Water Resources in Africa: Scarcity and Abundance

Jean-Jacques Seguin, Alexis Gutierrez

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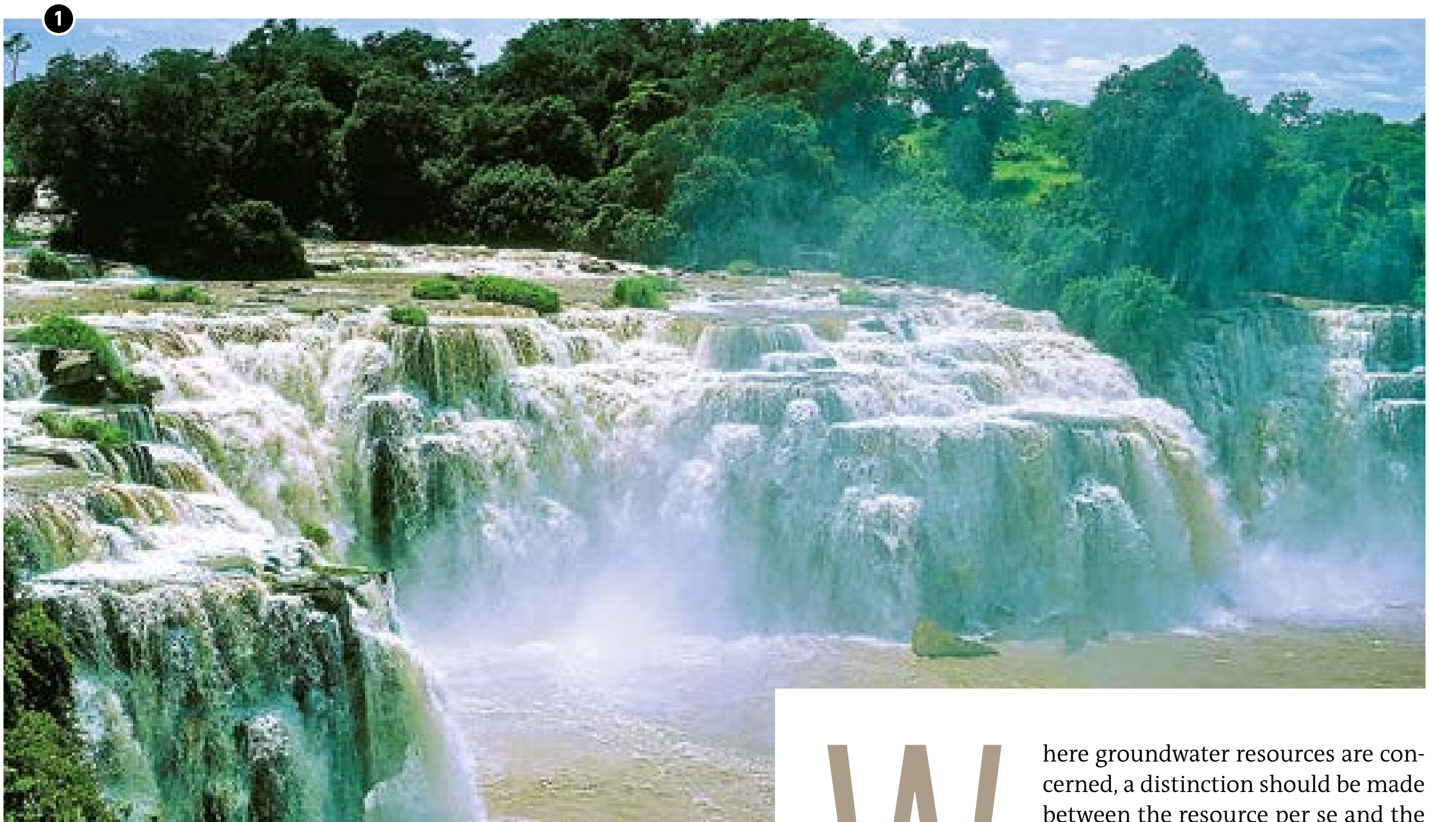

Water Resources in Africa: Scarcity and Abundance

Based on various calculations, Africa is thought to possess 9% of the world's freshwater resources, i.e. nearly 4000 km³ of water per year. This misleading abundance masks a very considerable disparity of resources and severe supply issues for at least 25 African nations by 2025. The continent must revert to optimizing its groundwater resources, more reliable than surface water, being less sensitive to climate variations and pollution.

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Where groundwater resources are concerned, a distinction should be made between the resource per se and the reserves. The resource (the recharge of aquifers by infiltration of precipitations) is dependent on flows fed by the water cycle and is accordingly largely renewable. As to groundwater reserves, these correspond to stores of water not currently replenished under present climate conditions. A special type of water reserve is represented by so-called fossil aquifers: when tapped, they can be assimilated to a mine deposit, that is, with the risk of exhaustion. The media have recently widely broadcast the estimations of a study [Mac Donald *et al.* (2012)] quantifying Africa's water reserves (660,000 km³)[1]. These appear to be over 100 times more abundant[2] than the renewable resources, the latter being estimated at nearly 4000 km³ per year (*table 1*). The tapping potential for these aquifers is debatable from technical, economic, environmental, and even geopolitical standpoints, and poorly compatible with sustainable management, which presupposes considering only the renewable resource. However, these resources are already widely called upon, on a local basis, because reserves and renewable resources are unequally distributed across the continent. The former depend on the position of the vast geological reservoirs, while the latter are closely related to climate.

The hydrogeology of Africa: geological reservoirs and replenishment

The hydrogeological map of Africa at the 1:10,000,000 scale established by BRGM [J.-J. Seguin (2008)] allows a simplified approach to the continent's hydrogeology. It displays 11 hydrogeological entities (*table 2*) regrouping

PHOTO 1
The waterfalls of the Lofoï River, a tributary of the Congo River, cascading across the Kundelungu sandstone formation (Kyubo, Katanga, Democratic Republic of the Congo).

TABLE 1 / **Precipitation and Africa's renewable internal water resources.**
SOURCE : AQUASTAT, FAO, 2014.

Region / Sub-region	Precipitation: Annual height (mm)	Precipitation: Annual volume (km^3)	Renewable internal water resources: Annual volume (km^3)	Renewable internal water resources: In % of worldwide freshwater resources	Renewable internal water resources: Per capita in 2013 (m^3)
North Africa	**96**	**550**	**47**	**0.1**	**274**
Subsaharan Africa	**815**	**19 821**	**3 884**	**9.0**	**4 143**
Sudan Sahel	311	2 679	160	0.4	1 062
Gulf of Guinea	1 356	2 877	952	2.2	3 650
Central Africa	1 425	7 593	1 876	4.4	15 261
East Africa	912	2 669	285	0.7	1 154
South Africa	656	3 107	270	0.6	2 057
Indian Ocean islands	1 514	896	341	0.8	1 342

geological formations from a lithostratigraphic standpoint and corresponding to environments having water-bearing potentials that vary according to their structure: a reservoir with interstitial porosity (the matrix porosity of so-called "continuous" media) or with dual porosity is presumed to be more productive than a cracked/fractured reservoir in the crystalline basement or in consolidated former sedimentary terrains. A given environment, whether continuous or discontinuous, will only constitute a promising aquifer if the geological formation concerned is both permeable and infiltrated by precipitations (recharge)[3].

These reservoirs are found over a wide range of climate zones: desert to arid semi-desert, humid tropical, equatorial… Climate variability naturally results in variable recharge of the aquifers, represented on the map by different zones (*figure 2 and table 3*). One third of Africa's surface area, with recharge values of less than 5 mm, thus seems to be poorly endowed with renewable groundwater.

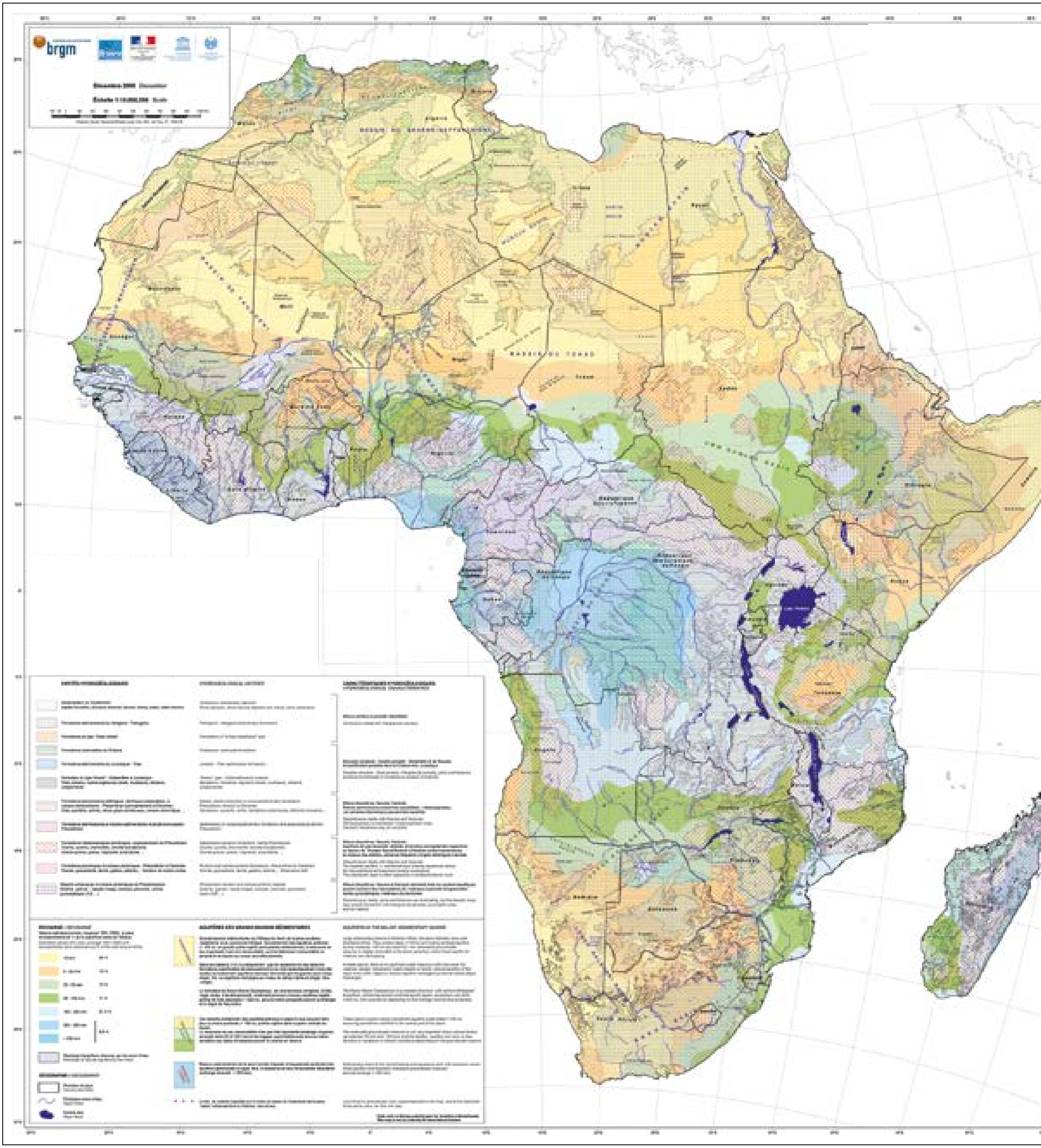
A simplified typology of aquifers into six large groups enables us to obtain an overall view of Africa's hydrogeology (Figure 3). Continuous medium aquifers (composed of Mesozoic or Quaternary sedimentary formations) account for 41.7% of the total surface area. Ancient sedimentary aquifers (Precambrian and Paleozoic), often assimilated with basement aquifers (fractured media), occupy, in equal proportions with the basement aquifers, 41.5% of Africa's surface area. The remaining 16.8% are composed of complex aquifers (including 4% of volcanic aquifers).

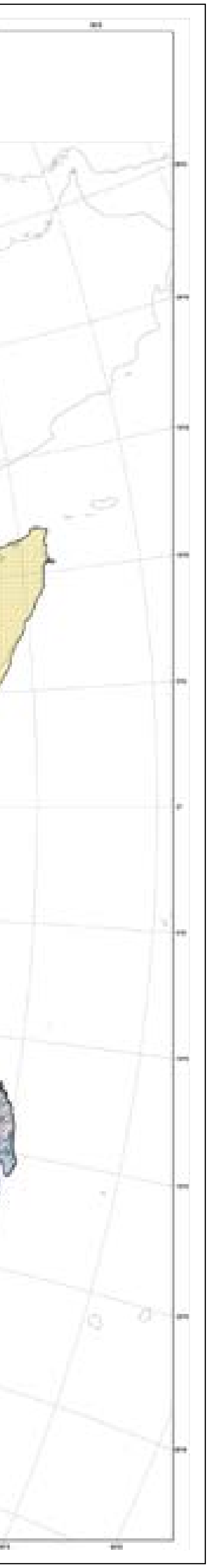
TABLE 2 / **Hydrogeological entities depicted on the hydrogeology map of Africa at 1:10,000,000 scale.** © J.-J. SEGUIN, 2008

Nature of the formations	% of the surface area	Type of environment
Sedimentary of the Quaternary	**22.4**	Continuous media with matrix or with dual porosity
Sedimentary of the Paleogene-Neogene	**14.4**	
Formations of the "Nubian sandstone" type	**4.9**	
Formations of the "Karoo" (Carboniferous to Jurassic) **type**	**3.5**	Complex structure with many superimposed reservoirs
Carbonated Cretaceous formations	**6.8**	Complex, locally karstic structures
Jurassic-Triassic formations	**2.5**	
1) Detrital/carbonated sedimentary to volcano-sedimentary formations (Neoproterozoic to Paleozoic and Precambrian)	**13.4**	Dominant cracked/ fractured
2) Sedimentary to volcano-sedimentary formations and associated volcano-plutonism (Precambrian)	**7.4**	
Plutonic and metamorphic complexes (Precambrian to Paleozoic)	**17.6**	Cracked/fractured
Plutonic massifs (Cambrian to Precambrian) **"Older Granites", "Bushveld Complex" Plutonism of "greenstone belts"**	**3.1**	
Volcanic and volcano-plutonic massifs of the Phanerozoic	**4.0**	Dominant cracked/ fractured, but possible intercalation of porous materials (e.g. tufa)

1/ *1 km^3 = 1 billion m^3.* ***2/*** *The comparison often made between reserve and resource does not concern two volumes, but only one volume (stock) and one flow (volume per unit of time, generally an annual mean).* ***3/*** *The recharge estimate is generally used to evaluate the resource. However, recharge does not constitute the exploitable groundwater resource in its totality. In fact, the groundwater itself contributes to the base flow rate of watercourses. Tapping the entire renewable resource provided by recharge, where technically possible, would cause watercourses to run dry under mean low water conditions.*

FIGURE 1 / **Extract from the plate of the hydrogeological map of Africa to the scale of 1:10,000,000.** © BRGM - 2008





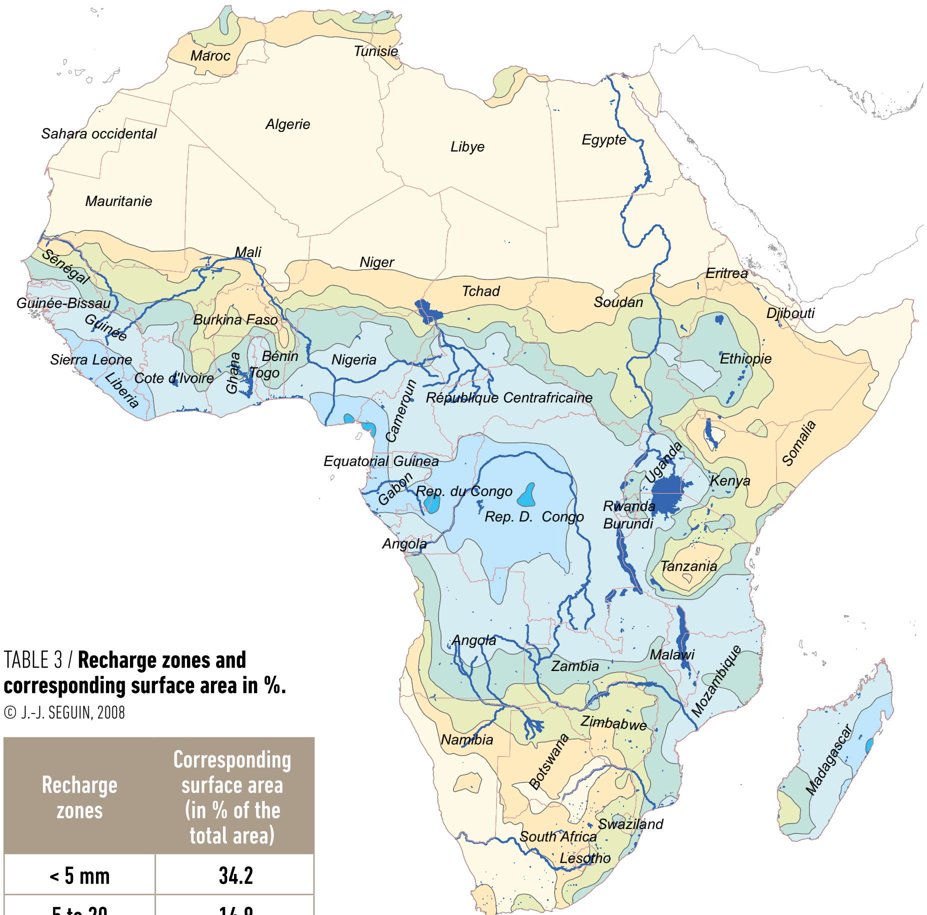


FIGURE 2 / **Delimitation of seven recharge zones (according to the 1:10,000,000 hydrogeological map of Africa where the recharge results from an interpolation of a grid of values provided by P. Döll, 2005).** © BRGM

Estimated water recharge (mm/year)

- < 5 mm
- 5-20 mm
- 20-50 mm
- 50-100 mm
- 100-300 mm
- 300-500 mm
- > 500 mm

0 500 1 000 2 000
Km

TABLE 3 / **Recharge zones and corresponding surface area in %.**
© J.-J. SEGUIN, 2008

Recharge zones	Corresponding surface area (in % of the total area)
< 5 mm	34.2
5 to 20	14.9
20 to 50	11.6
50 to 100	11.3
100 to 300	21.5
> 300 mm	6.5

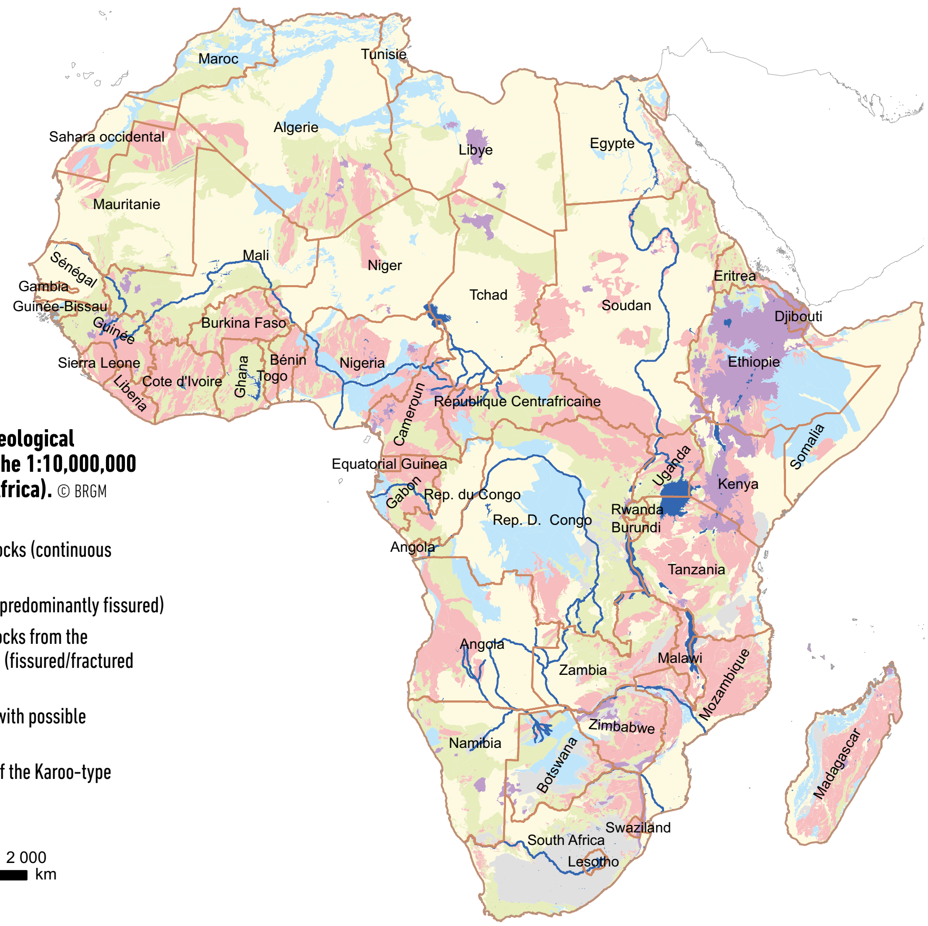


FIGURE 3 / **Main types of geological reservoirs (according to the 1:10,000,000 hydrogeological map of Africa).** © BRGM

- "Recent" sedimentary rocks (continuous environment)
- Old sedimentary rocks (predominantly fissured)
- Crystalline or foliated rocks from the metamorphic basement (fissured/fractured environment)
- Carbonate formations (with possible karstification)
- Geological formations of the Karoo-type
- Volcano-plutonic rocks

0 500 1 000 2 000
km

FIGURE 4 / **Boundaries of the major deep captive aquifers in North Africa.** © BRGM

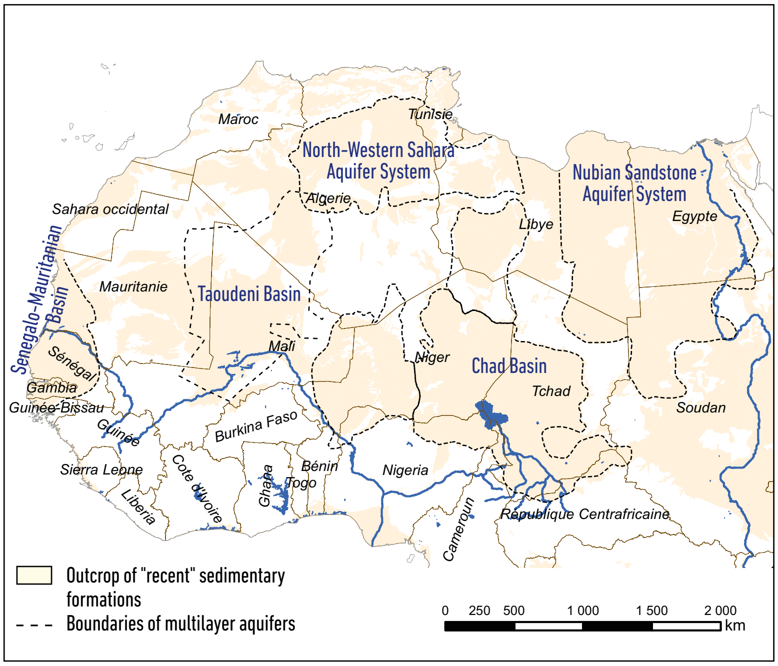


TABLE 4 / **Main deep aquifers in the North-African hemisphere and piezometric tendencies for the major captive aquifers.**
MODIFIED FROM SEGUIN, 2008; MARGAT, 2008, 2014, COMPLETED

Aquifer designation	Countries concerned	Surface area (10^3 km^2)	Mean piezometric evolution (m/yr)	Current abstraction (2011) (km^3/yr)
Nubian Sandstone Aquifer System (NSAS)	Egypt, Libya, Sudan, Chad	2200	**-2m/yr from 1955 to 1975**	2.3
North Sahara Aquifer System (SASS)	Algeria, Libya, Tunisia	1000	**-0.2 to -2m/yr over 50 yrs (1950 – 2000)**	2.9
Lake Chad Basin	Niger, Nigeria, Chad, Cameroun, Central African Republic	1500	**-0.1 m/an over 30 yrs (1963 – 1998)**	0.25 (2002)
Taoudeni (SAT) and Iullemeden (SAI) Aquifer Systems	Benin, Burkina Faso, Mali, Mauritania, Niger, Nigeria and Algeria	SAT: 2000 SAI: 500	**-0.2 m/yr (1980 –2000) compensated by a recharge over the period >2000**	SAT: 0.06 SAI: 0.28
Murzuk Basin	Algeria, Libya, Niger	450	**-1 to -2m/yr over 25 yrs (1974 – 2000)**	1.7
Senegalo-Mauritanian Basin	Mauritania, Senegal	300 000	**-0.2 to- 0.4 m/yr (1969 –1999)**	0.26 (2003)

Continuous aquifers of "recent" sedimentary basins

So-called "recent" sedimentary basins – Mesozoic to quaternary in age – represent more than half of Africa's surface area (*table 2*). In zones with low recharge, except the Nile Valley, there are no superficial aquifers having a significant renewable resource.

> *Deep aquifers in North Africa*

In the Mesozoic and Cenozoic sedimentary basins, two major geological sequences can be distinguished that contain deep, multi-layer and captive aquifers in the central part of the basins:

– The *Continental Intercalaire* formations are mainly Mesozoic in age (Triassic to Albian), although their deposition may have begun in the Permian. They are predominantly gritty, with clayey interbedding, very frequent in Saharan and Sahelian Africa (the northern Sahara, Taoudenni, Iullemeden Aquifer System, Chad and Murzuk basins). They are also found in the Congo and Bénoué basins, as well as in the Gabonese and Congolese coastal basins. Also associated with the *Continental Intercalaire* aquifer is the so-called *Nubian Sandstone* formation, present in Egypt, Sudan, Chad and Libya. In the latter country, it supplies coastal cities with 6,500,000 m³ of water per day *via* the "great artificial river", sourced from 1300, 500 m-deep wells.

– The formations of the *Continental Terminal* are Cenozoic in age (from the Middle Eocene to the Pliocene) and are essentially detrital, arenaceous or sandy clay.

Between the *Continental Intercalaire* and the *Terminal Continental*, we also find the *Continental hamadien*, with detrital formations dating to the Upper Cretaceous through the Paleocene, as well as the sandy Maastrichtian formation of the Senegalese-Mauritanian basin.

The largest aquifers of these basins, with a resource considered to be non-renewable, are shared among several countries (*figure 4 and table 4*). Modeling has been performed for some of these aquifers: the *Système Aquifère du Sahara Septentrional* (SASS, i.e., North-western Sahara Aquifer System), the Nubian Sandstone Aquifer System (NSAS) and the Iullemeden and Taoudenni basins, the latter revealing non-negligible recharge fluxes on the basins' southern slopes and *via* the Niger River.

> *Unconfined Aquifers of the Congo and Kalahari Basins*

The sedimentary Congo Basin covers a major portion of the Democratic Republic of the Congo. Northwards, it extends towards the People's Republic of the Congo

BOX 1

► AFRICA'S RIVERS, WHERE EXTREMES MEET

Africa's rivers, its sources of water, of life and sometimes of survival, are characterized by extremes in terms of power, streamflow or navigability: they are holders of many world records.

Thus the Nile, majestic and mythical, its course measuring 6670 km, is the world's longest river, but also one of the most regulated, for despite a catchment area of 2.87 million km², its flow rate today is a mere 0.3 km³ per year. Its discharge varies by a factor of 16 due to dikes and the Assouan dam, which moderate the excesses of its floods. The Congo, Africa's second-ranking river with a length of 4700 km, is the world's second river after the Amazon as to its basin (nearly 3.75 million km²) and its flow rate: 1200 km³ per year, i.e. nearly 40,000 m³ per second, which corresponds to Paris's daily drinking-water consumption every 14 seconds. The Niger River, Africa's third-ranking river in length with its 4200 km, conditions the existence of over 100 million individuals. With a basin covering 2.26 million km², it loses half its water to evaporation and its flow rate shrinks to 154 km³ per year. The Zambezi River, Africa's fourth in rank with a length of 2750 km, boasts the spectacular Victoria Falls – at 108 m, the highest in the world (*photo*). The Senegal River flows over a course 1790 km long across a catchment area measuring 2.26 million km². It features one of the greatest variations in flow rate in Africa, ranging from the lowest (3 m³/s) to the highest (over 5000 m³/s). In South Africa, the 1700 km-long Okavango River is Africa's only major endorheic river. A geological accident confines it to the continent, where it irrigates 15 000 km² in the Kalahari, after which it disappears into the desert. Lastly, we will mention the Alima and Lefini Rivers, flowing across the Bateke Plateaux (surface area 70,000 km²); they feed the Congo Basin and number among the world's rivers with the most regular flow (rate varying between 1.05 and 1.3 m³/s for minimum and maximum flow, respectively), due to their underground reservoir composed of sandstone and the buffering capacity of the groundwater on the flow of these rivers.

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The Zambezi waterfalls (Victoria Falls) viewed from the Zambian side.

and, southwards, towards Angola. Few studies have been devoted to this basin with an abundant superficial water resource.

In addition to the free water tables contained in the alluvia of the Congo River and its many tributaries, we may mention:

– the unconfined water table of the Batéké plateaus, composed of Neogene sandy loams and "soft" Paleogene sandstones of eolian origin;

– the unconfined, sometimes deep, water tables contained in the Tertiary sands of the southern and eastern parts of the Kwango plateau;

– the unconfined water tables of the Kasaï contained in the sands resulting from the weathering of Tertiary sandstones.

In the upper Kalahari basin (southeastern Angola and southwestern Zambia), drained by the upper reaches of the Okavango and the Zambezi and by the Kwango River, the aquifer formations are composed of sandy loam and sandstone.

> *Aquifers of the alluvial formations*

In arid and semi-arid climate zones, certain aquifers owe their existence to the major rivers that fill them regularly (*box 1*). This is the case for the alluvial plain of the Nile in Egypt, the Niger plain (the "*inland delta*" in Mali and Niger), Senegal's alluvial plain, etc.

Furthermore, alluvial filling in valley bottoms is commonplace in Africa. Even where there is no permanent

BOX 2

► MAPPING GROUNDWATER AVAILABILITY IN THE BASEMENT ROCKS: EXAMPLE OF BURUNDI

In Burundi, 90% of geological formations are basement rocks. In the valleys, superficial deposits (colluvia and alluvia) overlie these. Only the Moso plains, in the south, and the Imbo Valley, bordering on Lake Tanganyika, consist of a considerable thickness of sedimentary rocks, forming productive aquifers.

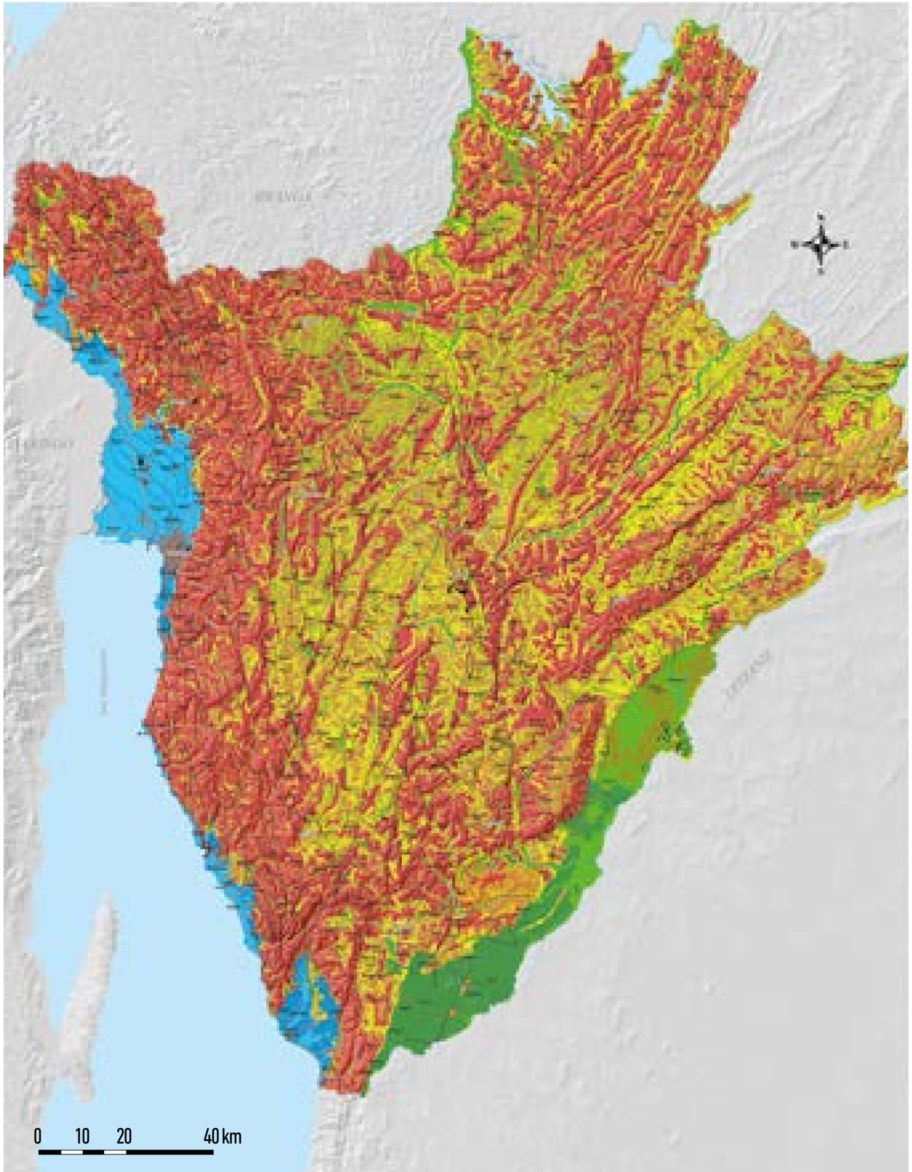
The map of Burundi's groundwater potential [Barrat *et al.* (2011)] was drafted under the "Water Management" component of the Water sector plan, funded by German cooperation. The resulting map to the scale of 1:250,000 was produced using digital processing tools and ground surveys, as well as some boreholes drilled in the country. Five categories were selected to define the hydrogeological potential of Burundi's geological formations should they be tapped *via* boreholes (*see map*). The various products obtained from this project were integrated into a Geographic Information System (GIS), with databases made available to the Institut géographique du Burundi (IGEBU).

In 2013-2014, a campaign of 14 reconnaissance boreholes allowed the working hypotheses of the mapping project [Barrat et Gutierrez (2015)] to be confirmed:

– the alterites of the Kirundo granites are highly water-bearing and can provide sustainable yields of as much as 20 m^3/h (provided the wellbores have been properly drilled). Their thickness may reach 100 m in the valleys. The transmissivities calculated vary between $2\ 10^{-4}$ and $6\ 10^{-6}$ m^2/s, with storage coefficients on the order of $5\ 10^{-4}$;

– in the Gitega schisto-quartzitic formations, where cracking is widespread, the sheet seems to be part of a compartmented aquifer. The transmissivities calculated vary between $1\ 10^{-3}$ up to over $1\ 10^{-2}$ m^2/s, with exploitation flows exceeding 60 m^3/h in most instances. But the continuous drawdown of the Gitega well-field water table would tend to point to isolated compartments and limited recharge.

Map of groundwater potential in Burundi. © BRGM



Areas with groundwater potential

- More than 10 l/s
- Between 1 and 10 l/s
- Between 0.3 and 1 l/s
- Between 0.1 and 0.3 l/s
- Less than 0.1 l/s
- Old alluvial terraces
- Lava flows - Basalts
- Urban areas
- Lakes
- Main roads
- Minor roads
- Faults
- Piezometric contour lines, Rusizi plain
- Provincial Capitals
- Rural Centers
- Inventory drillings (2011)

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hydrographic network, a groundwater flow is often present at the base of the alluvia. When these alluvia are thick (often several tens of meters), these aquifers represent an important water resource for village and pastoral hydraulics, such as the so-called Dallols (dry-valley) aquifers in Niger.

> Jurassic and Cretaceous carbonate aquifers

These aquifers are of considerable importance when they are karstified, which is especially the case in North Africa (Algeria, Morocco), in the coastal basins of East Africa (Tanzania) and in Madagascar.

Limestone formations cover a vast territory in the Democratic Republic of Congo, along the edges of the Congo basin (although presumably very little karstified), as well as in Ethiopia. They are also found in Gabon and in Nigeria.

> Aquifers of the Karoo formation

The Karoo formation (*Karoo Supergroup*), occupying virtually the whole of South Africa and extending into neighboring countries (Namibia, Botswana, Zambia and Tanzania), represents a particularly complex case (*figure 5*). Deposited between the Carboniferous and the Jurassic, it consists of a succession of sedimentary rocks (sandstones, argillites, siltstones, tillites...) interbedded with volcanic rocks. The aquifers are of the multilayered type.

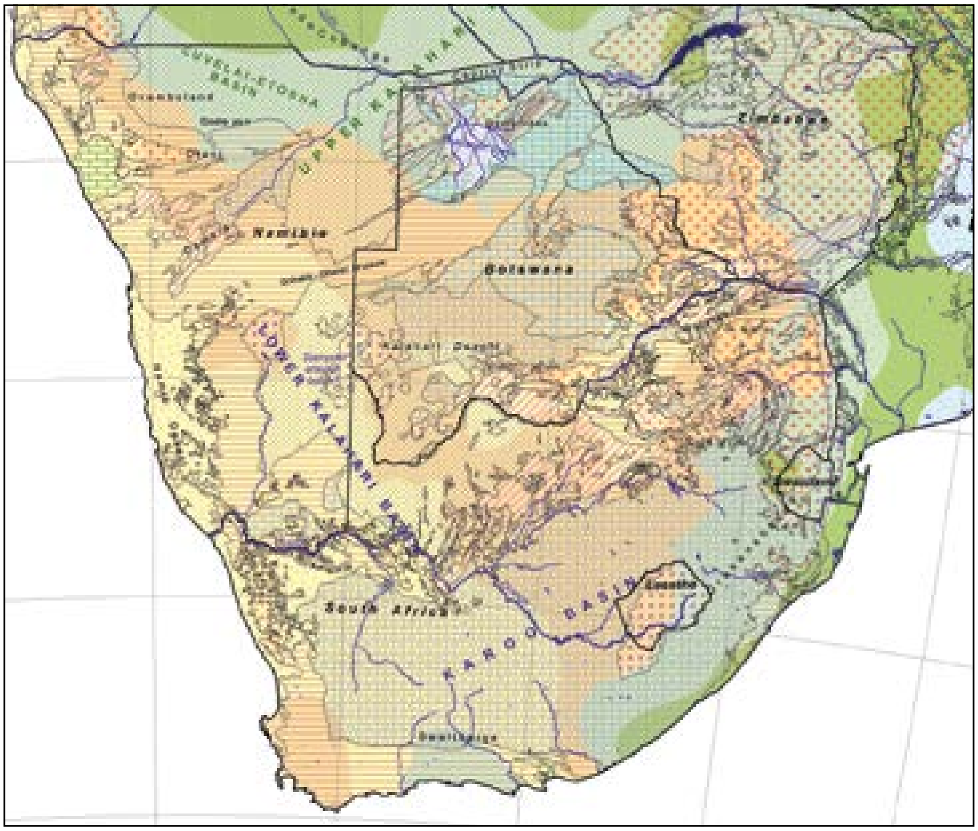

FIGURE 5 / **West Africa: Extract from the 1:10,000,000 hydrogeological map of Africa.** © BRGM

Taking the example of the *Localane-Ncojane* basin in Botswana, two main aquifers are found:
– the free-water table of the "Lebung Group" sandstones, characterized by the co-existence of two types of porosity: interstitial and fissural;
– the confined aquifer in the Boritse formation, the main aquifer of the *Ecca Group*, characterized by sequences of feldspathic sandstones alternating with carbonaceous rocks over a thickness of 100 to 200 m, with the roof encountered at a depth of 300 to 400 m in its central portion.

Discontinuous aquifers in the sedimentary formations of the Upper Precambrian and the Paleozoic.

These formations make up large sedimentary basins: those of Taoudenni, of the northern Sahara, of Tindouf, Murzuk, Katanga and of the Kalahari. Overlapped in their center by more recent (Paleogenic and Quaternary) formations, they outcrop:
– along the edges of the Precambrian basement formations of Sahelian Africa;
– at the perimeter of the Congo basin;
– in Namibia, southwest of South Africa, in Zambia, in Mozambique;
– along the Red Sea in Eritrea and Egypt.

They likewise outcrop in Madagascar, Kenya, Ethiopia, Chad, Algeria and, more locally, in Somalia, Libya and Morocco.

The *Precambrian sedimentary formations* are composed of highly consolidated (quite often indurated sandstones) and fractured rocks; they constitute aquifers with mediocre productivity and may, from a hydrological standpoint, be assimilated with so-called basement formations. At times they are cut through by dolerite intrusions with walls that may constitute preferential drains.

In the instance of Mali, for example, the gritty Precambrian formations outcrop mainly in the southern part of the country, between the Guinean border and the Gourma plain south of Gao. They do also outcrop in the north and on either side of the Adrar des Ifighas.

The aquifers located in the *Precambrian and Cambrian schisto-gritty and schisto-pelitic formations*, with poor storage capacity, are characterized by:
– a weathered horizon that is generally thick and clayey;
– pronounced lithological heterogeneity: schists alternate with sandstones, arkoses, conglomerates and graywackes.

These aquifers have characteristics quite similar to those of the schistose domain of the basement aquifers.

Basement aquifers

These consist of volcanic, plutonic and metamorphic formations, associated at times with volcano-sedimentary formations, known as *greenstone belts*. The majority are Precambrian in age (Archean to Paleoproterozoic), but they may also extend into the Cambrian.

They essentially occur in West Africa (*figure 3*), where they predominate in the heart of the Sahara, surrounding the sedimentary Congo basin, in East Africa and in Madagascar.

The rocks composing these formations (syenites, gabbros, diorites, gneisses, migmatites, schists...) are characterized by very low porosity (generally less than 1%, and 1 to 2% at most). Water storage and circulation, accordingly, are possible only if both a thick enough weathered zone with good porosity, playing a capacitive role, is present, and a network of fissures or cracks without infilling, playing a conductive role.

Among these formations, two hydrogeological domains are distinguished [R. Guiraud (1988)]:
– a domain dominated by granito-gneiss;
– a domain dominated by schist.

In the domain *dominated by granito-gneiss*, the alterite/cracked basement assemblage can be tapped *via* boreholes. The system behaves like a dual-layer type aquifer, in which the fractured rock substratum, locally highly permeable, acts as a transmitter allowing a proper instantaneous flow to be maintained. The overlying alterites, thanks to their good water-retention capacity, ensure a long-term supply of the borehole, being drained by the network of fractures.

Insofar as the fracturation decreases in density with depth, the boreholes do not need to penetrate deeply