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Comparison of RS/GIS analysis with classic mapping approaches for siting low-yield boreholes for hand pumps in crystalline terrains. An application to rural communities of the Caimbambo province, Angola

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Abstract

In poverty-stricken regions of Sub-Saharan Africa, groundwater for supply is often obtained by means of hand pumps, which means that low-yield boreholes are acceptable. However, boreholes are often sited without sufficient hydrogeological information due to budget constraints, which leads to high failure rates. Cost-effective techniques for borehole siting need to be developed in order to maximize the success rate. In regions underlain by granite, weathered formations are usually targeted for drilling, as these are generally presented as a better cost-benefit ratio than the fractured basement. Within this context, this research focuses on a granite region of Angola. A comparison of two mapping techniques for borehole siting-groundwater prospect is presented. A classic hydrogeomorphological map was developed first based on aerial photographs, field mapping and a geophysical survey. This map represents a considerable time investment and was developed by qualified technicians. The second map (RS/GIS) is considerably simpler and more cost-effective. It was developed by the integration in a GIS platform of six maps of equal importance- slope, drainage density, vegetation vigor, presence of clay in the soil, lineaments and rock outcrops- prepared from Landsat 8 imagery and a Digital Elevation Model (DEM). Similar results were obtained in both cases. By means of a supervised classification of Landsat images, RS/GIS analysis allows for the identification of granitic outcrops, house clusters and sandy alluvial valleys. This in turn allows for the delineation of low-interest or contamination-prone areas, thus contributing additional qualitative information. The position of a well that is going to be powered by a handpump is chosen also upon social and local matters as the distance to the stakeholders, information that are not difficult to integrate in the GIS. Although the second map needs some field inputs (i.e. surveys to determine the thickness of the weathered pack), results show that RS/GIS analyses such as this one provide a valuable and cost-effective alternative for siting low-yield boreholes in remote regions.

Keywords: Groundwater investigation · Africa · igneous rocks · weathered formations · low-yield wells · Remote sensing · Geographic Information Systems

1. Introduction and objectives

Groundwater is the main source of drinking water in rural Sub-Saharan Africa (SSA), where crystalline basement aquifers account for approximately 40% of the total land surface. These areas support a population of about 235 million people, most of which live in dispersed villages (MacDonald et al. 2008a, Carter and Bevan, 2008).

Groundwater in basement aquifers is most often found in weathered formations and fractures, a combination of the two being the optimal location for a borehole (Holland and Withüser 2011).

Boreholes drilled in such conditions (particularly so those that are drilled within the weathered zone and that reach down to the basement), are both cost effective and likely to yield enough water to support a hand pump (600 L/h) (Fig. 1) (Foster et al. 2006). This is the main reason why they are favored over other water supply options throughout most of sub-Saharan Africa (Foster et al. 2006; Foster 2012). From a geological standpoint, the average thickness of weathered zones usually ranges between 20 and 30 m, reaching up to 60 m in some areas (MacDonald et al. 2008a). The lower part is generally more transmissive due to its lower clay content. Thus, this is where most of the groundwater flow occurs. The upper part, with a greater clay content, is less pervious to circulation, but may remain important as a groundwater reservoir (Fig. 1). Fractures, on the other hand, can yield significant amounts of water, although they usually present little storage capacity (Fashae et al. 2014; Wright 1995; Foster et al. 2006). According to Wright (1992), rainfall is the dominant factor controlling recharge in crystalline basement aquifers. Recharge is estimated at between 10 % and 20 % of rainfall in areas where annual precipitation exceeds 800 mm. Edmunds (1988) estimates 400 mm/yr as the lower recharge threshold (i.e. the amount of rain below which recharge is slight or negligible). Hand pump-based rural supply is considered feasible with recharge rates of just 10 mm per year (MacDonald et al. 2008b).

Aside from geological and hydrogeological limitations, borehole location is constrained by a variety of social and economic factors. Hand pumps are perhaps the most robust and cost-effective means to supply drinking water to rural populations. This means that villagers need to walk from their homes to the pump every day, and hence, that the time and distance to fetch water needs to be minimized (Bazezew 2011). The existence of contamination sources such as latrines and the general absence of means to treat the water also need to be taken into account when establishing where to drill. A trained eye may be sufficient to site a successful borehole (Wurcel 2001). However, since yield requirements are relatively low and groundwater is usually found near the surface, boreholes are often drilled assuming that there will be water no matter what. This results in high failure rates and considerable economic losses (Wurcel 2001).Geomorphological factors are important when establishing where to drill a borehole. For instance, flat outcrop-free areas can be reasonably correlated to preferential infiltration paths, as well as to the existence of permeable regolith (Fashae et al. 2014; Teeuw 1995; Shahid et al. 2000; Singh and Prakash 2002; Chuma et al. 2013; Talabi and Tijani 2011; García-Rodríguez et al. 2014; Ndatuwong and Yadav, 2014). A sensible approach to site a borehole starts off by mapping the hydrological and geomorphological conditions of the area. Favorable sectors are then selected based on landforms and superficial signs (e.g vegetation), and then the choice of locations is narrowed down by taking into account the geographical proximity to end users. A geophysical survey ensues. This serves the purpose of establishing the existence and thickness of weathered pack. Resistivity is the geophysical method of choice when determining the depth of weathered formations (MacDonald et al. 2008b). In Africa, this technique has been used for hydrogeological purposes since 1933 (Barker 2004) and has underpinned water supply projects since the 1960s (Zohdy et al. 1974; Vouillamoz et al. 2001; ACF 2005; Detay et al. 1989). The depth of weathered materials is not only important in terms of borehole yield, but also because pumps will operate with greater efficiency in thicker permeable formations (Martín-Loeches and Rebollo 2014). This usually translates into a longer operational life.. On site field investigation is expensive, time-consuming and cumbersome to carry out at the regional scale (Ndatuwong and Yadev 2014; Sikakwe et al 2015). This was experienced first-hand by the authors in 2010, when they participated in a campaign to drill 20 boreholes for the water supply of 20 different villages in the Caimbambo province, Angola (Fig. 2). In that case, drilling locations were established by means of a classical method. Hydrogeomorphological units were thoroughly delineated based on the outcomes of a field survey and complemented with aerial photographs. These were then used to determine a series of theoretically appropriate locations prior to carrying out a geophysical survey.

For areas lacking appropriate geological maps and with some degree of isolation, the integration of remote sensing information and GIS platforms (RS/GIS) constitutes an efficient way of producing maps (Sikakwe et al. 2015; Nohanty and Behera 2010; Aslam et al. 2003; Gope Naik et al. 2016; Khadri and Pande 2015; Sethupathi et al. 2012; Pandey and Nathawat 2009; Martínez-Santos et al 2017). The main goal of this research is to show how RS/GIS methods may provide a cost- and time-effective substitute to delineating favorable drilling areas (i.e. weathered zones) in remote regions. This is achieved mainly through comparing the outcomes to those from a classic hydrogeomorphological map, which relies on cumbersome field surveys and considerably more expensive procedures.

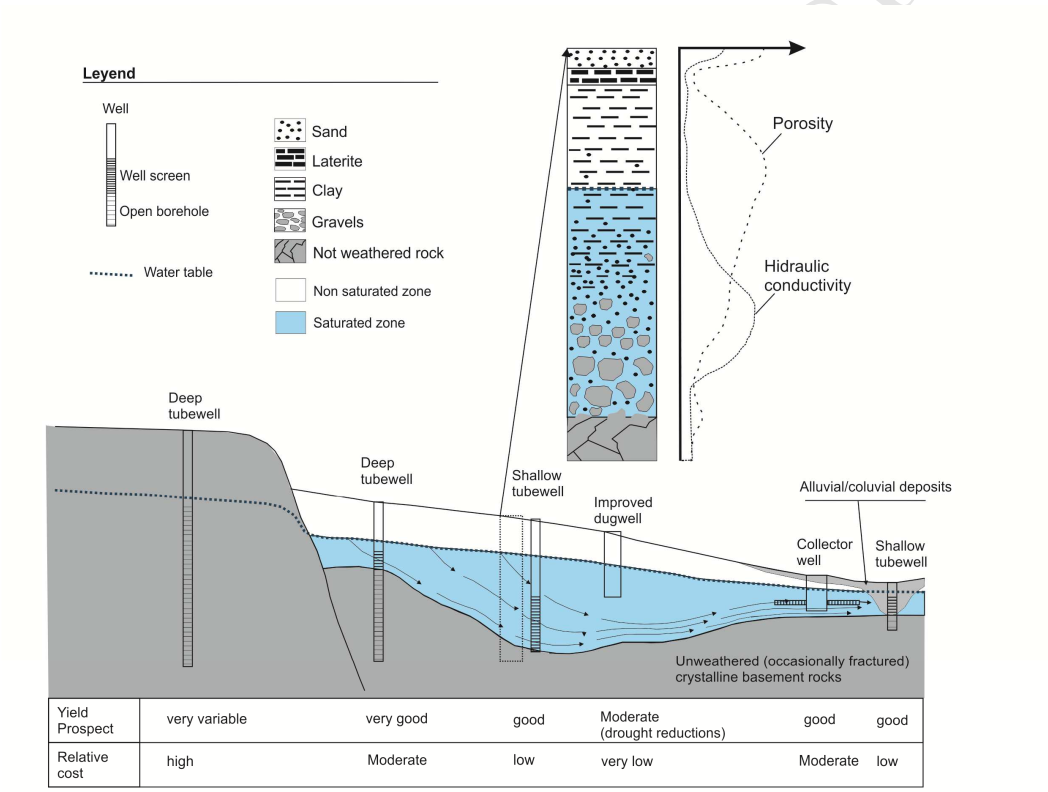

Fig. 1 Water-supply borehole design in crystalline basement terrain (after Foster et al. 2006).Detail of a typical weathered zone (Wright 1992)

2. Materials and methods

2.1 Study area

The Caimbambo municipality spans a surface of 3,285 km^2 and is located in the western part of the Bié Plateau,Angola (Fig. 2). This area constitutes the main dispersion zone of the country's drainage network because of its altitude and rainfall patterns (Zerquera et al. 2008). From a geological standpoint, it is associated to the Angola shield, which is made up of Precambrian igneous and metamorphic rocks. These are strongly fractured in the NNE-SSW, NNW-SSE, N-S and E-W directions (ING 1988).

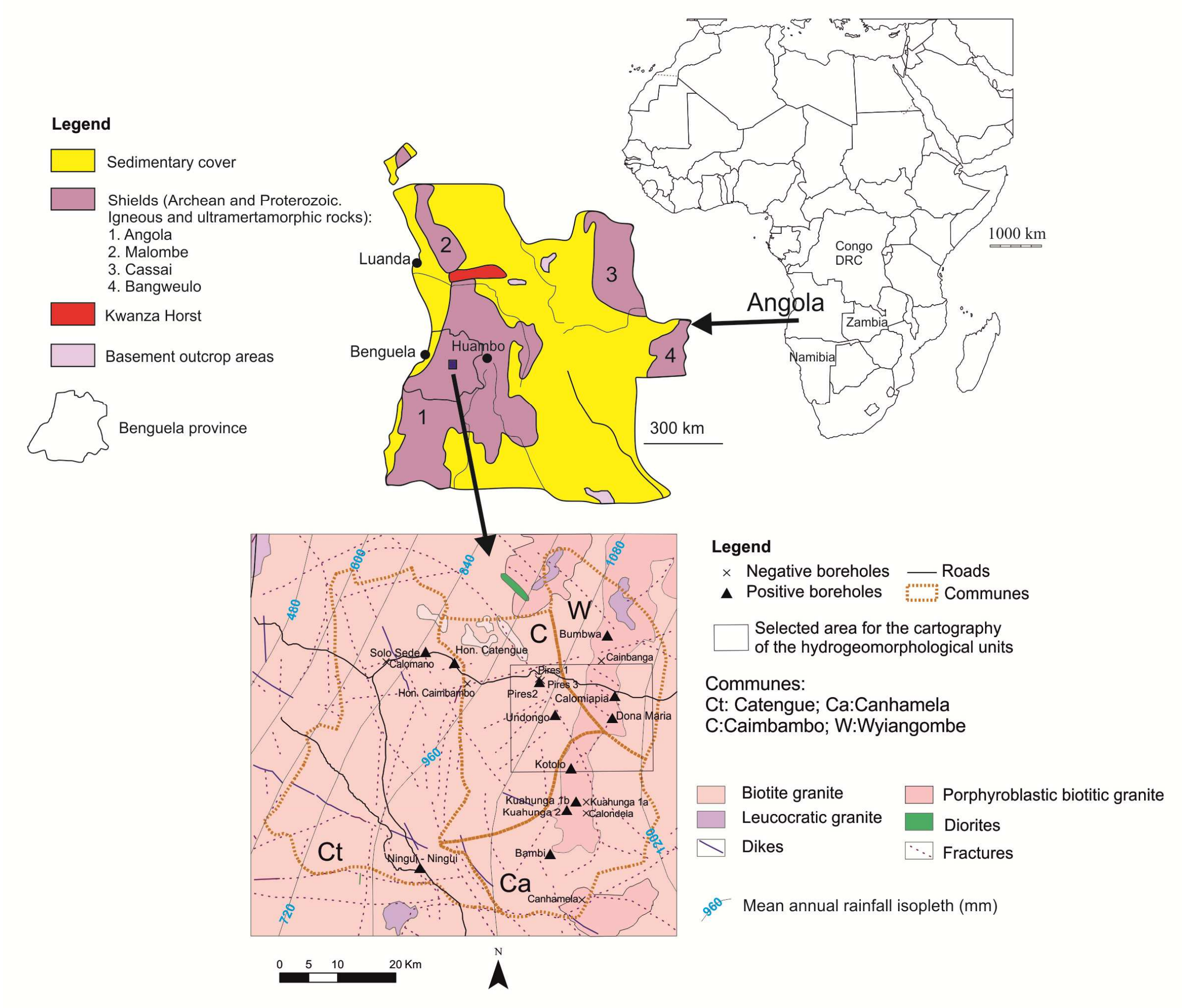

Fig. 2 Geological location of Caimbambo Province in Angola, with its main geologic features (ING 1988). Rainfall data after WTP (2007).

The Angola shield rises in elevation in successive steps, reaching up to over 2,000 m.a.s.l. The lowermost step includes a mountain range that crosses the municipality of Caimbambo in NW-SE direction, splitting it into two distinct regions. The western region has elevations between 600–700 m.a.s.l. while the eastern one ranges between 800 and 900 m.a.s.l. Inselbergs exceeding 1,000 m.a.s.l are relatively common (Fig. 3).

Fig. 3 Caimbanga creek. Upstream view from between the localities of Caimbambo and Cubal

Caimbambo is located in a transition zone between the arid coast of Benguela and the humid hinterland. Rainfall in the area is subject to a W-E gradient. The western part receives 500 mm/yr, while the easternmost part of the system averages 1,000 mm/yr (Fig. 2). Dry tropical conditions (*cacimbo*) dominate from May through October, while the rainy season lasts from November to April. The variation coefficient of annual precipitation in the municipality is very high, ranging between 40 % and 60 % (WTP 2007). The average yearly temperature is 22 °C, although it drops to 15 °C during the dry season.

The municipality of Caimbambo is located within the dry sub-humid region. It is made up of four communes (Fig. 2), with a total population of 89,715 inhabitants (2014). Over one half of the people live in sparsely-populated villages (150 to 400 inhabitants). Shallow wells are uncommon and surface water courses run dry throughout most of the year. The average distance for collecting water from streams or other unprotected sites is approximately two kilometers.

An area of 500 km^2 was selected for hydrogeomorphological mapping and RS/GIS mapping (Fig. 2). The study region is located within the humid part of the municipality, where rainfall ranges between 960 and 1200 mm. The area is geologically monotonous, granite accounting for approximately 99% of the total surface.

2.2 Spatial database development

2.2.1 Hydrogeomorphological mapping

The hydrogeomorphological map of the study area was created through the interpretation of aerial photographs. This technique was used for the recognition of fractures, lineaments and landscape units and grouping the later based on origin, slope and mean thickness of the weathered materials (Pedraza et al, 1989; Teixeira et al, 2013; Ratnakar et al, 2008). The criteria behind geomorphological delineation is the susceptibility to hold water. Thus, the map is best described as a groundwater potential map.

The shape of these units was validated during several field trips. Electrical resistivity surveys were implemented wherever the thickness of the weathered formation could not be estimated directly (see Figure 5). Electrical resistivity was chosen among other geophysical techniques because the contrast between weathered and fresh materials in terms of resistivity is substantial. Unlike other methods, resistivity offers a low-cost alternative because an inexpensive resistivity device can be constructed locally (Clark and Page 2011), and local workers can be trained in its use. The method involves applying electrical current (I) through two electrodes (A and B), the intensity of which is registered. The resulting potential difference (dV) is measured via two other electrodes (M and N). The apparent resistivity (ρa) from different materials at a depth related with the distance AB, using the Schlumberger array (MacDonald et al 2008a), is expressed as:

$$\rho_a = G\,\frac{(\Delta V)}{I},$$

where G is a factor that depends on geometry of the array.

In Vertical Electrical Soundings (VES), the central point of the array remains fixed while the distance AB increases, to obtain information from deeper sections. When profiling, the space between electrodes is fixed and the entire array is displaced along a straight line, providing information about lateral changes at the same approximated depth (ACF 2005).

The Schlumberger array was used in profiling with AB/2 measurements of 10, 15 and 30 m and in the VES with maximum AB distance = 200 m. The VES data were interpreted by curve matching with two-, three- or four-layered master curves (Orellana and Mooney 1966) using IPI2Win software (Bobachev 2002). A Syscal R1 Plus resistivity meter was used with four end reels and 11 copper and aluminum electrodes. In this study, five areas were surveyed with at least one profiling and two VES in each location (Martín-Loeches et al, 2014).

2.2.2 Remote sensing and GIS mapping

The prepared RS/GIS map provides a depiction of the suitability for drilling, rather than only an idea of groundwater potential. This facilitates interpretation by non-hydrogeologists, and is best understood in the case of alluvial plains. Theoretically, alluvial materials can be associated with good groundwater potential due to the widespread presence of loose sediments. However, in the case at hand these areas are not well suited to drilling because the boreholes would be likely to experience contamination during and after floods.

RS/GIS mapping of the selected area was undertaken through the integration, using a GIS platform, of 6 different thematic maps created from remote sensing images and Digital Elevation Models (DEM). The details of the adopted procedure are graphically summarized as flow chart in Figure 4.

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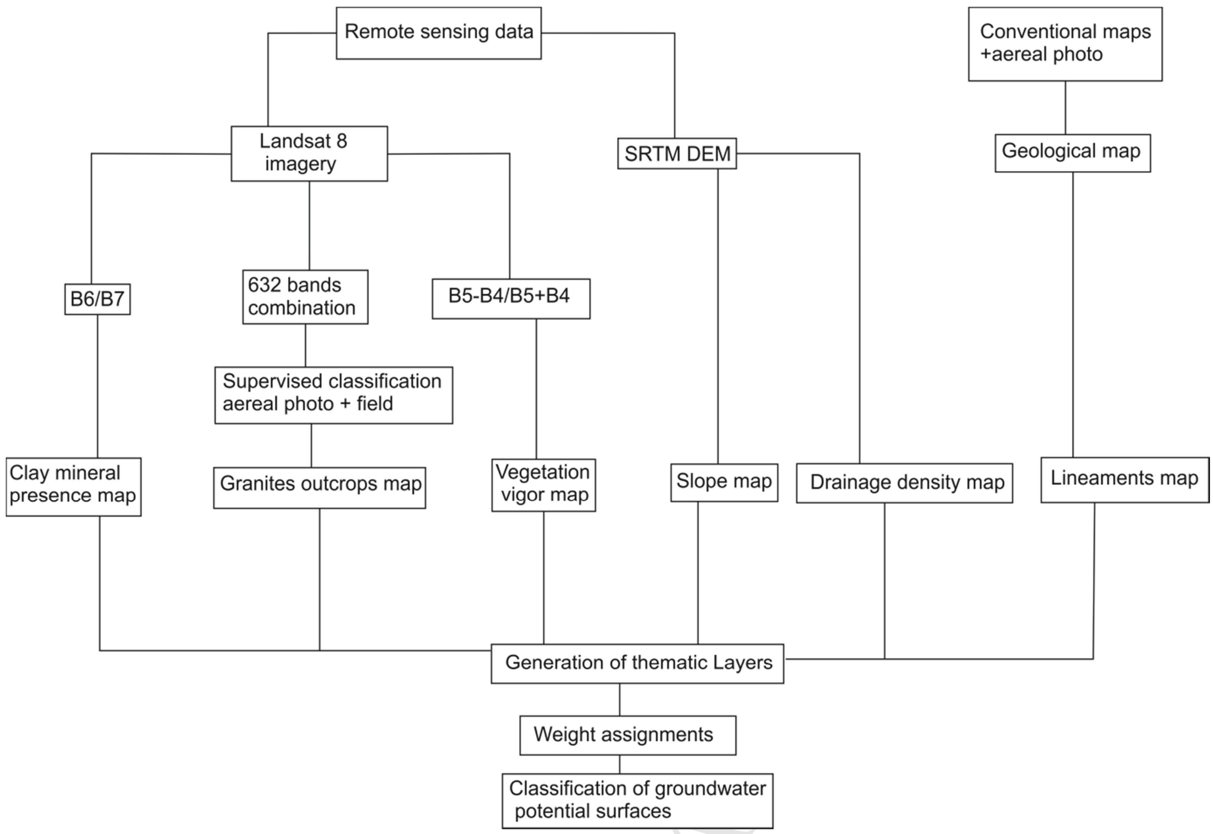


Fig. 4. Geographical database flowchart

Groundwater assessments carried out by means of remote sensing are contingent on a variety of elements or physical features of the landscape (Jha et al. 2007). These can be analyzed by means of satellite images to characterize certain hydrogeological aspects of a given region. Topography is relevant in the case at hand. More specifically, slope (S) proved to be a highly sensitive factor, as shown by the fact that eight out of twelve positive boreholes were located in predominantly flat land areas. Besides, geophysical data revealed the presence of altered granite in seventeen out of twenty-one boreholes located in flat areas.

Drainage density is also important. The drainage network seems to correlate inversely with weathering. A high drainage density (DD) is associated with erosion, and thus, results in thinner weathered formations. A small DD value allows for the identification of alluvial plains. This is useful to define these areas as unsuitable for drilling due to contamination risk. Both the slope and runoff density maps were prepared from a 90 m resolution DEM downloaded from the USGS web site (GLSDEM 2008) and compiled with ArcGis 10.1. A 30 m resolution DEM was used first, but the results did not match with coherent cartographic units, surfaces or drainage patterns.

The natural vegetation was also incorporated as the vegetation vigor using the Normalized Difference Vegetation Index (NDVI) computed from Landsat 8 bands as follows:

$$(B5 - B4)/(B5 + B4)$$

Vegetation vigor has often been associated with the presence of water in the soils and indirectly with groundwater. Since the dry season lasts for about six months, the vegetation vigor can be used as a good indicator.

Different authors define a number of indicators for groundwater potential in crystalline regions of Africa and India. These include geology, lineaments, land use, landforms or soils (Fashae et al. 2014; Teeuw 1995; Shahid et al. 2000; Singh and Prakash 2002; Chuma et al. 2013; Krishnamurthy et al (2000); Talabi and Tijani 2011). In this case, lineaments and soils were considered good for practical purposes. Lineaments (L) were obtained from the available geologic maps (ING, 1988) and Landsat 8 imagery visual interpretation. Soil mapping was used in order to take into account the presence of clays as a negative factor for infiltration and as an indicator of thin weathered formations (Chilton and Foster, 1995). The presence of clay minerals in the soil was extracted from the band ratio B6/B7 of Landsat 8 (clay mineral ratio – CMR -, after Drury, 1987). Geological maps were not directly taken into account due to the homogeneous nature of the selected area. Neither was the spatial variation of rainfall, as no important differences seem to exist in the study area (see Fig. 2).

Finally, rock outcrops (granite) (RO) are also incorporated to the analysis. Outcrops are more difficult to drill through than loose sediments and are unlikely to store much groundwater. Hence, those zones where outcrops are present are ruled out. The presence of outcrops in flat or eroded lands is not always evident, but can be identified by means of satellite images because the materials overlying shallow outcrops tend to acquire a distinct color.

Outcrops were satisfactorily recognized through a supervised classification over the false color RGB image 632 of Landsat 8 that is usually used for distinguishing differences in bare earth and is good for discerning variations in a landscape that does not contain an abundance of vegetation (Drury 1987). Aside from taking into account the field information, aerial photos were used to locate granite outcrops. Thus, a complete set of spectral signatures of the granite areas was obtained. Inselberg and other major outcrops were all clearly highlighted with this procedure, as were the majority of the smaller outcrops. Medium-size clusters of houses, bare soils and sandy valley fills present similar spectral signatures to granite. These were identified but not erased from the map, since these areas are all unfavorable for drilling. Drilling suitability in these areas is “very poor” or “poor” due to the presence of granite outcrops or to the risk of contamination.

All factors receive the same weighting for the purpose of “drilling suitability”. Geology and rainfall are often given a larger bearing on the results in other studies, while all other variables present a small range of variations (Fashae el al 2014). In this case, however, geology and rainfall can be assumed to be largely homogeneous across the site and were not considered in the analysis. Within this context, assigning a larger weighting to any of the factors under consideration might result in potentially suitable areas being “diluted” into low suitability zones. This means that the ranges need to be adjusted for each map, so that the highest ratings correspond to the higher likelihood of finding groundwater and the lowest to the lower groundwater potential.

The thematic maps were used to develop a multicriteria analisys (MCA). The range of values for each map was established first (Table 1). This was based on field observation, as well as on the experience of the authors with boreholes in the area. For instance, the 0º-2º slope owes to the fact that flat areas have been observed to favor successful boreholes. Then, each range is classified, so that the highest rating corresponds to the more favorable one. Whenever there is a significant difference between a certain range and the following one, a large gap of rating is established so as to ensure visual contrast. Negative ratings are used in those cases where a variable by itself is likely to rule out the possibility of drilling (for instance, a very steep slope). Rating in Table 1 are partially based on those by Talabi and Tijani (2011).

A weight is then given to each thematic layer based on its relative importance for drilling suitability. As explained before, in this case all maps are considered to have the same bearing on the results. Thus, the drilling suitability map (DSM) was developed by addition of all thematic layers. Drilling suitability (DS) in each pixel, i, was computed as:

$$DS_i = S_i+DD_i+NDVI_i+CMR_i+L_i+RO_i \quad (1)$$

Where DSM is drilling suitability, S_i corresponds to slope, DD_i is drainage density, $NDVI_i$ is Normalized Difference Vegetation Index, CMR_i is clay mineral ratio, L_i is lineaments, and RO_i means rock outcrops.

Table 1. Features and rating for raster classification. ***(.), with no units.***

Layer	**Range**	**Unit**	**Rating**
Slope (S)	0º-2º 2º-4º 4º-8º 8º-22º 22º-50º	*Degrees*	5 3 2 1 (-1)
Drainage density (DD)	0-5 5-8 8-15 15-20 20-22	*Km/0.031 km^2*	5 1 1 0 0
Vegetation vigor (NDVI)	0.53-0.22 0.22-0.18	*NDVI index*	4 3

	0.18-0.15 0.15 – (-1)		2 1
Soil clay content (CMR)	1.66 – 1.32 1.32 – 0.33	*Clay mineral ratio*	(-5) 0
Lineaments (L)	*Over a lineament* *Away from lineaments*	*(.)*	2 0
Rocky outcrops (RO)	*Over or near outcrops* *Away from outcrops*	*(.)*	(-5) 0

3. Results

3.1 Hydrogeomorphological mapping

Figure 5 shows the hydrogeomorphological map of the study area. It is presented alongside a set of representative VES curves. The identified hydromorphological units include:

1. Surfaces of the pediment with moderate weathering and slope < 2º. These are found throughout most of the study area. They represent smooth slopes and weathered zones with thicknesses ranging between 20 and 30 m, according to the interpretation of borehole logs and VES curves (Fig. 5). Groundwater is generally likely to be found, particularly in the rainier parts. Sandy soils predominate. Soils are well washed, which can be attributed to extensive alteration (Chilton and Foster 1995; Foster 2012). Calomiapia is a good example (Fig. 5).

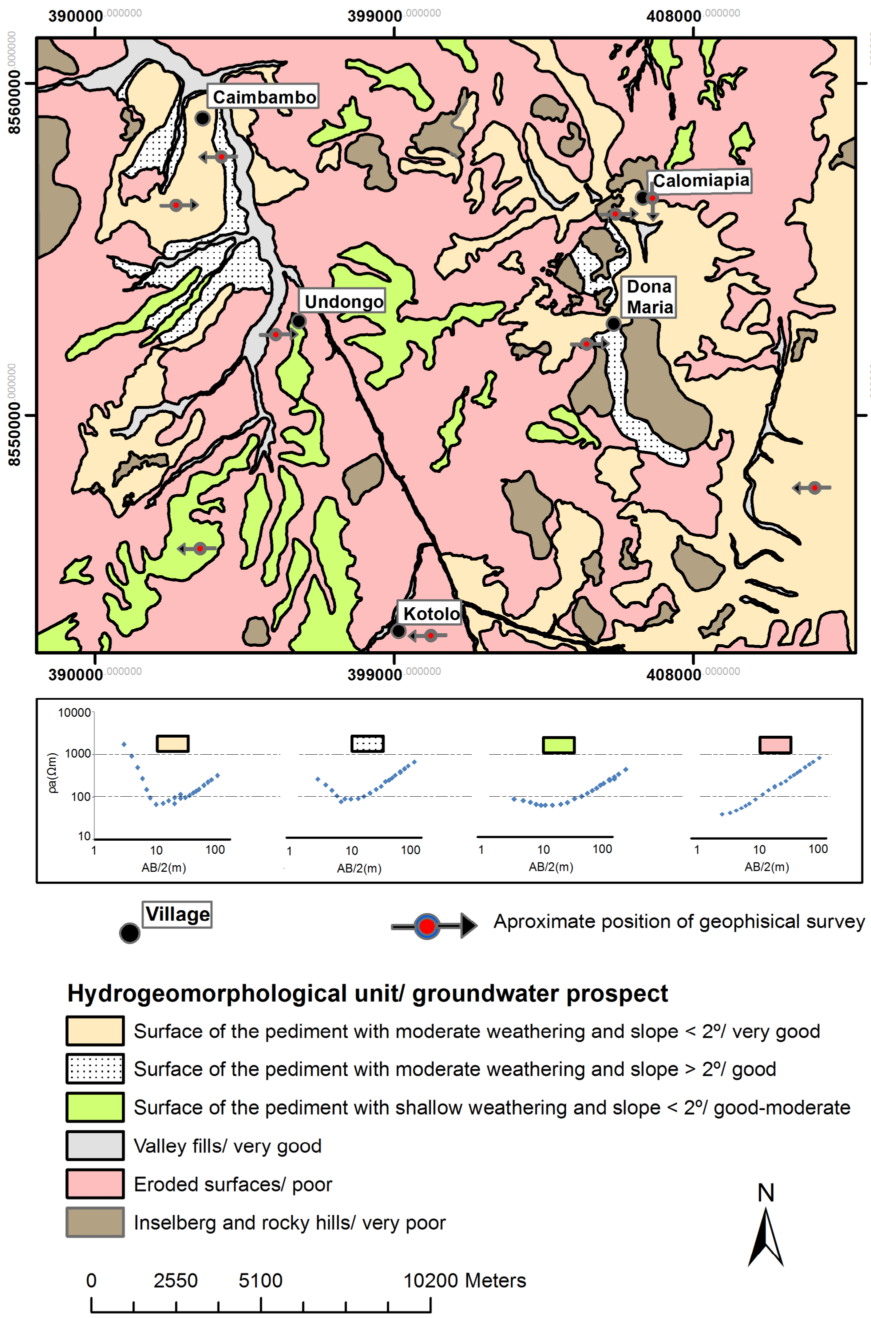
2. Surfaces of the pediment with moderate weathering and slope > 2º. These develop mostly around small elevations. Slopes are steeper than in unit 1. The thickness of weathered areas varies between 10 and 15 m (see a typical ***VES*** curve in Fig.5). Weathering products are sometimes mixed with other sediments. The most suitable areas for drilling are located in the central and outer parts, where the alteration can be expected to be greater. Examples can be found in Dona Maria (Fig.5).

3. Surfaces of the pediment with shallow weathering and slope < 2º. These areas present some groundwater potential. However, this is limited by the thickness of the weathered formation, which has been partially eroded away. Thicknesses may reach 10 meters. These parts have occasionally proven productive and are generally favorable for infiltration. An example is around the village of Undongo (Fig. 5).

4. Valley fills. These unconsolidated formations comprise a mix of pebbles, cobbles, gravels, sand and weathered materials. They present highly heterogeneous granulometries and are highly permeable. This results in substantial infiltration rates. Given the large amount of recharge, these may be considered favorable groundwater zones. However, extreme care must be taken to avoid contamination. Groundwater yield can be expected to depend ultimately on thickness of the subsurface sediments. Stagnant areas where the flow is poorly defined are also included. Kotolo provides a good example (Fig. 5).

5. Eroded surfaces. These correspond with areas where surface erosion is active, due to the presence of streams. Slopes exceed 2º and outcrops are common. Soils and weathered areas present an irregular spatial distribution. Groundwater is generally unlikely, although there is some probability of groundwater occurrence in between blocks or wherever a sub-superficial current can take place.

6. Inselbergs and rocky hills. Finding groundwater in these areas is highly unlikely..



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308 **Fig. 5. Hydrogeomorphological units of the study area with an indication of groundwater**

309 **likelihood. Typical SEV curves are included**

310 Table 2 summarizes the resistivity ranges for different materials in the studied region. These have

311 been completed with borehole logs.

Table 2 Resistivity values in the study area

Material	Resistivity (Ω.m)
Sandy-clayey superficial soils	60-150
Sandy soils	1500-2800
Dry clays	8-80
Laterites	100-150
Weathered granite	50-250
Weathered granite with clay	15-150
Fresh granite	>2000

VES curves were used to site a borehole in each surveyed unit. A good agreement was found between field information and the interpretation (Martín-Loeches et al, 2014).

3.2 Remote sensing and GIS mapping

Although all factors present the same weighting for the drilling suitability map, slope provides a solid ground to differentiate those landscape features identified by means of aerial photographs (compare Fig. 6 a with Fig. 5). This poses an advantage in terms of comparing both maps. In the case at hand, slopes range from flat to over 50 degrees. Gentler inclinations correspond to pediment units and valleys, while steeper zones are associated with inselberg, outcrops and other prominent features. A 90 m resolution DEM was used for optimal results. Rating (Table 1) was enhanced in order to obtain a sufficiently strong contrast between inselbergs (-1) and flat surfaces (5) in the final map (Figure 7).

The drainage density map (Fig. 6 b) is constrained by two main factors. The first one is that boreholes should be placed outside flooding areas, so as to avoid contamination. The second stems from the assumption that a greater drainage density results in a higher degree of erosion, and hence, in thinner weathered formations. Rating is considered (0) for the highest densities, (5) for the lowest density, and (1) for the medium density (see Table 1). In this way, channels are clearly depicted in the final map (Fig. 7). A 100 m buffer is assumed to be enough to prevent ordinary flooding. The 90 m resolution DEM avoids the disturbance caused by very small watersheds.

Vegetation vigor (Fig. 6 c) was classified between 1 and 4 based on NDVI values (Table 1). It is included in the analysis because clusters of trees, most notably baobabs, are associated directly with soil moisture and indirectly with groundwater. Thus, this indicator provides an idea as to where shallow groundwater can be found in the absence of surface water bodies. Riverside vegetation vigor is often high, which implies a high likelihood of groundwater occurrence. However, as explained earlier, areas near streams and rivers are unsuitable for drilling wells due to the ease with which these can become contaminated. Therefore, riverine vegetation was blacked out using the drainage density map (Fig. 6 c).

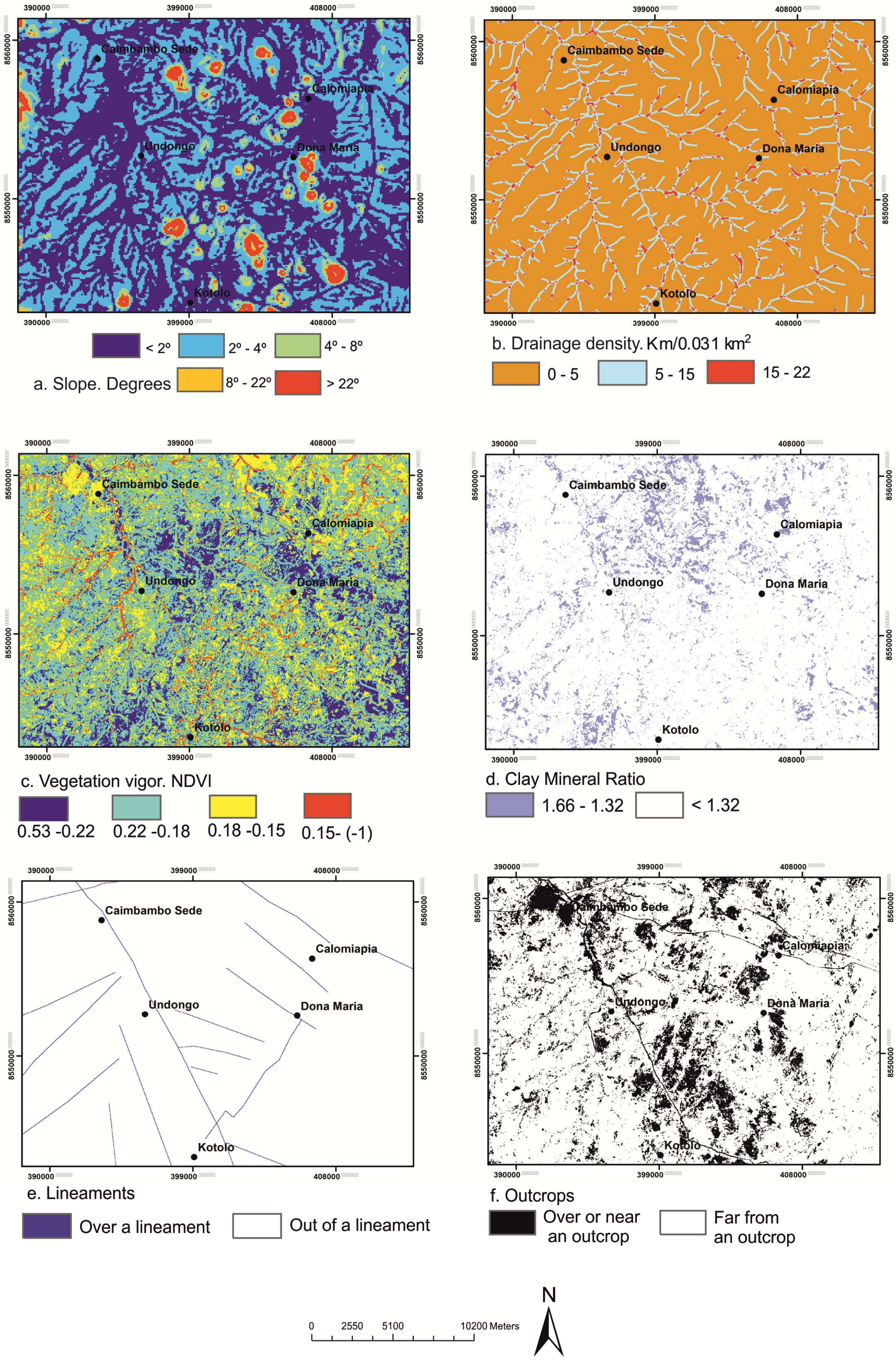
The presence of clay minerals in the soils (Fig. 6 d) is considered an indicator of poor infiltration potential. Additionally, it can be used to identify thinly weathered formations (Chilton and Foster, 1995). In this case, its absence in flat areas is useful to distinguish favorable drilling spots in terms of weathering thickness, permeability and flow. Areas with the highest presence of clay minerals in soils were assigned a rating of (-5) to reinforce their appearance, while 0 was assigned to the rest (Table 1). It is worth noting that this feature only works because the lithology across the study area is remarkably uniform.

Lineaments (Fig. 6 e) constrain groundwater flow and storage. They also delineate areas where the thickness of the weathered formation is potentially greater. The lineaments map is developed based on the available geological cartography, as well as on aerial photos. A 25 m buffer was defined to both sides of each lineament. Rating ranges between 0 and 2 so as to make lineament features recognizable in the final map.

Outcrops are also delineated and added (Fig. 6 f) because they are critical for drilling purposes. Aerial photographs are usually of limited use, particularly in the case of the smaller outcrops, but a reasonably accurate picture can be obtained by means of Landsat 8 imagery. A 25-meter buffer was applied to the delineation of outcrops so as to take into account the need to drill away from the influence area of the bedrock.

In Figure 6F, house clusters in the largest village (Caimbambo Sede) are marked as if they were granites. This is because building materials and bare soils present a spectral signature which is akin to that of granite. A similar reasoning applies to some alluvial plains where sand is widespread, as well as to the road that links Caimbambo and Cubal.

As boreholes are to be equipped with hand pumps, drilling areas are limited to a radius of 500 m around human settlements. Infrastructures such as houses are easily located by means of aerial photographs. Villages are also solid indicators of latrine-related pollution.



390000
399000
408000
8560000
8550000
Caimbambo Sede
Calomiapia
Undongo
Dona Maria
Kotolo
< 2º
2º - 4º
4º - 8º
a. Slope. Degrees
8º - 22º
> 22º
b. Drainage density. Km/0.031 km2
0 - 5
5 - 15
15 - 22
c. Vegetation vigor. NDVI
0.53 -0.22
0.22 -0.18
0.18 -0.15
0.15- (-1)
d. Clay Mineral Ratio
1.66 - 1.32
< 1.32
e. Lineaments
Over a lineament
Out of a lineament
f. Outcrops
Over or near an outcrop
Far from an outcrop
N
0
2550
5100
10200 Meters

365

Figure 6. Thematic maps integrated in the RS/GIS analysis. Slope, drainage density, vegetation vigor, clay mineral ratio, lineaments and rock outcrops

Figure 7 presents the drilling suitability map that results from applying formula (1). Pixel values (DS_i) range between (-5) and 16. These need to be reclassified so that the map is useful in the context of boreholes equipped with hand pumps. Favorable areas correspond to DS values in excess of 11, while poorly suited areas are below 10. Thus, alluvial plains and house clusters are shown as “poor” and can be ruled out for drilling. The higher scores (“very good”) are located within “good” areas, and typically correspond with the presence of faults (in weathered zones), with a positive NDVI, or with both. “Good” zones may also contain some small “poor” or “very poor” spots due to the presence of minor outcrops or clayey soils in flat areas.

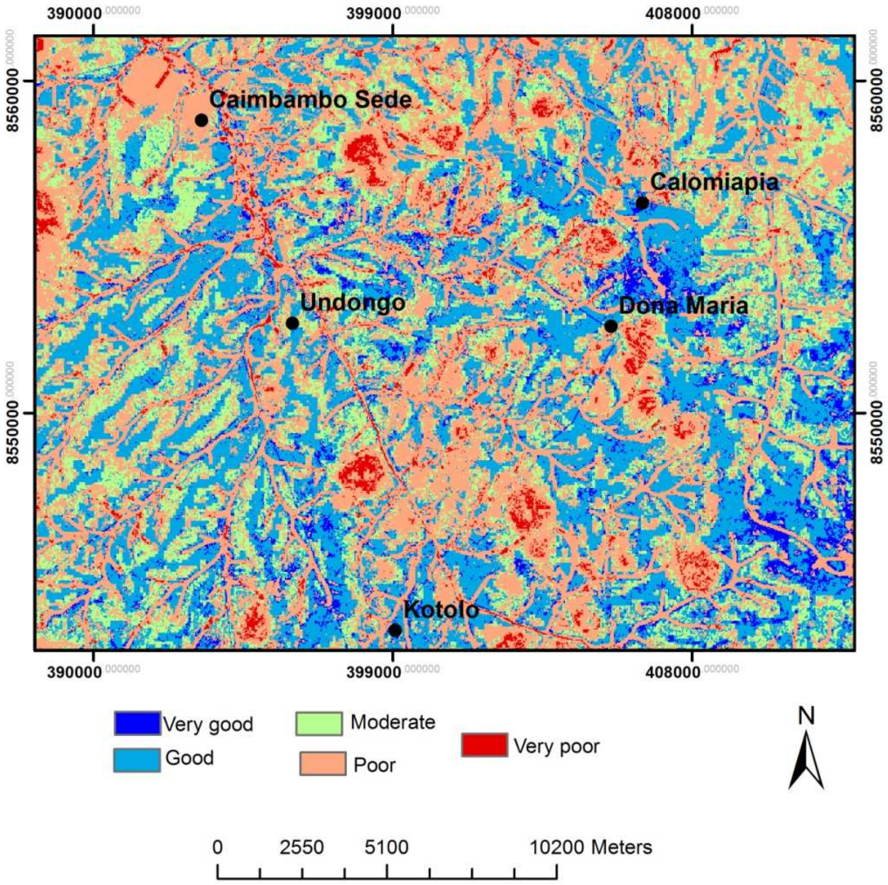


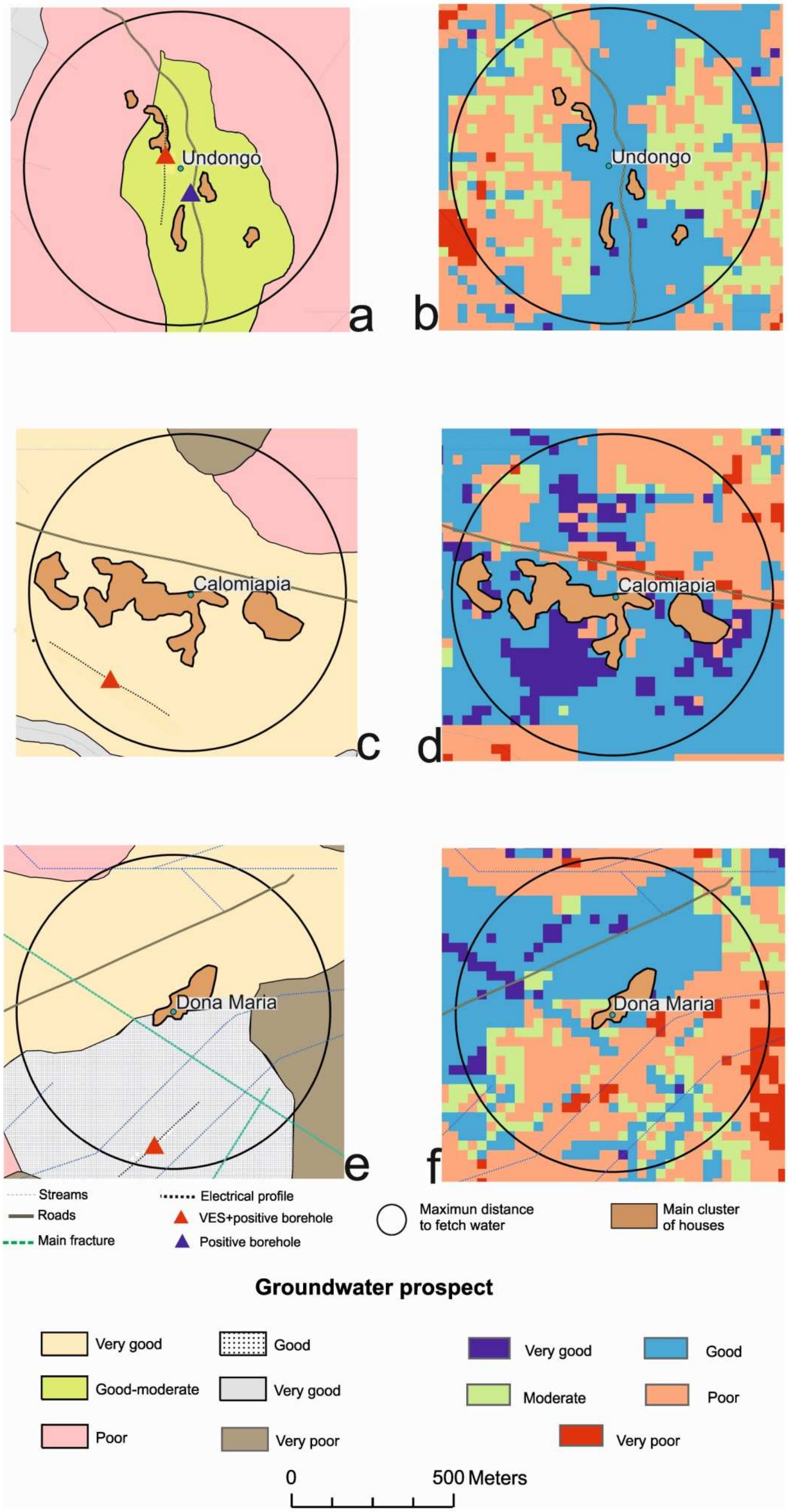
Figure 7. Drilling suitability map of the studied area. This is the result of integrating the six thematic maps

4. Discussion

For the purpose of the ensuing discussion it is useful to distinguish three geographical domains, namely Undongo, Calomiapia and Dona Maria. Figure 8 presents the outcomes of the classic and RS/GIS approaches for all three sites. A black circle represents the area within five hundred meters from each village, which is considered the maximum tolerable distance for fetching water.

In the case of the Undongo area, the RS/GIS method (Fig. 8 b) and the classic hydrogeomorphological map ("classic map" hereon) (Fig. 8 a) render similar outcomes. The RS/GIS map perhaps does a better job in terms of distinguishing areas of greater prospect. For instance, it is more accurate at separating the flatter and more promising zone of the pediment (i.e. the "good-moderate" zone identified during the field survey) (Fig. 8a). This area is narrower in Fig.8b than in Fig. 8a, a feature that can be attributed to the presence of small granite outcrops. These were detected by means of the supervised classification, but could not be identified in the aerial photo or during the field survey. In this case, neither the absence of clayey soils nor the presence of mapped fractures result in better groundwater potential. However, vegetation vigor is highlighted in three dark-colored isolated pixels to the south of the village, corresponding to clusters of trees (Fig. 8b). This suggests that these three points present a better groundwater prospect. The fact that they fall approximately along a line implies the likely presence of a major fracture. Based on this information, economic factors would determine whether to undertake a geophysical survey (possibly through a series of transects perpendicular to the fracture line), or to drill directly.

In practice, the "Good-moderate" prospect zone in Fig 8a was used as the basis to determine where to carry out a geophysical survey, whose outcomes were used to site a successful borehole (red triangle in Fig. 8a). A second borehole was drilled near the trees several months later (black triangle in Fig. 8a). In this case, the location was established without a geophysical survey. In spite of this, the second well presented a higher yield. This highlights the potential usefulness of the RS/GIS approach, which would have identified that as a more favorable location from the outset.


Undongo
Undongo
a
b
Calomiapia
Calomiapia
c
d
Dona Maria
Dona Maria
e
f
Streams
Roads
Main fracture
Electrical profile
VES+positive borehole
Positive borehole
Maximun distance to fetch water
Main cluster of houses
Groundwater prospect
Very good
Good-moderate
Poor
Good
Very good
Very poor
Very good
Moderate
Good
Poor
Very poor
0
500 Meters

409

Figure 8. Standard mapping approach versus remote sensing and GIS cartography. The pictures to the left correspond to the classical approach, while the pictures to the right present the outcomes of the RS/GIS database. The black circles represent a five hundred meter radius around the village, which is considered the maximum reasonable distance for fetching water.

Both procedures are able to distinguish the area of greater groundwater potential in the Calomiapia area (Fig. 8c and d). Gently-sloping pediments are classified as “very good” groundwater prospects by the classic approach and as “good” prospects by the RS/GIS map. The RS/GIS method also includes some “very good” pixels, corresponding to clay-free spots where vegetation vigor is high (Fig. 8d). While these do not show the thickness of the weathered formation, they do provide valuable information as to where to drill (or where to refine the existing hydrogeological knowledge via geophysical investigation). As it turns out, a geophysical survey revealed that the weathered formation in this area is about 25 meters thick. Houses were observed to generate enough noise to be taken for granite outcrops. Hence they were discarded based on aerial photos.

Dona Maria is located on a flat pediment surface that is classified as a “very good” groundwater prospect by the classic map (Fig. 8e).The RS/GIS approach classifies it as a “good” zone (Fig. 8f). Vegetation vigor and lineaments mark a series of dots that could be enough to make a first decision as to where to drill. Lineaments are drawn over the classic map (Fig. 8e), thus delineating high groundwater potential zones. However neither of them could be evaluated, since the geophysical survey and the borehole that was drilled to supply the village was finally located on an adjacent piedmont (Fig 8e). The 26-meter borehole yielded over 2 m^3/hr and did not reach the granitic basement (Martín-Loeches et al 2014). Piedmonts may present high groundwater potential because they are essentially a mix of weathered and transported materials. Nevertheless, the RS/GIS analysis does not recognize them as good prospects due to the presence of steep slopes (around 6º-8º). This is a consequence of the low rating (2) given to sloping areas (Table 1). Indeed, slope was identified as one of the single most important factors in the RS/GIS approach.

Finally, the case of Kotolo also deserves a short comment, as it exemplifies some of the differences between the outcomes of the two approaches. Kotolo is located near an alluvial plain. While the classical map classifies the alluvial plain as "very good", it is known that rivers often act as pollution vectors and that floods can contaminate the wells. Also, floodplains may become inaccessible during the rainy season. This means that these areas need to be avoided and that drilling should focus on other geomorphological units.

The village actually lies on flat eroded terrain. Small outcrops are present throughout this area. These result in a "poor" classification as per the classic map (Fig 5). However, RS/GIS imagery renders a "good" classification due to the average slope of the land (Fig 7). It also manages to recognize the outcrops and represents them as "poor" or "very poor" isolated pixels, thus rendering a more accurate picture of the field conditions. The outcome of the Kotolo borehole is consistent with the RS/GIS map. The well is located within the area, but away from the outcrops. It yields 2.5 m^3/hour, which is considered sufficient to meet the needs of the local population.

5. Conclusions

The integration of thematic maps within a RS/GIS environment can be useful to identify areas where borehole drilling is likely to render adequate results for the installation of hand pumps in crystalline environments. This approach allows for the identification of the more suitable areas, i.e. those where weathered materials are more likely to be encountered. A good agreement was found between the RS/GIS final map and the one drawn by means of a classical approach. Both provide a hydrogeomorphological classification of the region and provide an idea of the spatial distribution of its groundwater potential.

It is concluded that slope and drainage analysis of medium-size areas (DEM resolution 90 m) coupled with other relevant information, may provide useful groundwater potential estimations at the village scale. This is perceived as a more realistic approach than evaluating the outcomes on a pixel-by-pixel basis, as crystalline environments tend to be highly anisotropic.

The RS/GIS procedure provides a welcome addition to hydrogeomorphological mapping. This is mostly because it distinguishes small changes in slopes. In this case, steep slope was considered to be a determining hydrogeological factor. Thus, even the moderate slopes were classified as poor groundwater prospects. This leads to ruling out some theoretically favorable surfaces such as piedmonts.

In the absence of borehole data, groundwater potential can be estimated from indirect indicators such as vegetation vigor, lineaments and soil clay content. This provides a cost-effective approach whose main advantage is the potential to narrow down the geographical area of field surveys, including geophysical investigations. While expert judgement will always be required, the method is sufficiently simple for local technicians to learn and apply.

The RS/GIS approach can be considered useful in view of its application to three distinct areas of the Caimbambo province. However, it must be acknowledged that it also has some limitations. In particular, it is restricted to identifying suitable areas. In other words, it cannot point out specific spots. This is largely because the most important parameter, i.e. the thickness of the weathered formation, is also the most uncertain one. Thus, even if there is good information in terms of vegetation vigor, sandy soils (or absence of clays) or lineaments, the heterogeneity of subsurface geology is greater than the precision that can be reached with this procedure.

Moreover, the study area was selected based on a specific set of physical, climatic and geological conditions. While it is safe to assert that this method has the potential to be useful in many regions across the African continent, it is also true that it needs to be applied in uniform geological domains. Whenever different lithologies co-exist, the presence of various weathering products are likely to induce errors in the conclusions.

In addition, it must be acknowledged that the randomness of subsurface geology is greater than the precision that can be reached with this procedure, and that the approach is contingent on the quality of remote sensing data. Hence, outcomes are only valid as a first approximation, and further work is needed to refine the methodology.

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Highlights of

Comparison of RS/GIS analysis with classic mapping approaches for siting low-yield boreholes for hand pumps in crystalline terrains. An application to rural communities of the Caimbambo province, Angola

1. Remote sensing/GIS and classic hydrogeomorphological maps yielded similar results

2. Layers of vegetation vigor, soil clay and rocky outcrops can differentiate areas of high hydrogeological interest

3. Granite outcrops´ spectral signature marks areas of bad suitability for hand pump equipped boreholes.

4. Thickness of weathered formations is a key factor that must be still cheked in the field in any approach

5. Remote sensing/GIS is cheaper and easier to implement but expert decision is needed