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Piezometric Modelling of a Hard Rock Aquifer System in An Intertropical Zone: The Case of the Batouri Mining District (South-East Cameroon)

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Abstract The economic growth of Batouri and the surrounding area has considerably increased the population. This situation has led to a high demand of water, which much of it is met at the hard rock aquifer system. However, understanding the hydrodynamic functioning of this system remains unveil, which has turn a challenge for water management in the region, due to mining and agricultural activities that is being practised there. To overcome the consequences of these activities, a study was carried out using the modelling technique, by exploiting the linear correlation among the levels of the ground surface and the water table surface, with the thalwegs base surface; in order to map the geometry of the water table over an area of 189 km2. The data used includes boreholes data sheets, field measurements (static and dynamic levels) and a digital elevation model (DEM). The water table elevation deduced from the mathematical model were compared with those measured on the field; this has been revealing a variation of ±1.43 metres. This variation at the scale of the study and the non-synchronous conditions of the measurements is largely acceptable. The comparison indicates satisfactory consistency between the modelled and the observed data, reinforcing the validity of the model. The water table map obtained highlights the presence of numerous domes and reveals a groundwater flow pattern that follows the topography, draining towards surface water. Although the inverse relationship between groundwater and surface water was not clearly established at the study's scale, it is interesting to note that the hydrological and hydrogeological catchment areas coincide, suggesting a close connection between the two systems. These results provide a solid basis for understanding groundwater flow in the Batouri area. They are essential for scientists and water managers, as they will enable more integrated management of water resources, taking into account the region's expanding economic activities.

Keywords: *modelling, piezometry, hydrodynamics, hard rock aquifer, batouri, cameroon*

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1. Introduction

Knowledge and information of groundwater dynamics is crucial for its effective management [1,2]. From all the methods to obtain groundwater informations, piezometry represents a classic approach in hydrogeology.

Water table maps provide a cartographic representation of the various variations in the surface of the groundwater table. They provide invaluable information on the growth of the water table, with levels of uncertainty depending on the number of structures used in their representation, but also on the direction of water flow. They are therefore an effective tool for managing aquifer systems.

In Cameroon, the basement formations cover around 90% of the country's surface area, but are still largely unknown from a hydrogeological point of view [3], particularly with regard to their piezometric aspects. Several factors contribute to this situation, such as the lack of information access technologies, difficulties in accessing certain areas at certain times and the challenges inherent in the complexity of these aquifer formations [4,5,6]. As a result, these resources remain largely under-exploited compared with similar formations in other regions of the world, such as West Africa and India [7].

The Batouri area, located in the south-east of Cameroon is found in a forest environment, it is also an important mining district where artisanal gold mining has been practised for over 50 years [8]. In addition to mining activities, agriculture and logging are also practised in the region [9]. These activities are likely to mobilise pollutants that could contaminate groundwater [10,11], which is one of the main sources of drinking water for Batouri's population, which has grown from 25,000 in 1976 [12] to 103,154 in 2018 [9]. In fact, only part of the urban area is served by a water supply network [9], underlining the importance of understanding groundwater circulation will help to prevent contamination during degradation.

Most of Batouri’s and the surrounding area is still covered by dense vegetation, which makes it difficult to access hydrogeological informations, particularly dynamic levels, via structures that are not sufficiently representative to produce water-table maps. In this study, we used piezometric surface modelling to overcome this problem. This approach overcomes the limitations associated with the absence or inadequacy of data by establishing equations to determine water table levels over an entire surface [13]. Hydrogeological modelling is increasingly used for a variety of purposes, including contaminant transport, catchment analysis, saline intrusion, climate change effects and groundwater reserve mapping, using a variety of tools [14,15,16]. However, to our knowledge, this is the first piezometric study carried out in the region.

The main objective of this study is to model the water-table elevation surface of the Batouri basement aquifer system and its surroundings in order to study its dynamics. More specifically, we aim to (a) study the relationship between topography and water-table elevation surface, and (b) examine the configuration and evolution of groundwater in the region.

2. Description of the Study Area

2.1. Geographical and Climatic Characterisation

Located in south-east Cameroon, the study area covers an area of 189 km^2 and comprises five sub-basins of the Kadey river, which itself is a tributary of the Congo river. It is bounded by coordinates 04°21' and 4°31' north latitude and 14°19' and 14°28' east longitude (see Figure 1). The prevailing climate is a warm, humid equatorial Guinean type, characterised by four distinct seasons: two rainy seasons interspersed with two dry seasons. The short rainy season extends from mid-March to mid-June, followed by a short dry season from mid-June to mid-August, then the long rainy season from mid-August to mid-November, and finally the long dry season from mid-November to mid-March. Annual rainfall varies between 1500 and 2000 mm, with an average temperature hovering around 23°C [9].

From a geomorphological point of view, the study area is characterised by gently undulating hills, with altitudes ranging from 550 m to 700 m, resulting from erosion processes. These hills open out into deep river valleys [17], through which flow permanent rivers such as the Belégonga, Bokoto, Kpangala and Djengou. The region's soils are mainly ferralitic and hydromorphic, covered with forest-type vegetation. However, this vegetation is increasingly being exploited and degraded for industrial (timber and gold) and agricultural purposes, giving way to a growing expansion of the savannah. This economic attractiveness is leading to an increase in the population and greater pressure on water resources [9,12].

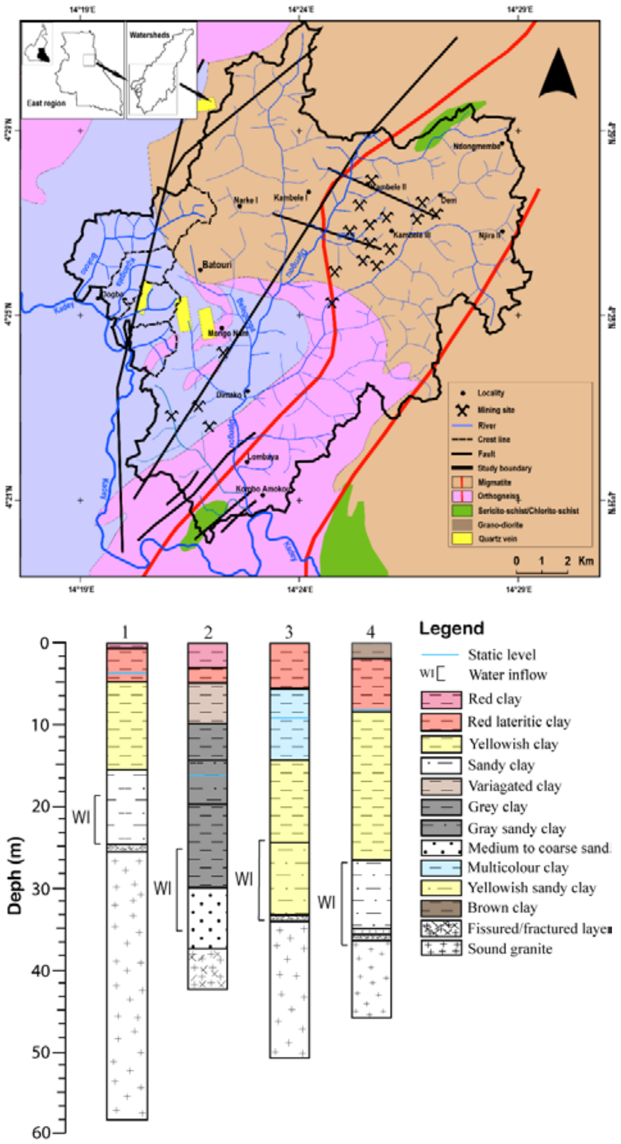

Figure 1. Location of the study area, superimposed on the geology (source [23]), and lithostratigraphic logs of some boreholes showing the vertical structuring of the aquifer system

2.2. Geological and Hydrogeological Context

The study area lies geologically within the Adamaoua-Yaoundé domain, the largest of the three that make up the Central African Pan-African Chain (CPAC) in Cameroon, and is intensively studied because of its significant economic potential [8,17,18]. This area is characterised by an abundance of potassium-rich calc-alkaline granitoids dating from 640 to 610 million years ago. These granitoids are intrusive in the gneisses, which form the basement of Palaeoproterozoic age [19].

The Batouri area has a variety of granitic rocks, including potassium feldspar granites, granodiorites, tonalites and syenomonzogranites [17]. These formations have been subjected to deformation and are intruded by gold-bearing quartz veins, pegmatite dykes and aplite granites. Enclave biotite gneisses are also present in these rocks, interpreted by [20] and [21] as fragments of basement rocks of Paleoproterozoic and Archean age, or meta sedimentary rocks of Neoproterozoic age.

Structurally, the area is characterised by strong fracturing at both regional and microscopic scales [17]. The main directions of these fractures are NNE-SSW, NE-SW, and ENE-WSW [19]. The most significant fracture extends over 13 km with a NE trend. Gold-rich quartz veins are mainly located along these fractures and have been mined for several decades [8].

In this geological context, a composite aquifer system is formed hydrogeologically, consisting of different superimposed reservoirs [5,22]. From top to bottom, the weathering reservoir, mainly composed of clay and sand with low permeability, plays a capacity role [22]. Below this is the fissured/fractured layer, resulting from the swelling of certain minerals such as biotite contained in the rocks. It has a higher permeability, conferring a transmissive function [22]. Finally, beneath these two reservoirs, discontinuous geological structures such as faults, quartz veins, aplites, pegmatites and diaclases may be locally water-bearing [4,6].

3. Materials and Methods

3.1. Data

Different types of data were used in this study. These included the Batouri East sheet geological map drawn up by [23], borehole data sheets containing various items of information such as their location and water table elevations. A 12.5 x 12.5 m resolution Alos palsar DEM and the water table levels of a set of 95 structures spread across the area and measured seasonally between 2019 and 2020.

3.2. Method

The production of a water table map requires an adequate density of points and an effective distribution over the area studied. However, due to the lack of data on piezometric levels and their poor spatial distribution, the modelling method proved necessary. The technique used here is based on that developed by [16], which was successfully used in the tropical zone of Côte d'Ivoire by [13]. This method is based on several fundamental observations. Steady-flowing rivers act as natural groundwater dischargers. Thus, the water table surface is considered to be outcropping in thalwegs. Consequently, when following the ridges, the water table surface is always between the topographic surface and the envelope surface at the base of the thalwegs. A schematic representation of this method is shown in Figure 2.

To obtain the surface of the base of the thalwegs, a series of steps was undertaken. Firstly, the drainage network was automatically extracted using the DEM, then transformed into a network of points, and finally kriging the altitude of each point thus obtained. The region is crossed by permanent rivers that never dry up.

The water table levels of the structures measured in the field (Wt) were corrected according to the altitude of the ground on the digital elevation model (DEM), in order to compensate for errors due to variations in the values provided by the GPS in the field. Similarly, when calculating the water table levels modelled in the study area, the ground elevation is obtained from this DEM to ensure data uniformity.

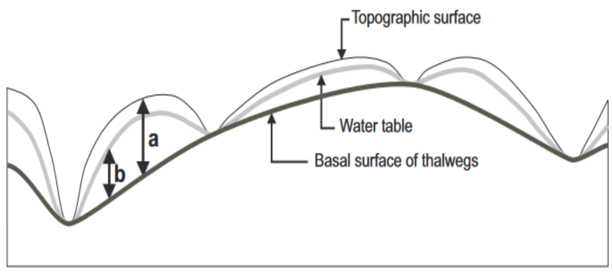

Figure 2. Principle of water-table modelling (after [16]). a: difference in level between the ground surface and the base surface of the thalwegs. b: difference in level between the water table elevation and the base surface of the thalwegs

In this way, it is possible to determine the point elevation of the surface at the base of the thalwegs (Zt) and the ground elevation (Zs) for each point used in the model. The parameters a and b of the model (Figure 2), whose correlation has been demonstrated by [16], are defined as the difference in level between the ground surface and the surface at the base of the thalwegs (Zs - Zt) and the difference in level between the water table elevation surface and the surface at the base of the thalwegs (Wt - Zt) respectively, can be obtained.

4. Results

Fluctuations in the water table were analysed at a number of points (wells and boreholes) whose behaviour is representative of the area (Figure 3). In the wells, the lowest level is 18.9 m (P266) observed at the end of the long dry season in March. This point (P266), located at altitude, maintains the same value in June, corresponding to the end of the short rainy season. It only reacts in November, at the end of the long rainy season, with its highest value at 16.3m. The highest level in the wells is 1.6m, in well P136, located at the bottom of the slope. This position was maintained during the following two seasons, with values of 1.3m and 1.2m respectively. Some points show atypical behaviour, with lower values at the end of the short rainy season than during the long dry season (P211, PA40, P284, P201).

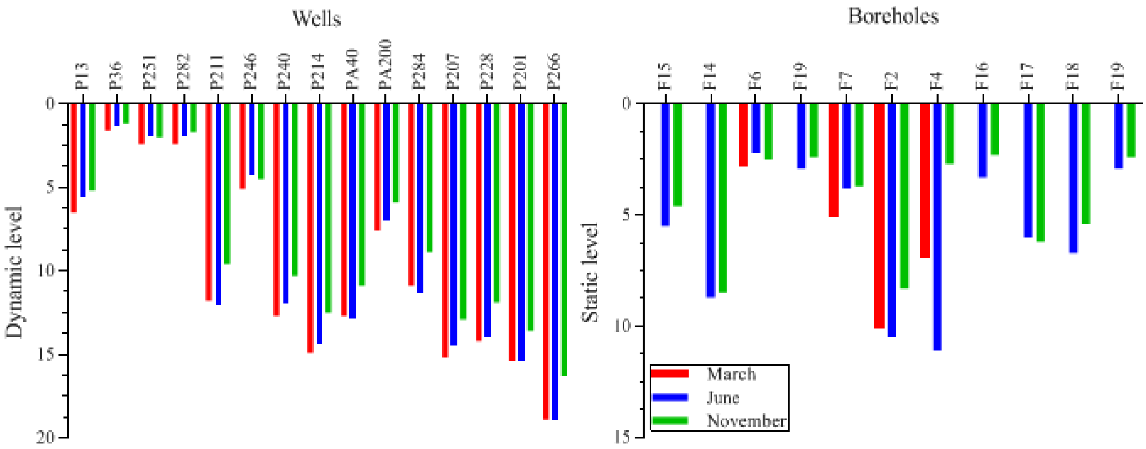

Figure 3. Spatial and temporal evolution of water levels in structures

Static levels in the boreholes are stabilising at similar levels to those in the wells. For the deepest wells, they ranged from 10.1m (F2) to 2.8m (F6) in March. Then from 11.1m (F4) to 2.2m (F6) in June, and finally from 8.5m (F14) to 2.3m (F16) in November. It should be noted that some measurements could not be carried out due to the absence of the managers, and that some points were identified as the seasons progressed. Like the wells, some boreholes show water level values that sink at the end of the rainy seasons, the most spectacular being borehole F4. Its level rises from 6.9m at the end of the long dry season to 11.1m at the end of the short rainy season, reaching a level of 2.7m at the end of the long rainy season.

After extracting and transforming the drainage network into points, kriging them using a simple spherical model produced the distribution of the surface of the base of the thalwegs shown in Figure 4. It has a resolution identical to that of the Alos palsar DEM (Figure 5), which reflects the geomorphology, on which all the structures measured in the field and used in the modelling are located.

Using the variation in the base of the thalwegs, the DEM and the water table level data from the structures measured in the field, it is possible to express the parameters a and b of the model, whose linear relationship is shown in Figure 6. This relationship is adjusted by the mathematical model in equation 1.

$$y = 0.5677x - 2.3768 \qquad (1)$$

With R^2= 0.85.

The coefficient of determination obtained on the basis of equation 1 is close to 1, thus validating the significant relationship between the parameters. The relationship in Figure 6 also shows that the parameters a and b for a number of points have negative values. By eliminating these points, which theoretically describe either an artesian water table (negative a) or a water table level above the measured level (negative b), we do not obtain an improvement in the coefficient of determination in the relationship between the two parameters (R^2=0.80).

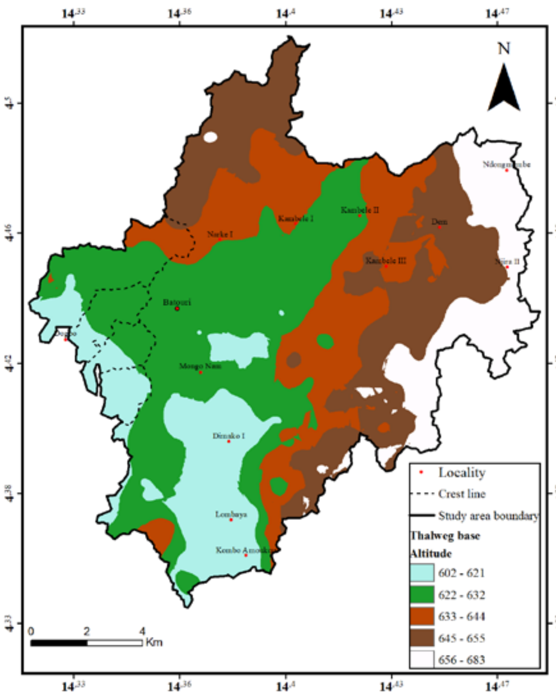

Figure 4. Variation in the base area of the thalwegs derived from kriging the elevation of dranage network transformed into points

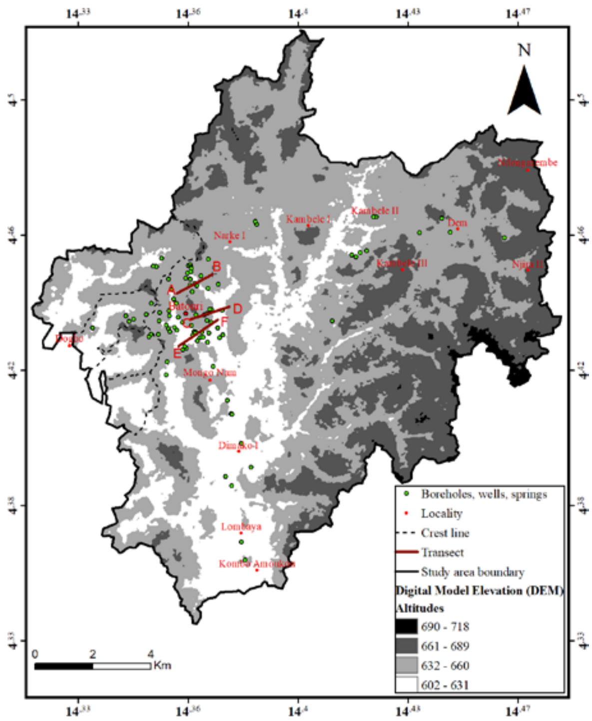

Figure 5. Digital Model Elevation (DEM) and location of the 95 points (boreholes, wells, springs) used for modelling

From this relationship, it is possible to calculate the water table elevation at any point in the study area, using equation 2, where a is equal to the difference between the altitude at ground level and that at the base of the thalwegs, and b is the difference between the water table elevation and the altitude at the base of the thalwegs.

$$Wtc = 0.5677(Zs - Zt) + Zt - 2.3768 \qquad (2)$$

Zs and Zt represent the ground elevation and base elevation of the thalwegs, obtained respectively from the DEM and the variation map of the thalweg surface base (Figure 4), and Wtc the water table elevation calculated at each point in the study area.

Applying equation 2 to each point in the study area produced the water table map shown in Figure 8.

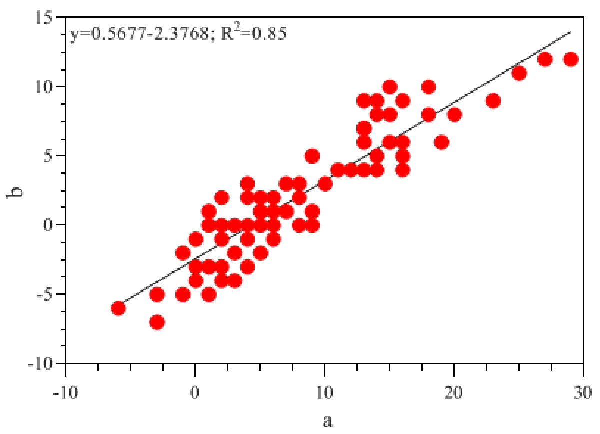

Figure 6. Relationship between model parameters a and b

5. Discussion

The production of piezometric maps is a classic approach in hydrogeology. It is complex in basement areas, where the aquifer systems are discontinuous [4,5,6]. At the scale of the study and given the strong development of fracturing and alteration in the area, this is considered to be continuous [2,13]. The surface at the base of the thalwegs (Figure 4), which is the lower limit that is never exceeded, has the same resolution as the DEM (Figure 5). Strictly speaking, this implies that the calculated values of the model parameters a and b must be positive. However, the relationship between these two parameters (Figure 6) shows a negative y intercept (-2.3768). This means statistically that the water table levels are below the surface of the base of the thalwegs [16]. The water levels measured during the field surveys are the unstabilised values of the water table, most often in the wells, which are sometimes in constant activity unlike the boreholes. In addition, the position of certain points provided by the GPS could be tainted by a certain uncertainty caused by the meteorological conditions at the time of the measurements and the canopy of the area, thus causing a shift in the values obtained on the DEM (Yao et al., 2015). This would explain why an improvement in the model is not obtained when the negative parameters are eliminated exclusively. In detail, [13,24] explain that:

- a < 0: the heads of some boreholes may be located in depressions not taken into account when modelling the surface of the base of the thalwegs.
- b < 0: dry valleys have been considered during the automatic extraction of watercourses from the DEM, or else by the lowering of the water table due to the pumping of water in the borehole or in its vicinity.

The mathematical model used to calculate water table elevations (equation 1) has a slope of 0.56, which is far from the values close to 1 generally found in modelling [13,16,24,25]. This value indicates a relatively high permeability environment at the scale of the study area, which seems unlikely given the hard rock context. Indeed, when the slope tends towards a zero value, the permeability tends towards infinity; this is reflected in the field by confusion of the water table surface with the surface of perennial rivers, whereas when the slope tends towards unity, the permeability tends towards zero, and the water-table and topographic surfaces are confused [13,16]. The data used in our modelling includes both boreholes tapping the fissured/fractured layer and a certain number of wells and springs (more numerous), which tap the alterites, unlike the work cited above, which only considers the fractured/fissured layer. Work on hard rock aquifers has shown that, from a hydrodynamic point of view, alterites have high permeability and low porosity, and vice versa for the fissured/fractured layer [4,5,6]. This therefore explains the relatively high permeability described by the slope obtained in our study.

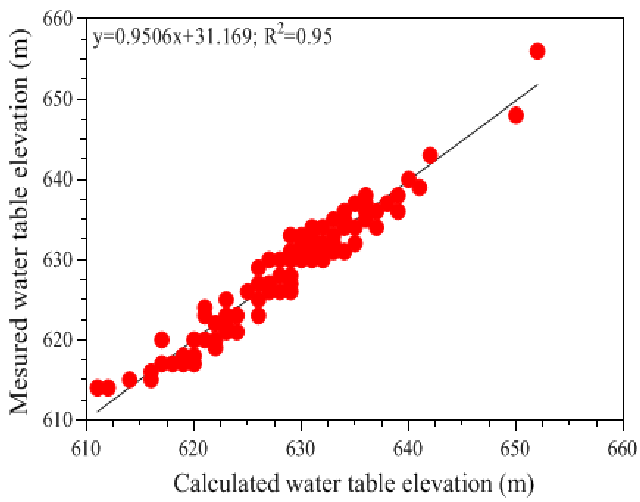

Figure 7. Relationship between calculated and measured water table elevation in the study area

A comparison of the water table levels measured and those calculated using equation 2 is shown in Figure 7. It shows a regression line with a slope close to 1 (0.95) and a coefficient of determination R^2= 0.95. There is therefore a significant similarity between the measured and calculated values. The average error expressed between the two observations is ± 1.43 m, which is largely acceptable, given the scale of the study and the fact that field measurements are not made synchronously and do not always represent the static levels of the structures. This value can be considered as representing the fluctuation of the water table, linked to the various withdrawals.

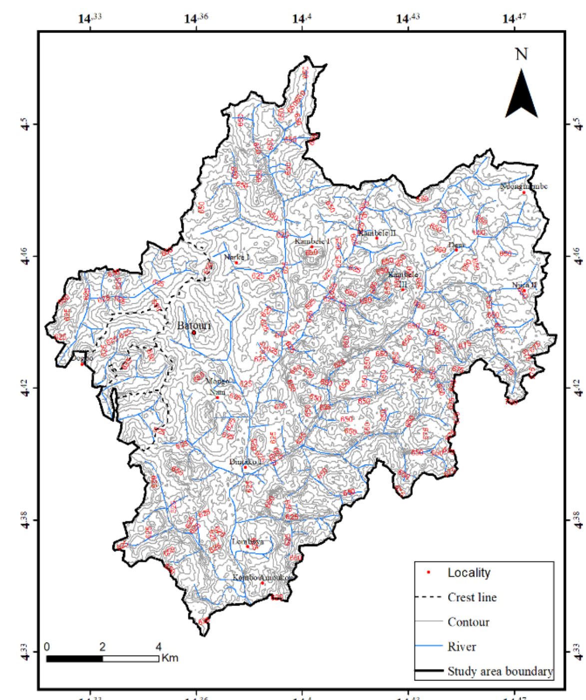

Figure 8. Variation map of the water-table surface calculated at each point in the study area

The modelled water-table map of the aquifer system is shown in Figure 8. The map shows the presence of numerous piezometric domes, such as those located at Batouri, to the NW of Narké I, to the South of Kambélé I and Mongo-nam, located in the high altitude zones. These areas are the main recharge points for the water table, which flows towards the rivers, hence the presence of numerous springs. This hydrodynamic functioning is characteristic of this style of environment [3]. This configuration is supported by seasonal observations made on certain structures, depending on their distance from the rivers (Figure 9).

It can be seen from this figure that, whatever the position within the zone, the further away from the rivers (higher topography), the lower the dynamic levels. The structures furthest away show wide fluctuations, linked to the fact that they only receive rainfall as a source of recharge. As you move closer to the rivers, these fluctuations become less and less significant (depending on the transect) until they become almost stable over time for the nearest structures. This is due to the fact that, in addition to receiving direct recharge from precipitation like those located upstream, they also receive indirect recharge from underground flow towards the rivers [26]. Analysis of seasonal fluctuations (Figure 3) in the structures suggests that topography is not the only factor influencing changes in the water table. Some structures dry up at the end of the short rainy season, suggesting that the quantity of water supplied was not sufficient to cause the water table to react, or that the thickness of the unsaturated zone is greater. [27] highlighted the effects of these two parameters on the seasonal recharge of this type of formation. However, this interpretation needs to be qualified, due to possible effects linked to withdrawals.

Groundwater therefore flows according to the topography, and in conformity with surface water, which implies that at the scale of the study, the hydrological and hydrogeological catchment areas fall within the same boundaries [13]. High anomalies in water table elevations reflect local groundwater recharge by rivers, while low anomalies reflect drawdown linked to natural or artificial drainage (Figure 8) [28]. The first observation is not visible on the water-table map, given the scale of the study, but also the inaccuracies associated with the DEM and the method applied [25,29]. This aspect should be investigated in future approaches because of the mining activity taking place in the rivers in the area and the rapid recharge of groundwater by surface water that may exist through fractures [1,30].

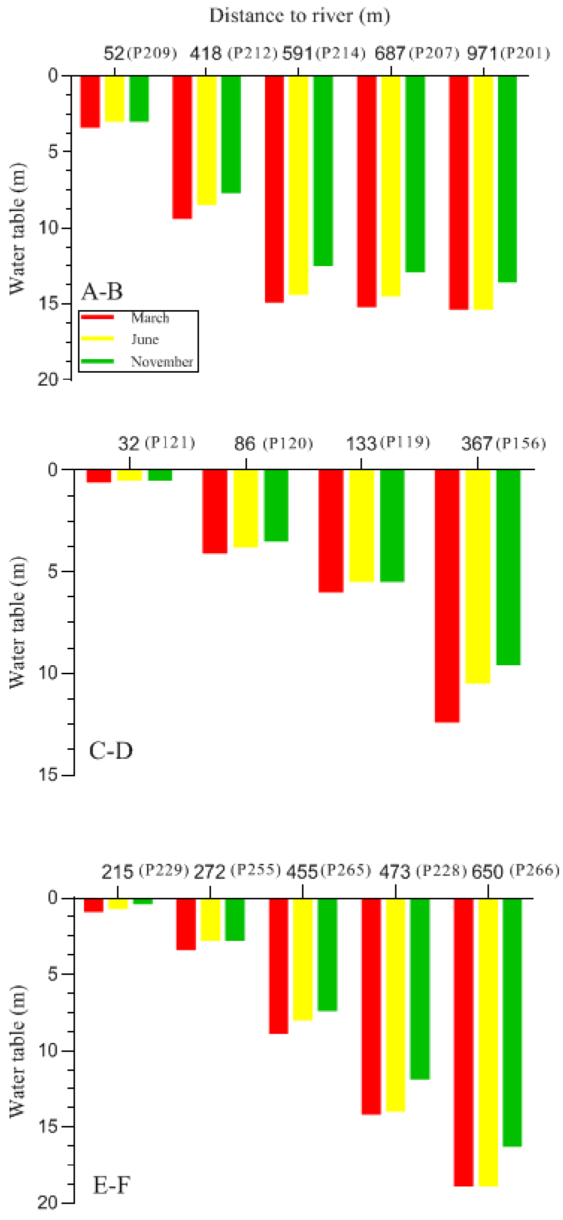

Figure 9. Seasonal changes in dynamic levels in some structures as a function of distance from the river in 2019 (transects in Figure 5)

6. Conclusion

The aim of this study was to model the water table elevation surface of the Batouri hard rock aquifer system and its surroundings, in order to analyse its hydrological dynamics. By mapping the surface of the base of the thalwegs, using field data and a Digital Elevation Model (DEM), we were able to establish a mathematical model, enabling us to calculate the water table levels throughout the study area. The results obtained showed remarkable agreement between the water table levels measured in the field and those calculated by the model, with an average accuracy of ± 1.43 metres, which is considered acceptable given the scale of the study.

The analysis of seasonal variations in dynamic levels in the structures identified topography, the thickness of the unsaturated zone and the intensity of rainfall as factors affecting groundwater recharge. The water-table map obtained showed the presence of numerous piezometric domes and highlighted the flow of groundwater towards surface water, following the topography. These observations confirm the hydrogeological consistency between the hydrological and hydrogeological basins in the study area.

The approach used, although relatively simple, has proved effective in providing valuable information on groundwater dynamics in the Batouri mining area. However, improvements are required, including a densification of the spatial and temporal data, as well as the use of high-precision GPS and higher resolution DEM, in order to further refine the accuracy of the results and better understand the complex hydrological processes in the region. Ultimately, the results of this study can be of great use to scientists and water managers, helping them to develop integrated water resource management strategies for the region, particularly in the face of anthropogenic activities such as agriculture, mining and forestry, which are likely to have an impact on the local hydrological balance.

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Declaration of Competing Interest

The authors declare no conflict of interest or affiliations with any organization or entity that could have a financial or non-financial interest in the subject matter or materials presented in this manuscript.

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