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Spatial Distribution of Groundwater Production and Development Potential in the Volta River basin of Ghana and Burkina Faso

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***Abstract**: In order to evaluate the contribution of continuing groundwater resources development on the improvement of water supply and to assess the impact of increasing abstraction on the overall water budget, the spatial distribution of groundwater production for rural and urban water supply in the Volta River basin in West Africa is quantified and compared to population densities, groundwater recharge, and groundwater potential. Annual groundwater production through boreholes, hand dug wells, and piped systems have increased substantially over past decades and have reached an estimated 88 MCM/y, giving approximately 44 percent of the population improved access to groundwater. Seventy percent of the groundwater production is delivered by boreholes equipped with hand pumps. Despite the rapid development, groundwater production is still less than 5 percent of the average annual groundwater recharge in most of the basin, so that the present production should not be expected to have any significant impact on the regional water balance. In the face of water scarcity still prevailing in the Volta River basin, further development of groundwater resources is desirable. The assessment of groundwater recharge and development suggests that it would be sustainable from a geo-scientific point of view, at least in the foreseeable future.*

***Keywords:** Groundwater, groundwater use, hydrogeology, development potential, West Africa, Volta River basin*

Introduction

The Volta River basin in West Africa extends from the equatorial forest of Southern Ghana to the Sahel-Savanna of northern Burkina Faso. Eighty five percent of its 400,000 km² lie in Ghana and Burkina Faso, the remaining area is in Benin, Togo, Ivory Coast, and Mali (Figure 1). In this study, only the Ghanaian and Burkinabe parts of the Volta Basin are considered due to data availability limitations in the other countries. Over 90 percent of the Volta basin population lives in Ghana and Burkina Faso; therefore this study covers the major part of groundwater use and demand.

In 1998, 52 percent of the rural population in Ghana was dependent on groundwater tapped by boreholes with hand pumps and open wells with and without pumps (Gyau-Boakye, 2001). In Burkina Faso, wells and boreholes are also the main source of drinking water in rural areas, and are estimated to account for 60 percent of the total domestic water demand (DGH, 2001). The role of groundwater for urban water supply by mechanized, piped systems in these countries has previously received less attention and is covered in more detail here. Urban areas refer here to towns having more than 10,000 inhabitants.

The average total annual rainfall in the Volta River basin equals that of the wet regions in Europe (Global Climate Dataset 1961-1990, New et al., 1999), but rainfall is unreliable and mostly restricted to a short rainy season with a pronounced dry season of increasing duration from south to north. The combination of unreliable rainfall, an extended dry season, and ephemeral surface flow makes groundwater a relatively safe source of water preferable in both quality and availability to surface water. However, drying of open wells during the dry season is common (WRI/DANIDA, 1993), and even drying and reduced yields in the deeper boreholes are experienced in many regions. Pronounced drops in groundwater levels were observed during the drought of the 1980s (Wardrop Engineering, 1987; Thiery, 1990). Gyau-Boakye and Tumbulto (2000) suspect that increasing abstraction of groundwater has led to a depletion of groundwater resources in some areas in Ghana.

The question arises of whether the continuing development of groundwater resources is sustainable and what

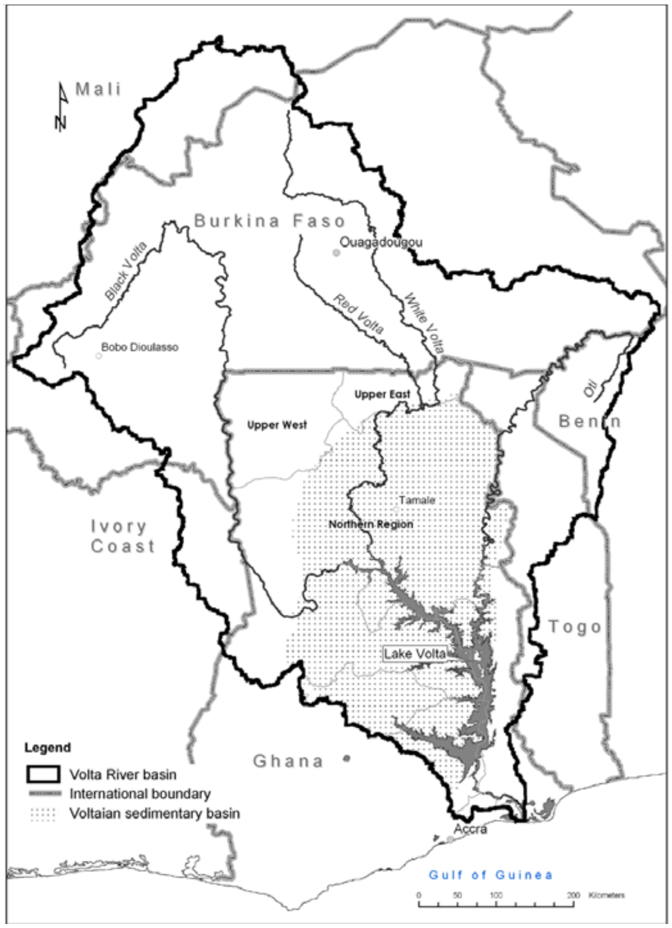

Figure 1. Location map of the Volta River basin

the impact on the overall water balance might be. While the number of boreholes drilled for rural water supply in Ghana and in Burkina Faso has been documented (Kortastsi, 1984; DGH, 1997; Gyau-Boakye, 2001), the magnitude and the spatial distribution of groundwater withdrawal was not specified. Both amount and distribution are required to determine the impact of groundwater resources development.

Groundwater development potential is usually understood as the expected success of groundwater resources exploitation. It is often expressed in terms of expected borehole yields (Dapaah-Siakwan and Gyau-Boakye, 2000) or the expected yield per unit of draw-down (Darko and Krasny, 2003). Aiming at a more inclusive and reproducible way of evaluating the groundwater development potential, this study follows an approach first introduced by the Inter-African Committee for Hydraulic Studies (ICHS, 1986), which defines groundwater development potential in terms of the accessibility, exploitability, and supply reliability of a groundwater resource.

This article quantifies the spatial distribution of groundwater production for rural and urban water supply. Population coverage by groundwater supply is assessed by comparing groundwater consumption to population densities. Based on both borehole data and national geological maps, the groundwater development potential is also assessed. Finally, groundwater production is compared to recharge and to groundwater development potential in order to evaluate the sustainability of the current production and to draw conclusions about opportunities and hydrogeological limitations for future development.

Database Development

In this study, drilled wells that are equipped with hand pumps are referred to as “boreholes,” while systems of mechanized, drilled wells connected to a piped distribution system are referred to as “piped systems.” There are also hand dug wells (HDWs), from which water is withdrawn either by a hand pump or a bucket. Groundwater production in the Volta River basin was quantified on the basis of data on boreholes, piped systems, and hand dug wells. These data were gathered from national and regional water authorities, private borehole drilling companies, Non-Governmental Organizations, and Research Institutions in Ghana and Burkina Faso in 2002 and 2003 (Table 1). The resulting numbers of groundwater production facilities are summarized in Table 2.

Borehole Data

After correcting known errors and eliminating overlapping data and double entries, the available data on boreholes from different sources were combined into one database.

Many borehole records lacked geographic coordinates. To the extent that location maps were available, they were used to digitize missing borehole coordinates. In those cases where no further information on the well location was available, the center of the village in which the borehole was located was taken as the location of the borehole.

Most hand pumps in use are of the Afridev, India Mark II or Nira type, which have a capacity of 0.6 to 1.7 m^3/h, depending on the brand and the installation depth. Given the fact that information on the installed pumps is often not available, an average pumping rate of 1 m^3/h was used. Groundwater abstraction from boreholes was calculated assuming an average daily pumping duration of eight hours, resulting in an average annual production of 2,920 m^3/y per borehole.

Data on Hand Dug Wells

Data on HDWs are scarce. There is no central collection point of this data. In general, the locations of HDWs are not known. A difference is made here between modern HDWs, which have an improved design and are generally constructed with the support of NGOs, and traditional HDWs, which are constructed by communities or families without external help.

Modern HDWs serve a smaller number of households than boreholes, often dry up for part of the year, and are not often equipped with a pump. Consequently, abstraction is less than that from a borehole. The abstraction rate from modern HDWs is estimated to be 600 m^3/y using a

Table 1. Groundwater Production Data Sources

	Data sources	*Remarks regarding data quality*
Boreholes		
Ghana	National borehole database Water Research Institute, Accra Borehole database CWSA Northern Region Borehole database CWSA Upper East Region Borehole database CWSA Upper West Region Borehole database CWSA Volta Region BGR borehole database for West Africa (Part Ghana) from 1984 Prakla Seismos / Geomechanik reports(from Acquah, 2002) WaterAid reports Unihydro Ltd. reports	Mismatch between national and regional databases due to an abundance of data entry mistakes and missing data.
Burkina Faso	BEWACO borehole database at the Direction de l'Inventaire des Ressources Hydraulique (DIRH), Ouagadougou	Database only accounts for 88% of boreholes in national water resources inventory from 1996.
Piped Groundwater Supply		
Ghana	Water Research Institute, Accra GWC Ltd. Upper East Region GWC Ltd. Volta Region Association of Water Boards, Tamale	Production figures for some smaller systems are not recorded and had to be estimated from pumping capacities.
Burkina Faso	ONEA, Office National de l'Eau et de l'Assainissement, Ouagadougou	Annual figures listed for all systems since 1982.
Modern Hand Dug Wells		
Ghana	Water Aid reports	Only information on total numbers per region
Burkina Faso	National water resources inventory (DGH, 1997)	Only information on total numbers per province

Note: CWSA is Community Water and Sanitation Agency, and GWC is Ghana Water Company Ltd.

bucket (four hours a day, ten months a year, at a rate of 0.5 m^3/h) and 2,200 m^3/y for a well equipped with a pump (four hours a day, ten months a year, at a rate of 1.7 m^3/h).

Traditional HDWs are mentioned here only for sake of completeness and are not included in further analysis. Information on traditional HDWs is extremely limited. As traditional HDWs are not equipped with a pump, are generally shallow, and dry up frequently, abstraction rates are on average much lower than for a borehole. The total amount of groundwater production from traditional wells can be expected to be less than 20 percent of that from boreholes. Since traditional HDWs are often bacteriologically contaminated and dry up during the dry season, they are usually not considered as a safe source of water and are therefore of minor relevance for water resources planning. For this reason traditional HDWs are neglected here in the calculation of groundwater production.

Table 2. Sources of Groundwater Supply, Volta River basin in 2001

Boreholes with Hand Pumps	*Number*
Number of boreholes Ghana	7,285
Number of boreholes Burkina Faso	11,391
Total	18,676
Piped Groundwater Supply	*Number*
Number of systems > 20 000 m^3/y Ghana	36
Number of systems > 20 000 m^3/y Burkina Faso	23
Total	59
Modern Hand Dug Wells	*Number*
Number of modern hand dug wells Ghana	3,960
Number of modern hand dug wells Burkina Faso	6,430
Total	10,390

Population Data

The assessment of population coverage by groundwater supply required the estimation of population data for 2001 from available figures. District data from the Ghana population census 2000 (Ministry of Works and Housing, 2001) and provincial population figures for Burkina Faso for 1996 (DGH, 1997) were used to extrapolate population figures for 2001, applying an annual growth rate of 2.6 percent (FAOSTAT). Where the Volta River basin boundary cuts through administrative boundaries, the Global Population Density Grid (Deichmann, 1994) was used to estimate population numbers for the part falling within the basin from the district and provincial values.

Hydrogeology

For the assessment of groundwater development potential, a digital hydrogeological map was developed on the basis of the geological maps (1:1 Million) of Ghana and Burkina Faso. A few available larger scale geological maps (Ghana Geological Survey, 1964; 1973; 1991a; 1991b) were used to improve the precision of the rather general geological map (1:1 Million) of Ghana. Information from the established borehole database on lithology, boreholes depths, water level, yields and specific capacity as well as information from hydrogeological reports and publications (Wardrop, 1977; Kwei, 1997; Gombert, 1998; Ministry of Works and Housing, 1998; IGIP, 1999; Dapaah-Siakwan and Gyau-Boakye, 2000; Banoeng-Yakubo and Skjernaa, 2000) was used to group together the stratigraphic units of the geological maps based on similarity of lithological and hydrogeological characteristics, or to divide them, where significant differences occurred. The original delineation of the formation units in the geological 1:1 Million maps was thereby slightly modified.

Groundwater Production

Boreholes equipped with hand pumps are the main means of groundwater extraction in the Volta River basin today. A total groundwater production from boreholes of 61 MCM/y was calculated for the year 2001 following the procedure described above. Despite their large number, hand dug wells supply a much smaller amount of water than boreholes (12 MCM/y).

Abstraction through piped systems using groundwater is 15 MCM/y, less than one fifth of total groundwater production. Table 3 summarizes the production of groundwater from different sources as calculated from the database.

The calculation of borehole groundwater production was repeated, this time only considering those boreholes in the database that were drilled in 1971 and earlier, including those which have since been abandoned. The calculation reveals the strong increase in groundwater production over the past decades, achieved with technical and financial aid from bilateral and multilateral donors. Groundwater withdrawal through boreholes with hand pumps increased from an estimated 1.5 MCM/y in 1971 to 61 MCM/y in 2001.

Groundwater withdrawal through piped systems developed more recently and even more rapidly. In Burkina Faso, production from piped systems in the Volta River basin grew more than eighty fold from 0.15 MCM/y in 1982 to 12.49 MCM/y in 2001 (data from the ONEA, 1999).

An analysis of groundwater production through piped systems shows that groundwater is not only an important source of water for the rural population, but that it is also a major source for urban water supply. In Ghana, about half of the population living in towns with piped water lives in a town with a system based on groundwater. There is no detailed information available revealing what percentage of the town population is actually connected to the distribution system. Neglecting that there might be large differences in the connection rates and considering total town population figures only, it seems that groundwater is as important a source of urban water supply in the Ghanaian part of the Volta River basin as surface water. Groundwater is especially important for urban water supply in the Upper East and Upper West regions, where more than 80 percent of the urban population is served by piped systems. Conclusively, in 11 of the 20 towns in the Ghanaian part of the Volta River basin with more than 10,000 inhabitants, water supply systems are based on groundwater. In contrast, surface water is the main source of urban water supply in the Northern region, where the largest Ghanaian town in the Volta River basin, Tamale, is located.

In the Burkinabe part of the Volta River basin, 69 percent of the urban population is served by public water supply, 35 percent with surface water, and 34 percent with groundwater as calculated with information from ONEA (1999). The largest piped systems are found in Bobo-Diolasso (7.2 MCM/y), which relies on spring water (70 percent) and boreholes (30 percent), and in the capital Ouagadougou (2.2 MCM/y). Ouagadougou alone, where 85 percent of the public water supply comes from dams, accounts for most of the surface water use. In 19 of the 23 towns in the Burkinabe part of the Volta River basin with more than 10,000 inhabitants, water supply systems rely exclusively on groundwater, making piped groundwater the most important urban source of drinking water.

Using loss rates documented for 1998 for water supply systems in Burkina Faso (ONEA, 1999) results in overall system losses of 23 percent of the water production in 2001 so that groundwater consumed by households from piped systems is estimated at 9.6 MCM/y . This equals an average consumption rate of 31 liters per person per day by the 848,000 urban consumers. Information on system losses for piped groundwater in Ghana is not available. Assuming similar average system losses of 23 percent reduces groundwater consumption from piped systems in Ghana to 2.4 MCM/y.

GIS raster processing was applied to generate a grid of total groundwater production by boreholes with hand pumps, modern HDWs and piped water systems. The resolution of the analysis was set to a 9 x 9 km² grid. Groundwater production per water point was summed for each grid cell to obtain the spatial distribution (Figure 2). Actual abstraction rates may differ from the calculated rates because of the limitations on data quality, lack of knowledge on actual pumping durations, and borehole performance. Given the uncertainty about the absolute amount of groundwater abstraction, the spatial pattern can still be regarded as representative of the true distribution, and the analysis that follows can be seen as a first order approximation. The final conclusions are robust, however, because they are based on order of magnitude differences over space

Table 3. Groundwater Production in 2001 in Volta River Basin in Ghana and Burkina Faso (estimates for 1971 in brackets)

Source	*Ghana (MCM/y)*	*Burkina Faso (MCM/y)*	*Total Production (MCM/y)*	*Share of source in production(%)*
Borehole with hand pump	21.5	39.7	61.2 [1.5]	69%
Modern hand dug well	5.0	6.7	1.7 [-]	13%
Piped system	2.9	12.5	15.4 [0.6]	18%
Total	29.4	58.9	88.3 [2.1]	100%
Share of country in production (%)	33%	67%	100%	

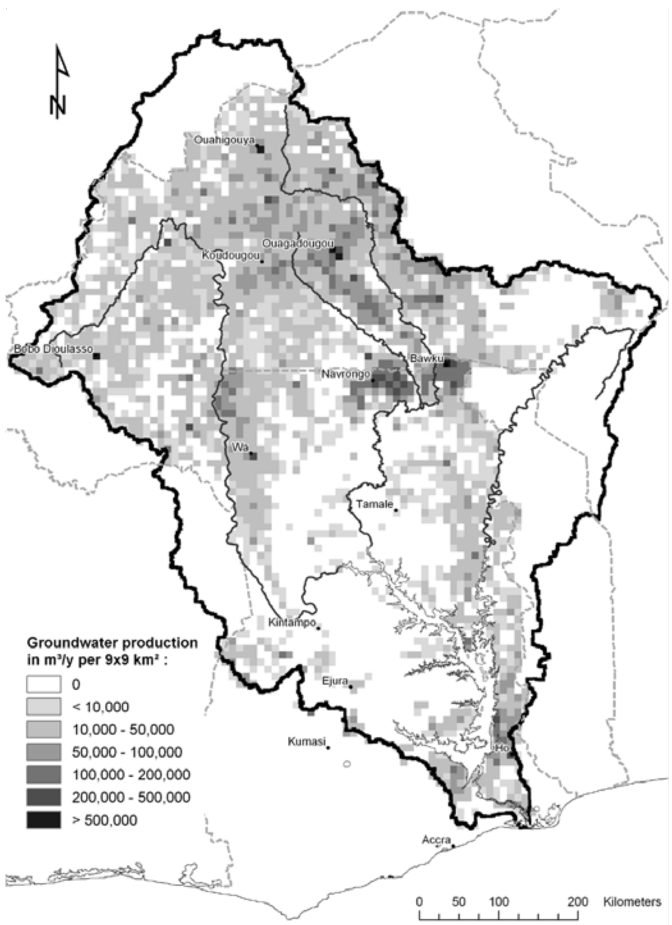

Figure 2. Spatial distribution of groundwater production in m^3/y per 9x9 km^2 cell

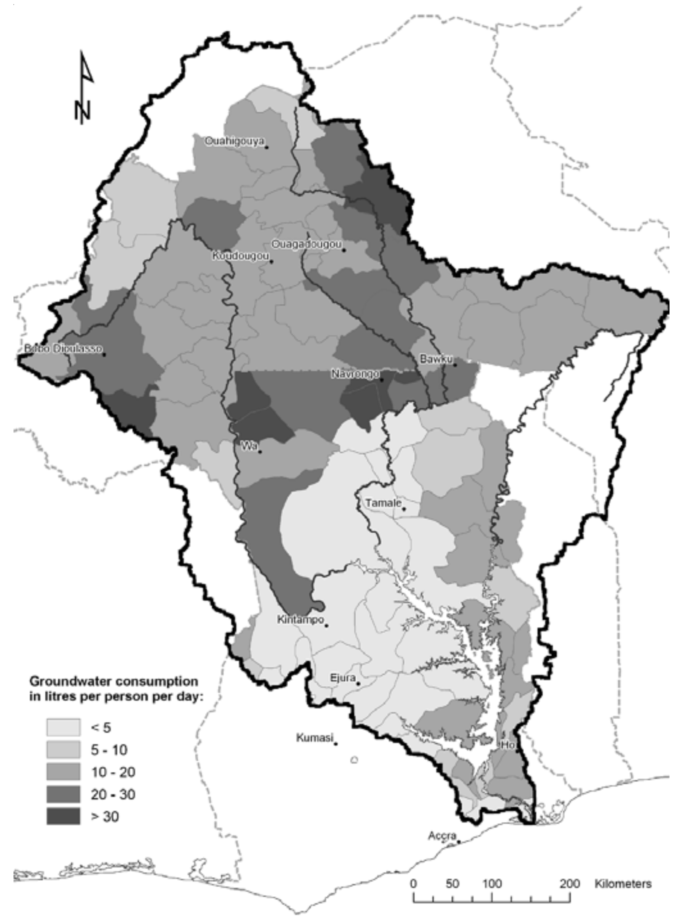

Figure 3. Average daily per person groundwater consumption by district

and between water production and availability.

At first sight, the pattern of groundwater production follows the population pattern, being highest in densely populated areas such as the Upper East Region in Ghana, and lowest in the Voltaian sedimentary basin, which extends to the north and west of Lake Volta (location see Figure 1) and where population is sparse. To analyze the spatial pattern of groundwater production in more detail, we studied per person groundwater consumption. This analysis is described next and will show that not only population density, but also hydrogeology is reflected in the pattern of groundwater production.

To identify regional variations in the access of households to groundwater resources, population densities were compared to groundwater consumption rather than production thus excluding system losses from piped systems. Average per person groundwater consumption for each district (Ghana) and province (Burkina) was calculated from the generated grid of groundwater consumption and the population dataset (Figure 3).

The map shows the large regional variations in per person groundwater use. Groundwater consumption reaches 25 to 50 liters per capita per day (lcd) in most of the Upper West and Upper East Regions of Ghana and in some provinces in Burkina Faso, while it is less than 5 lcd in most districts lying in the Voltaian sedimentary basin. This means that the low groundwater production in the Voltaian sedimentary basin associated with low population densities is further reduced through very low per capita groundwater consumption. This is understandable as the development of groundwater resources is generally regarded as difficult in the layers of shales, siltstones, and consolidated sandstones forming the Voltaian sedimentary basin, and low drilling success rates have been experienced in previous attempts. Low per capita groundwater consumption indicates that people in these areas strongly depend on less safe water sources such as water from dams, rivers, and dug outs. It is likely that due to this limited availability of safe water sources, total per capita water consumption is also reduced.

Population Coverage by Groundwater Supply

An evaluation of Canadian technical aid programs in Ghana estimates that borehole drilling and redevelopment programs have provided 75 to 80 percent coverage for rural domestic water supply in the Upper West and Upper East Region of Ghana (CIDA, 1998). Subtracting the ur-

Table 4. Population Coverage by Modern Groundwater Supply in 2001

	Burkina Faso	*Ghana*	*Total*
Population (Millions)	9.96	6.91	15.97
Percent of population served by piped systems using groundwater	9.5%	9.1%	9.3%
Percent of population served by boreholes with hand pumps and modern hand dug wells	38.9%	28.5%	37.6%
Percent of population supplied with groundwater	48.4%	37.6%	43.7%

ban population served by piped systems from the total regional population gives the population dependant on rural water supply. Piped water systems serve 69 percent of the urban population in Burkina Faso. If it is assumed that coverage rates of urban piped water supply systems in Ghana are similar, dividing groundwater production from boreholes and modern open wells by the population dependent on rural water supply results in an average groundwater consumption of 29 lcd in the Upper West and Upper East Regions, and of 15 lcd in the Volta River basin as a whole. If 29 lcd corresponds to 80 percent coverage, 42 percent of the population not served by piped systems use groundwater for domestic water supply. Groundwater supply coverage of the rural population is significantly higher in Burkina Faso (17 lcd or 48 percent) than in Ghana (13 lcd or 35 percent).

About 44 percent of the total population in the Volta River basin depends on modern means of groundwater supply. The calculated coverage of the total population by groundwater supply is presented in Table 4.

The analysis outlined above stresses the importance of groundwater for domestic water supply not only for the rural population, but also for the urban population.

Groundwater Recharge

It is important to know whether current groundwater production significantly affects groundwater levels and the overall water balance. To acquire insight into the possible impact of groundwater production, it was necessary to make a first order assessment of groundwater recharge.

Recharge rates called from a variety of studies were used to estimate the annual renewable groundwater resource from rainfall data. The studies show a high spatial heterogeneity of groundwater recharge in West Africa, especially in weathered rock aquifers. Linear regression was applied to available data for two different lithologies, sandstone and weathered rock, to describe the relationship between annual rainfalls and recharge rate (Figure 4). A study carried out through BRGM in Burkina Faso (BRGM, 1991) indicates substantially larger recharge rates of 5 to 12 percent in weathered granite aquifers. This study would have been an outlier and was not included in this regression, thereby keeping recharge estimates conservatively low. The resulting regression lines indicate that there is no recharge below an annual rainfall of 170 mm for sandstone aquifers and below 380 mm for weathered rock aquifers. Furthermore recharge rates vary with the amount of rainfall up to 13 percent in sandstone and up to 8 percent in weathered rock. The influence of land use on groundwater recharge has not been sufficiently investigated in any of these studies to allow quantification, and differences in land use are therefore not considered in the calculation. This preliminary assessment also neglects the influence of slope on groundwater recharge. However, the impact of varying slope is small in comparison to the main factors rainfall and lithology, and the occurrence of pronounced elevation differences is limited to the south eastern border of the basin.

To calculate recharge, the basin was first divided in sandstone and weathered rock sections according to the digitized geological maps 1:1 Million of Ghana and Burkina

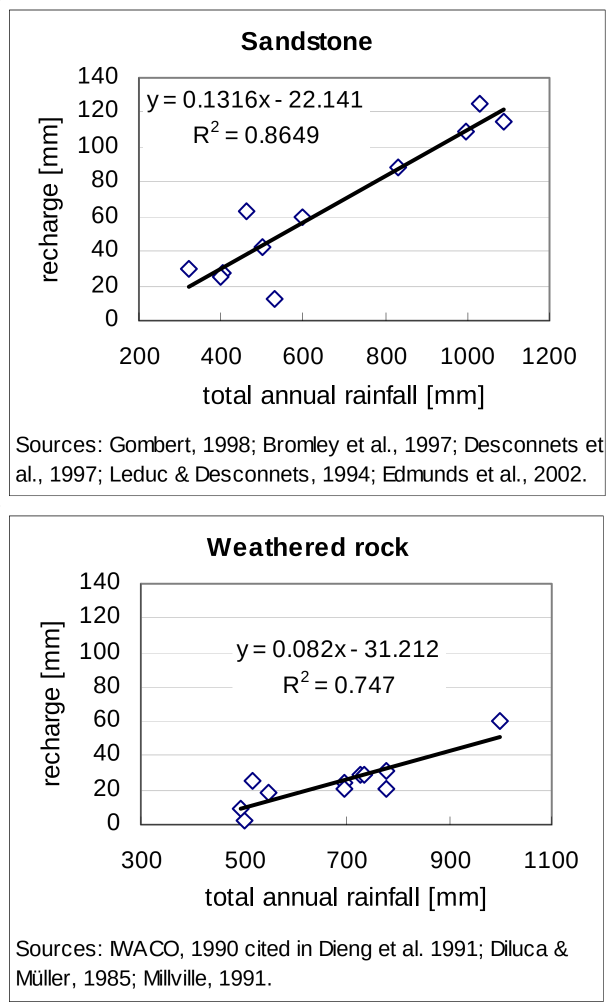

Figure 4. Groundwater recharge as a function of lithology and total annual rainfall

Faso. Consolidated and argillaceous sandstones were classified as weathered rock so that the more conservative regression equation was applied. Rainfall figures were derived from the 0.5° resolution grid of mean annual rainfall (1961 to 1990) of the Global Climate Dataset prepared by the Climatic Research Unit (CRU) of the University of East Anglia (New et al., 1999). Recharge was then estimated by applying the respective rainfall-recharge regression equations with rainfall as independent variable.

In most of the geological formations, groundwater flow follows the direction of surface topography so that boundaries of groundwater catchments coincide with those of surface water. We find these flow characteristics in our current field investigations in the granitoids of the Upper East Region, and it has been described as well for Voltaian sedimentary rocks (Minor et al., 1994) and the Zone Sédimentaire in western Burkina Faso (Gombert, 1998). The ratio of groundwater production to groundwater recharge was calculated from generated grids for every river sub-basin as delineated in the HYDRO1k elevation derivative dataset provided by the USGS (Danielson, 1996) applying GIS spatial analysis (Figure 5).

The results show that in most of the basin, groundwater production is still less than 1 percent of groundwater recharge. Only towards the arid northern part of the basin withdrawals amount to a significant fraction, more than 5 percent of average groundwater recharge. For the area of the basin that falls within the borders of Ghana and Burkina Faso, the average annual rainfall is 340,000 MCM/y, resulting in an estimated groundwater recharge of 12,600 MCM/y or 3.7 percent of rainfall. The calculated groundwater production of 88.3 MCM/y corresponds to 0.7 percent of average annual groundwater recharge. All these recharge estimates were conservative. Even if this first order recharge assessment were, inexplicably, 100 percent higher, abstraction would still only be 1.4 percent of the recharge.

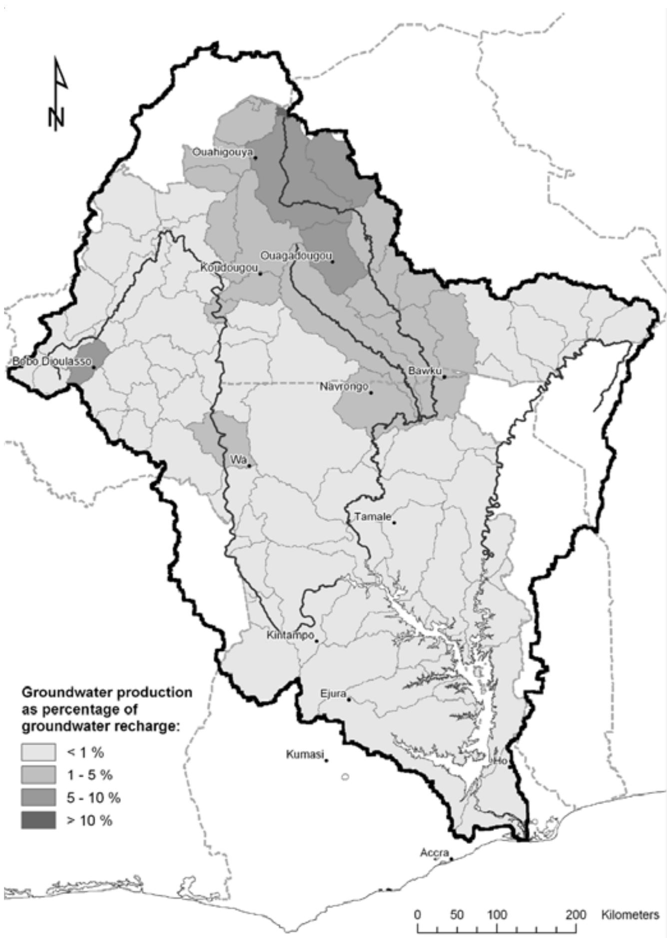

Figure 5. Ratio of groundwater production to groundwater recharge (%)

This assessment strongly suggests that groundwater over-exploitation is a problem confined only to local occurrence within the basin. Withdrawals exceeding the sustainable yield at a given water point have been observed, causing a strong decline of the water table at the well or borehole during the dry season and especially in years of drought. However, these problems are usually caused by low transmissivities unable to sustain a yield large enough to match the pumping rate and should not be expected to have regional impacts. Given the anxiety with respect to over-exploitation of groundwater, even to the extent that it would affect water levels of Lake Volta (Gyau-Boakye and Tumbulto, 2000) this is an extremely important result. Average annual evaporation from the surface of Lake Volta alone of 10,200 MCM/y (Andreini et al., 2000) is more than one hundred times higher than the calculated total annual groundwater production, so that an increase in the mean annual temperature of 1 °C would have a larger impact on the overall water budget than a doubling of the current groundwater abstraction.

Groundwater Potential

Groundwater availability is not only determined by the amount of groundwater recharge, but by the accessibility of the resource and whether its development is worthwhile. A measure for this is the groundwater development potential.

The groundwater development potential depends on a number of variables, not only on expected borehole yields. The required capital costs for construction of a borehole, the suitability of the aquifer for village or urban water supply and the reliability of the groundwater resource in the event of a drought all have an impact on the development potential. The Inter-African Committee for Hydraulic Studies (ICHS) published a scheme for the evaluation of groundwater potential in 1986 (ICHS, 1986). A modified version of this scheme was used to draw a map of the groundwater potential. The modified scheme is summarized in Table 5 and evaluates the groundwater potential as a function of:

- Accessibility (depending on borehole drilling success rates)
- Exploitability (depending on borehole yield and extraction depth), and

Table 5. Scheme for Assessing Groundwater Potential

Table 5a. Accessibility

Success rate	*Assessment*
> 80 %	very good
65 - 80 %	good
50 - 65 %	moderate
< 50 %	poor

Table 5b. Exploitability

	Extraction Depth		
Yield	*< 25 m*	*25 - 50 m*	*> 50 m*
> 80 l/min	very good	good	moderate
30 - 80 l/min	good	good	moderate
13 - 30 l/min	moderate	moderate	poor
< 13 l/min	poor	-	-

Table 5c. Supply Reliability (Specific capacity [(l/min/m] as indicator of the mobility of groundwater)

	< 2.5	*2.5 – 7.5*		*> 7.5*
Storage		*recharge < 20 mm*	*recharge > 20 mm*	
< 150 mm	poor	poor	moderate	-
150 – 300 mm	poor	moderate	moderate	-
300 – 450 mm	moderate	moderate	good	good
> 450 mm	-	-	-	very good

(storage = saturated thickness x storage coefficient)

Table 5d. Groundwater Potential

Points	*Potential*
< 6	poor
6-7	moderate
8	moderate - good
9-10	good
11-12	very good

Note: Individual evaluations in each category a to c are rated according to: poor = 1; moderate = 2; good = 3; very good = 4. The sum of points in Tables 5a to 5c is used in Table 5d to derive the groundwater potential

- Supply reliability (depending on the amount of water stored in the aquifer, its mobility to the well and on the amount of recharge in non-drought years).

The main modification concerned the assessment of supply reliability. As an addition to the original scheme, the mobility of water was included in the evaluation, while the weight of average annual recharge was reduced. Where rainfall is highly variable and unreliable, a resource of small storage capacity and low transmissivities will be highly vulnerable to drought conditions even if it receives ample recharge in years of average rainfall. The modified scheme only distinguishes two classes of recharge rates. Below a recharge rate of 20 mm/y, which corresponds approximately to the 600 mm rainfall isohyets for weathered rock aquifers, the depth to the water table increases while drilling success rates are significantly reduced, marking a decline of supply reliability. Above recharge rates of 20 mm/y reliability can still be limited depending on the amount of water stored and its mobility. While the original scheme assumed that supply is always ensured when effective rainfall exceeds 450 mm, which corresponds approximately to an average annual rainfall of 1000 mm, occasional water shortages in boreholes in some locations of the Voltaian sedimentary basin show that this might not be the case. A more detailed gradation of recharge rates in the evaluation scheme was therefore abandoned.

The classifications of accessibility, exploitability, and reliability of each hydrogeological unit were based on median values of yield, extraction depth, specific capacity, and saturated thickness of the records in the borehole database located within the unit and estimated values of storage coefficients (Thiery, 1990; Gombert, 1998). Drilling success rates were partly determined from the ratio of positive and negative boreholes in the database. However, because of an obvious bias in favor of positive boreholes in the databases from Ghana, success rates were rather derived from drilling reports and values previously published in a description of hydrogeological properties of geological formations in Ghana (Dapaah-Siakwan and Gyau-Boakye, 2000). It should be kept in mind, though, that success rates achieved in past drilling campaigns do not necessarily determine future success, as they are sometimes distorted by inadequate siting methodology. One example is the blind application of geophysical measurements in borehole siting in the northern part of the Volta Region, which interpreted resistivity lows as an indication of prospective sites irrespective of rock type. In this case, borehole success rates in the Voltaian sedimentary basin were heavily increased when geophysical siting was abandoned in the year 2001 (personal communication with K. Klitten, DANIDA). On the other hand, when applied wisely and in combination with other methods, geophysical methods can greatly improve drilling success rates (Taylor et al., 1999).

Figure 6 presents the distribution of the groundwater potential. A region of very good groundwater potential is in the area of the “Zone Sédimentaire” in the northwestern part of the basin, which lies in the West of Burkina Faso. This region extends over the headwaters of the Black Volta, which due to the inflow of groundwater is the only perennial river in the basin. At the other end of the scale is the area of the Middle Voltaian Obosum sediments, which consists of alternating layers of predominantly shale, siltstone and consolidated sandstone, and the massive Dahomeyan gneisses south of the Volta Lake. These two geological formations have a poor groundwater potential. A large part of the basin is underlain by Birimian rocks consisting of granites, granodiorites, migmatites, gneisses, metasediments, and metavolcanics, which have a moderate or moderate to good groundwater potential. Even though the hydrogeology of the Voltaian sedimentary basin is not well known, the borehole records suggest that a good groundwater potential occurs in the Middle Voltaian Oti beds, which consist predominantly of sandstones. The Buem formation, which stretches from the eastern shore of the Volta Lake to the eastern corner of Burkina Faso, also has good

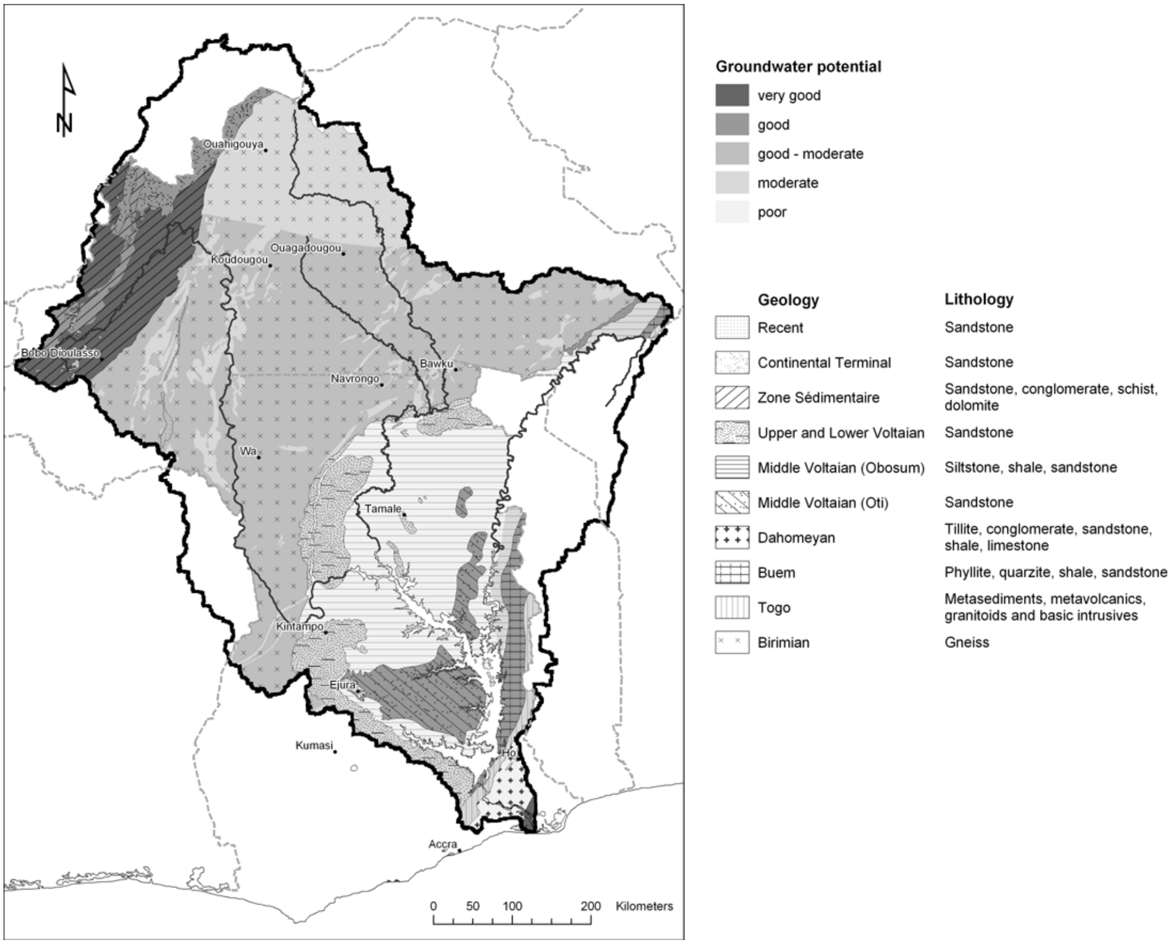

Figure 6. Groundwater development potential

groundwater potential as well as the sandstones of the Continental Terminal at the north-western edge of the basin.

A comparison of groundwater production with groundwater potential allows the identification of opportunities and limitations in water resources development. To maximize the impact of limited financial resources, further groundwater development should be focused on areas where currently a relatively low percentage of the population has access to improved water sources, despite favorable groundwater conditions. This applies for example to the northwestern edge of the basin: here the very good and good groundwater potential of the "Zone Sédimentaire" and the Continental Terminal should be utilized to expand groundwater production. Groundwater is underexploited along the southwestern edge of the basin. Here the groundwater potential is only moderate or moderate to good, but does not justify the extremely low groundwater use of less than 5 lcd. The commissioning of water supply systems using groundwater for district capitals in this area (Kintampo, Nkoranza, Ejura) since 2001 will help to improve the situation, and there is still room for additional development.

Areas of low per capita water supply from groundwater are most vulnerable to waterborne diseases as well as drought conditions. However, if the groundwater potential is poor, alternative means of improved water supply such as rainwater harvesting should be considered as more appropriate. This applies to the extension of the Middle Voltaian Obosum beds, which in general have a poor groundwater potential due to low drilling success rates and to low median specific capacity. Nonetheless, isolated high yielding locations have been encountered. A water resources development strategy aiming at full use of the few high yielding water points through a mechanized distribution system on the one hand and more effective rainwater harvesting as a decentralized means of water supply on the other hand might be more promising than installing more boreholes fitted with hand pumps.

Conclusion

Groundwater production through boreholes, modern hand dug wells, and piped systems has increased substantially over the past decades in the Volta River basin and has made groundwater an important source of water for rural and urban water supply. Despite these developments, almost half of the population still has inadequate access to safe drinking water, and further development of groundwater resources is desirable. The assessment of groundwater recharge and development potential presented in this article suggests that it would also be sustainable. In particular, this study shows that groundwater production is much too small to affect the regional water balance or water levels in Lake Volta. The maps, which were introduced, can help to identify areas that should receive priority attention in the further development of groundwater resources. Nonetheless, an increase of groundwater exploitation needs to be carried out with prudence to avoid local over-abstraction and the negative impact this might have on supply reliability and vegetation.

To ensure the sustainability of groundwater resources development, long-term monthly monitoring of groundwater tables is highly necessary. Monitoring should be supplemented by competent data interpretation and regular reporting mechanisms. Special care should be taken to secure data in the event of institutional restructuring, which has especially resulted in loss of data in Ghana.

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