Chapter

Hydrogeological Characteristics of Shallow Hard Rock Aquifers in Yaounde (Cameroon, Central Africa)

Jules Rémy Ndam Ngoupayou, André Firmin Bon, Guillaume Ewodo Mboudou, Nasser Ngouh Abdou and Georges Emmanuel Ekodeck

Abstract

The groundwater contained in the alterites is one of the main sources of water supply for many households in the city of Yaounde and its surroundings. Information from the field and laboratory studies was compiled and analyzed in order to understand the hydrogeological context of this superficial aquifer. Preliminary results show a staged morphology of the alteration mantle (regolith) of Yaounde migmatitic representative of the polyphase character of alteration processes observed in all granito-gneissic formations of the world. This mantle has a multilayer system whose soil sets could have a different hydrodynamic functioning. The values of the hydraulic conductivity have a normal distribution and vary over four orders of magnitude, attesting the variability of the hydraulic conductivity of the soft materials. The hydrometric and piezometric characteristics indicate that the aquifer has highly heterogeneous zones that would be related to the morphostructural character of the region. The $\delta^{18}O$ mean values of the rain (−2.47‰) and shallow groundwater (−2.57‰) are not significantly different. They indicate that the recharge of the shallow aquifer of Yaounde Precambrian basement is recent and is done directly by infiltration of precipitation without any notable change due to evaporation.

Keywords: hydrological context, polyphase character, hydraulic conductivity, morphostructural character, recharge, shallow aquifer, Precambrian basement, Yaounde, Cameroon

1. Introduction

Hard rocks (plutonic and metamorphic rocks) constitute the basement of the continents and outcrop over more than 40% of the entire African continent [1–3]. About 90% of the Cameroon area is occupied by Precambrian basement rocks and the rest by sedimentary formations [4]. The former were transformed in the humid tropical zone into a thick alteration mantle (>20 m) due to the infiltration of rain on the ground surface [5, 6]. The aquifers of these metamorphic formations (gneiss, migmatite, schist, etc.) are exploited through wells and boreholes for the supply of drinking water to the populations of rural and urban areas. In Yaounde, as a little everywhere in sub-Saharan Africa's urban areas, exploitation of groundwater is an alternative to the deficit of surface water resources. It represents, with the exception of the northern part of the country, the main source of drinking water supply captured and distributed by the national body in charge of water supply, that is, Camwater. This deficit is generally due to joint action of population explosion, hydroclimatic conditions, and social progress. Beyond its alternative character, the efficient exploitation of groundwater resources, particularly those of basement areas, requires a better understanding of the characteristics of their reservoir. Thus, two research programs were initiated by the

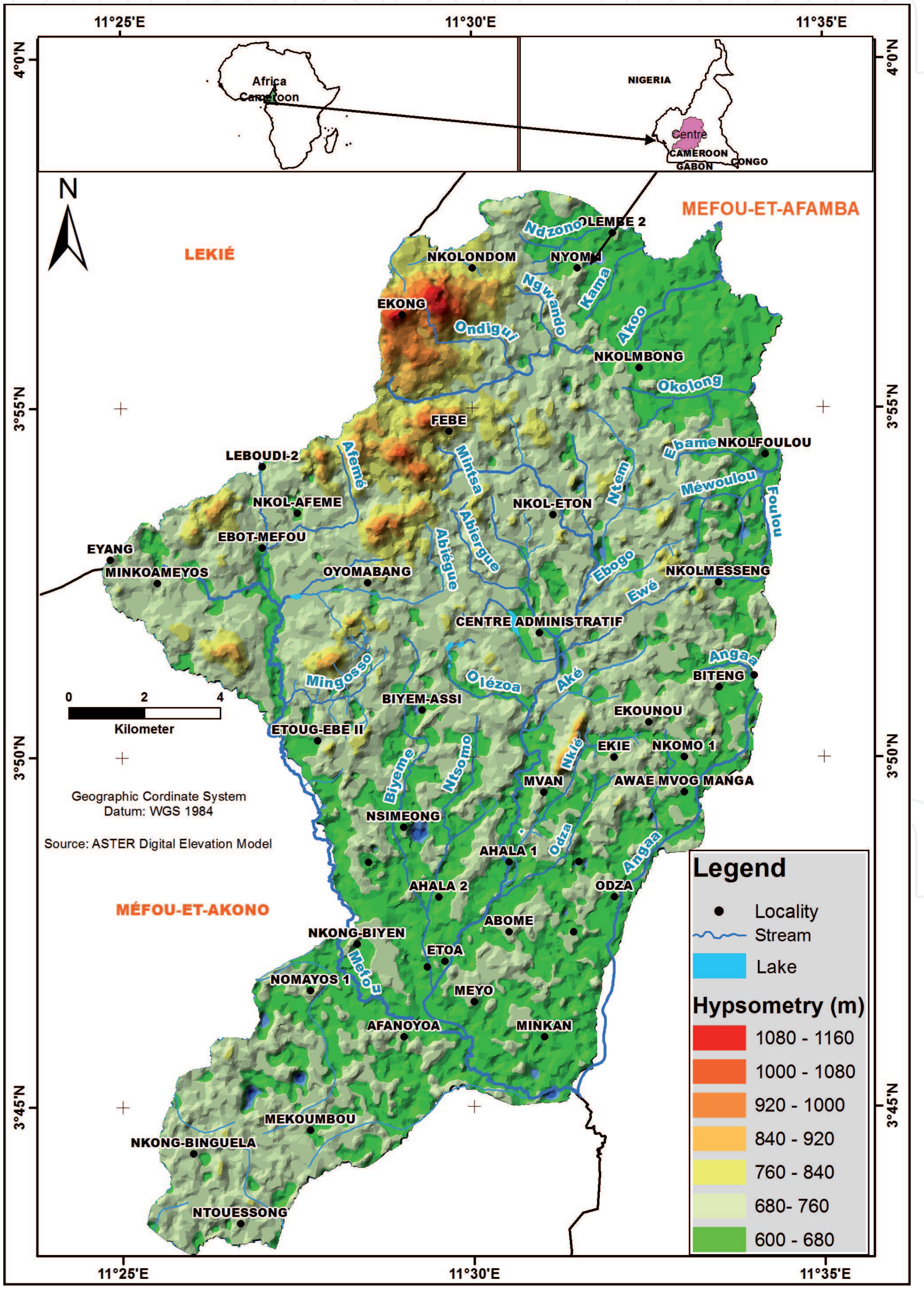

Figure 1.
Geographic location of the Yaounde region.

DOI: http://dx.doi.org/10.5772/intechopen.84631

Laboratory of Geology of Engineering and Alterology (LAGIA) of the Department of Earth Sciences of the University of Yaounde I. These programs relate to (a) "physical, hydrodynamic, and bacteriological characterizations of groundwater resources in the sedimentary and basement areas of Cameroon" and (b) "the impact of climate change and human activities on the water resources of Cameroon." The activities carried out within the framework of these programs are more implemented in the alterites of the geological formations of the South Cameroon Plateau specifically those of the region of Yaounde and its surroundings [7–12]. In fact, because of the deficit service of the water distribution network, the groundwater of shallow unconfined aquifer constitutes, for many households in this region, one of the main sources of water supply.

This chapter is a review of the main results obtained during the research carried out in the aquifers of the Pan-African basement of the Yaounde series in Central Africa. It is a synthesis of the results of the Theses [4, 13–17], DEA, DESS, and Master [11, 18, 19] studies focusing on the hydrogeological context of the upper part of the weathered and cracked basement of the Mfoundi watershed, which includes 11 sub-basins, Anga'a and Mingosso in Mefou (**Figure 1**). This compilation makes it possible to fill the gaps and/or to improve the knowledge of the aquifers of the weathered mantle in humid tropical zone, particularly in this part of South Cameroon facing the problems of drinking water supply.

2. Geographical and geological setting

The Yaounde region is located between latitudes 3°45′ and 4°00′ N and longitudes 11°20′ and 11°40′E (**Figure 1**). It has a humid tropical climate marked by two rainy seasons (mid-March to mid-June, mid-September to mid-November) alternating with two dry seasons (mid-November to mid-March, mid-June to mid-September) unevenly distributed. This region is located in the South Cameroonian Plateau (average altitude 750 m) and dominated by smooth rocky hills (>800 m) with large

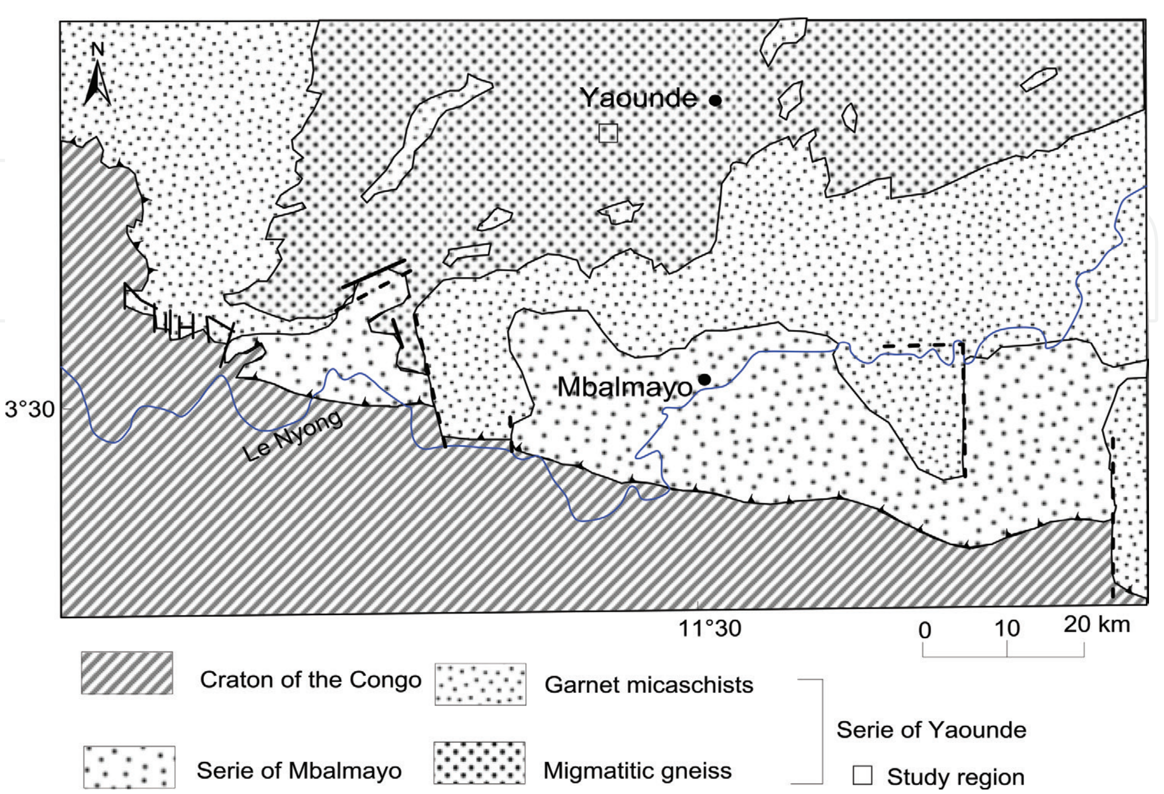

Figure 2.
Geological units of the southern domain of the North-Equatorial Pan-African Chain (modified after [22]).

convex slopes relayed by large swampy valleys (<700 m) of different widths (ranging from 50 to 150 m) [5]. The vegetation corresponds to a semi-deciduous forest [19] that has been degraded and replaced by traditional plants in urban areas.

The region of Yaounde by its rapid extension is drained to the north by the Foulou tributary of the Sanaga river and to the south by the Mefou, tributary of the Nyong river. The Mefou drains the urban part of Yaounde and has for tributary Anga'a to the southeast and Mfoundi in the center of the city (**Figure 1**). The latter flows along an oriented fracture N30 at N40 in downstream and N0 at N10 in upstream [13]. The Yaounde group constitutes a part of the Central African Mobile Zone (CAMZ) and is Pan-African in age [20, 21]. It is limited in its southern part by the Congo Craton and includes the series of Mbalmayo-Bengbis-Ayos and Yaounde (**Figure 2**) [22]. Metaplutonites and metasediments constitute the migmatitic sets of the Yaounde series [23] metamorphosed between 911 and 1127 Ma [24]. On these rocks, two geomorphologically controlled systems developed: (i) a lateritic system on the hillside and (ii) a hydromorphic swamp system [25].

3. Structure of the alteration mantle (shallow aquifer)

Basement environments have local variations in thickness of weathered materials (alterites). Their formation depends on the geological facies, the rainfall, the geomorphology, and the latitude [1]. Several authors [3, 26–29] have realized descriptions of alteration profiles in various regions of the world. These authors agree that the geological environment of the basement aquifers comprises two main stratiform horizons parallel to the paleo-surface contemporaneous with the weathering processes. From the bottom up, there is a fissured/fractured compartment above the fresh rock and an altered compartment or regolith. In the humid tropical zone, rock alteration leads to the formation of lateritic profiles [6, 30, 31]. The distinct horizons developed within it depend on short- or long-term alteration processes [5, 6]. The generic model of the weathering mantle of the Yaounde geological formations belongs to the lateralization regime and is identical to whatever the lithology is [5, 25, 32]. It is composed of the base toward the top, of a (**Figure 3**):

- Weathering set (5 m and more) constituted, from bottom to top, of:
    - Isalterite or coarse saprolite (2 m and over) with preserved parent rock structure and overlying fresh gneiss at the base; the alteration front is surmounted by a laminated part; there are relics of the original rock (quartz, rutile, and disthene) and the development of a fissured system parallel to the original orientation; and the fissures are millimeter and filled with alteration products composed of kaolinite and oxyhydroxides of iron and alumina.
    - Alloterite or fine saprolite (1–2 m), consisting of goethite and hematite and with ghosts of original minerals; this horizon has, in places, small depressions or alveoli which are dry at the edge of the nodular horizon above or present a water circulation when they seem to mark the transition with the soft level; these cells are comparable to karst forms described by [33]. They are, respectively, characterized by the rarity or the absence of alteration products at the level of these pseudo karts, and the presence of a water circulation can explain the departure of the finest materials.
- Glebular set of iron oxyhydroxide accumulation and kaolinitic clay, set of iron redistribution and deferrugation; he understands, from bottom to top:

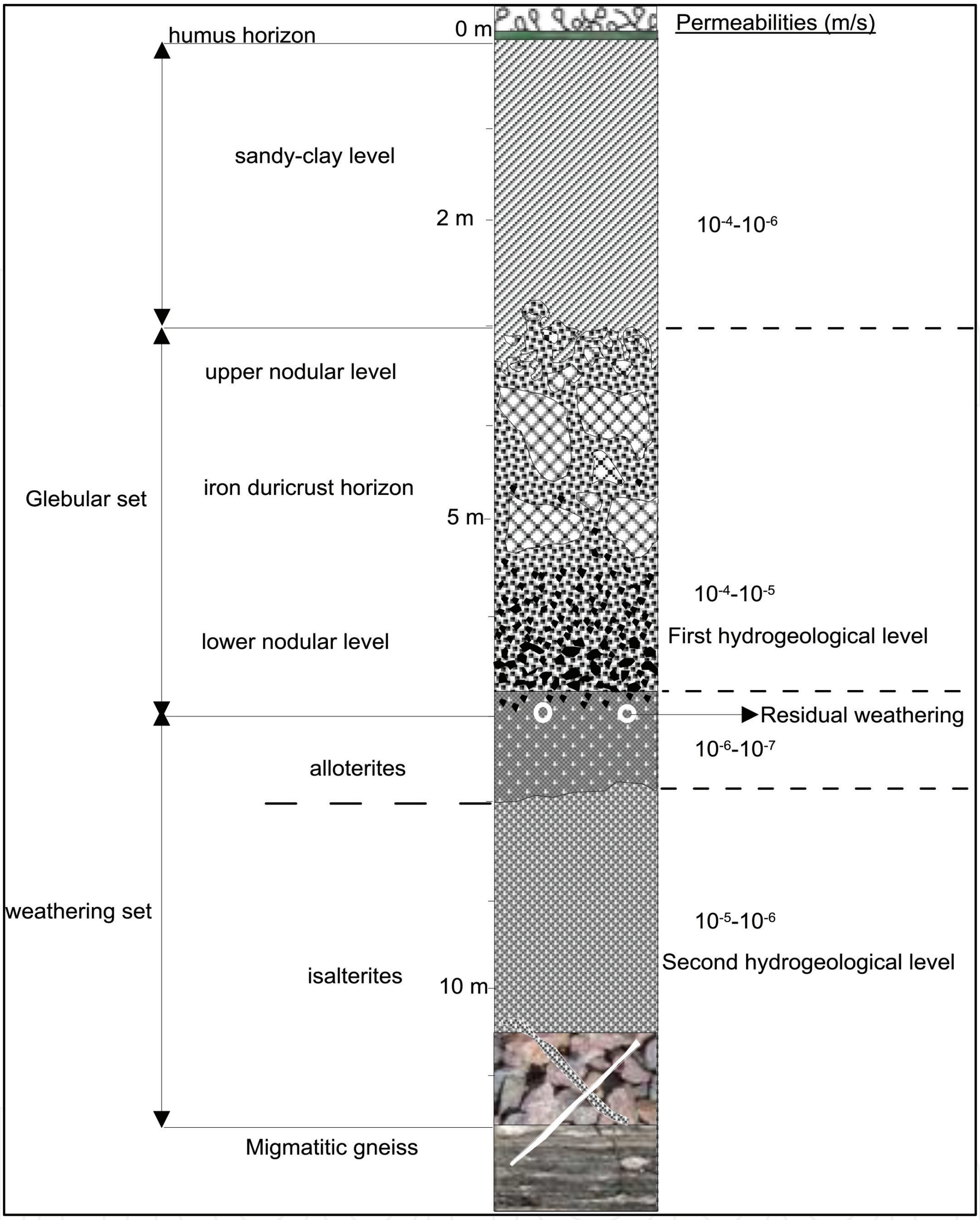

Figure 3.
Graphic illustrating the macroscopic organization of the alteration profile.

- ○ A lower nodular material (ferruginous nodule litho-relictual dominant, irregularly shaped platelet)
- ○ The iron duricrust blocks with facies varying according to the sites
- ○ A heterogeneous upper nodular material

- Loose superficial level of variable thickness depending on the site (1–6 m); it is sandy-clay (predominantly kaolinite, hematite, and goethite) and red in color, red-brown to red-yellow. It may be absent where the glebular set is developed or outcrop.

The iron crust hillocks appear between 700 and 800 m of altitude [25]. These hillocks correspond, at the level of each sub-basin of the Mfoundi, to areas of high altitudes (760–800 m) and moderate altitude ridges on the slopes (740–760 m). The sandy clay-sandy layer has a thickness between 2 and 47 m. Soil profiles are generally thicker (>20 m) in areas where these topographic shelves are observed and less thick (<5 m) in areas with high topography (>850 m) where the fissured/fractured compartment is by places observed. These different regional shelves are the result of successions of alteration and erosion phases (biostasis and rhexistasia) [5, 6]. These mounds are separated by flat valleys including the Mfoundi Valley. The distribution of the shelves with respect to the Mfoundi watercourse shows a predominance of the highest mounds on the right bank (770–800 m) and the lowest ones on the left bank (see **Figure 1**).

4. Hydrodynamic properties of shallow unconfined aquifer

Various techniques, as reported in the literature, are used to determine the hydrodynamic properties of aquifers in basement areas in general and its superficial part in particular. They include but are not limited to field methods (pumping test, slug test and tracer test, Porchet test) [12, 22, 34]; laboratory and mathematical methods [35], empirical formulas [36], and regional methods [37, 38]. Even though accurate estimation of hydrodynamic proprieties (effective porosity, permeability, and transmissivity) may be conducted in the field environment, poor knowledge of aquifer geometry sometimes limits their potential application [39]. The general characteristics of the altered compartment of the hard rock show that the alterites are of sandy-clay nature and have a generally low hydraulic conductivity but significant water retention capacities [29, 37]. These alterites show a heterogeneity marked by a range of variation in hydraulic conductivity between 10^{-8} and 10^{-5} m/s [28, 35, 40, 41], depending on the clay content which is low in the laminate level (base of saprolite). The variation of this hydraulic conductivity is related to topography and a weathering processes [43]; [12, 30] and presents elsewhere a decrease with the depth of the soil. This decay obeys, depending on the case, a power law or an exponential function [31, 44–47]. Transmissivity is a function of the thickness of the saturated zone and varies between 10^{-6} and 10^{-2} m^2/s [1, 31]. The altered compartment (alterite) ensures, when saturated, a capacitive function, and its porosity is considered an "interstice" type [34]. The effective porosity depends on the geology and structure of the alteration profile and varies between 3 and 10% [27, 28, 38, 41].

The work leading to the determination of the hydraulic conductivity (based on the Porchet tests) in the Yaounde weathering formations is in majority carried out at depths between 0 and 100 cm. In "classical" soil profiles (with low rhexistasia), these depths generally correspond to bioturbated soils where the permeabilities are, in general, higher. In the case of this study, the morphopedological data of the studied area indicate that the processes of alteration or erosion make appear, in places, the glebular set or alteration set in surface [5, 11]. The hydraulic conductivities corresponding to these depths are therefore representative of the whole subsurface aquifer. In addition, depth investigation data (beyond 8 m), based on pumping tests or slug tests, indicating the level/horizon actually investigated, were also taken into account in the hydraulic description of this aquifer. Hydraulic conductivity values from infiltration tests range from 10^{-7} to 10^{-3} m/s [12, 36]. The normal distribution (**Figure 4**) of the hydraulic conductivity values is unimodal and varies over four orders of magnitude, attesting the variability of this propriety of the loose materials. At the scale of the soil profile (**Figure 3**), the hydraulic conductivity varies between 10^{-6} and 10^{-4} m/s in the loose superficial level, 10^{-5} and 10^{-4} m/s in the glebular set, 10^{-7} and 10^{-6} m/s in alloterite, and 10^{-6} and 10^{-5} m/s in isalterite horizon [11, 17]. At the well scale (slug test), these values vary from 5.13×10^{-6} m/s

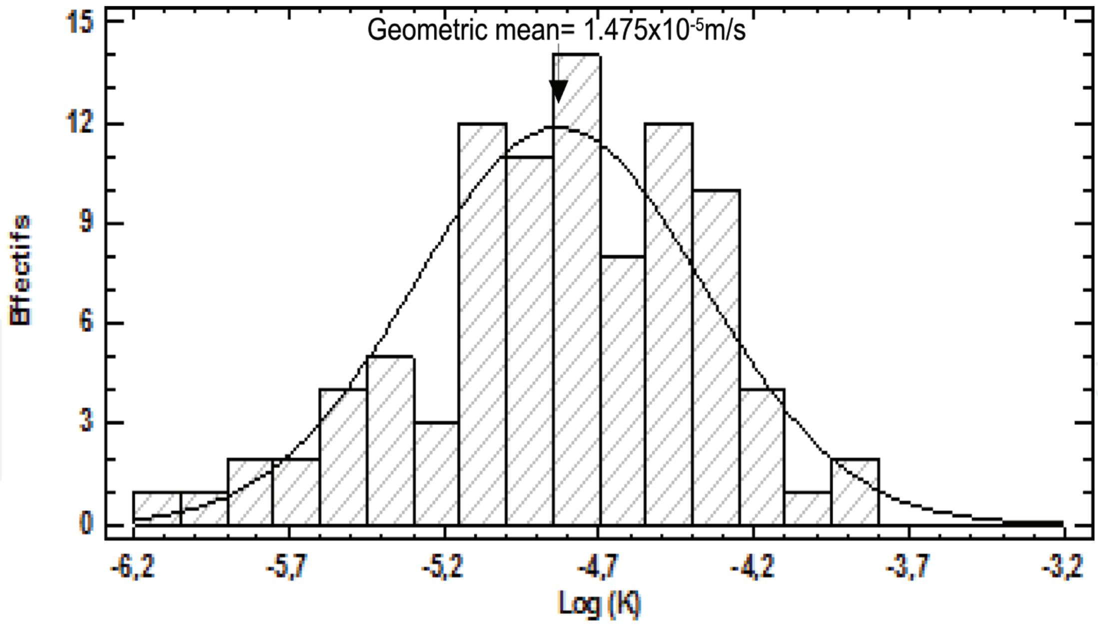

Figure 4.
Histogram of hydraulic conductivity distribution determined by Porchet hydraulic tests (constant head).

in the glebular set [36] to 5.8 × 10^{-5} m/s in saprolite [17] for a transmissivity of 2.3 ± 1.5.10^{-4} m^2/s [8]. The effective porosity determined at the sample scale is 7.4% [47]. These properties are important for the movement of shallow groundwater, both in the altered compartment (regolith) and in the underlying bedrock [30, 48].

5. Hydrodynamic of the weathering mantle

5.1 Hydrogeological levels

The hydrodynamics of the alteration mantle in the tropical zones present, globally, two hydrogeological levels illustrated in **Figure 3**. These distinctions are based on the hydraulic characteristics of confining layers.

5.1.1 Perched aquifer of iron crust

The iron crust has alveolar permeability due to its structure and fracture permeability due to its dismantling [48]. It promotes rapid infiltration into areas where it is preserved from subsequent erosion. The voids present below the indurated level (**Figure 3**) can create a strong permeability contrast with the altered level (alloterite), giving rise to a locally perched aquifer with a few sources that exhibit an epikarst-type function [3]. In the case of heavy precipitation, the temporary water table in this aquifer can be loaded under the iron crust and give rise locally to artesian sources [48].

5.1.2 Aquifer of alterite

Its hydrodynamic properties (high porosity and low permeability) give it the capacitive function of the aquifer system [3, 17]. Seepage areas may be locally observed on outcrops of laterites during high water events [48]. Its lower part (coarse saprolite), composed of very weathered rock and relatively healthy blocks, facilitates the circulation of water. This gives it a transmissive function, thus feeding the main resurgences of the slopes and the streams base flow. The rates obtained in the aquifer of alterites are of the order of 1 m^3 h [49]. The distinction between different types of aquifers is often difficult. It is necessary to have data about subsurface lithology, water levels, and hydraulic parameters of aquifer and confining layers for identifying a particular type of aquifer.

5.2 Hydrometry and piezometry

The common groundwater structures used to study the hydrodynamic operation of aquifers are wells, springs, and boreholes. Wells are generally dug to the base of loose alterite as the springs emerge either between the alloterite and the overlying horizon or between the isalterite (coarse saprolite) and the upper fissured horizon (saprock). Boreholes most often pick up the basement or basement-alterite system whose behavior is sometimes comparable to that of a shallow unconfined aquifer [41]. The data presented in this work relate only to springs and wells. The discharges of springs vary between 0.04 and 6.2 m^3/h against 0.06 and 0.5 m^3/h in the wells. The recession coefficients of springs vary between 0.001 and 0.016/d against 0.06 and 0.39 m/month at wells [11]. Springs emerging on the coarse saprolite-saprock continuum generally have the highest flow rates [11]. This observation is consistent with that of the other authors [26, 35, 38] which indicates that it is at fissured horizon that the hard rock aquifers owe their productivity. At the lithological scale, the order of magnitude of productivity of the springs is between 0.03 and 3.2 m^3/h and between 0.03 and 6.2 m^3/h, respectively, in metaplutonites and metasediments. This difference of a factor of 2 is not significant with the depths of groundwater which vary between 0.0 and 17.7 m, with an average of 5.7 ± 6.2 m in the whole of the area. In the Mfoundi watershed, these depths differ by about 4 m between the two banks either between 0.0 and 13.5 m on the right bank or 0.1 and 17.7 m on the left bank. Its hydrodynamic characteristics indicate that the aquifer has, in places, highly heterogeneous areas. The ancient tectonic structuring E-W at NW-SE (592 Ma at 658 Ma [24]) controls the orientation of the hydrographic network. Thus, the landscape form, which is shaped by the hydrographic network, is at the origin of the upstream-downstream underground flows conforming to the outline of the topography, namely, NNE, NS, EW, and ESE to SE [11]. The average piezometric amplitudes corresponding to this altitudinal distribution range between 1.3 and 3.1 m in the summit zones, between 0.7 and 1.1 m in the mid-slope zones, and between 0.3 and 0.6 m in the valleys where the watercourse is generally the imposed potential [11]. The seasonal dynamics of the Yaounde shallow unconfined aquifer (alterite) are, in general, similar to those observed in the basement zone, in humid tropical climates [11, 49–51]. The piezometric increases are observed during the great rainy season and vice versa during the dry season (**Figure 5**). The discharge of the aquifer evolves according to an exponential law characteristic of environments with high inertia. This inertia and/or the continuous/discontinuous nature of the aquifer reservoir may be at the origin of piezometric anomalies (**Figure 6**) characterized by a piezometric increase in the dry season and a decrease in the rainy season [52]. According to [42], these piezometric anomalies indicate areas of high transmissivity. The relationship between well and springs behavior and rainfall has a lag of about 1 month (**Figures 5** and **6**) that can be attributed to morphopedological processes. Some authors attribute this lagging to delayed drainage between recharge and drainage areas [50] and the evapotranspiration of one part of the rain, so the degree of soil moisture during the periods proceeding rainy phases [51]. Some wells have a rapid response to precipitation (**Figure 6**). This rapid response of the water table to rainfall depends on the geological units [53] or the water-level position [54]. This position classifies the water table at local, regional, and continental

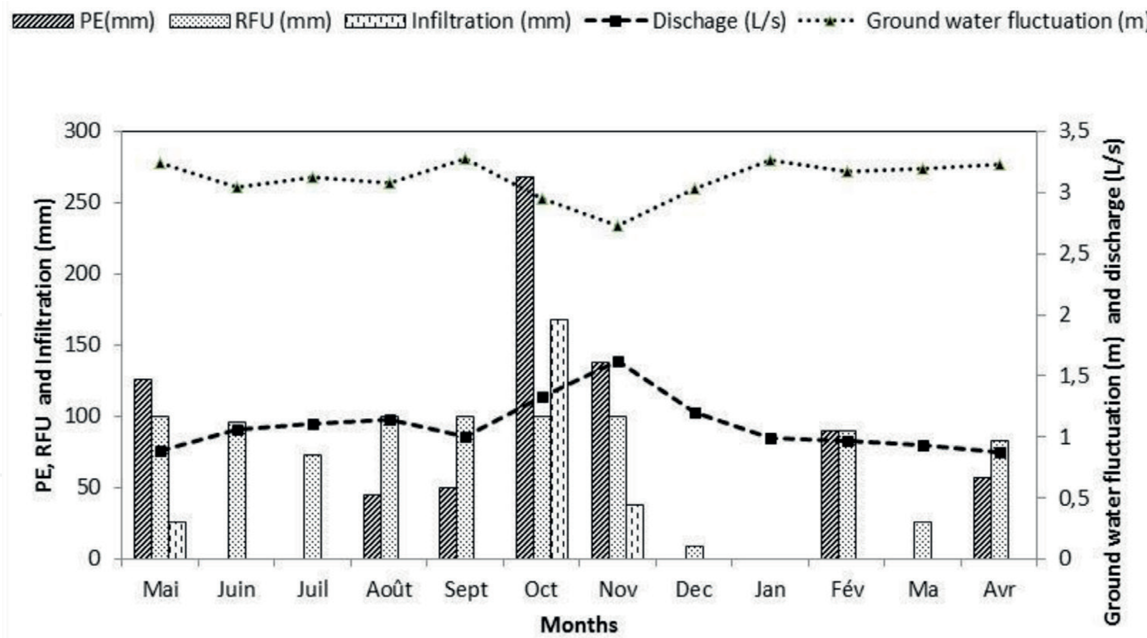

Figure 5.
Graphic illustrating the evolution of the average values of the flow of the sources and the fluctuations of the piezometric levels in the Olezoa watershed (2010–2011). PE = effective precipitation, RFU = available water content of the soil.

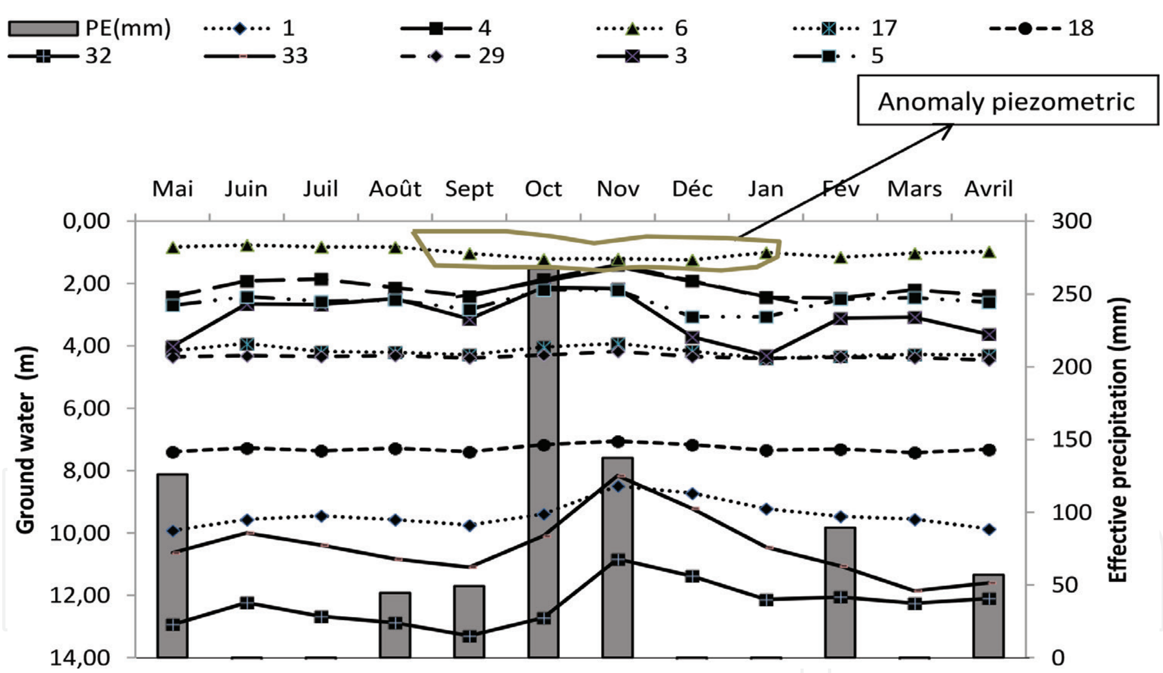

Figure 6.
Graphic illustrating the evolution of the groundwater depths of some dug wells showing the piezometric anomaly in the Olezoa watershed (2010–2011).

scales. Indeed, the character of the water table is fundamental to conceptualize the groundwater flow systems and to examine the connections between groundwater, surface water, and climate [55]. Unfortunately, studies on the classification of groundwater at various scales are limited throughout the Mfoundi basin and surrounding areas.

However, ongoing work in the Olezoa watershed has identified two topographic scales highlighting the concept of hierarchical groundwater flow systems [56]. Beyond this hierarchy, the two scales nevertheless suggest that the piezometric surface is much more controlled by the topography than by the recharge. In the first case, water table generally coincides with the topographic surface, and the depths of water table are small. In the second case, the depths are high, and the water table is totally disconnected from the topography [54].

5.3 Estimation of aquifer recharge

In the humid tropical zones, the fluctuation of groundwater levels in weathered layer (alterites) is controlled to varying degrees by effective rainfall [51], the streams, topography [11, 57], the thickness of the saturated portion of the saprolite [58], and pumping extracting [57]. Fluctuations in groundwater levels are dynamic responses of the system to recharge (input water) and discharge (loos water) [57]. The evolution of the discharge according to an exponential law (**Figures 5** and **6**) is characteristic of a water table fed mainly by vertical contributions [59]. Several approaches are used to evaluate these input water (recharge/infiltration) including empirical methods, base flow measurement methods, water-table fluctuation (WTF) method, chloride balance method, soil moisture method, isotope method, or mathematical methods [49, 57]; [60]. The application of some of these methods in the Yaounde area indicates that the recharge of shallow aquifer of Yaounde migmatitic basement is recent and is done directly by infiltration of precipitation without any notable change due to evaporation [61]. The average isotope contents of ^{18}O of rain and shallow groundwater are, respectively, −2.47 and −2.57‰ Vs-SMOW [61] with annual and monthly isotope signature differences in precipitation values [62]. Groundwater recharge appears to occur in May, October, and November (**Figures 5** and **6**) and increase from 30 mm/yr in the lowland to 40 mm/yr in the highland [60]. The infiltration coefficient varies between 5.7 and 7.5% according to the chlorine balance method [60, 61], 6% with the WTF [17], and between 5 and 23% according to the Thornthwaite method with an available water content of the soil (RFUmax) of 100 mm [14, 15, 17].

6. Hydrogeological model of the weathered mantle of Yaounde migmatitic basement

This model is based on the following observations:

- A thick weathered mantle with two hydrogeological levels within it.
- The iron crust hillocks appearing between 740 and 760, between 760 and 780, and between 780 and 800 m.
- An altimetric phase shift of the topographic shelves between the two banks of the Mfoundi watercourse, showing a Miocene flattening surface [63].
- A variation of the piezometric surface related to this altimetric phase shift, but the piezometric level is close to the ground surface.
- Recharge to groundwater is by direct infiltration of rain into the altered aquifer to the fractured aquifer. This is more important on the high points where the piezometric fluctuations are high.

All these observations are summarized in **Figure 7**.

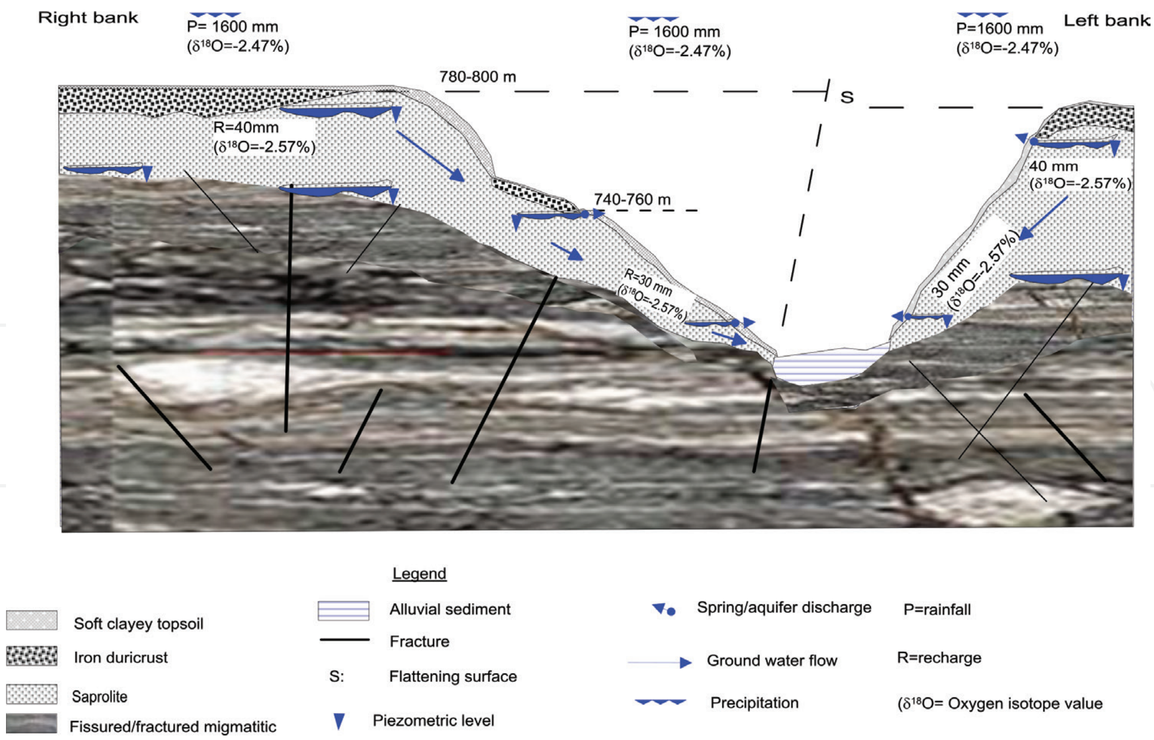

Figure 7.
Conceptual hydrogeological model of the weathered mantle of Yaounde migmatitic basement.

7. Conclusion

Hydrogeological studies in the city of Yaounde and its environs are conducted in a context where the extension of public drinking water supply does not follow unregulated urbanization, fueled by population growth, and internal migration. The compilation and analysis of the information acquired during these studies allowed to propose an image of the hydrogeological characteristics of the alteration formations of this city. The weathered mantle of migmatitics of the Pan-African series of Yaounde presents the characteristics of a hard rock aquifer in a humid tropical environment. A perched aquifer is identified, overlying the alterite aquifer and a hydraulic conductivity decreasing with the depth of the soil. The upper part of the weathered mantle (regolith) is sometimes assimilated to a homogeneous aquitard under which the saprock aquifer develops. This mantle shows an old alteration resulting from the dismantling of old lateritic systems on the one hand and, on the other hand, a polyphase alteration model, with relatively recent alterites developed on a morphology presenting a significant relief. If this structure is similar to those of the granito-gneissic formations of the world (India, France, other African countries), there are nevertheless specificities that can be related to the local scale to those of limestone environments. Indeed, the solubility of silicates in a humid tropical environment allows the formation of voids or microreliefs of weathering. These microreliefs can have a local influence on the hydrodynamism of the shallow aquifer (regolith). Hydrodynamic characteristics indicate a recent recharge by direct infiltration of precipitation without any notable change due to evaporation. These highlight the effect of several forms of heterogeneities that are related to the relief model and to the physical and hydraulic properties of the terrain.

Acknowledgements

The authors thank †Dr. H.B. Djeuda Tchapnga for initiating research programs; some of whose results have been synthesized and presented in this chapter.

Conflict of interest

No conflict of interest.

Author details

Jules Rémy Ndam Ngoupayou[3], André Firmin Bon[1,2,3]*, Guillaume Ewodo Mboudou[2,3], Nasser Ngouh Abdou[3] and Georges Emmanuel Ekodeck[3]

1 Department of Meteorology, Climatology, Hydrology and Soil Science, National Advanced School of Engineering, University of Maroua, Maroua, Cameroon

2 Department of Hydraulics and Water Control, National Advanced School of Engineering, University of Maroua, Maroua, Cameroon

3 Department of Earth Sciences, Faculty of Science, University of Yaounde I, Yaounde, Cameroon

*Address all correspondence to: bon_andr@yahoo.com

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