	40–60	10–15	500–1000	50–100	50–100	75–100	3
Low	20–40	5–10	1000–5000	100–150	25–50	50–75	2
Very Low	<20	<5	>5000	>150	<25	<50	1
Maximum	1.00	100.0	5779	185	185	1000	-
Minimum	0.15	0.9	15	34	0	5	-
Arithm. Mean	0.81	8	416	64	60	70	-
Standard Deviation	0.17	7	417	14	35	37	-

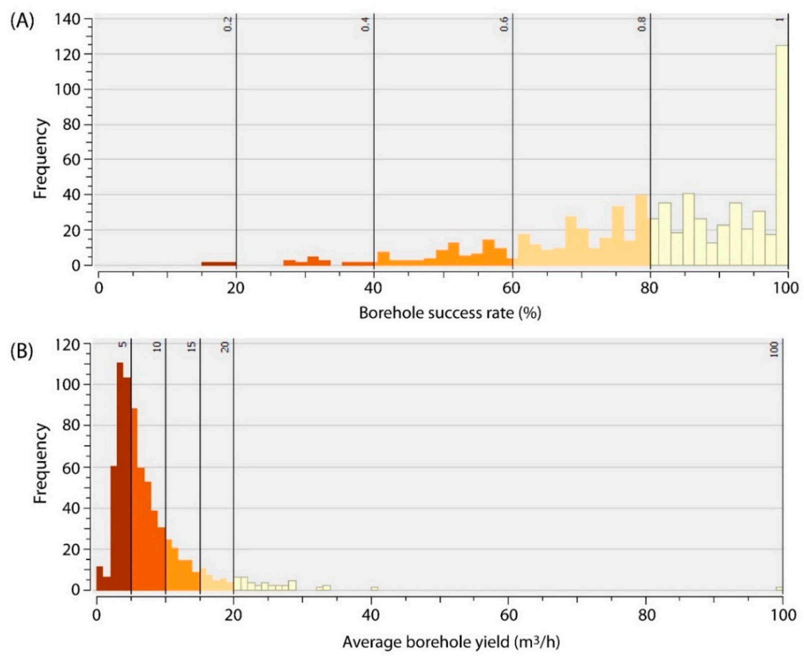

Figure 5. *Cont.*

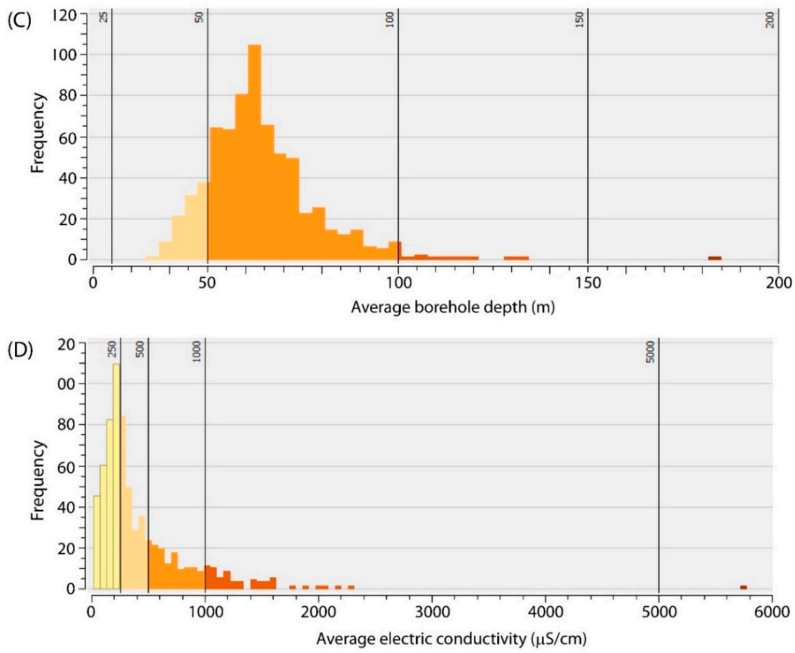

Figure 5. Frequency analysis of the available borehole data for each of the four borehole-related variables. (**A**) Borehole success rate (%). (**B**) Arithmetic mean of borehole yield (m^3/h). (**C**) Arithmetic mean of borehole depth (m). (**D**) Arithmetic mean of electrical conductivity (µS/cm).

3. Results and Discussion

3.1. National Classification of Groundwater Potential

Figure 6 presents the thematic maps for borehole success, yield, electrical conductivity and depth. The borehole success rate is better than 60% across 76% of the country. The Tombouctou Region has the highest rate (88%), closely followed by the Bamako District (86%), Ségou (85%) and the Sikasso and Gao Regions (both 83%). In contrast, Kidal is the only region to score well below the national average (44%). The borehole success rate is as low as 18% in parts of this region, as well as in northern Kayes and northern Koulikoro. In contrast, borehole yield is typically low, with an average of less than 8 m^3/h (standard deviation 7 m^3/h). The Mopti Region has the highest yields, up to 100 m^3/h in some cases.

Borehole yield controls the rate at which groundwater can be pumped. Community water supplies fitted with a hand pump need yields on the order of 1 m^3/h, although yields less than 0.5 m^3/h may be appropriate in some circumstances. In contrast, commercial irrigation schemes require much larger abstraction rates, typically in excess of 18 m^3/h [6]. This suggests that the current extraction potential is still limited across most of the country. Higher borehole yields are associated with certain geological and hydrogeological characteristics (Figures 2 and 3). For instance, the Inner Delta area accounts for most of the higher-productivity areas, more so around the recent alluvial deposits that overlay the Continental Terminal aquifer. This can be readily observed in the area between Mopti and Tombouctou, where several communes report mean yields in excess of 30 m^3/h and where boreholes occasionally exceed 100 m^3/h. Lower yields are consistently found around the granitic domains of the Adrar des Iforas and the borders with Niger, Mauritania and Burkina Faso (Cambrian and Infracambrian Metamorphic areas). Low yields (1–5 m^3/h) with occasional medium-to-high productivity can be expected around the sedimentary and basement regions.

Comparison of these results with the success map leads to two contrasting conclusions: Groundwater is widely available across nearly 80% the country, but highly productive boreholes are rare. The Inner Delta, where both success rate and yield are high, is the only really meaningful exception to this rule (Figure 7). In this context, the fact that the official aquifer units encompass the whole surface of the country (i.e., no areas are defined as "impervious" for management purposes) makes sense, even if this masks the uneven distribution of groundwater potential.

Borehole depth is reasonably even in most regions. Boreholes typically reach depths between 50 and 75 m (Figure 5). The deepest boreholes are found in the eastern parts of the Gao and Kidal Regions, near the Niger border. The shallower ones are widely distributed. In some cases, like in the Precambrian domains of the south, this may have to do with the fact that many boreholes are drilled to capture groundwater in the weathered pack overlying the granite basement. Conversely, in areas such as the Inner Delta, this could be attributed to the fact that sufficient water can be obtained without drilling deeper.

Electrical conductivity values are suitable for human consumption across most of the country, averaging 416 µS/cm. A clear north–south gradient is observed (Figure 6). The more saline waters are found in the drier parts of the country, where evapotranspiration rates are high and groundwater replenishment is generally low [25,26]. Commune-scale arithmetic means in excess of 1000 µS/cm are found in vast expanses of land in the Tombouctou, Gao and Kidal Regions. Exceptionally high values (5500 µS/cm) have been reported in communes of the Nara area, near the Mauritanian border.

Borehole yield, depth and electrical conductivity tend to offset each other's potential in some areas. Take for instance the case of the Inekar Commune (eastern Gao), the only one in the entire country where the arithmetic mean of borehole depth exceeds 150 m. While the static groundwater level in this area is typically 50 m beneath the surface, a clear difference in yield is observed between those boreholes that fall short of 150 m (yields less than 2 m^3/h) and those which exceed this depth (yields over 10 m^3/h). Exceptionally deep boreholes (600 m) yield over 55 m^3/h. However, electrical conductivity is usually above 2500 µS/cm (reaching up to a maximum of 10,000 µS/cm), making the waters unsuitable for most uses.

Integrating the above outcomes renders a groundwater potential map (Figure 7). The central Niger basin, including the Inner Delta, presents the highest overall groundwater potential index due to consistently high grades in all categories. Borehole yield and success rates are very high due to the widespread permeable formations. Recharge is average by national standards, but this is largely compensated for by infiltration from the river during the wet season [25]. It is noticeable that most of the communes for which data are not available are in this area, where groundwater potential is observed to decrease gradually in both directions along the River Niger. Communes near the river tend to obtain better scores than those further away. This is also attributed to the presence of alluvial materials, which provide an added groundwater potential to the underlying formations.

The Infracambian Tabular region, which includes the country's thoroughly populated southern plains and plateaus (Figures 3 and 4A), have average to high groundwater potential. Aquifers in this area are typically multi-layered and semi-confined. The metasediments present dual hydrogeological behavior: Low permeability layers provide greater storage, while more fractured layers have higher permeability and lower storage. Dolerite intrusions may increase fracture density [26]. The outcome is consistent with the fact that many of the main human settlements in the area rely exclusively on groundwater. On the other hand, the lowest groundwater potential is found in the northeast of the country, as well as around the Mauritania and Burkina Faso borders. The low potential can be attributed to less-favorable geological materials. Negligible recharge, desertic climate and generally poor groundwater quality hamper groundwater potential in the northeast and Mauritanian borders.

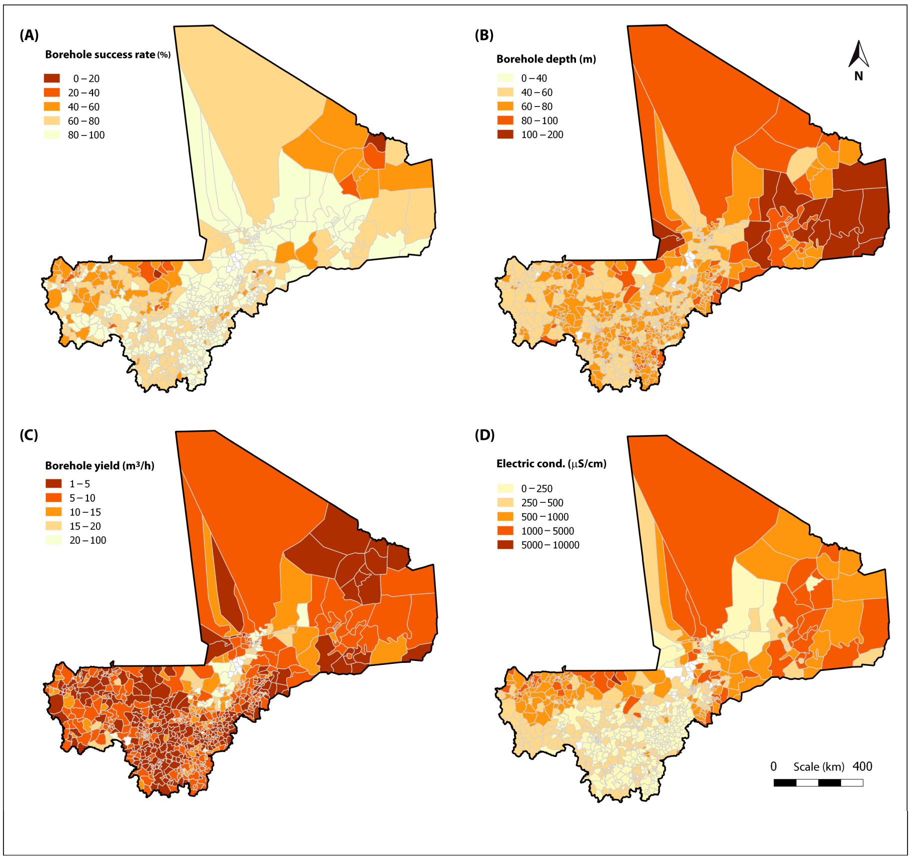

Figure 6. Spatial distribution of the key borehole variables at the commune scale. (**A**) Borehole success rate (%). (**B**) Arithmetic mean of borehole depth (m). (**C**) Arithmetic mean of borehole yield (m^3/h). (**D**) Arithmetic mean of electrical conductivity (µS/cm).

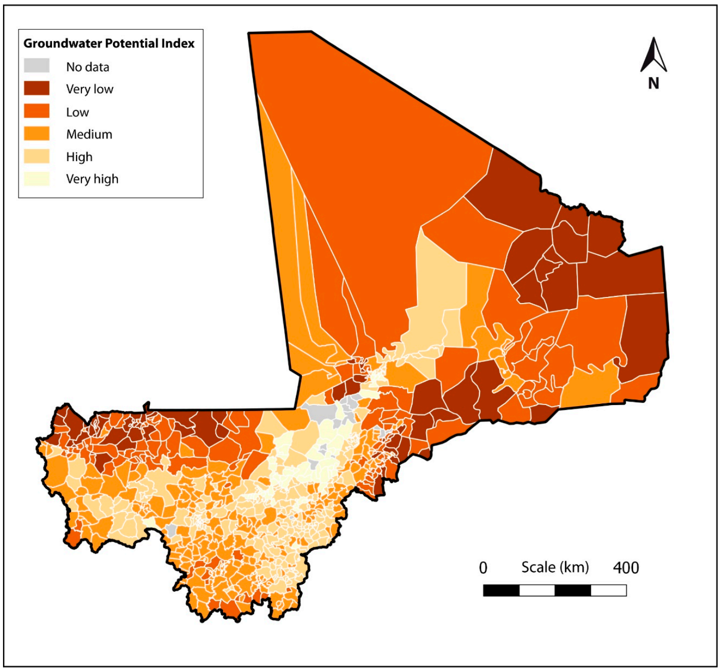

Figure 7. National-scale groundwater potential index. Data aggregated at the commune scale. Communes in gray are those where data were not available for at least one of the borehole-related variables.

3.2. Methodological Aspects and Limitations

Geographical information systems and remote sensing have provided a cost- and time-effective means to handle complex spatially-distributed information. Because satellite imagery does not currently allow detection of groundwater, hydrogeologists have come up with indirect methods to explore the potential of groundwater resources. This is particularly useful in developing regions, where hydrogeological surveys are seldom systematic and the potential of groundwater resources is largely unknown. In most cases, groundwater potential mapping relies on the combination of several indirect indicators (slope, lineaments, lithology, elevation, drainage density, soil moisture, geomorphology). For example, areas where the lineament density is high can be expected to store more groundwater in the fractures than those areas where lineaments are absent; landscape features such as scarps and ridges are typically assumed to indicate a poor groundwater potential.

In this context, the main methodological novelty of our work consists in using borehole data in the spatial analysis. This provides a more-direct measure of groundwater potential than the above indicators. Take for instance borehole yield. Borehole yield is a highly informative measure of groundwater potential because it provides a clear-cut estimate of how productive the aquifer is and because boreholes are typically developed to maximize yield. Of course, this assumes that boreholes are well constructed and that groundwater conditions are near-stationary. Thus, it can be misleading if drilling standards are poor or if groundwater resources are being depleted. These potential inconsistencies in the data are smoothed out by the sheer size of the database, together with the fact that the aquifers of Mali are generally underexploited. Analogous reasoning applies to borehole depth, success rate and electrical conductivity.

Commune-scale work provides an optimal spatial resolution, as outcomes are informative at the local, regional and national scales. A shortcoming is that the boundaries of groundwater potential areas are expressed in terms of administrative divisions, rather than purely hydrogeological criteria. In a country where hydrogeological domains are often measured in hundreds of thousands of square kilometers (Table 1), the distortion can be expected to be minimal when dealing with the smaller communes (southern half of the country). In the case of large communes (notably the northern Tombouctou Region), the data had to be averaged over large expanses of land, which may traverse one or several hydrogeological boundaries. Take for instance the Salam Commune, the largest one in Tombouctou, whose territory extends across five of the country's nine major aquifer systems. All this implies that the outcomes for the southern part of the country are generally more reliable, and that groundwater potential in some areas of the northern part of the country could be subject to additional qualification.

The mean number of successful boreholes per commune is 28, with a standard deviation of 21. Bearing in mind the above reasoning, this appears to be enough to cancel out potential anomalies, thus providing a reasonable representation of the hydrogeological conditions (Figure 4A). Nevertheless, there are a few communes in the northern part of the country where the number of available boreholes may be insufficient. This is typically because there are too few boreholes in relation to surface area or because the boreholes are too concentrated in space to provide a representative overview of a much larger area. In these cases, data inconsistencies such as poor execution of one borehole can be expected to have strong effects on the final outcomes. The only way to improve this is to enhance the borehole database with new information as it becomes available.

Another potential limitation of the outcomes has to do with the reclassification of groundwater potential for each of the key variables. In cases such as the one at hand, using thresholds is important to make the results understandable. This almost necessarily incorporates an element of expert judgement because the outcomes ultimately rely on what is considered to be "low", "medium" or "high" (Figures 5 and 6). As explained earlier, thresholds in this case were established by combining a frequency analysis of the existing data with the intent of reaching a result that is both informative and aesthetically pleasant. It is recognized, however, that slightly different results could be expected for different threshold criteria.

The existing data is considered sufficient to compute groundwater potential, but cannot be used to estimate water access. This is largely because there is no information on groundwater extractions or pumping devices. In many parts of the country, particularly in rural areas, groundwater is frequently extracted by means of hand pumps, whose flow rates do not usually exceed 1 m^3/h. There are also no data on pumping patterns or on whether pumps are used for domestic supply or irrigation. In other words, borehole yield as currently stated cannot be used as a proxy for groundwater extraction, nor can it be used to compute per-capita groundwater availability.

4. Conclusions

Approaches to mapping groundwater potential are gaining recognition as tools that may underpin aquifer management in developing regions. From the methodological perspective, the main contribution of this research has been the mapping of groundwater resources based on a combination of extensive borehole data with spatially distributed estimates of recharge and aquifer thickness. This provides an estimate of groundwater potential that is based on actual borehole yield, depth, success rate and water quality, rather than on indirect indicators such as geomorphology, soil parameters or geological cartography. Outcomes are computed at the commune scale. This is an optimal spatial resolution because it is informative at both the regional and national scales. While detailed borehole information will not always be available, we advocate its inclusion, when this is possible, to enhance the quality of groundwater potential studies.

The importance of groundwater in Mali cannot be overstated. The purpose of this research was to contribute to the existing knowledge of Mali's aquifers by presenting a groundwater potential map based on a large borehole database. The outcomes suggest that groundwater is widely present across the country, even if there are substantial differences in groundwater potential from one region to another. The Inner Delta of the River Niger presents the greatest groundwater potential, whereas areas such as western Gao or Kidal have limited availability. Approaches such as the one presented in this paper may improve our knowledge and provide additional support for groundwater management.

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