Journal of the Faculty of Enviromental Science and Technology,
Okayama University
Vol.8, No.1, pp.39-52, March 2003

The Hydrogeological Setting of Ghana and the Potential for Underground Dams

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(Received November 29, 2002)

Increasing human population, changing lifestyles and environmental considerations have resulted in increased utilization of groundwater resources worldwide. This, in turn, has led to the decline of groundwater levels in some countries and Ghana is no exception to this problem. To augment the availability of groundwater resources for various uses, numerous techniques have been developed in many parts of the world, one of which is the construction of underground dams. The successful construction and utilization of underground dams, however, depends very much on the physical and hydrogeological conditions at the dam sites. Ghana is underlain by Precambrian crystalline igneous and metamorphic rocks; and Paleozoic consolidated sedimentary formations. These are further subdivided and described locally as the Birimian, Dahomeyan, Buem, Togo Series, Tarkwaian, Granites, Voltain, Coastal Block Fault, Coastal Plain and Quaternary Alluvium. The review of these and the pre-requisite conditions necessary for the construction of underground dams indicate that underground dams could be constructed and utilized in some parts of Ghana, especially where the overburden is shallow, in the Dahomeyan granites and in the recent formations consisting of alluvial and coastal sands and gravels. This paper is part of a continuing research programme being carried out by the authors.

Key words: *hydrogeology, geology, underground dam, sand-storage dam, sub-surface dam, water supply*

1 INTRODUCTION

More groundwater resources are being exploited worldwide as a result of increased human population and water demand, changing lifestyles and environmental degradation which has affected surface waters. This over exploitation has in turn led to the decline of groundwater levels in many parts of the world, including Ghana. To arrest this situation and still be able to meet the water demands of households, farms and industries, new ways of exploiting the groundwater resources are being searched for. One of such is the construction of underground dams. This has proved to be very useful in storing groundwater to meet the water supply needs of rural communities and farmers in such countries as Japan, India and Brazil. The technology could be adopted in Ghana, and other sub-Sahara African countries, where water supply is inadequate. The successful construction and utilization of underground dams, however, depends on the hydrogeological setting of the site. This paper , as part of an on-going research, reviews the hydrogeology and other physical characteristics of Ghana, underground dam construction pre-requisites and describes the potential for the construction and utilization of such dams in the country for groundwater supply.

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2 GHANA

2.1 Climate

Ghana is located in West Africa and lies between latitude 4°44'N and 11°11'N, and between longitudes 1°12'E and 3°15'W. The country covers an area of 238,540 km^2, of which 3.6 % is covered by surface water bodies.

High temperatures throughout the year and seasonal rainfall characterize the climate of Ghana. It is humid in the south and dry in the north. The mean monthly temperature is 28 °C, with a diurnal temperature range of 6 – 8 °C along the coast and 10 - 13 °C further north. Generally, there is a gradual increase of temperature from the south to the north of the country.

Rainfall in Ghana is under the influence of the movement of the Inter Tropical Convergence Zone (ITCZ). The hot, dry and dusty harmattan air mass from the Sahara in the north meets the cool, moist monsoon air from the South Atlantic. From December to February, the ITCZ lies across the Gulf of Guinea and the dry harmattan prevails over the whole country. Between March and November, the ITCZ moves across Ghana crossing the southern areas twice thus, resulting in bimodal rainfall patterns at these areas. The major rainy season in the south begins in April/May and the minor one occurs in September/October. The peak rainfall periods are June/July and September/October for the major and minor seasons, respectively. At higher latitudes, the interval between the 2 peaks decreases until, at the limit, only a single peak is evident (WARM, 1998). Therefore, in the north of the country, a single rainfall season occurs between June and September, with the maximum monthly rainfall normally occurring in September.

The wettest part of Ghana is the south-west, with an annual rainfall of 2190 mm at Axim. As one moves to the north, the rainfall reduces to 1370 mm in Kumasi, 1100mm at Tamale and 995 mm at Navrongo. There is, however, a departure from this general trend at the south-eastern part. This is evidenced by the very low rainfall recorded at stations stretching from Takoradi to Ho and southwards, resulting from an orographic anomaly of the Akwapim Range. Rainfall decreases from 1250 mm at Takoradi to less than 800 mm at Accra. The area forms the southeast coastal plains and is the driest part of Ghana. It must be noted that, in recent years, there has been wide variability in the rainfall regime.

The annual potential open water evaporation ranges from 1350 mm in the south to 2000 mm in the north of the country (WARM, 1998). These exceed the mean annual total rainfall of the corresponding areas.

2.2 Geology and hydrogeology

Two major hydrogeologic provinces have been delineated in Ghana. They are the (a) Basement complex, which is composed of Precambrian crystalline igneous rocks and metamorphic rocks, and (b) Paleozoic consolidated sedimentary formations (Darko, 2001; Dapaah-Siakwan and Gyau-Boakye, 2000). The basement complex forms 54 % of the land area of Ghana and the Paleozoic sedimentary formations form 45 %. The remaining 1 % is covered by minor provinces, such as the (a) Cenozoic, Mesozoic and Paleozoic sediments along the coast, and (b) Quaternary alluvium along major stream courses. **Figures 1 – 3** show the hydrogeological provinces of Ghana. On the basis of the rocks genesis, characteristics and chemical compositions the major geological provinces are further divided into sub-provinces. These are locally named as Birimian, Dahomeyan, Buem, Togo Series, Tarkwaian, Granites, Voltain, Coastal Block Fault, Coastal Plain and Quaternary Alluvium. The characteristics of these sub-provinces are presented in **Table 1**.

The warm humid climate and high rainfall in certain parts of Ghana has led to the development of appreciable thickness and extensive layers of regolith, especially along joints and fractures in areas underlain by crystalline rocks to form extensive aquifer system. Groundwater is therefore tapped by wells located in the fractures and the extensive weathered zones which are mainly recharged by rainfall. In the northeastern parts of the country, the regolith reaches about 140 m and if saturated, such regolith can be exploited to obtain sustainable yields for water supplies (Kesse, 1985). Where the saturated regolith is thin or absent, sufficient permeability has to be identified in the fractured bedrock such that aerial drawdown interacts with storage in the overlying or adjacent regolith to provide sustained yields.

Rocks of the Buem, Birimian and Tarkwaian Formations have high yields and the lowest failure rates. On the other hand, the Dahomeyan gneiss has very low yields and the highest drilling failure rate. The Voltain Formations are intermediate. The crystalline rocks have very little inter-granular pores and are thus characterized by negligible primary porosity (<1 %) and permeability. Where the rocks occur near the surface, they are usually fractured and weathered and they acquire some significant secondary porosity (Darko, 2001). The aerial extent, thickness and physical character of the weathered layer vary from one area to another. This depends on the regional climatic conditions, topography, lithology, degree of fracturing and vegetation cover.

2.3 Physiography

Ghana is zoned into several physiographic regions (**Fig. 4**): the low-lying coastal plains, the south-west forest dissected plateau, the north and northwest savanna high plains, the Volta sandstone basin and the ridges and escarpments bordering the Voltain sandstone basin (Kesse, 1985; Dickson and Benneh, 1980). The coastal plain is broad in the east and west, where it stretches over 80 km inland and narrow in the middle where it does not extend more than 16 km inland from the sea. The south-east coastal plains are very flat and only a few isolated hills which rise abruptly from the surrounding plains can be found. The general elevation of the land, apart from the isolated hills, is not more than 75 m above sea level. Rocks of the Dahomeyan formation and tertiary and recent sedimentary deposits are found here.

West of Accra the land is not flat but rather undulating and, at some places, the hills are steep and rise abruptly from the surrounding plains. Various types of rocks are found here but the most widespread are the granites which also form the hills. The forest-dissected plateau is underlain by the Birimian and Tarkwaian formations and the elevation of the terrain is between 240 and 300 m above sea level. The strongly dissected nature of the plateau is explained by the heavy rainfall and the consequent forest vegetation which prevents sheet erosion. Erosion is, therefore, restricted mainly to the river channels which cut up the plateau surfaces. A gently rolling landscape is found over the Lower Birimian rocks. Hills composed of these rocks stand about 60-90 m above the broad flat valleys through which rivers flow. On the other hand, the hills made up of Upper Birimian rocks are steep-sided and they rise to 240 m above the broad flat-bottomed valleys. Over the Tarkwaian rocks, the topography is rugged and hilly rather than smooth and flat or gently undulating.

The savanna high plain is more gently rolling than the forest-dissected plateau and is the most widespread rocks are granites. The average height is between 180 and 300 m above sea level. Isolated and small rounded hills of either Birimian rock or granite origin are commonly found in the plains.

The Volta sandstone basin occupies an area of about 112,768 km^2 (Dickson and Benneh, 1980), made up of either gently-dipping or flat-bedded sandstones. Thus, the basin is almost flat. The elevation in the south of the Black Volta River is between 60 and 150 m and about 180 m to the north of the river. To the west of the Oti River, there arise a north-south range of hills with elevations between 180 and 300 m above sea level.

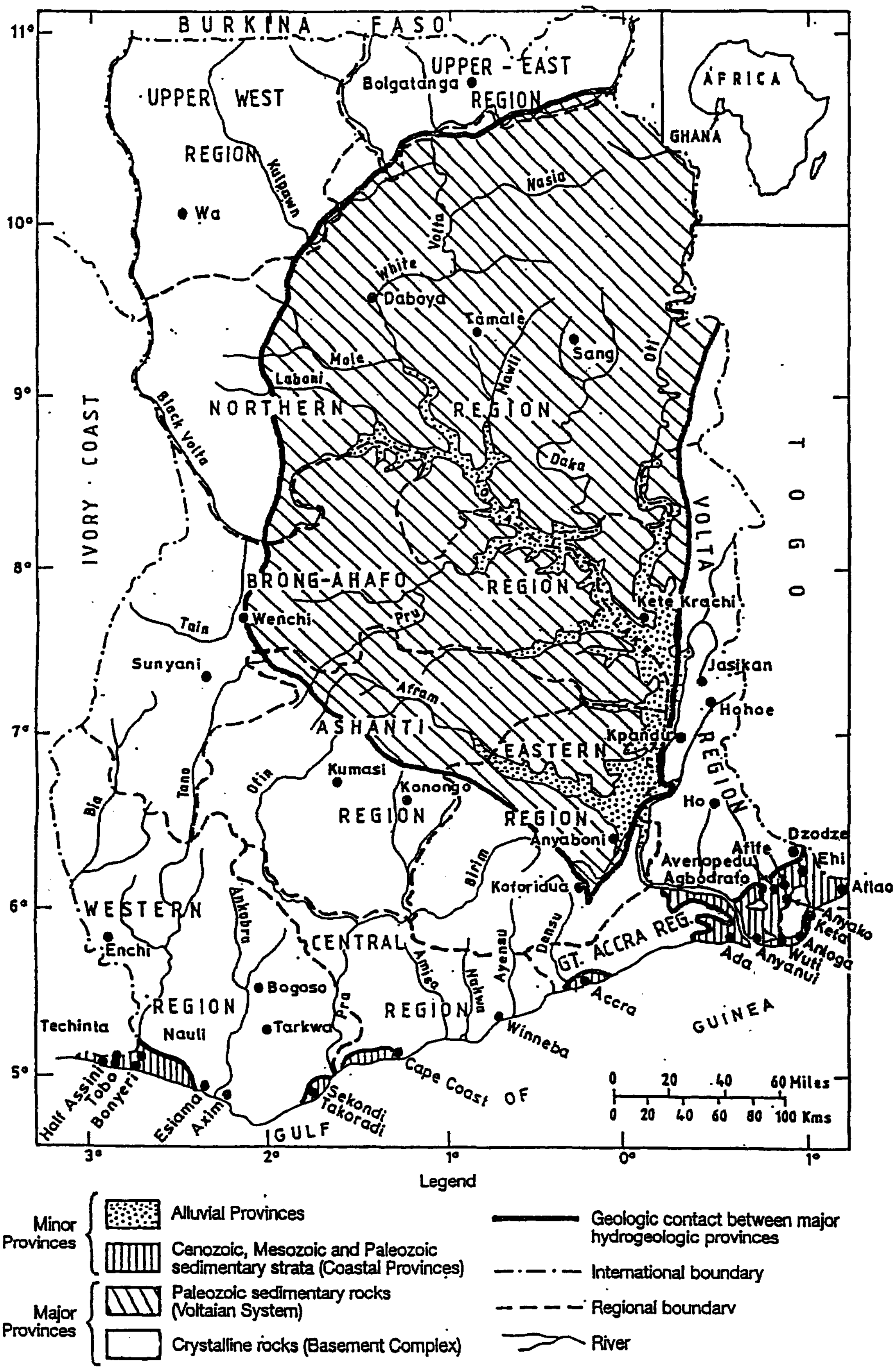


Fig. 1 Hydrogeological provinces and river systems of Ghana (Geological Survey of Ghana, 1969)

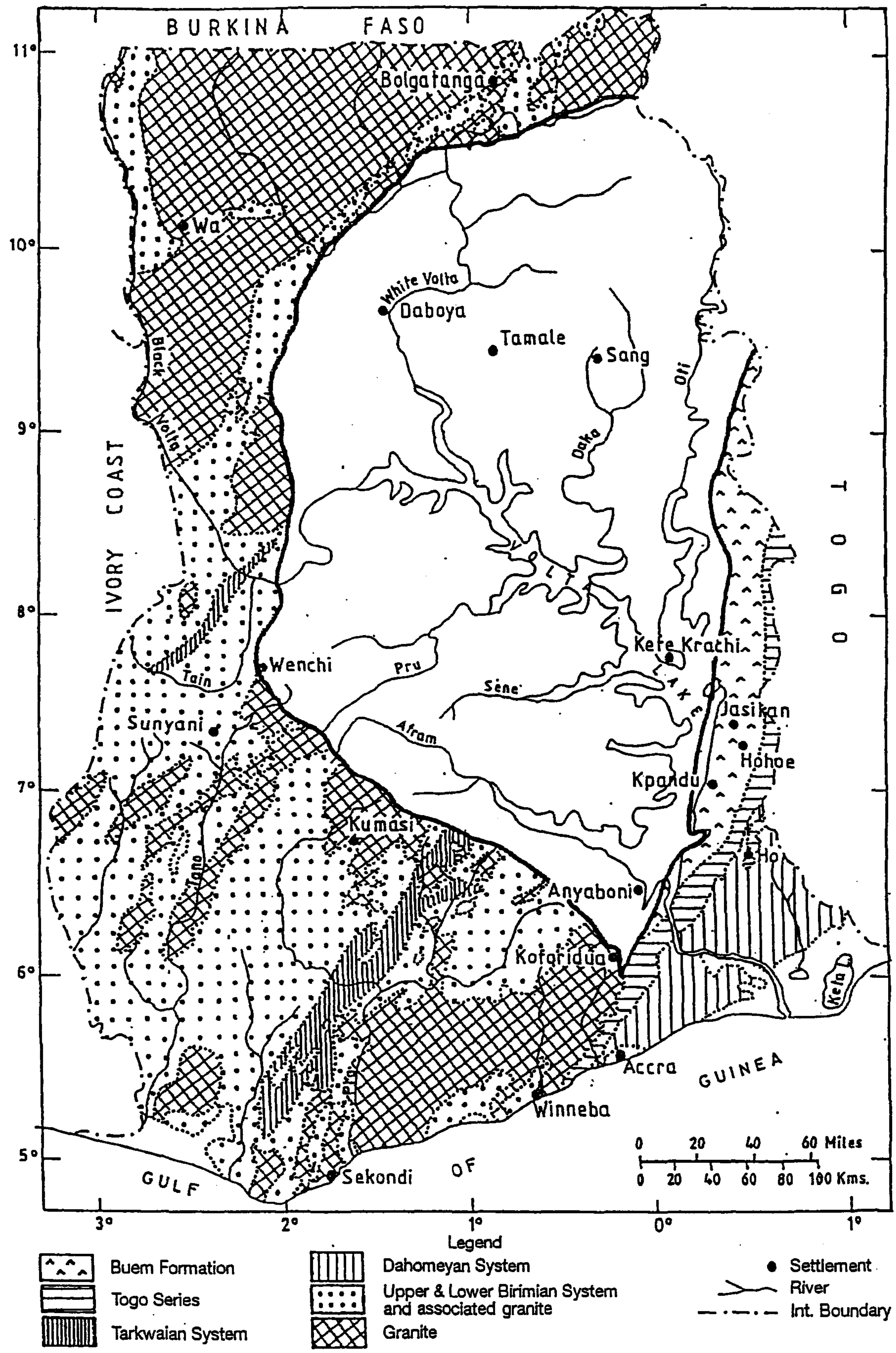


Fig. 2 Hydrogeological sub-provinces of the Basement Complex (Geological Survey of Ghana, 1969)

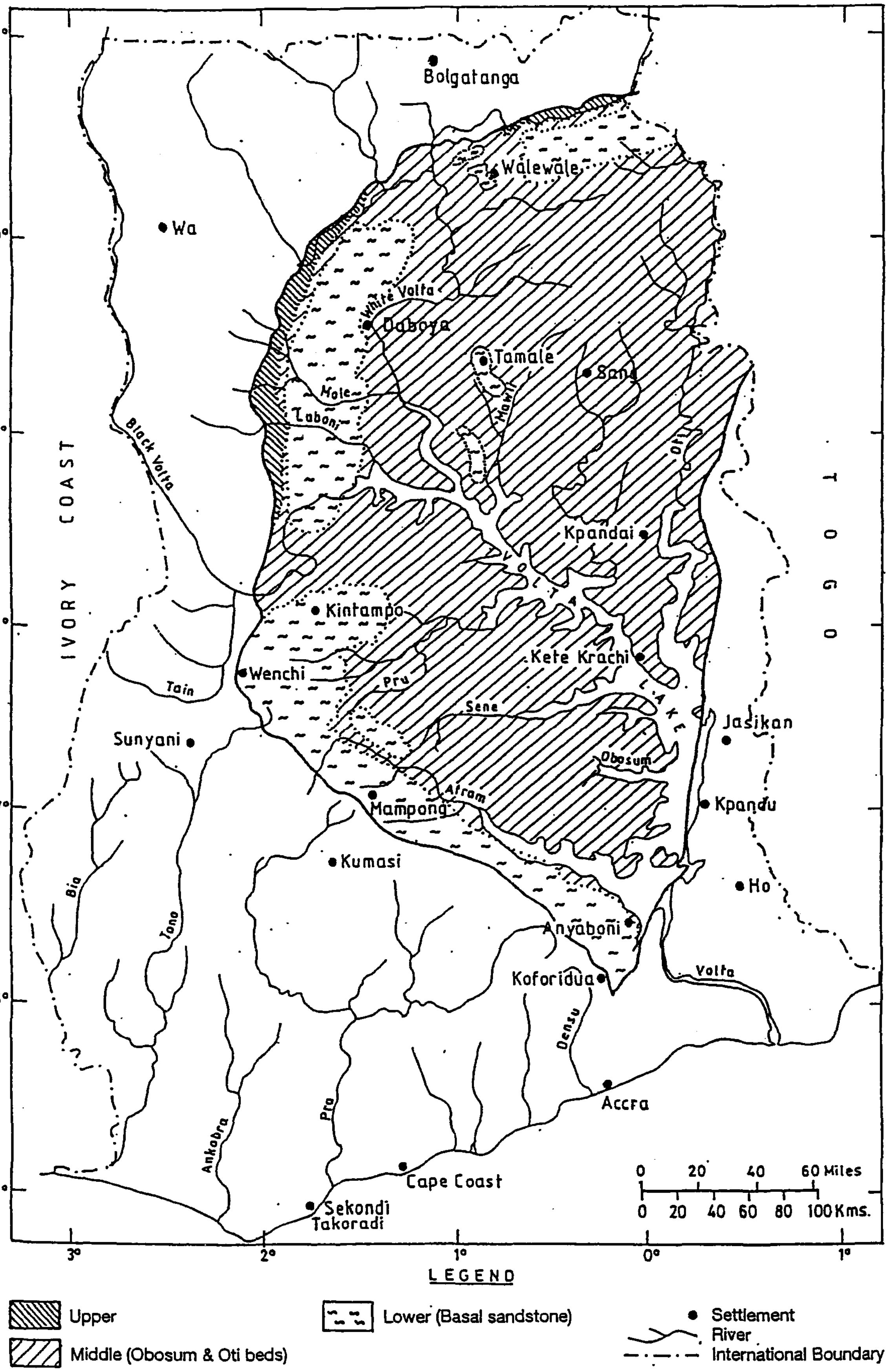


Fig. 3 Hydrogeological sub-provinces of the Voltain System (Geological Survey of Ghana, 1965)

Table 1 Geological provinces of Ghana (Geological Survey of Ghana,1969)

Province	Lithological characteristics
Basement complex (covers 54 % of Ghana)	
Buem Formation (Upper Precambrian)	Thick sequence of shale, sandstone and volcanic rocks with subordinate limestone, tillite, grit and conglomerate. 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 inter-bedded with shale, limestone and sandstone.
Togo Series (Upper Precambrian)	Indurated sandstone, quartzite, quartz schist, shale, phyllite, sericite schist and some limestone. Metamorphosed, highly folded arenaceous and argillaceous sedimentary strata.
Tarkwaian (Upper/Middle Precambrian)	Slightly metamorphosed sedimentary strata. Sandstone, quartzite, shale and conglomerate, resting 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 Buem, Togo and Tarkwaian rocks are lithologically similar but of different ages. The rocks are largely impervious but contain openings along joints, beddings and cleavage planes. The weathering of the quartzite has resulted in an unconsolidated alluvium of sand and quartzite fragments.
Birimian (Middle Precambrian)	Great thickness, isoclinally folded, metamorphosed sediments intercalated with metamorphosed tuff and lava. The entire sequence is intruded by granite and gneiss and has metamorphosed to schist, slate and phyllite, with some inter-bedded greywacke. The granite and gneiss are not inherently permeable but secondary permeability and porosity has developed as a result of fracturing and weathering. The thickness of the regolith ranges from 70 to 140 m and they form permeable groundwater reservoirs in some areas.
Granites (Middle Precambrian)	Granite and granidiorite with associated gneiss. Secondary porosity developed as a result of jointing, fracturing and weathering.
Dahomeyan (Lower Precambrian)	Crystalline gneiss and magmatite, and quartz schist, biotite schist and other sedimentary rock remnants. The gneiss is generally massive, has some few fractures and is of two types. They are the silicic and the mafic gneisses which weather into slightly permeable clay sand and nearly impermeable calcareous clay, respectively.
Lower Paleozoic Sedimentary Formation (Volta System: covers 45 % of Ghana)	
Upper Voltain	Sandstone
Middle Voltain (Obosum-Oti Beds)	Inter-bedded sandstone, arkose, conglomerate and some sandstone. Flat-lying or gently dipping. Well consolidated and not inherently permeable. Shale outcrops in the central parts of the sub-province. Where sandstone outcrops, the shale lies at a shallow depth and is generally capped by a few feet of laterite.
Lower Voltain	Basal sandstone, consisting mainly of quartz-sandstone and pebbly grits. Regoliths of sandy surficial deposits.
Cenozoic/Mesozoic, Paleozoic Sedimentary Strata and Alluvial Province (covers 1 % of Ghana)	
Coastal Block Fault	Accraian and Sekondian Formations (Devonian age). Subjected to post-depositional igneous activity and major block faulting. Sandstone, grit, and shale with conglomerate, pebble beds, grit and mudstone. Unconformably overlie a complex of granite, gneiss and schist of Precambrian age.
	Amissian Formation (Jurassic age). Poorly sorted, semi-consolidated sedimentary rocks, large pebble and boulder shale and sandstone.
Coastal Plain	Cretaceous to Lower Tertiary sedimentary rocks. Thick section of alternating sand and clay with occasional thin beds of gravel and fossiliferous limestone.
Quaternary Alluvium	Deposits of permeable water-bearing alluvium in valleys of rivers and streams.

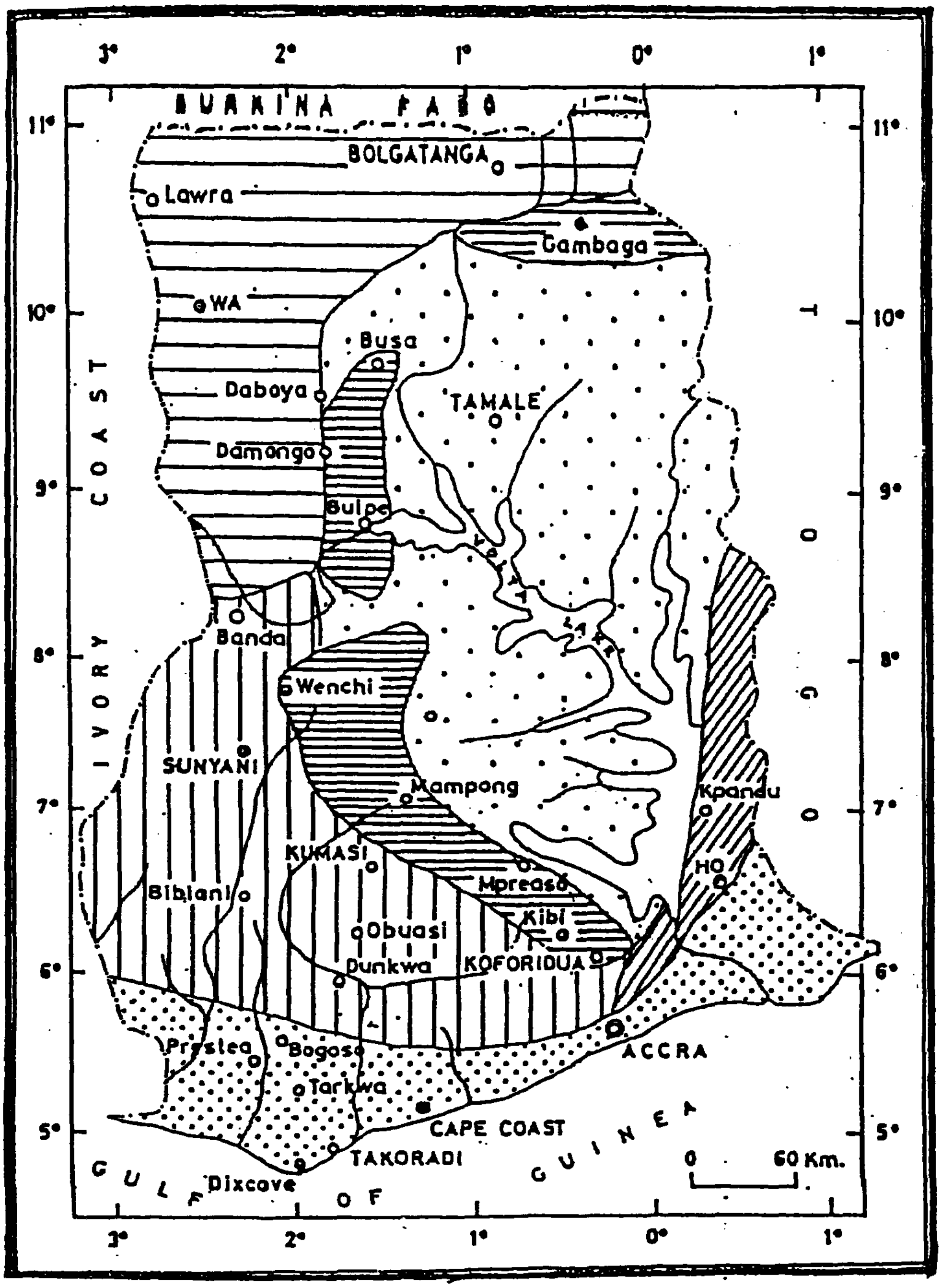


Fig. 4 The physiographic regions of Ghana (Dickson and Benneh, 1980)

The ridges and escarpments bordering the Voltain sandstone basin consist of the Southern Volta plateau, the Gambaga escarpment and the Akwapim-Togo ranges. The Southern Volta plateau is made up of horizontal layers of sandstones and it marks the southern boundary of the Volta basin. It runs from south-east to north-west, with an average elevation of 450 m above sea level.

The Gambaga escarpment marks the northern limit of the Voltain sandstone basin and is also made up of horizontal layers of sandstone. It trends from east to west and is bounded on the north and south by scarps. The average elevation does not exceed 450 m above sea level.

The Akwapim ranges are fold mountains of the Togo series rocks, forming the eastern boundary of the Voltain sandstone basin. They stretch from the west of Accra and run in a north-easterly direction, through Togo and Dahomey, into the Niger River valley. The average elevation is 450 m above sea level and the highest altitude in Ghana, Mount Afadjato (890 m), is found here.

2.4 Soils

The soils of Ghana are derived from rocks of the mid-Paleozoic age or older, comprising mainly of Siluro-Devonian sandstone and shales and some igneous and granitic material (Dickson and Benneh, 1980). In the forest zone, where the annual rainfall is between 1,000 and 2,000 mm, forest ochrosols are found. These soils developed from a wide range of highly weathered parent materials including granite, Tarkwaian and Birimian rocks. The soils are porous, well-drained and generally loamy. In the wetter forest areas, sandy Oxysols are found. Lithosols are usually found on steep slopes made up of hard resistant rocks.

The soils in the Voltain and savanna plains are mainly of groundwater laterites and savanna ochrosols. The laterites are developed over both the Voltain shales and granites. They are characterized by the presence of cemented layer of ironstone (also called iron pan) at shallow depths below the surface of the soil, through which rainwater does not percolate easily. Thus, the top layers of the soil become waterlogged right up to the surface in the rainy season but dry up in the dry season. The savanna ochrosols are formed over granites, Birimian rocks and Voltain shales. They are well drained, porous and loamy.

In the coastal plains, the soils are younger and are closely related to the underlying rocks. They are mainly a mixture of savannah ochrosols, lateritic sandy soils, tropical black earths, sodium vleisols, tropical grey earths and acid gleisols and coastal sands (Dickson and Benneh, 1980). The lateritic soils found here are developed over acid gneiss and granite and consist of sandy soils overlying a hardened layer of clay, not iron pan. It is this layer of clay which impedes downward drainage and causes water logging in the wet season.

The tropical black earths are developed over basic gneiss. During the rainy season, they are heavy, plastic and sticky but in the dry season they become hard and compact and develop wide cracks. The tropical grey earths consist of a few centimeters of firm grey sand overlying a very hard and compact clay layer.

2.5 Drainage

Ghana is dendritically drained by three major river systems. These are the Volta, the South-Western and the Coastal River systems. They, respectively, cover 70 %, 22 % and 8 % of the area of Ghana. The Volta River system consists of the Red Volta, Black Volta, White Volta and the Oti Rivers. The basin formed by the Volta River system is shared with Cote d'Ivoire, Burkina Faso, Mali, Togo and Benin.

The South-Western River system comprises the Bia, Tano, Ankobra and Pra Rivers. The Bia River basin is shared with Cote d'Ivoire and the lower reaches of the Tano River forms the boundary between Ghana and Cote d'Ivoire.

The Coastal River system consists of several river basins along the Gulf of Guinea (Atlantic Ocean). They include the Kakum, Amissa, Ochi-Nakwa, Ayensu and the Densu Rivers.

The total annual runoff of Ghana is estimated at 54.4 billion m^3, of which 38.3 billion m^3 is accounted for by the Volta River system (WARM, 1998). The annual runoff from Ghana alone is 39.4 billion m^3, which is 68.6 % of the total annual runoff. The Volta, the South-Western and Coastal systems contribute 64.7%, 29.2% and 6.1%, respectively, of the annual runoff from Ghana.

2.6 Aquifer Characteristics

Typical values of some aquifer parameters in some geological formations are shown in **Tables 2 and 3**. From **Table 2**, the range of the overburden thickness in the Tertiary is 38 - 90 m and 10 - 21 m in the highly weathered granites of the high rainfall areas in the country. The overburden is mainly clayey and quite often underlain by the weathered rocks which constitute the aquifers. The construction of sub-surface dams in such areas with thick overburden may not be feasible. However, in the areas where the overburdens are shallow such dams are feasible. For example, the range of the overburden thickness in the Dahomeyan granite in the low rainfall areas and Togo series is relatively low. These and the recent formations, consisting of the alluvial and coastal sandy and gravel formations, are ideal sites for sand storage dams. The transmissivity values indicate that, in the Buem and Dahomeyan formations, the aquifers are quite good. Even though high yields (13 m^3/h or more) could be obtained from the Dahomeyan formation, it has the highest failure rate of drilling (as shown in **Table 3**).

3 UNDERGROUND DAMS

Environmental degradation has contributed to the drying out of surface water resources of the country in recent years and a high dependence on groundwater resources for domestic water, especially in the dry seasons. Generally, aquifers in Ghana are phreatic, structurally dependent and discontinuous in occurrence (Darko, 2001). Drilled wells have a wide range of yields, with significant failure rates. Thus, groundwater is unevenly distributed and that it is difficult to come by in large quantities in some geological formations in Ghana. For rural water supply programmes in Ghana where boreholes are fitted with hand pumps, a minimum yield

Table 2 Information and aquifer characteristics of mechanized boreholes in some geological formations (Dapaah-Siakwan and Agyekum, personal comm.).

Geological Formation	Yield		Transmissivity (m^2/s)		Overburden Thickness (m)		Aquifer Zone (m)
	Average	Range	Average	Range	Average	Range	
Buem	18	12.0-25.5	4.0×10^{-4}	$0.97 - 7.01 \times 10^{-4}$	10	8.3 - 14.5	16 – 30
Granite	11.1	4.5-15	2.2×10^{-4}	$0.41 - 7.62 \times 10^{-4}$	15.1	10 – 21	21 – 61.3
Dahomeyan	13	4.5-35	2.9×10^{-3}	$0.12 - 9.65 \times 10^{-3}$	15.4	4 – 26	14 – 65
Tertiary	7.1	3.8-21.1	1.1×10^{-4}	$0.01 - 2.51 \times 10^{-4}$	70.2	38.1 – 90.1	38 – 90

Table 3 Handpump borehole yields and failure rates data in Ghana (After Dapaah-Siakwan and Gyau-Boakye, 2000; Darko, 2001).

Geological Formation	Percentage coverage (%)	Yield (m^3/hour)		Depth (m)		Failure rate (%)
		Average	Range	Average	Range	
Buem		9.2	0.72 - 24.3	44	21 - 146	12
Togo						
Granite		4	0.3 - 36	37	13 - 152	22
Upper Birimian	54	7.4	0.45 – 23.6			24
Lower Birimian		12.7	0.41 – 29.8	54	16 - 187	
Tarkwaian		8.7	1 – 23.2			17
Dahomeyan		2.7	1 – 3	39	22 - 122	64
Upper Voltain	45	8.5	1 - 9			44
Middle Voltain		6.2	0.45 - 9	42	22 - 355	
Lower Voltain		8.5	1 - 9			45
Cretaceous-Tertiary		3.9	1 - 5	142	19 305	64
Cretaceous-Recent	1	15.6	4.5 – 54	68	36 - 108	22
Alluvium		11.7	1 - 15	-	-	33

of 10 l/min is said to be satisfactory. For mechanized boreholes, the minimum yield required is 5 m^3/h. More and more communities depend on these and there is, therefore, the need to improve upon the water supply situation. One such means is the construction and utilization of underground dams.

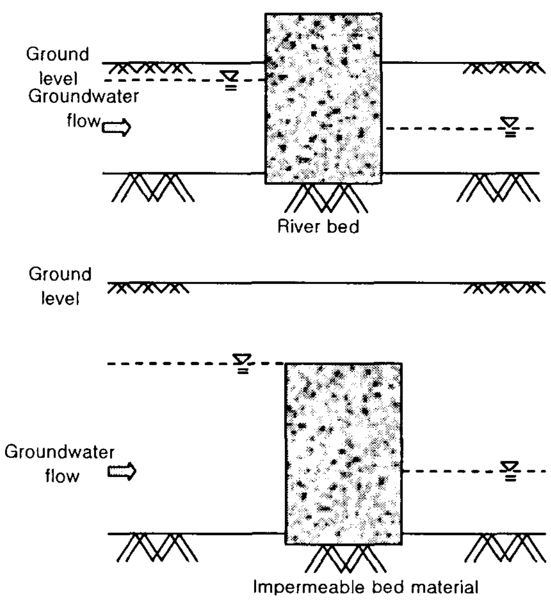
3.1 Basic concept of an underground dam

An underground dam is a facility consisting mainly of a dam body or cutoff wall, which is constructed on an impermeable sub-stratum in the soil to block the flow of either groundwater in a river bed or in an alluvial valley. Many of such type of dam have been constructed and utilized in Japan (Aoki, pers. comm.; Katsuki and Mizokami, 2002; JGRC, 2001; Osuga, 1997; Tanabashi et al., 1996; Nagata et al., 1994; Kamon and Aoki, 1987; Aihara et al., 1983; Kurokawa, 1981), Indian (CSE 2000; Faillace 1999; Raju, 1999, 1998, and 1983) and Brazil and several other countries (UNEP, 1998; Nilsson, 1988).

Depending on the height of the dam crest, an underground dam may either be a *sand-storage* dam or *sub-surface dam.* The schematic drawings of the two are shown in **Fig. 5**. A sand-storage dam is constructed across river beds, with the dam crest at a desired height above ground level. The dam impounds water in sediments, especially sand, caused to accumulate by the dam itself.

A sub-surface dam is constructed to the underlying impervious material, with its crest at a desired depth below the ground level. By this means, groundwater flow in the natural aquifer is arrested and can thus be pumped for agricultural and household uses, especially in the dry period of the year. Excess groundwater flows above the dam crest and recharge downstream aquifers. A combination of the two, sub-surface dam and sand-storage dam, may be built to take advantage of site conditions that favour the construction of both.

(a) Sand-storage dam



(b) Sub-surface dam

Fig. 5 Types of underground dams

3.2 Advantages and disadvantages

Compared with conventional surface dams, underground dams have the following advantages:

(a) evaporation losses are reduced; (b) there is no reduction in storage volume due to silting; thus, the life span of the underground dam can be more permanent because of the absence of the built up of sediments in reservoirs; (c) since the pumped water is spread on the upstream side of the underground dam, part of the abstracted water returns to the storage thus allowing for water recycling; (d) the stored water is less susceptible to pollution; (e) health hazards due to mosquito and other vector breeding are avoided; (f) since water is stored underground, the submergence of land and houses can be avoided; therefore, the land above the underground dam can be utilized as it was prior to the construction of the dam; (g) potential disasters caused by the collapse of the dam can be excluded; and (h) the construction cost of the dam wall is relatively low.

On the other hand, some disadvantages are associated with the construction of underground dams and they include the following: (a) since underground dams store water within the soil sub-stratum their capacities, which is a function of the effective porosity of the medium, are low compared with those of conventional surface dams; (b) the downstream aquifer may experience low groundwater flow due to the construction of the underground dam; (c) the lowering of downstream groundwater level may lead to land subsidence; (d) the lowering of groundwater level downstream may cause sea water intrusion; (e) the storage and retention of groundwater may cause liquefaction and other seismic activities in the surrounding aquifer; (f) the increased and decreased groundwater levels upstream and downstream, respectively, may lead to changes in the vegetation and soil fauna and flora; (g) the storage and retention of groundwater may cause the soil pore pressure to increase, thereby resulting in increased uplift pressure on underground infrastructures and groundwater leakage; (h) an accurate estimation of the reserve volume of groundwater could be difficult; and (i) quality control of construction work of sub-surface dam could be difficult because of the invisibility of the dam.

3.3 Physical conditions for under-ground dams

(a) Climate

The climatic regions where underground dams are used for water supply are those that experience irregularity in rainfall, arid and sahel areas where "every drop counts", sub-tropics and tropics where seasonal shortages in dry seasons are common and, dry, monsoon and tropical wet-and-dry climatic areas of the world. Increasing the quantity or raising the groundwater level in such areas makes water available throughout the year.

(b) Topography

Topography dictates the technical possibilities of constructing underground dams, achieving sufficiently large storage reservoirs with suitable recharge conditions and low seepage losses (Nilsson, 1988). Underground dams are best sited in well defined and narrow valleys.

This reduces costs and makes it possible to assess storage volumes and to control possible seepage losses.

The gradient of the groundwater table and the extent of flow depend on the topographic gradient. A gentle gradient of 0.2 – 4 % is generally preferred. Some underground dams, have however been constructed on extreme gradients of 10 – 16 %. The most favourable sites for underground dams are gentle slopes in the transition zone between hills and plains (Nilsson, 1988).

It is also recognized that the storage efficiency and methods of dam construction depend on the topography of the impermeable beds or underlying bedrock. For example, a dam sited in an aquifer of even thickness in a wide valley with gentle gradient and draining through a narrow passage between outcropping rock will create a large amount of storage at comparatively low cost.

(c) Hydrogeology

The most favourable sites for underground dams are sand/gravel river beds and in-situ weathered layers and deeper alluvial aquifers. However, in-situ aquifers may have less favourable storage and flow characteristics. Sites having high hydraulic conductivities are desirable, for such sites transmit water for extraction at the dam wall. Underground dams constructed in aquifers with very fine grained materials are said to have low storage volumes. The specific yield (Sy) of such water bearing strata may be 5 – 50 %, depending on grain-size distribution, particle shape and compaction. In Namibia and India, the specific yields of river bed underground dam sites range from 7.5 to 25 (Nilsson, 1988).

Underground dams are generally unconfined in terms of hydraulic properties. However, confined cases can be found, as is the case of the Kaba Island dam in Japan. The cut-off wall of this dam was constructed in the gravel aquifer by injecting bentonite to 10 – 25 m. The recharge to the aquifer was increased by an extensive system of sand piles penetrating the confining layer. By this method, a large quantity of water is controlled with a relatively small dam.

For a successful construction and utilization of an underground dam, the following site conditions are recommended (Osuga, 1997):
(a) an aquifer with high effective porosity, sufficient thickness and great aerial extent; (b) an impermeable bedrock or material under the aquifer; (c) sufficient groundwater inflow to the underground area or the recharge of the aquifer should be easy; (d) an underground valley where an underground barrier can be built; and (e) land-use practices that do not contribute to groundwater contamination.

3.4 Dam wall

The relatively impermeable dam wall, or cut-off wall, is the underground dam itself. This is needed to arrest the flow and store the groundwater in either the aquifer or alluvial deposits for later use. Depending on the locality and availability of construction materials, several types of dam walls could be used. These include clay dike, brick wall, stone masonry dam, concrete dam, ferroconcrete dam, plastic-tarred-felt sheets, sheet pile of steel, corrugated iron or PVC, and injection screen of bentonite and grout (Nilsson, 1988).

Clay dikes and brick walls are suitable for small schemes in highly permeable aquifers of limited depth, such as sandy river beds and where manual labour is cheap. The use of stone masonry dam, concrete dam, ferroconcrete dam, plastic-tarred-felt sheets, and sheet piles of steel, corrugated iron and PVC requires skilled personnel and know-how. Injection screens of bentonite and concrete grout are used to arrest and tap flow in large or deep seated aquifers and to protect groundwater from sea water intrusion (Kamom and Aoki, 1987). The utilisation of these materials requires highly skilled personnel and is used for the construction of large sub-surface dams, as is the case in Japan.

Osuga (1997) recommends that the sites of the dam walls should be decided from the following points of view: (a) the dam wall should be sited at the most downstream point, so that the necessary water volume can be stored; (b) the dam wall should be sited at the narrowest point in the valley so as to reduce the cost of construction; (c) the site should be located at a place where no obstacle will impede construction; (d) sites with caverns should be avoided in order to avoid leakage problems; and (e) the height of the dam wall should be less than 70 m from the surface, taking into consideration the drilling capacity of machines.

3.5 Height of wall

The height of an underground dam depends on slope stability, depth of groundwater at the time of construction and the cost involved. **Table 4** shows the average heights of some small dams in India, constructed with various cut-off materials. These seem small when compared to dams in Japan, where dam walls are constructed by cement grouting and injected bentonite methods and heights of up to 50 m have been reached.

Table 4 Dam types and heights in India (After Nilsson, 1988).

Dam type	Average height (m)
Injection screen	10
Brick wall	6
Concrete dam	6
Stone masonry dam	5
Ferroconcrete dam	4
Clay dike	3
Plastic sheets	2

4 POTENTIAL FOR UNDERGROUND DAMS IN GHANA

Considering the hydrogeology, physiography and the drainage pattern of Ghana, it is evident that underground dam technology is a feasible option for areas in the country that lack more traditional sources of water for agricultural and other uses. This is more so in the alluvial valleys of the numerous rivers that drains the country, especially in the Voltain System. In order to realize this potential, consideration should be given to proper site investigations, design and construction, environmental assessment and the socio-economic dynamics of the user communities. From the Japanese, Indian and Brazilian experiences, the following should be considered.

4.1 Availability of underground storage and recharge capacity

In order to use the underground reservoir to store a significant volume of water, possibly of the same order of magnitude as the annual runoff with the intent to use it at a later stage, it is necessary to ascertain the potential storage capacity of the groundwater reservoir as well as its suitability for being recharged by the surface water and for easily returning the stored water when needed. The groundwater reservoir should present sufficient free space between the ground surface and the water table to accommodate and retain the water to be recharged, for the period during which water is not needed. This requires accurate hydrogeological investigations, including geological mapping, geophysical surveys and reconnaissance drilling. These will help in determining the configuration and the storage capacity of the underground reservoir.

It is also important to pay attention to the recharge capacity of the aquifer. The suitability of an underground reservoir for recharging may be conditioned on: (a) surface materials of high permeability so as to allow water to percolate easily; (b) the unsaturated zone of high vertical permeability, and vertical flow of water not restrained by less permeable clayey layers; (c) the depth to water level should not be less than 5 to 10 m; and (d) the aquifer transmissivity should be high enough to allow water to move rapidly from mounds created under recharge basins but should not be too high (as in karstic channels) so that water cannot be recovered; an adequate transmissivity for recharge is also a good indicator of the aquifer's capacity to produce high well discharge and therefore easy to return the water stored.

4.2 Dam body

The dam body must have blocking water properties that maintain the volume of leakage from the dam body at a value equal to or lower than the allowable design value. Generally, a design coefficient of permeability of 1×10^{-5} cm/s or less is recommended. In order to prevent leakage from the interface of the constructed cut-off wall and the impermeable bedrock, an embedding depth in the bedrock of 1 m or more is recommended.

The elevation of the bottom edge of the underground dam is determined according to the elevation and embedding depth of the impermeable bedrock. The higher the crest elevation is set, the greater is its efficiency. However, because flooding on the surface must be prevented, the crest elevation is set by means of groundwater analysis and by treating the distance from the dam crest to the ground surface as the overflow section or freeboard. A maximum execution depth of 4 m is recommended for sand-storage dam and 70 m or less for sub-surface dams.

Underground dams are supported in place by the passive unconfined compressive strength of the soil strata in which they are constructed. However, the wall should be designed to minimally account for water pressure in the soil strata.

4.3 Water abstraction

The method of abstracting the underground water depends on the use to which the water shall be put. For domestic water supply to small communities hand pumps could be used. In the case of irrigation, motor pumps may be used.

4.4 Environmental impact

If planned and executed properly, underground dams have no negative impact on the surrounding environment. Upstream water-logging is not a problem if the crest of the cut-off wall is well below the ground surface or if a sluice is provided in the dam. However, there is the tendency of salt accumulation if water is used for irrigation and seasonal rainfall is not sufficient to wash out the salts. The potential effects of blocking groundwater flow on downstream infrastructures should be determined and measures put in place to minimize detrimental effects.

4.5 Institutional arrangements

National institutional arrangements should be made to co-ordinate the design and implementation of the various underground dam projects and to build a data base to record the experience. There is the need to systematically collect and collate data on surface and groundwater resources, soil, natural vegetation and land use, cropping pattern, rainfall amount and distribution, and crop and their water requirements for the effective management of constructed underground dams.

Printz (1996) and Printz and Wolfer (1999) recommended that local resource users should be involved in all aspects of the planning, designing, implementation, and monitoring of underground dams. The planning should explicitly determine the potential effects on downstream water users and the hydrological changes that are likely to arise from the construction and use of underground dams.

Critchley and Siegert (1991) and Siegert (1994) recommended that performance assessment of underground dams should be carried out to facilitate comparison of the "before-" and "after-" and "with-" and "without-" effects of constructing the dams, and also with other water technologies, if available. This should include suitability data and information on the size and type of the system, crop grown and yield levels, annual rainfall, water use, socio-economic impact and social acceptance.

The possibility of adopting underground dam technology shows that this is possible in principle. A close examination of the other factors determining their success, such as socio-cultural environment, the possibility of adapting the population to agricultural innovations and the development policy objective of the country, are important for final consideration. This can be achieved by detailed agro-ecological and social-economic feasibility studies covering the particular area under consideration, in addition to the engineering design and construction.

5 CONCLUSION AND RECOMMENDATIONS

In an effort to improve upon the water supply situation in Ghana, the physiography and the hydrogeological setting of the country and the pre-requisite conditions for constructing underground dams have been reviewed in the paper. The country is underlain by a Basement Complex of crystalline rocks, the Voltain System of shale and sandstone and Cenozoic, Mesozoic and Paleozoic sedimentary strata. In terms of aerial extent, they, respectively, cover 54 %, 45 % and 1 % of the country. The failure rate of drilling boreholes in Ghana ranges from 12 % in the Buem Formation to 64 % in the Dahomeyan and Coastal Block Fault. Borehole yields are generally low throughout the country. From the general conditions necessary for the construction of underground dams, it is noted that underground dams could be constructed, especially in the alluvial valleys of the numerous streams and rivers that drain the country; and also in the various formations which have shallow overburdens and the Dahomeyan granites in the low rainfall areas and the Togo series. The recent formations consisting of the alluvial and coastal sandy and gravel formations are also ideal sites for underground dams.

One big advantage of underground dams is that, once water has been stored in the soil, evaporation is low. The Government of Ghana, in collaboration with her development partners, could support communities to construct the dams for water supply.

The use of underground dams can be combined with other technologies, such as soil and water conservation techniques and dug wells upstream. The productivity of arable and grazing land could be increased by reducing the risk of crop failure, if underground water is used for irrigation. Agro-forestry and fruit tree planting could also be facilitated. With regard to tree establishment, underground dams can contribute to the fight against desertification.

Clearly, further research work is necessary in order to clarify several issues that relate to the design, construction and use of underground dams. These include (a) the acquisition of detailed hydrogeological data on both mechanized boreholes and boreholes fitted with hand pumps in order to have an accurate information on aquifers in various geological formations in the country ;(b) the search for suitable and cheaper construction materials and methods; (c) seepage flow analysis to detect and minimize leakage through the dam; (d) determination of the permeability, specific yield and quantification of the additional storage effect resulting from the construction of the dam: (e) estimation of extent of flow in the aquifer – using the estimated permeability and effective porosity values, measuring the actual gradients of the existing water table and hammer sounding and geophysical measurement and (f) hydrological and hydro-geological surveys to estimate the depth and shape of aquifers.

The research is on-going and the output will be presented in future papers and reports to enable water resources' managers, civil engineers, geologists, hydrogeologists, hydrologists and construction specialists incorporate the findings into the effort to improve upon groundwater supply for potable, agricultural and industrial uses in Ghana and other developing countries.

ACKNOWLEDGEMENTS: We are very grateful to Mr. J. Nigata of the Ministry of Land, Infrastructure and Transportation (Japan), Professor K. Aoki of the Osaka Institute of Technology (Japan) and Dr. K.C.B. Raju (SVRTI, India) for their valuable information on underground dams. Our thanks also go to Dr. P. Darko of CSIR-Water Research Institute and the numerous other specialists who offered us information on the hydrogeology of Ghana.

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