Hydrogeologic framework and borehole yields in Ghana

S. Dapaah-Siakwan · P. Gyau-Boakye

Abstract In Ghana, 68% of the population live in rural communities, which are scattered and remote. Groundwater is the most feasible source of potable water supply for most of these dispersed and remote settlements. To meet the present and future challenges of population expansion vis-à-vis the observed declining rainfall in most parts of Africa including Ghana, it is necessary to assess, efficiently manage, and utilize the groundwater resources. The objective of this paper is therefore to describe the hydrogeologic framework and analyze borehole yields as part of the groundwater-resources assessment of Ghana. The hydrogeologic units are broadly categorized as: (1) the Basement Complex (crystalline rocks), which underlies about 54% of the country; (2) the Voltaian System, which underlies about 45%; and (3) the Cenozoic, Mesozoic, and Paleozoic sedimentary strata (Coastal Provinces), which underlie the remaining 1% of the country. The Basement Complex and the Coastal Provinces have higher groundwater potential than the Voltaian System. This is particularly significant, because the Basement Complex and the Coastal Provinces underlie the most densely populated areas of the country and can hence be tapped for human use. The average borehole yields of the Basement Complex, the Coastal Provinces and the Voltaian System range from 2.7–12.7, 3.9–15.6, and 6.2–8.5 m^3/h, respectively.

Résumé Au Ghana, 68% de la population vivent dans des collectivités rurales dispersées et éloignées. L'eau souterraine est la source la plus intéressante pour l'alimentation en eau potable de la plupart de ces villages. Afin de faire face au défit actuel et à venir de l'explosion démographique dans un contexte de diminution observée des précipitations dans la plupart des régions d'Afrique, dont le Ghana, il est nécessaire d'évaluer, de gérer et d'exploiter efficacement les ressources en eau souterraine. Le but de ce papier est par conséquent de décrire les conditions hydrogéologiques et d'analyser les rendements des forages, dans le cadre de l'évaluation des ressources en eaux souterraines du Ghana. De façon schématique, on distingue les unités hydrogéologiques suivantes: (1) le complexe du socle (roches cristallines), qui couvre environ 54% du territoire, (2) le système de la Volta, qui couvre environ 45%, et (3) les formations sédimentaires tertiaires, secondaires et primaires (provinces côtières) qui occupent environ 1% du pays. Le complexe du socle et les provinces côtières possèdent un potentiel en eau souterraine plus élevé que le système de la Volta. Ce fait est très significatif, car le complexe du socle et les provinces côtières sont les zones les plus densément peuplées du pays, celles où l'on peut capter de l'eau pour l'alimentation humaine. Les rendements moyens des forages dans le complexe du socle, dans les provinces côtières et dans le système de la Volta sont respectivement de 2.7 à 12.7, 3.9 à 15.6, et 6.2 à 8.5 m^3/h.

Resumen El 68% de la población de Ghana vive en comunidades rurales, generalmente dispersas y remotas. Las aguas subterráneas constituyen la fuente más fiable para el abastecimiento de agua potable a estos asentamientos. Para enfrentarse al aumento de población y a la disminución de la precipitación – observada en la mayor parte de África y, en particular, en Ghana – es imprescindible evaluar, gestionar con eficacia y utilizar los recursos de aguas subterráneas. Dentro del proceso de evaluación de las aguas subterráneas en Ghana, el objetivo de este artículo es describir el marco hidrogeológico y analizar los rendimientos de los sondeos. A grandes trazos, se distinguen tres unidades hidrogeológicas: (1) el Complejo Basal (rocas cristalinas), que ocupa el 54% de la superficie del país; (2) el Sistema de Volta, que abarca un 45%; y (3) los estratos sedimentarios (Provincias Costeras) del Cenozoico, Mesozoico y Paleozoico, en el 1% restante del territorio. El potencial de las aguas subterráneas en el Sistema de Volta es inferior al de las otras dos unidades. Esto es muy importante, ya que las zonas más densamente pobladas del país se situan en el Complejo Basal y las Provincias Costeras, cuyos recursos pueden aprovecharse para abastecimiento

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humano. Los rendimientos medios de los pozos del Complejo Basal, las Provincias Costeras y el Sistema del Volta son de 2,7–12,7, 3,9–15,6, y 6,2–8,5 m^3/h, respectivamente.

Key words general hydrology · geologic fabric · groundwater exploration · Ghana · water supply

Introduction

Rural communities in Ghana are defined as those with populations of fewer than 5000 inhabitants. Based on the 1984 population census, 55,967 rural communities are known in Ghana, and these account for 68% of the total population (Statistical Services 1984), as seen in *Table 1*. A water-resources "Sector Studies" was commissioned by the government of Ghana in 1969–1970 with the task of formulating a framework for the supply of potable water to the rural communities. Following these studies, it became the official policy that communities with fewer than 500 inhabitants were to be helped to construct hand-dug wells to obtain potable water supplies. Supplies to communities of 500–2000 in population were to be from hand-dug wells or boreholes fitted with hand pumps, while those with populations of 2000–5000 were to be supplied by means of piped distribution systems. Whereas the source of some of these piped distribution systems should be from surface water, most of them would be supplied by groundwater. Where these water-supply technologies are not feasible, rain-collection equipment, spring sources, and simple techniques for obtaining surface water from dams were to be tried. Thus, the rural water-supply schemes are to be obtained largely from groundwater resources.

Historically, diverse sources have been used to obtain domestic water supplies for rural inhabitants. Where some rural communities are close to or within the environs of urban water-supply systems, some of these communities have benefitted by tapping into extensions of these systems. However, most rural settlements have traditionally relied on sources of surface water, such as streams, rivers, lakes, ponds, dug-outs, and impoundment reservoirs (Ayibotele 1969). Often these surface waters are heavily polluted and are the source of water-borne and water-related diseases, such as guinea worm, bilharzia, typhoid fever, and malaria.

Some rural communities have depended mostly on hand-dug wells. The rural dwellers developed their own traditional methods for the siting of wells. They were usually dug through the overburden and weathered rock material and were 3–6 m deep. During the dry season, when the hand-dug wells were not yielding sufficiently or were dry, other sources were resorted to until the aquifers were recharged during the wet season. More often, due to the poor management of these wells, polluted surface waters seeped into the wells, which then became sources of water-borne diseases. Most rural dwellers had to supplement their water-supply needs by collecting high-quality rainwater. However, since the rain harvesting was done on a small scale, i.e., by individual households, the amount of rainwater that could be collected was quite small and would generally last for only a few days.

The solution to the problems of traditional rural water-supply systems lies basically in the efficient utilization of groundwater and the efficient management of aquifers, hand-dug wells, and boreholes. Not surprisingly, the utilization of groundwater to meet water-supply needs of rural communities in Ghana has in recent times been on the increase. This increased popularity of groundwater has resulted from the fact that this resource is characterized by certain features that make it attractive as a source of potable water supply (Quist et al. 1988). Firstly, aquifers underlie geographically large areas of the country, and these can commonly be tapped at shallow depths near the water-demand centers, even though rural settlements are widely dispersed. Some of these aquifers in certain geological formations have been assessed and their characteristics are fairly well known. Secondly, water stored in aquifers is, for the most part, protected naturally from evaporation, and well yields are in many cases adequate, offering water-supply security in regions that are prone to protracted droughts, such as in the northern parts of Ghana. Thirdly, with adequate aquifer protection, groundwater has excellent microbiological and chemical quality, and it therefore requires minimal or no treatment. Lastly, the capital cost of groundwater development as opposed to the cost of conventional methods of treating surface waters is relatively modest, and the resource lends itself to

Table 1 Distribution of localities/communities and populations in Ghana (Statistical Services 1984)

Population range of localities/communities	No. of localities/ communities	Size of population	Percentage of population
Below 200	46,063	1,796,763	14.6
200–499	5891	1,855,452	15.1
500–1999	3495	3,185,951	25.9
2000–4999	518	1,519,301	12.4
Total (rural)	55,967	8,357,467	68.0
5000 and above total (urban)	203	3,938,614	32.0
Grand total	56,170	12,296,081	100.0

flexible development capable of being phased to meet rising demand.

The objectives of the study are therefore to describe the hydrogeologic framework and to present analysis of borehole yields, in order to provide the basis for future research work toward the overall assessment of groundwater resources of Ghana. As part of the groundwater-resources assessment, an evaluation of borehole yields provides the basis for the planning of water-supply development schemes for rural areas and other communities that may require supplementary supplies of groundwater. The locations of such areas and communities are shown in *Figure 1*.

Overview

Hydrogeologic Provinces

Two major hydrogeologic provinces exist in Ghana: (1) the Basement Complex, composed of Precambrian crystalline igneous and metamorphic rocks, and (2) Paleozoic sedimentary formations (*Figure 1*). Minor provinces consist of (1) Cenozoic, Mesozoic, and Paleozoic sedimentary strata along narrow belts on the coast; and (2) Quaternary alluvium along the major stream courses.

The Basement Complex underlies about 54% of the country and is further divided into subprovinces on the basis of geologic and groundwater conditions (Gill 1969). Generally, these subprovinces include the metamorphosed and folded rocks of the Birimian System, Dahomeyan System, Tarkwaian System, Togo Series, and the Buem Formation; the distribution of these units is shown in *Figure 2*. The Basement Complex consists mainly of gneiss, phyllite, schist, migmatite, granite-gneiss, and quartzite. Large masses of granite have intruded the Birimian rocks.

The Paleozoic sedimentary formations, locally referred to as the Voltaian Formation, underlie about 45% of the country and consist mainly of sandstone, shale, arkose, mudstone, sandy and pebbly beds, and limestone. The Voltaian Formation is further subdivided on the basis of lithology and field relationships into the following subprovinces (Junner and Hirst 1946; Soviet Geological Survey Team 1964–1966): (1) Upper Voltaian (massive sandstone and thin-bedded sandstone); (2) Middle Voltaian (Obosum and Oti Beds); and (3) Lower Voltaian. Their distribution is shown in *Figure 3*.

The remaining 1% of the rock formations is made up of two coastal provinces, the Coastal Block-Fault Province and the Coastal-Plain Province, and the Alluvial Province (*Figure 1*). The Coastal Block-Fault Province consists of a narrow discontinuous belt of Devonian and Jurassic sedimentary rocks that have been broken into numerous fault blocks and are transected by minor intrusives (Kesse 1985). The Coastal-Plain hydrogeologic Province is underlain by semiconsolidated to unconsolidated sediments ranging from Cretaceous to Holocene in age in southeastern Ghana and in a relatively small isolated area in the extreme southwestern part of the country. The Alluvial hydrogeologic Province includes narrow bands of alluvium of Quaternary age, occurring principally adjacent to the Volta River and its major tributaries and in the Volta delta.

Borehole Yields

An analysis of borehole yields has been made for the various geologic formations in the country (Water Resources Research Institute 1996). The least-explored geologic unit is the Voltaian System, due to the low population density in the area where it occurs.

At the time of this study, about 11,500 boreholes had been drilled nationwide. The yields, static water levels and other vital information from these boreholes are well documented. Based on these data, the Water Resources Research Institute (WRRI) of the Council for Scientific and Industrial Research (CSIR) prepared a borehole-yield map of Ghana, shown in *Figure 4* (Water Resources Research Institute 1994). This map indicates the borehole yields to be expected in any particular area, whereas *Table 2* gives a summary of the data on borehole yields for the various hydrogeologic units. The estimates of borehole yields (*Table 2*) sometimes differ from those of the map (*Figure 4*) for the following reasons: (1) the data sets are not based on the same number of boreholes, and because the degree of weathering and fracturing varies within each geologic formation, the choice of boreholes could make a difference in results of yield analysis; and (2) the boreholes are not uniformly and evenly distributed in the country, resulting in the need to interpolate and extrapolate some of the data, which may introduce errors in the demarcation of areas of equal borehole yields within any particular geologic formation.

From *Table 2* the yields of boreholes in the Basement Complex range, on average, from 2.7–12.7 m^3/h for the various subprovinces. For the various subdivisions of the Voltaian System, average borehole yields range from 6.2–8.5 m^3/h. In the Coastal Provinces, average borehole yields range from 3.9–15.6 m^3/h. The average yield of boreholes in the Alluvial Province is 11.7 m^3/h.

Hydrogeologic Provinces and Borehole Yields

Precambrian Crystalline Igneous and Metamorphic Rocks (Basement Complex)

Upper and Lower Birimian System, and associated granite

This region, which extends from the north through the mid-west to the southwestern parts of the country, is made up of rocks of the Birimian System and associated intrusives (*Figure 2*). The Birimian System consists of a great thickness of isoclinally folded, meta-

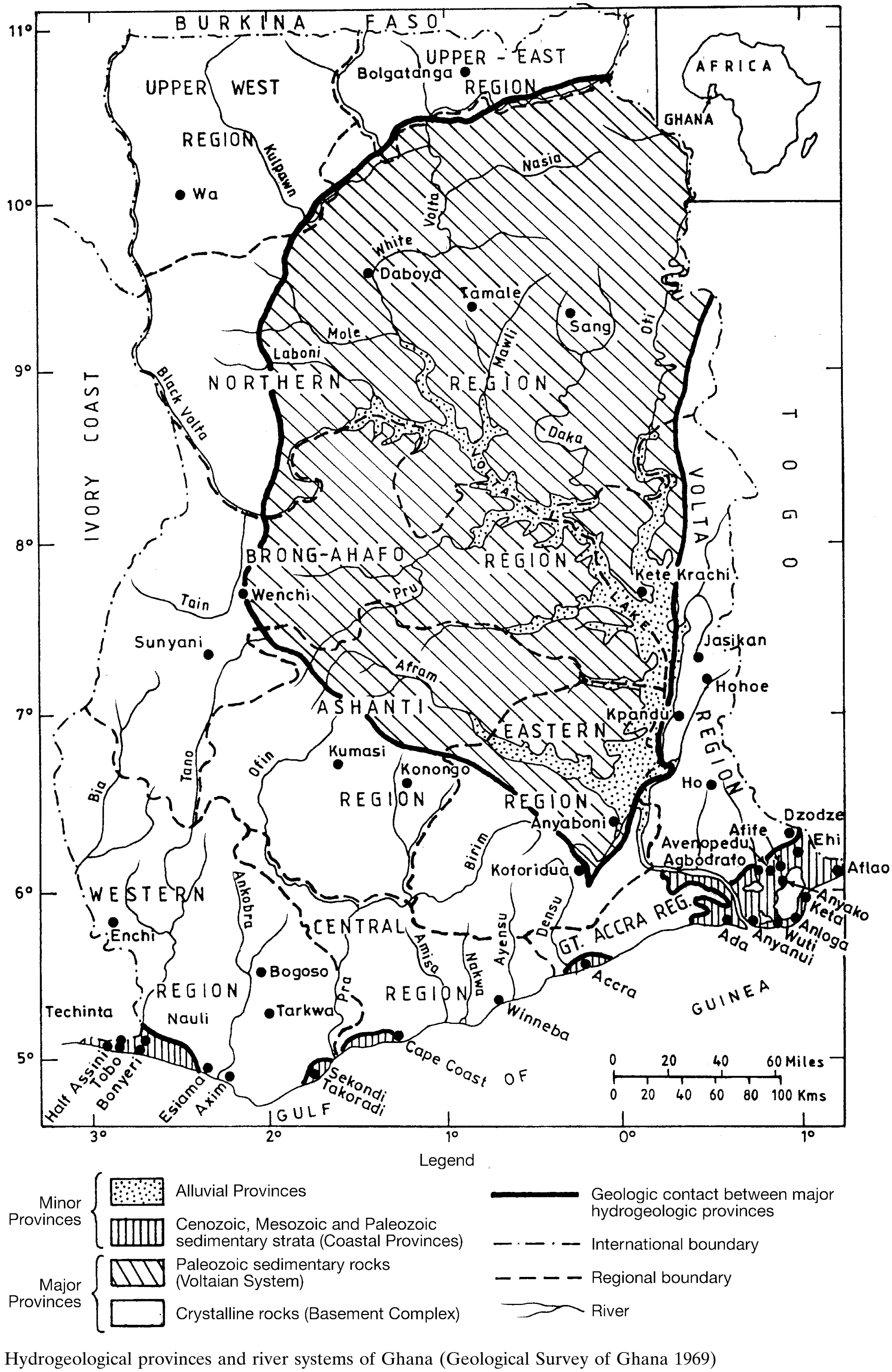

Figure 1 Hydrogeological provinces and river systems of Ghana (Geological Survey of Ghana 1969)

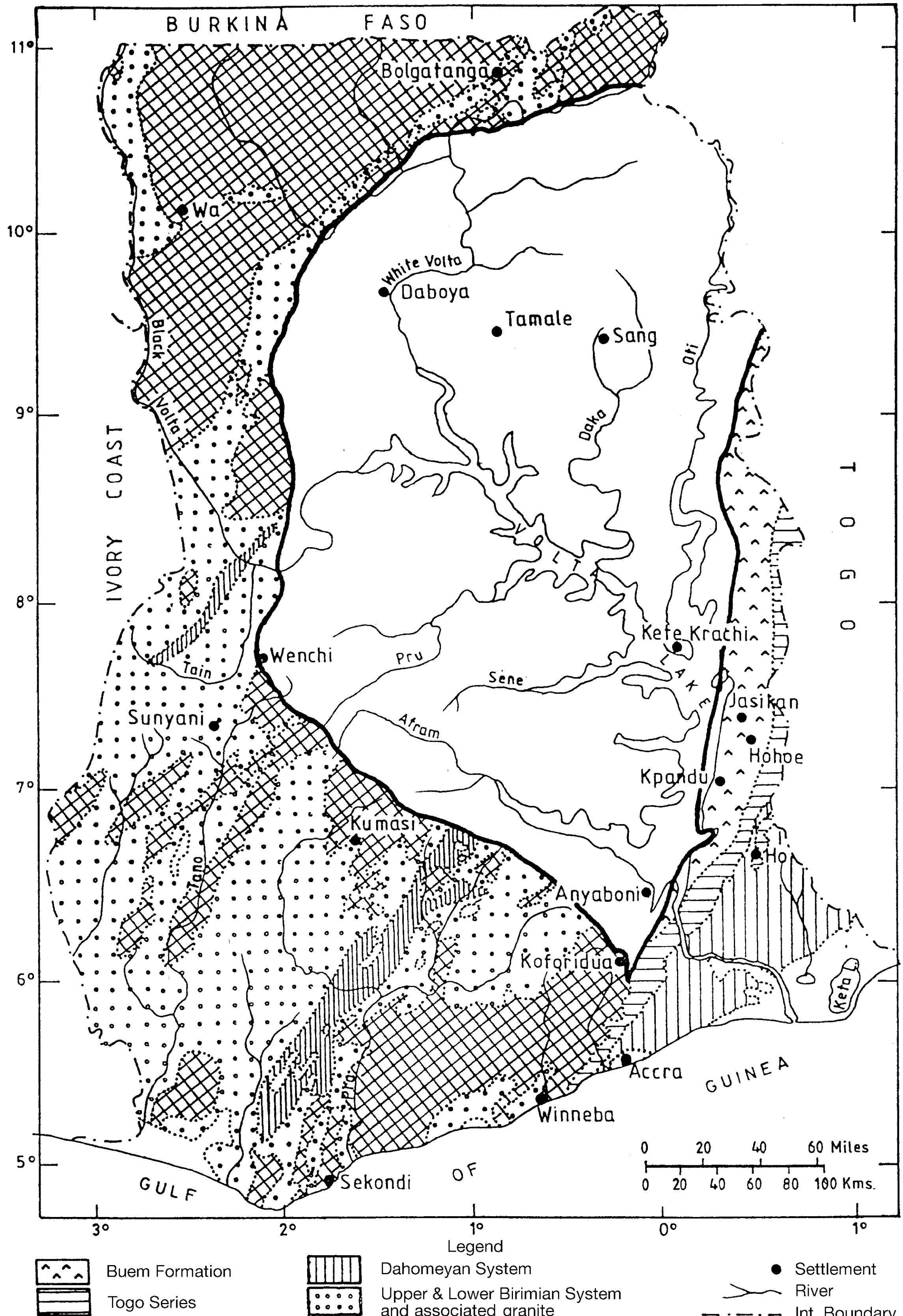

Figure 2 Hydrogeological subprovinces of the Basement Complex (Geological Survey of Ghana 1969)

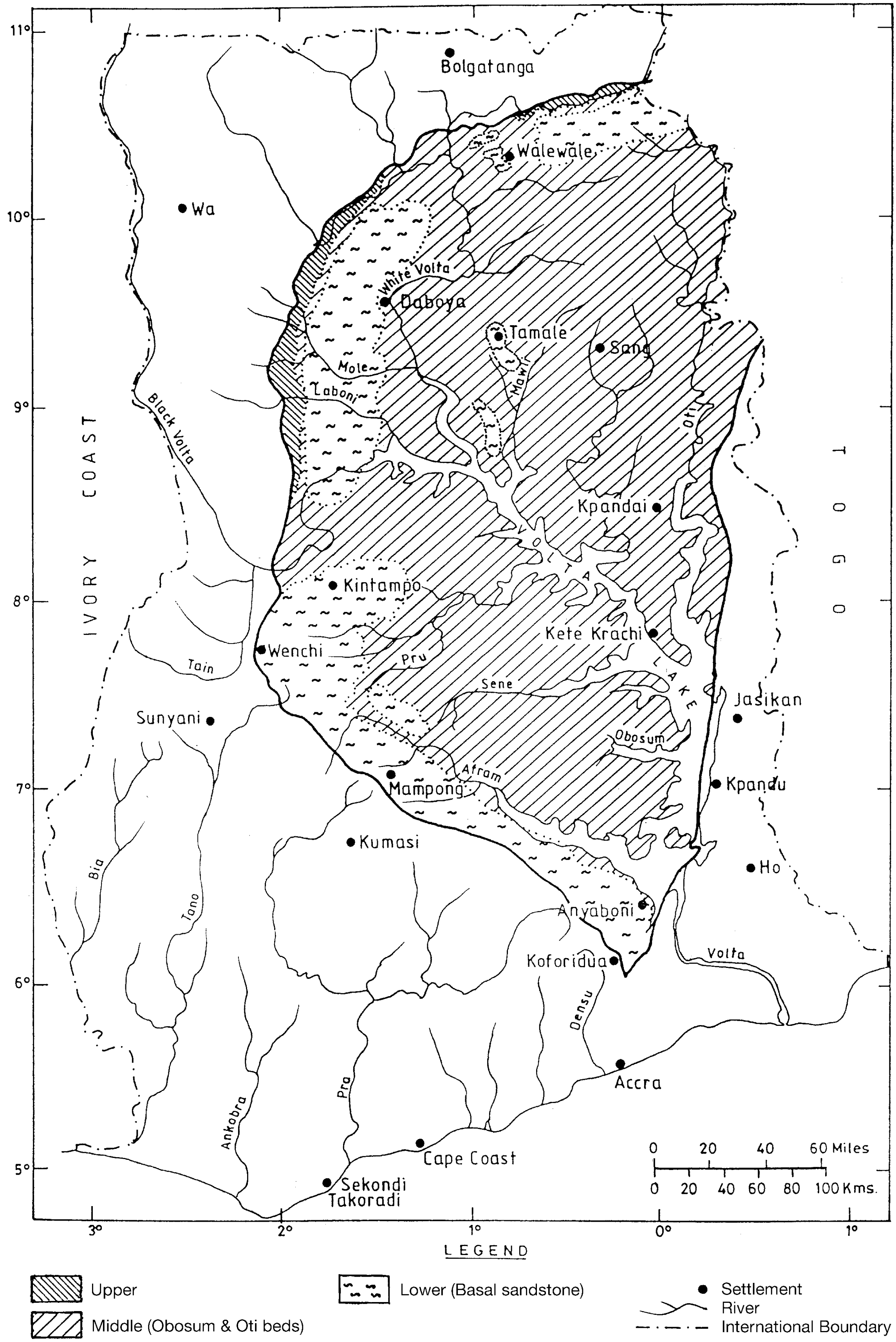

Figure 3 Hydrogeological subprovinces of the Voltaian System (Geological Survey of Ghana 1965)

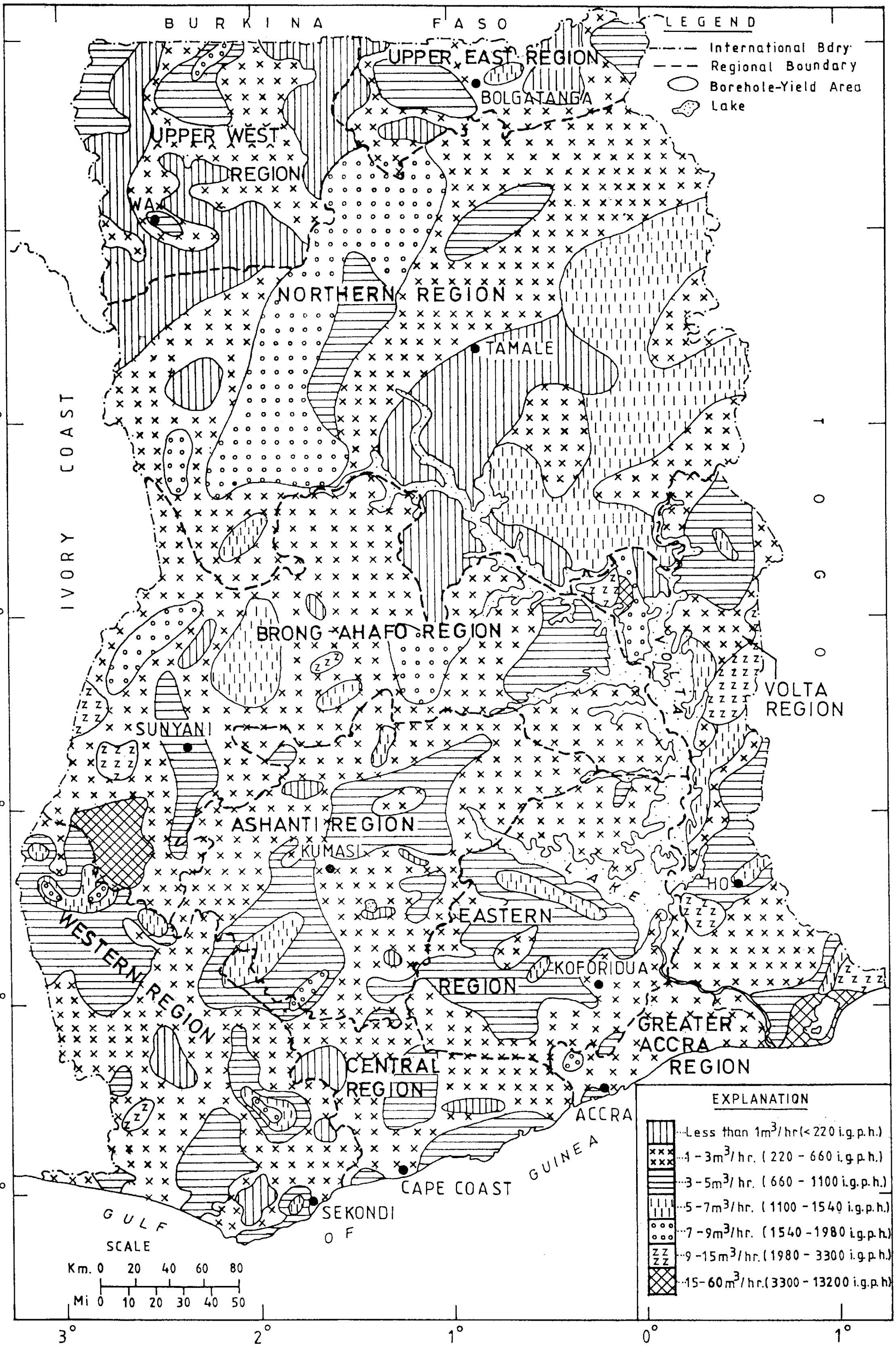

Figure 4 Distribution of borehole yield in Ghana (Water Resources Research Institute 1994)

Table 2 Summary of borehole yields of hydrogeologic provinces and subprovinces

Hydrogeologic province and subprovince	Borehole-completion success rate (%)	Range of yield (m^3/h)	Average yield (m^3/h)
Basement Complex			
Lower Birimian System	75	0.41–29.8	12.7
Upper Birimian System	76.5	0.45–23.6	7.4
Dahomeyan System	36	1–3	2.7
Tarkwaian System	83	1–23.2	8.7
Togo Series	87.9	0.72–24.3	9.2
Buem Formation	87.9	0.72–24.3	9.2
Voltaian System			
Lower Voltaian	55	1–9	8.5
Middle Voltaian (Obosum and Oti Beds)	56	0.41–9	6.2
Upper Voltaian	56	1–9	8.5
Cenozoic, Mesozoic, and Paleozoic Sedimentary Strata (Coastal Provinces)			
Coastal Block-Fault Province	36	1–5	3.9
Coastal-Plain Province	78	4.5–54	15.6
Alluvial Province	67	1–15	11.7

morphosed sediments intercalated with metamorphosed tuff and lava. The tuff and lava are predominant in the upper part of the System, whereas the sediments are predominant in the lower part. The entire sequence is intruded by batholithic masses of granite and gneiss. These dominantly argillaceous sediments were metamorphosed to schist, slate, and phyllite, with some interbedded greywacke.

The granite and gneiss associated with the Birimian rocks are of considerable importance in the water economy of Ghana because they underlie extensive and usually well populated areas. They are not inherently permeable, but secondary permeability and porosity have developed as a result of fracturing and weathering. Where precipitation is high and weathering processes penetrate deeply along fracture systems, the granite and gneiss commonly have been eroded down to low-lying areas. On the other hand, where the precipitation is relatively low, the granite occurs in massive, poorly jointed inselbergs that rise above the surrounding lowlands. In some areas, weathered granite or gneiss form permeable groundwater reservoirs. Major fault zones also are favorable locations for groundwater storage.

In the northwestern sections, around the Wa district (*Figure 2*), the zone of weathering is about 137 m thick, but in the eastern districts, the zone of weathering generally is only half as thick. According to Kesse (1985), locally in the Wa district, the regolith is as thick as 140 m.

In the Wa granite area, the success rate for completing all boreholes is reported to be 85%. The yields obtained from successful boreholes average 5.4 m^3/h [1188 imperial gallons per hour (igph)] and range from 0.45–23.6 m^3/h (99–5192 igph). Boreholes tapping the Winneba granite of the southwestern section of the hydrogeologic subprovince have lower yields. The success rate is about 68% and the average yield of successful boreholes is 0.41 m^3/h (90.2 igph). In the mid-sections around Kumasi and surrounding areas, the boreholes have higher yields than in other areas; the average is 9.3 m^3/h (2046 igph). The rainfall around Kumasi and surrounding areas is greater than around the Wa and Winneba areas; hence the zone of weathering is thicker and well yields are greater. The thicker zone of weathering and the greater groundwater recharge from the relatively high rainfall in Kumasi and surrounding areas result in higher borehole yields. Most of the boreholes in the Birimian System are fitted with hand pumps and have an average depth of about 35 m. In the granite, where it is more difficult to construct successful wells, boreholes are drilled to an average depth of 60 m.

The Birimian phyllite, schist, slate, greywacke, tuff, and lava are generally strongly foliated and fractured. Where they crop out or are near the surface, considerable water may percolate through them. Boreholes tapping the Upper and Lower Birimian rocks have an average yield of about 12.7 m^3/h (2794 igph). In the midwestern part of the Brong-Ahafo Region (*Figure 1)*, boreholes in the Birimian rocks have a slightly smaller average yield of 11.8 m^3/h (2596 igph). The success rate for boreholes tapping the Upper Birimian rocks in the Western Region is about 75%. The areal concentration of boreholes in the Upper Birimian rocks is low; the greatest concentration of high-yielding boreholes is in the Enchi and Bogoso areas (see *Figure 1* for locations). Around Axim, near the coast in the Western Region, the boreholes have much lower yields (Water Resources Research Institute 1996).

Dahomeyan System

Rocks of the Dahomeyan System underlie the Accra Plains and the southern parts of the Eastern and Volta Regions. They extend from Ho in the Volta Region to

Accra, the nation's capital (*Figure 1*). The rocks consist mainly of crystalline gneiss and migmatite, with subordinate quartz schist, biotite schist, and other sedimentary-rock remnants. The gneiss is generally massive and has few fractures. The two main varieties are the silicic and mafic gneisses, which weather, respectively, to slightly permeable clayey sand and nearly impermeable calcareous clay. The generally impervious nature of the weathered zone and the massive crystalline structure of the rocks limit the yields that can be obtained from hand-dug wells or boreholes.

An analysis of about 200 boreholes drilled in the Accra Plains and elsewhere in this hydrogeologic province indicates that the success rate for developing wells is about 36%, based on the use of geophysical surveys as an aid to site selection. Borehole yields average 1–3 m^3/h (220–660 igph). With improved site-selection methods, including the detailed study of aerial photographs and the use of geophysical surveys, the average borehole yield probably could be increased to as much as 11 m^3/h (2420 igph).

Tarkwaian System, Togo Series, and Buem Formation

Although different in age, these three groups of rock formations are similar in lithology. The Tarkwaian rocks comprise slightly metamorphosed, shallow-water, sedimentary strata, chiefly sandstone, quartzite, shale, and conglomerate, resting unconformably on and derived from rocks of the Birimian System. The rocks are intruded by thick laccoliths or dikes and sills of epidiorite and, like the Birimian rocks, are folded along axes that trend northeast. The rocks of the Tarkwaian System are not as extensive as the Birimian rocks. The largest area lies in a band (*Figure 2*) that extends from Konongo to Tarkwa (*Figure 1*).

The Togo Series consists of metamorphosed arenaceous and argillaceous sedimentary strata. The rock types include indurated sandstone, quartzite, quartz schist, shale, phyllite, sericite schist, and some limestone. These rocks are highly folded and form the chain of hills known as the Akwapim-Togo Ranges that extend northeast from the coast near Accra to the Togo border (*Figure 2*). The quarzites and related rocks commonly form hills, and the shale and phyllite occur in intervening valleys.

The Buem Formation consists of a thick sequence of shale, sandstone, and volcanic rocks with subordinate limestone, tillite, grit, and conglomerate. The rocks underlie an elongated area of very considerable size on the western side of the Akwapim-Togo Ranges, including the areas around Kpandu, Jasikan, and Hohoe, and extending northeast to the Togo frontier (*Figure 2*). The sandstone overlies the basal beds of shale and the conglomerate and tillite overlie the sandstone. Rocks of volcanic origin form the upper part of the Buem Formation and include lava, tuff, and agglomerate interbedded with shale, limestone, and sandstone.

The three groups of rock formations (the Tarkwaian System, Togo Series, and Buem Formation) are similar lithologically. Also, the rocks in all three are largely impervious but contain openings along joint, bedding, and cleavage planes. Where these openings are extensive, good supplies of groundwater can be developed from boreholes. Springs frequently occur along the flanks of hills where quartzites are in contact with argillaceous rocks of the valleys, such as in the Akwapim-Togo Ranges. Weathering of the quartzite yields an unconsolidated alluvium of sand and quartzite fragments that are a source of good supplies of groundwater from shallow wells. Generally, these upper Precambrian rocks have a relatively good potential for groundwater development, the most favorable areas being in the valleys where the rocks are highly fractured.

In the Volta Region, the success rate for obtaining water from boreholes in the Togo Series and Buem Formation is about 88%. The average yield from these boreholes is about 9.2 m^3/h (2024 igph), ranging from 0.72–24.3 m^3/h (158.4–5246 igph). The higher-yielding boreholes in this area probably tap large fracture systems or fault zones. Boreholes are drilled to an average depth of 65 m in sandstone.

Paleozoic Sedimentary Formations (Voltaian System)

This hydrogeological province is underlain by rocks of probable Cambrian to Silurian age. The province occupies approximately 45% of the country and extends northeastward beyond the borders of Ghana almost to the Niger River. The rocks underlie the central and eastern parts of the Northern Region, the central and eastern parts of the Brong-Ahafo Region, the northeastern parts of the Ashanti and Eastern Regions, and the northern part of the Volta Region (*Figure 1*). The Voltaian System consists of Lower, Middle, and Upper subprovinces (*Figure 3*).

Lower Voltaian

The Lower Voltaian subprovince occupies a narrow band in the western and northern parts of the area underlain by the Voltaian System (*Figure 3*). This subprovince is underlain by the Basal sandstone, consisting mainly of quartz-sandstone and pebbly grits, and grits with ripple marks and galls. Even though weathering of the Basal sandstone produces sandy surficial deposits and it probably is well jointed in many places, it has virtually not been explored for groundwater because the area is relatively sparsely inhabited.

Middle Voltaian

In the Middle Voltaian subprovince, the rocks, which occur in a large sedimentary basin and include the Obosum and Oti Beds, form the most extensive sedimentary sequence in Ghana. The subprovince consists of interbedded mudstone, sandstone, arkose, conglomerate, and some sandstone. The rocks are mainly flat-lying or gently dipping. They are generally well consolidated and are not inherently permeable except for a few places, such as the long belt between Kete Krachi and Sang (*Figures 1* and *3*), where the strata may be permeable locally. Shale crops out in the central part of the subprovince. Where sandstone crops out and the relief is low, the shale lies at shallow depth and is generally capped by a few feet of laterite.

In the wet season, large areas are covered by shallow ephemeral lakes or ponds that disappear during the dry season. The lack of springs on permanent tributary streams indicates the absence of shallow groundwater. The success rate for obtaining water from boreholes in the Northern Region is about 56% and the average borehole yield is about 3.6 m^3/h (729 igph). Saline water is fairly extensive in the northern part of the basin. Salt beds are known to crop out in the Tamale and Daboya areas. The boreholes in the Voltaian sandstone of the Kete Krachi area in the Volta Region have much higher yields than those in the north. The average yield obtained in this area was about 8.7 m^3/h (1914 igph). Also, the discharge characteristics of some of the boreholes in this area indicate artesian conditions at shallow depths.

Upper Voltaian

The Upper Voltaian subprovince lies to the south, west, and north of the Middle Voltaian subprovince (*Figure 3*). The sandstones in the Upper Voltaian subprovince, particularly those to the west and south of the Middle Voltaian subprovince, store considerable amounts of groundwater, which discharges in springs along joints and bedding planes at many localities. These springs maintain many permanent streams that rise in the sandstone hills. Along the escarpment between Wenchi in the Brong-Ahafo Region and Anyaboni in the Eastern Region (*Figures 1* and *3*), the average yield of boreholes is about 8.5 m^3/h (1870 igph).

Cenozoic, Mesozoic, and Paleozoic Sedimentary Strata (Coastal Provinces)

Coastal Block-Fault Province

The Coastal Block-Fault hydrogeological Province is underlain by rocks of the Accraian and Sekondian Formations of Devonian age and the Amisian Formation of probable Jurassic age. The rocks have been subjected to post-depositional igneous activity and major block faulting. The Devonian rocks, which underlie Accra, Takoradi, and Sekondi, crop out along the coast between Sekondi and Cape Coast. The rocks at Accra include sandstone, grit, and shale, whereas the Sekondian Formation near Sekondi and Takoradi consists mainly of sandstone and shale with conglomerate, pebble beds, grit, and mudstone. The rocks of both formations unconformably overlie a complex of granite, gneiss, and schist of Precambrian age. The Amisian Formation, which crops out near the mouth of the Amisa River, is composed of poorly sorted, semiconsolidated sedimentary rocks, largely pebbly and bouldery shale and sandstone deposited in a freshwater environment. Boreholes tapping the Accraian, Sekondian, and Amisian rocks yield on the average about 3.9 m^3/h (858 igph).

Coastal-Plain Province

In southwestern Ghana, from near Esiama to the Ivory Coast frontier (also known locally as the Tano basin; *Figure 1*), Cretaceous to lower Tertiary sedimentary rocks of the Coastal Plain extend inland 8.0–24.1 km. The sedimentary sequence includes a thick section of alternating sand and clay with occasional thin beds of gravel and fossiliferous limestone. The limestones are known to have an oil and gas potential. Seepages of oil and gas have been reported at several places along the coast near Bonyeri, Technita, Tobo, and Nauli (*Figure 1*). Groundwater supplies from boreholes in the Cretaceous to lower Tertiary sediments between Esiama and Half Assini are obtained largely from the upper 91.4 m of the section. The average yield of the boreholes is 12.6 m^3/h (2772 igph).

Southeastern Ghana, in the vicinity of Keta and other districts, is also underlain by Cretaceous to lower Tertiary consolidated and semiconsolidated marine sedimentary strata. In this area, locally known as the Keta basin, these strata are covered by younger continental deposits. Two limestone horizons have been traced in the subsurface in the Keta basin. The upper limestone is equivalent to the limestone penetrated by boreholes farther inland at Anyako (*Figure 1*), northwest of Keta. In boreholes at Anloga, Anyanui, and Ada, however, this limestone was apparently not penetrated, even at depths of 609.6 m. This is because land subsidence and (or) the transgression of the seas did not affect the basin uniformly, which may account for the discontinuity in the overall marine and non-marine strata, as typified in the Miocene rocks (Akpati 1975).

The lower limestone aquifer in the Keta area probably represents a single hydrogeologic unit that is recharged from intake areas at higher altitudes farther inland. Two recharge areas have been identified: one is centered at Avenopedu and Agbodrafo on the west, and the other at Dzodze and Ehi on the east (*Figure 1*). These recharge areas are separated by an area of negative head from Wuti to Afife, where flowing wells are common, as typified by the Anyako well (Akiti 1977). A third possible recharge area is at the Mono River in Togo, which flows from north to south along the limestone outcrop (Akiti 1977) and at least 112 km northeast of the Keta area.

Records of boreholes in the limestone aquifer in the Keta area indicate that the average yield of wells is

13 m^3/h (2860 igph). Boreholes tapping limestone aquifers along the coast from Aflao to Keta and around Anyako yield 21.3 m^3/h (4686 igph) on average, and range from 4.5–54 m^3/h (990–11,880 igph).

Alluvial Province

Surface deposits of Quaternary age are generally not areally extensive in Ghana. Locally, however, relatively thick deposits of permeable water-bearing alluvium are present in valleys of the larger streams, such as the Volta River and its tributaries, which are shown in *Figure 1*. Extensive but relatively thin alluvial deposits also occur on the delta of the Volta River in southeastern Ghana. Although the alluvial deposits have not yet been developed to any significant extent for water supply, they have considerable potential. In areas where the deposits are permeable, relatively thick, and located adjacent to perennial streams, they offer desirable locations for shallow wells, particularly for irrigation purposes.

Discussion

Because most of the boreholes in Ghana are fitted with hand pumps and are meant to supply rural communities, a successful borehole yield (airlift) is considered to be at least 13 L/min (0.78 m^3/h, or 171.6 igph) or more. This minimum yield per borehole is designed to meet the demand of rural communities with populations of 200–2000 in accordance with the Government policy of providing 25 L/person/d. In a few localities where sufficiently high yields are difficult to obtain close to rural settlements, borehole yields as low as 6.8 L/min (0.41 m^3/h, or 90.2 igph) are developed for rural communities to replace the polluted traditional sources of water supply. Groundwater investigations and exploration in Ghana have been limited mostly to areas of the more concentrated human settlements.

Until the late 1980s, almost all consultants and organizations involved in groundwater prospecting did not use geophysical investigations to aid in selecting drilling sites, with the exception of the WRRI of the CSIR, Accra, and the Geology Department of the University of Ghana (Legon, Accra). The main methods used for groundwater investigations included: (1) review of reports; (2) interpretation of topographic maps; (3) interpretation of geological and structural maps; (4) survey of existing boreholes and other water sources, including terrain evaluation; and (5) discussions with residents of communities. In the late 1980s, a national policy was adopted involving the implementation of detailed studies of aerial photographs and the use of geophysical surveys to help in siting boreholes, before any drilling projects are undertaken, to help improve the success rate of drilling programs and the resulting yields of boreholes.

Because geophysical surveys did not become fully incorporated into groundwater exploration until the late 1980s, it follows that the success rate for borehole development quoted in some earlier literature was based primarily on results where other methods of groundwater exploration had been used. The success rates of borehole development given in this paper are based only on instances where geophysical surveys were used. As such, the number of boreholes is much fewer than the total number of boreholes that had been used to construct the borehole-yield map (*Figure 4*). Some of the rates of success for borehole completion given in this paper are the same as those quoted in the earlier literature. As more of the data from geophysical surveys are generated and analyzed, better estimates of the rates of success together with other groundwater data are expected.

Because groundwater prospecting until the late 1980s had been done without the benefit of detailed studies of aerial photographs and the use of geophysical surveys, development of groundwater was restricted to the areas where it was most likely to achieve success, such as the weathered parts of the Birimian System and the limestone aquifers of the southeastern part of the country. Consultants and groundwater developers avoided the areas where it was more difficult to develop adequate water supplies, such as the rocks of the Dahomeyan and the Voltaian Systems. Probably because of the low population densities where these formations occur, and because of their hydrogeologic characteristics, they are among the least explored in the country. In many parts of the country, particularly where the lithologic nature of the formations makes it difficult to locate aquifers, a problem exists in selecting suitable sites for drilling. These constraints together with the lack of information on aquifer geometry and the recharge characteristics of the aquifers are manifested in the low yields of some wells. Part of this problem is being overcome by the increased use of detailed aerial photographs and geophysical surveys to interpret hydrogeologic conditions. These studies improve the chances of identifying fractures and weathered zones in the impermeable rocks, thereby significantly helping to improve the likelihood of identifying aquifers in the more massive and less permeable formations.

Various additional problems are associated with the siting of boreholes in Ghana. Many times, potentially suitable sites are ignored because of difficult accessibility for heavy-duty drilling rigs due to topographic limitations. Some potentially favorable sites are also rejected because of their proximity to rubbish dumps and pit latrines. Many potentially favorable sites, particularly on formations of the Voltaian and Dahomeyan Systems, are located in swampy areas, flood-prone areas, and intermittently dry valleys where, during the rainy season, polluted surface water could enter the boreholes.

Current methods of borehole completion consist of casing off the loose, unconsolidated upper strata or clay strata in the Dahomeyan System to prevent caving.

Screens are then installed through the entire aquifer thickness and extend about 1 m above the top of the aquifer. A plain PVC pipe is then placed above the screen, extending to and above ground level for the installation of hand pumps. In recent times, boreholes are cased with 5-in (127-mm) diameter PVC pipe and, for wells yielding 5 m^3/h (1100 igph) or more, 6-in (152.4-mm) PVC casing is used. Apron walls are then built around the hand pumps and drainage is provided to prevent the inflow of surface pollutants. Selected wells yielding 5 m^3/h (1100 igph) or more are mechanized for some communities.

Even though many hand-dug wells have been constructed in various hydrogeologic formations (a total of about 60,000 as of March 1998; Ministry of Works and Housing 1998), these were not taken into consideration in the analyses for this paper due to the dearth of data from these sources.

Summary and Conclusions

As part of the overall groundwater resources assessment of Ghana, the hydrogeologic framework has been described and the borehole yields for the various hydrogeologic units have been analyzed. These hydrogeologic units are broadly categorized as: (1) the Basement Complex (crystalline rocks), which includes about 54% of the country; (2) the Voltaian System, which underlies about 45%; and (3) the Cenozoic, Mesozoic, and Paleozoic sedimentary strata (Coastal Provinces), which underlie the remaining 1% of the country. Yields of boreholes in the Basement Complex range, on the average, from 2.7–12.7 m^3/h for the various subprovinces. For the various subdivisions of the Voltaian System, average borehole yields range from 6.2–8.5 m^3/h. In the Coastal Provinces, average borehole yields range from 3.9–15.6 m^3/h. The average yield of boreholes in the Alluvial Province is 11.7 m^3/h.

In conclusion, the Basement Complex has a higher groundwater potential than the Voltaian System. This is particularly important because the Basement Complex in general and its subprovince of Birimian rocks in particular underlie the most densely populated areas in Ghana and can hence be tapped for human use. The Basement Complex has thus been more extensively explored than the Voltaian System, which underlies sparsely populated areas. However, within the Basement Complex, the Dahomeyan System has very low groundwater potential, as typified by low borehole yields of 1–3 m^3/h. The Coastal Provinces generally have good groundwater potential, with the exception of the Coastal Block-Fault where low borehole yields of 1–5 m^3/h are obtained.

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