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Discontinuous Nature of Phreatic Aquifers in Granitic Rocks at Watershed Scale: A Stratiform Model from Perennial Streams and Well Data

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Abstract

The study was carried out within 4,000 km² segment of Sassandra watershed located in Soubré, south-west of Côte d'Ivoire where coffee and cocoa production are preponderant. This work aimed to provide a general methodology in order to draw the flow directions and map the potential productive aquifer in hard-rocks. Drilling data, remote sensing, and geomorphic data in a context of weathered plutonic and metamorphic Precambrian were used. The regional water table was modeled through a linear relationship between the topographic surface of the digital elevation model and the base surface of the perennial streams thalwegs. As result, a map of regolith thickness obtained has been compared with the geology to emphasize their relationship. Furthermore, other correlations have been found between the hydraulic data and geomorphological features to get more precise stratification model. Concealed by the regolith, the hard-rock aquifer is made up of three layers. From top to bottom we have the saprolite (< 10 m), the weathering induced fissured layer (35 m mean thickness) below the base of the saprolite and finally, the unweathered with very low hydraulic conductivity. Each layer is characterized by a constant density of water-bearing fissures. This shows the impact of a stratiform weathering profile on the layering of the aquifer. High variability of observing yields is mainly due to thickness heterogeneity of the higher-storage regolith and underlying higher-conductive fissured saprock. Also, the wells tapping water under a regolith with medium or high thickness were the most productive justifying that regolith thickness mapping is a first rank tool in hydrogeology prospecting. The thickness map obtained from the interpolated base surface of the regolith and the DEM represents a useful tool for groundwater management.

Keywords: Precambrian, DEM, Regolith, Saprock, Fracture.

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Contents

1. Introduction

Côte d'Ivoire, surface and subsurface geology of are made up of 97% of crystalline and metamorphic bedrock [1]. Here and all over the world, bedrock aquifers are considered among the least understood groundwater resources. Although these aquifers have a regional extension, they actually respond in a discontinuous model that often shows a wide range of yields in the well. This is generally attributed to the abundance of all scales fractures, which more often playing the role of water conduit. However, different types of fractures (primitive joints, tectonics-inherited faults, and secondary weathering-fissures) have not similar hydrogeological functions. Moreover, all conclusions have to be drawn from the heterogeneity conception to the vertical weathering profile. Observed hydraulic gradients are not able to explain the variability of yields and heterogeneous permeability due to fracture networks and/or weathering profiles [2]; [3]. The induced significant borehole failure rate, around 50% in the granitoids of Côte d'Ivoire, with little or no improvement since the first statistics published by Lenck [4] testifies to the difficulty of predictive exploration for groundwater in this environment. This comes from the limited sensitivity of current exploration techniques and above all, poor understanding of the controls on hard-rock aquifer occurrence and flow direction. While the most immediate need is to improve borehole's success rate, to assist present actions and planning a crucial issue for longer-term sustained development in the context of human migrations and climatic changes. In addition, we need to evaluate overall resource and aquifer occurrence within a regional watershed, not only specialization of the groundwater occurrence, but also the direction of groundwater's flow is problematic. The last one is often presumably controlled by topography and geological structure but the relative influence of these factors in crystalline rocks still raises basic interrogations [5].

Aquifers contained into the fresh bedrock are of rare occurrence due to negligible intergranular porosity and low tectonic fracture network storativity. Higher porosity and permeability of hard-rock may locally arise within major brittle structures [6]; [7]; [8]; [9]. Tunnel engineering in saturated rock masses also provides opportunities to develop understanding on the subsurface hydraulic behavior of Recent studies in relation to mining or radioactive waste disposal, especially from borehole data in low permeability bedrock at depth, have also increased knowledge of the detailed hydraulics of fracture systems fractured media [10]; [11] at local scale. However, although it was proposed by De Dreuzy, et al. [12]; Kouame, et al. [13] and other advocates of the percolation theory, a regional approach cannot be mainly a geometrical extrapolation of the local hydraulic mechanisms of fresh bedrock by computing a regional permeability of a lineament network. Rather, it is necessary to focus on the granitic rocks and combine at greater scale lithology, morphology, hydrology, structural geology, weathering profile and well data [14].

Indeed, in those rocks, in the absence of any sedimentary cover, groundwater flows through discontinuous aquifers characterized by a vertical weathering gradient with variable porosity from the surface below to almost unfractured rock at depth [15]. At the top, weathered disaggregated rocks are both sandy and clay-rich and so have very low intergranular permeability. Clay strata, especially in the saprolite which is the bottom layer of the regolith, may in places support some isolated perched aquifers [16]. Between the regolith aquifer and the deeper unfractured bedrock, both with low permeability, it is usual to distinguish the fissure aquifer with low porosity but much higher permeability, almost entirely dependent on secondary fissures due to weathering.

The work conducted here in a part of Sassandra watershed located in Soubré is intended to provide a general methodology for the investigation of flow directions and mapping of favorable areas for the occurrence of a productive aquifer in hard rocks and to contribute to the comprehension of groundwater flow in hard rock.

The borehole dataset including regolith thickness, initial hydraulic head and well yield, is examined in relation to the topographic surface and the perennial streams. We focus on a 4,000 km² area within the granitoids. The model took from Wyns, et al. [17]; Yao, et al. [18] allows for mapping the water table and the regolith-saprock interface. Then a map of regolith thickness achieved is compared to the geology of this area.

2. General Information of the Study Area

The study region comprises a segment of the Sassandra River's watershed located in west Africa especially in the Southwest of Côte d'Ivoire between latitudes 5°19 - 6°34 and longitudes 6°12 - 7°08, and has a surface area of 8 590 km² (Fig. 1).

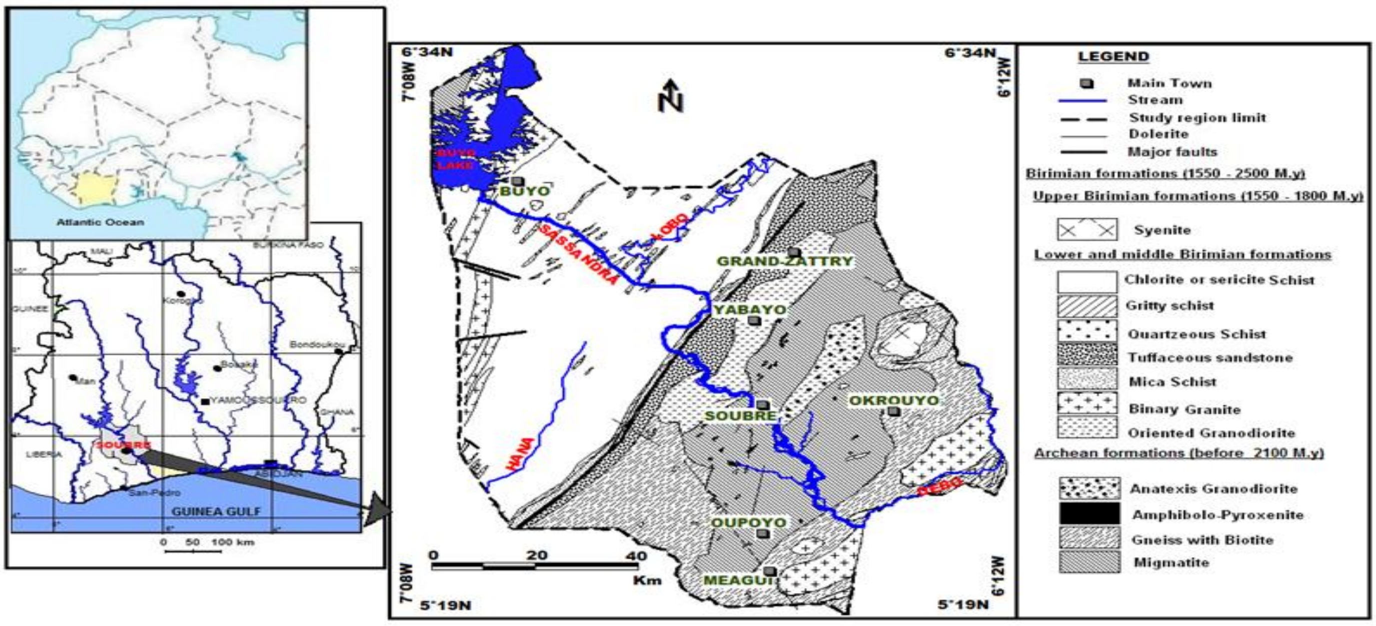

Figure-1. Location and geology of the study area

Source: Yao [19].

The geomorphic setting is a vast and slightly waved plateau formed by Precambrian crystalline rocks, with 200 m average elevation and inclined 0.1% southwards, incised by a dense pattern of tributaries. The region is drained by Sassandra River which offers a variety of configurations along its course and benefits from a subequatorial climate (hot and humid). The study region comprises a 100 km segment of the Sassandra River's watershed. A 210 m elevation seems to be characteristic scale of the water table along the limit of the watershed. Excluding the isolated peaks at an elevation exceeding 300 m around the more recent granitoids (Fig. 2), the typical elevation gradient in the direction transverse to the Sassandra River implies a hydraulic gradient of about 0.2%.

It is the case of the Lobo valley, a major tributary of Sassandra River: its stream south-westwards is controlled by the HLFZ (Hana-Fault Zone) which plays the role of a hydraulic barrier as outlined by the great meander of Sassandra River where abutting on the fault. The barrier effect due to fault gouge has been reported elsewhere for such fault zones through Precambrian rocks in other geological contexts [20]; [21].

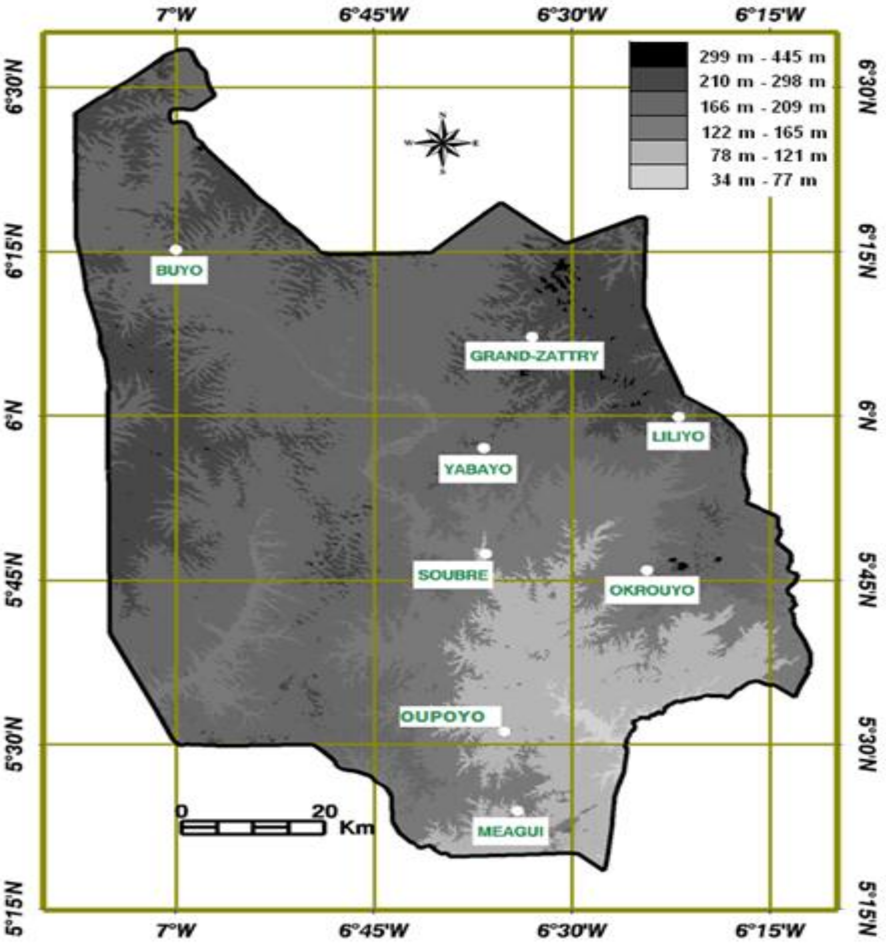

Figure-2. Digital map of the relief from the DTM of studied area
Source: Primary data analysis (2017)

Actually, rains are abundant (between 1600 mm and 1800 mm) and reach a peak around June and July. During the year, temperatures vary between 26 °C and 32 °C.

The great N-S Sassandra Fault belongs to a family of impressive structures which may have originated [22] as ductile shears or sutures during the early stage of the Eburnean orogeny with repeated subsequent movement to include late brittle faulting in the intrusives. These faults zones guide the course of the main continental streams as for instance the Sassandra River North of the main SW-NE trending crustal structure typical of the Baoule-Mossi domain [23] that we will refer to HLFZ, the northern part of the study area belongs to the main supracrustal sequences of Birimian [24]. At the south of the HLFZ, outcropping rocks associate varied intrusive granitoïd lithologies of the Eburnean orogeny with reworked metamorphosed Archean components (*cf.* Fig. 1).

The relatively sodic early rocks underlie featureless plateau whereas the latter potassic plutons form positive outcrop features, locally with a thick saprock. The high potassium content and abundance of quartz prevented the saprock to be broken down into a thick soil cover and now allows it to be a good aquifer. Retrogressive metamorphism replaced biotite by other hydrous mineral phases (chlorite, amphibole) which made the host rock less susceptible to weathering [25].

3. Method and Data

In order to tackle both questions, groundwater occurrence and flow direction, we referred to the conceptual scheme of a stratiform bedrock inherited from a single phase weathering paleoprofile, proposed by Wyns, et al. [17] and further developed in Dewandel, et al. [26] and Yao, et al. [18]. The layering roughly follows the paleotopography and presents a gently dipping sequence at regional scale. The model stands for two superposed aquifers, the regolith and the saprock or "fissure aquifer" with possible exchange between them and with some vertical tectonic fault zones allowing for a deeper flow component. The used model was demonstrated in Yao, et al. [18] which was being forwarded. In this model, other fracture zones being isolated from both the surface and fissure aquifer are therefore non-conductive. The base surface of the perennial streams' thalwegs, denoted Sr (r for reference), is obtained by kriging of the values extracted from the DEM along the perennial streams. The real potentiometric surface Sp, including borehole data, is still unknown at this stage. Following Chilton and Foster [16] let us define the parameters *a* and *b* at every point by: $\mathbf{a = St - Sr}$ **and** $\mathbf{b = Sp - Sr}$. *(1)*

Next to a perennial stream, the surfaces Sp and St are likely to intermingle. When increasing the distance, however, we can hold the following tendency for true: the higher a point between two streams (nearer to interfluves), the deeper the hydrostatic level. Now, considering the three surfaces Sr, Sp, and St, we could better write b = p x a – h with p, h, real numbers.

Finding such a relation will allow determining the hydraulic head as a direct function of the soil elevation. The 1-degree digital elevation model (DEM) is obtained from the Shuttle Radar Topographic Mission (SRTM), with 3 x 3-arc-second data spacing (90 m). The drainage network and topography were extracted from the DEM and three paper elevation maps, 1:200,000 scaled, elaborated in 2001.

The borehole dataset provides the depth of a mechanical interface which is the contact between saprolite, i.e. the disaggregated but structure-preserved lower horizon of the regolith, and underlying saprock which is still cohesive but weathered fissured bedrock. Below this interface, with increasing depth, the saprock to fresh bedrock junction is transitional or even fluctuating in banded sequences. Thus, the depth of the mechanical interface is also the thickness of the regolith and we denote it by *Na* (*a* for alteration).

The depth of the hydrostatic level measured at the borehole completion is denoted *Np* (p for potentiometric), and also the terrain elevation Zt is transformed to Zp into an altimetric level. Even when the elevation of the site was recorded in the borehole file, it did not turn out to be more precise that by pointing the X, Y position on the DEM. Proceeding this way to acquire Zt, systematically, one deals with an absolute error of 10 m along the vertical axis. Then, the main source of uncertainty resides in X, Y positions of the boreholes: locations are estimated to be accurate to ± 100m. Gathering boreholes drilled at years of distance, the hydrostatic level database obviously is diachronous. Here we advocate that the effect of the year or month of borehole completion is negligible for our purpose: the diachronous database will be considered as a homogeneous source of data.

We compile water-well yields reported from drillers' logs. The yields are modest, typically less than 5m^3/h, and many boreholes had run dry or been abandoned on completion. In this study, we only analyze data from wells that were considered as successful and are still productive to date. Detailed water level and yield evolution are not available, only being registered the first air lift test when the borehole has been completed. Yields were generally determined as the rate of water that can be air-lifted on a continuous, short-term (tens of minutes) basis. Such method introduces an unquantifiable variance in measured yields but is acceptable for a statewide or regional evaluation.

4. Results and Interpretations

4.1. Flow Directions: A Model of the Water Table

It turned out to be sufficient to extract 220 values of Zt, each one representative of a 90 m x 90 m cell, since the 220 points are scattered enough to make an interpolation (Fig. 3) and get a map of Sr. The extracted value is a superior bound of the water level in the stream. However, as soon as we will observe boreholes at a distance of a few hundreds of meters from a perennial stream, the value of Zt extracted at the river is a good local minimum for Sr and Sp.

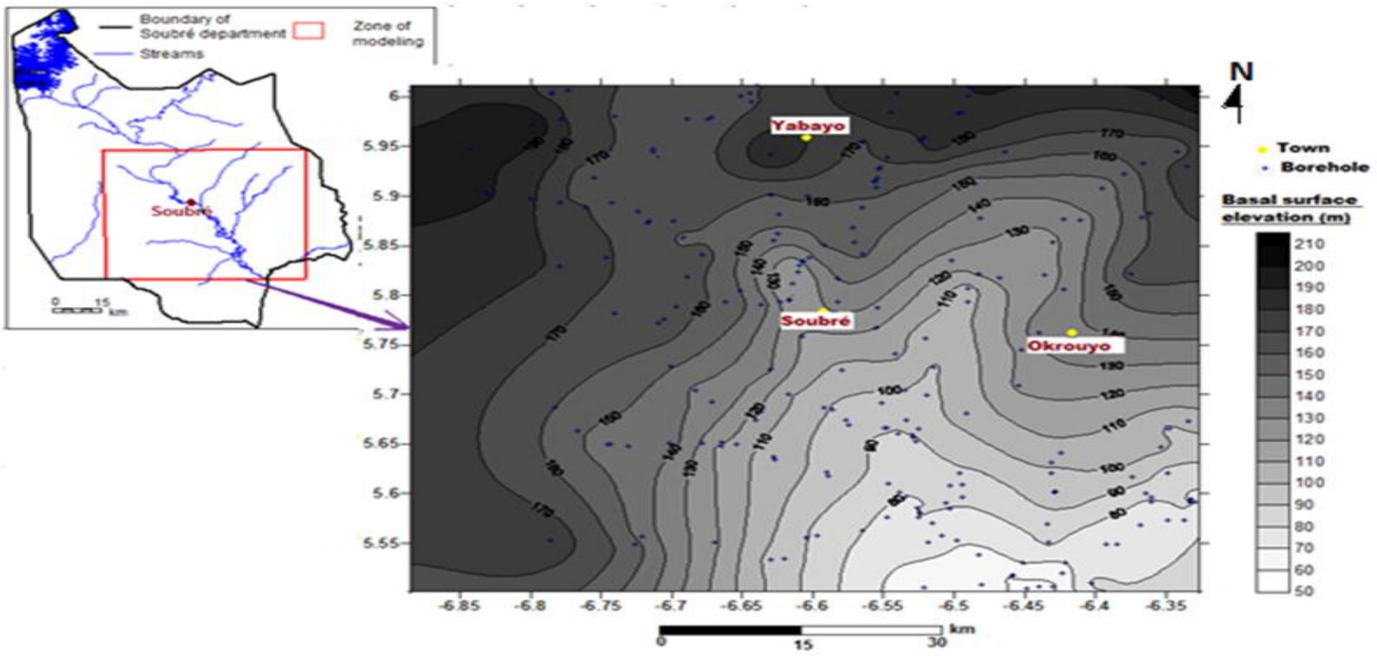

Figure-3. Elevation of the basal surface of the thalwegs of perennial streams (Surfer7®), kriged from 220 values pointed along low elevation channels of the DEM
Source: Yao, et al. [18]

Working on a population of 55 boreholes (Fig. 4), three correlations were found but a good correlation factor found for b is: $b = 0.92\ a - 7.00\ m\ (R^2 = 0.95)\ (2)$

We continued to improve the correlation achieved; So, with another dataset, wells taken away from the streams, we found this time: $b = 1.00\ a - 9.64\ m\ (R^2 = 0.97).\ (3)$

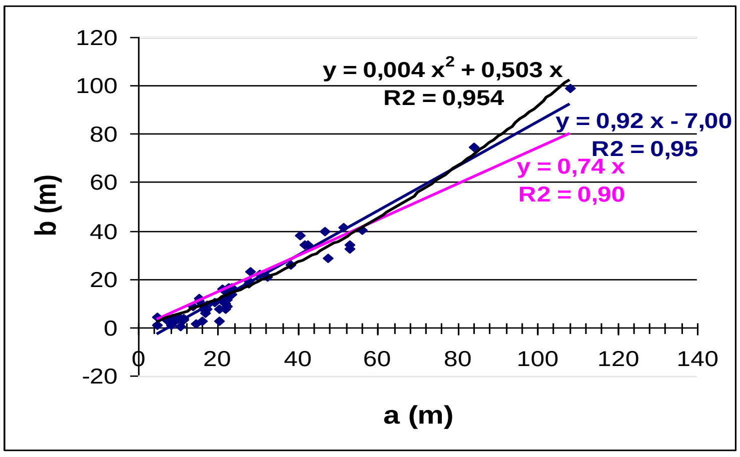

Figure-4. Relation between the land surface, the base surface of the thalwegs of perennial streams, and the hydrostatic level in 55 boreholes
Source: Yao, et al. [18]

The slope very close to unity of this relation means that Sp lies about 9.6 m in average under St in a quasi-parallel fashion.

Working on the b/a relation, Wyns, et al. [17] have interpreted the negative value of y-axis at the origin as the depth between the water surface and the banks. However, the water surface of the rivers in the study area is incised 1 m or 2 m below the banks. Our result is rather consistent with the mean Np value (7.33 m) and with the fact that most of the studied boreholes are sited away from perennial streams for safety towards flooding hazard. Thus, we are induced to distinguish two relations: one in the neighborhood of the thalwegs and another at longer distance. In the vicinity of the perennial streams, we suggest making possible the convergence of the surfaces Sp and Sr, i.e. with an assumption the negligible incision below the banks. To satisfy this condition, we need to force the relationship to respect linearity in a strict sense: then, we find b = 0.74 a without losing too much signification level (R^2 = 0.90), valid in the range of values up to 60 m. Let notice that the value 0.74 is very close to the value found by Wyns, et al. [17] through the "with bank incision" assumption.

From these linear relations, we deduce the elevation of Sp in any 90 m x 90 m cell with the help of a simple transformation of the base surface Sr. The relation Zp – Zr = 0.74 (Zt – Zr) gives: Zp = 0.74 Zt + 0.26 Zr. Beyond the value a = 60 m, the best linear fitting with a slope close to 1 should be used since Sp, despite its variability, is roughly parallel to Sr. We obtain the map of Figure 5 from which local flow directions are very clear. The standard error of the regression line (±1.85 m) is likely to include the natural variability of the water table, which gives a backward argument favorable to the neglecting of the diachronous character of well data at section 3.

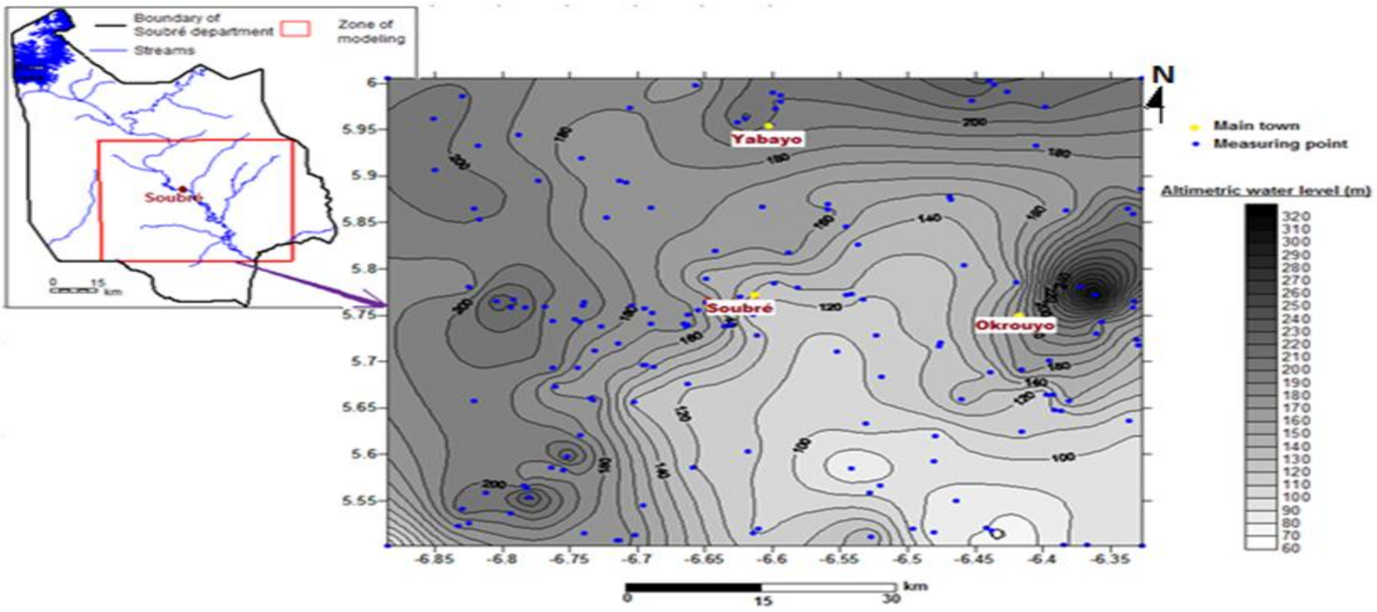

Figure-5. Surface of the water table computed from the basal surface of the thalwegs of perennial streams and the DEM
Source: Yao, et al. [18]

4.2. Water Occurrence: Strata Function and Thickness

In order to target some interesting sites for new population settlements, and given the storage function of the regolith, it is essential to understand the regional control on the distribution of the thickness parameter. The spatial distribution of the residual regolith thickness is obtained by direct kriging of data from 183 boreholes (Fig. 6A). Despite the low resolution, significant zones emerge from this map and the distribution is compared with the maps of lithology and relief. The thickness, 15 m in average, displays distinct mapped domains.

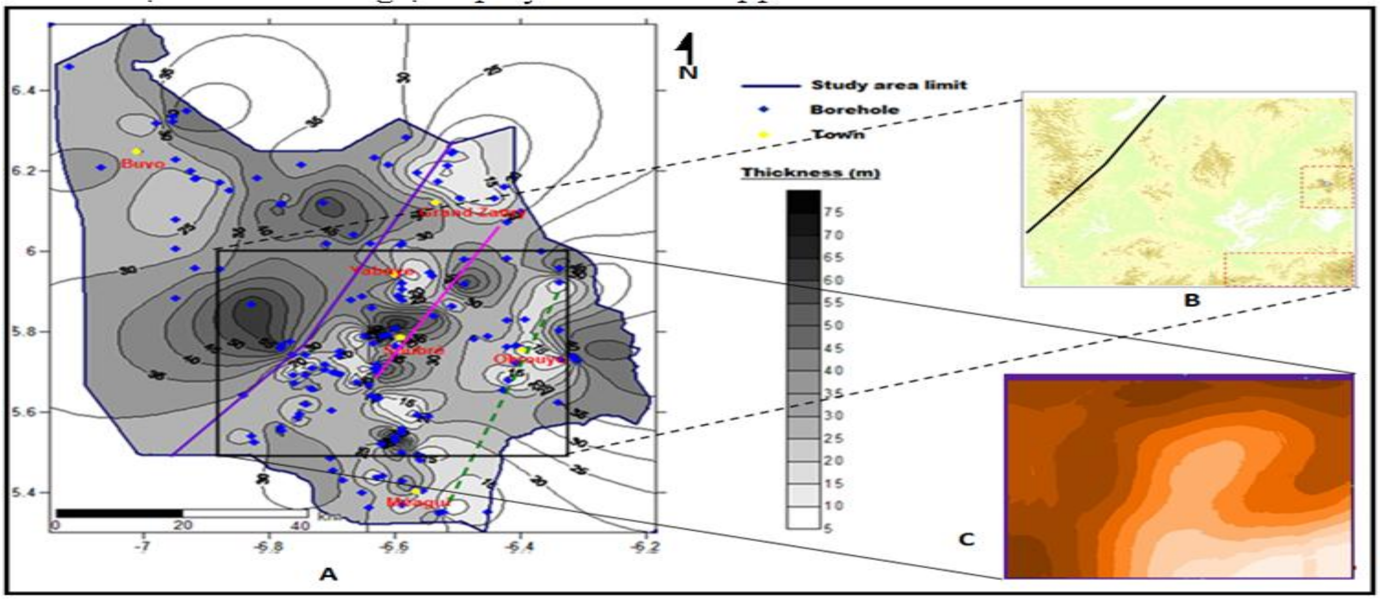

Figure-6. A: Raw values of the regolith thickness (183 borehole data). B: Regolith basal surface (RBS) interpolated from 105 boreholes. Kriging by 250 m step with a Gaussian variogram. The regolith thickness is obtained (Fig. 6C).
Source: Primary data analysis (2017)

Low thickness (< 25 m) light zones are observed on the highlands of both hillsides of the Sassandra, also characterized by higher values of slope giving access to the interfluve limits of the watershed. This is consistent with lower weather ability of the rocks around the inselbergs. Another set of low-thickness values are concentrated into a SW-NE alignment passing through Okrouyo and Meagui within the gneiss and intrusive syenite or binary granite bodies: its trend is N10 and marked as a dotted bold line on Fig. 6A. Two major gneiss enclaves within migmatite are the sites of main tributary confluents of the Sassandra River and display low regolith thickness.

High thickness (> 50 m) dark zones are in an alignment trending N30, beginning within migmatite near the Sassandra and continued along the anatexis granodiorite: it is marked as a continued bold line on Fig. 6A**.** Another high thickness zone is well characterized around Oupoyo within migmatite, south of the two major gneiss enclaves.

Thus, differential weathering as a function of lithology appears to be the main control for the spatial distribution of the regolith. The advocated influence of lithology is consistent with the results of Moore, et al. [27] orWalsh and Clark [28] under different climatic conditions but similar geology: migmatites display higher regolith thicknesses and yields than foliated plutons.

In order to reduce the variance and the nugget effect [17] the base surface of the regolith on the 4,000 km^2 study area has been kriged by using a Gaussian variogram (Fig. 6B). This map explains why regolith thickness Na is not correlated with the soil elevation Zt. At the time of weathering, the basal surface of the regolith was parallel to the ancient topography. Differential erosion has made the present-day morphology of the landscape mainly independent from the inherited weathering profile. Then, an improved map of the regolith thickness is obtained (Fig. 6C) by subtracting the regolith's base surface from the topographic surface (DEM). On this new map, both the correlation with lithology and the effect of erosion by streams are highlighted.

Well yields generally give mediocre correlation with other parameters and it is the case here. This is caused by the heterogeneity of the yield values and the interferences between the various influences involved. Nevertheless, in our data values of regolith thickness inferior to 10 m do not allow for high yield values (> 10 m3/h) but higher yields arise around the average thickness (15.7 m for this borehole population). Thus, wells tapping water under medium or high thickness regolith are the most productive.

As the main aquifer component is the fissure layer, the linear yield or yield by well depth must be defined with reference to the well height below the base of the saprolite rather than the total well depth or saturated height [29]. From Fig. 7, 95% (respectively 80%) of the cumulative linear yield of a well population is obtained within a 35 m layer (respectively 25 m) under the base surface of the regolith. The first segment of the cumulative curve shows that half the total linear yield comes from a thin horizon (no more than 5 m thick) immediately under the contact and which is likely to drain the regolith. Almost all of the other 50% (second segment on the curve) comes from the 5 m to 35 m layer and it is noticeable, with a constant gradient. The gradient changes again between 35 m normalized and 40 m under the base of the regolith and drilling deeper becomes less profitable.

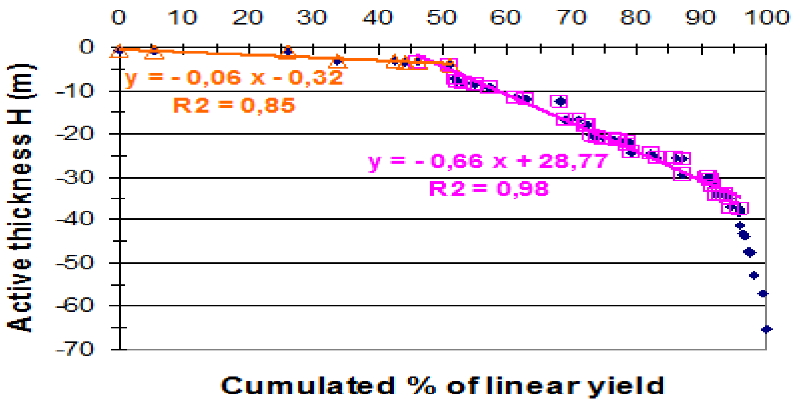

Figure-7. Linear cumulated yield as a function of the effective saturated height under the base of the regolith, 55 boreholes
Source: Yao [25].

5. Discussion

Using the base surface of the perennial streams' thalwegs, we model the potentiometric surface in the regolith + saprock aquifer. Near to the interfluves, the water table is deeper and the hydraulic gradient is lower. This may explain why well yield is often negatively related to local slope, i.e. the rate of change in soil elevation surrounding a well. Convergence and merging of the potentiometric surface with the base surface when approaching the perennial streams' thalwegs is quantified by a linear relationship. In this frame, we question the respective role of the regolith and saprock.

The fissure layer or saprock is the most productive part of the hard-rock aquifer, as already shown elsewhere Houston and Lewis [30]; Maréchal, et al. [31]; Taylor and Howard [32]. Following Wright [33] effective development of the saprock component requires interaction with storage available in the overlying saturated regolith. We observe as Barker, et al. [34] that thicker the regolith, greater the saturated thickness of regolith. Moreover, it is generally accepted that the frequency of clusters of subhorizontal fissures within the top of the saprock is greatest where the regolith is thickest. Thus the rational in borehole siting is to try to locate the deepest regolith on the assumption that this will maximize yields from both the regolith and the saprock [35].

The average regolith thickness is about 30 m in West Africa and only 15 m in the study area. The main phreatic aquifer occurs within the variable layer of saprock. The more fissured and productive parts of the aquifer have transmissivity values up to 100 m^2/day. Wells in the bedrock tap groundwater from the fissure aquifer mainly in semi-confined conditions under the clayey regolith, or rarely unconfined. Yields range from a few m^3/day in some upland or slope areas to 43 m^3/h in wells adjacent to a perennial stream.

However, mapping the regolith thickness [17] is still a new approach in hard rock hydrogeology and is not fully accepted. We advocate that the thickness map obtained from the interpolated base surface of the regolith and the DEM is a useful tool for groundwater management which should be integrated for vulnerability mapping [36] and favorability mapping [37] through GIS methodology.

Our improvement of the stratiform model arises from the study of linear yield against depth. Decrease in linear yield or hydraulic conductivity is not progressive since we can distinguish three sub-zones sharply contrasted. Within each sub-zone, the density of fissures opened to flow is not decreasing with depth. However, dilation of fissures continuously reduces at depth with overburden pressure. So, in contradiction with a recurrent idea in the literature, the role of exhumation pressure release cannot account for these subzones. Our observation is rather in conformity with the leading part of mica swelling in the inherited weathering and fissuring profile of the bedrock [17]. For instance, small thickness of the saprolite above syenite (9 m) is mainly attributed to poor weather ability of this rock due to lack of biotite. The two micas or binary granite which contains some biotite has thicker regolith (17 m).

The contrasted susceptibility to weathering between different lithologies is not the only control on the formation of the weathering profile: contrasts in tectonic joint and fracture density and in relief amplitude also play a part. As for the role of the local tectonic fracture network, it is often stated that high density of local fractures is favorable to deeper and more penetrative weathering and secondary fissuring, thus leading to higher well yields. We don't think so. At the time of weathering, opened tectonic joints in uplands allowed through the flow of meteoric waters to the level of the water table deep beneath the hills [19]. Once in relief, the fresh bedrock masses tended to remain dry and tectonic fracture density had a conservative function. The late plutons as unfoliated syenite are representative of this case in the study area. At present in this environment, rapid infiltration through thin overburden and diffuse tectonic joints down to the saprock still prevents water from mineralizing.

6. Conclusions

Dealing with the concept of stratiform aquifers in relation with the acquired weathering profile in hard-rocks, the region of Soubré (Côte d'Ivoire, West Africa) provides a rich example of how Precambrian multiphase magmatism and final tectono-thermal events controlling lithology and jointing, on the other hand, Tertiary weathering and Quaternary erosion controlling bedrock layering and morphology, are both responsible for present infiltration, groundwater storage and flow within the regional regolith + saprock aquifer.

Using the base surface of the perennial streams' thalwegs, we model the potentiometric surface within the regolith + saprock aquifer. The direction of shallow groundwater flow in the study area directly deduces from the local gradient of the potentiometric surface in sub-catchments.

Wells tapping water under a regolith with medium or high thickness are the most productive, which justifies for regolith thickness mapping as a first rank tool in hydrogeology prospecting. We conclude against the general statement that incremental yield continuously decreases at depth, leading to the idea of lithostatic pressure controlling the openness of fractures more commonly called "sheeting fractures". At the opposite, the saprock under the regolith is parted into three sub-layers, each one being characterized by a constant density of water-bearing fissures. This highlights the impact of a stratiform weathering profile on the layering of the aquifer. In this frame, the high variability of observed yields is mainly due to thickness heterogeneity of the higher-storative regolith and underlying higher-conductive fissured saprock.

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