GROUNDWATER RESOURCES OF NORTHERN GHANA: INITIAL ASSESSMENT OF DATA AVAILABILITY

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Contents

BACKGROUND

The spatial and temporal variability of water resources in sub-Saharan Africa (SSA) is influencing agricultural development that can ultimately affect food insecurity and poverty in the region. Although groundwater development has relatively low cost and does not require expensive infrastructure, groundwater is still underused in the SSA. Studies from the International Water Management Institute (IWMI) indicate that groundwater irrigated agriculture is a competitive investment option to improve the socioeconomic standings, particularly in rural areas where agriculture is predominant and surface water is either nonexistent or prone to pollution. Nevertheless, careful planning and management strategies should be undertaken to minimize groundwater degradation. Groundwater development will contribute to meeting the commitments of the Millennium Development Goals in the SSA, especially under uncertain upcoming challenges such as climate change, population growth, urbanization, and land degradation.

For the purpose of understanding the groundwater potentials of SSA, IWMI established a project titled "Groundwater in sub-Saharan Africa: Implications for food security and livelihoods [see IWMI, 2008]." The goal of this project is to enhance the role of groundwater to improve food security and livelihoods in the Alliance for a Green Revolution in Africa (AGRA) countries, namely Burkina Faso, Mali, Ghana, Kenya, Malawi, Ethiopia, Mozambique, Niger, Nigeria, Rwanda, Tanzania, Uganda, and Zambia. Detailed studies will be conducted in four countries; Mali and Ghana in West Africa, Kenya in East Africa, and Tanzania in Southern Africa. Eventually, intensive field work and analysis will be conducted in these regions.

As a part of this effort, IWMI developed a collaborative research partnership with Utah State University (USU) to understand the natural recharge mechanisms in the northern part of Ghana and the impacts of climate change on groundwater resources. For this purpose, a region within the Volta River Basin will be selected as a study site for detailed analysis. This report was prepared subsequent to a field study conducted in July to collect available data from the region. The purpose of the report is to provide a broad overview of data and information collected from the field trip.

INTRODUCTION

Water is an indispensible resource for life quality and subsistence. Globally, however, 1.1 billion people, mostly in developing countries, do not have access to safe water and 2.4 billion have no access to sanitation facilities [WHO/UNICEF, 2000]. Water scarcity becomes a severe concern to most sub-Saharan African countries [Osei-Asare, 2004] and the data show that 67% of the rural population have no access to safe water supply while 81% do not have access to sanitation services [Rosen and Vincent, 1999].

As in most semi-arid regions, surface water resources are considerably unreliable due to the high inter- and intra-annual variability in rainfall. In addition, surface water bodies are highly vulnerable to contamination due to natural alteration and anthropogenic intervention. In the long term, groundwater resources are reliable, consistent, safe, and more importantly accessible to people. Since agriculture is the predominant land use within the Upper East Region (UER) of northern Ghana, groundwater irrigated agriculture becomes vital for economic development of that region. Nevertheless, groundwater irrigated agriculture does have limitations. In a relevant study in the UER, crop marketing, crop diseases, and water shortages are found to be the major problems related to groundwater irrigation [Laube et al., 2008].

Mygatt [2006] estimated that about 2 billion people in urban and rural communities worldwide depend on groundwater for daily consumption. Groundwater is often the sole water resource in arid and semi-arid regions; therefore the assessment of quantity and quality of groundwater is vital [Anayah, 2006]. Such an assessment will provide better understanding of the dynamics of groundwater for sustainable use and help planning and management of resources. To assess groundwater availability especially in water deficit regions, one needs to accurately estimate groundwater recharge to determine the safe yield. In the case Volta Basin, the resources are shared by six countries in West Africa where semi-arid climates dominate. Therefore, planning and management of groundwater in the Volta basin is a shared common goal of all stakeholder countries.

Water resources in Ghana play a central role in the promotion of living standards, enhancing economic growth, provision of food security and livelihood, and eventually alleviation of poverty. As in most parts of the world, Ghana too is experiencing population growth and associated demand on food production. Therefore, demand on water increases steadily while producing stress on available water resources. In addition, climate change impacts on the limited water resources in semi-arid regions can be significant [Herrera-Pantoja and Hiscock, 2008]. An accurate assessment of climate change impacts on recharge, temporarily and spatially, is challenging and complex [Jyrkama and Sykes, 2007]. Some of these global impacts on water resources will definitely affect security and sustainability of the environment and society in the future.

DESCRIPTION OF VOLTA RIVER BASIN, GHANA

Figure 1 shows the physical layout of the Volta River Basin in West Africa. The area of the basin is about 400,000 km^2 of which 42% lies in Ghana. The region occupied in Ghana is divided to 10 regions of which three regions are in northern Ghana. These three are the UER, the Upper West Region, and the Northern Region. It is found that the UER is the best region to conduct the designated study for the following reasons:

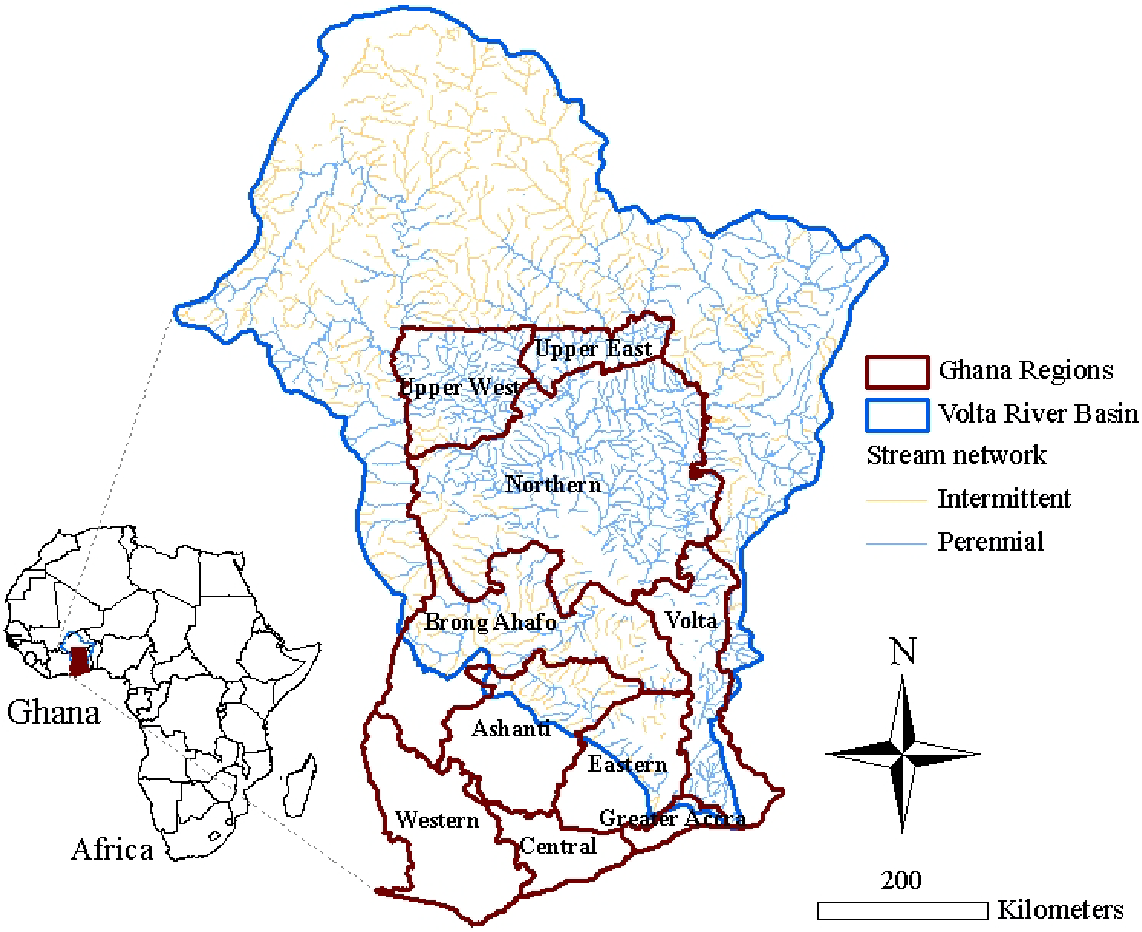

Figure 1. Regions of Volta Basin located in Ghana and the stream network.

1. The UER is characterized by shallow and accessible groundwater resources compared to other northern regions;
2. Residents in urban (> 5000 inhabitants) and rural (< 5000 inhabitants) areas largely rely on groundwater for drinking water and sometimes for irrigation purposes [see Carrier, 2008].
3. Groundwater resources in the UER experience localized water quality degradation due to high concentrations of pollutants such as fluoride [Dapaah-Siakwan et al., 2006], manganese, and iron [Carrier et al., 2009].
4. A reasonable amount of data is available from the UER. Among the three northern regions, the UER has the highest percentage of borehole representation with the widest geographic coverage [Mainoo and Dapaah-Siakwan, 2007].

Geography and Geology

The UER is divided into eight districts as shown Figure 2. The region borders the Upper West Region from the west and the Northern Region from the south. Burkina Faso and Togo border the northern and eastern boundaries of the UER, respectively. The total area of UER is 8689 km^2 and the average elevation is 197 m above mean sea level [Liebe, 2002]. Minimum and maximum elevations are 128 and 455 m, respectively.

The northern Ghana region has two distinct geologic characteristics; Precambrian basement rocks and Palaeozoic rocks from the Voltaian sedimentary basin. These rocks are generally covered by a thin (< 30 m) weathered layer that significantly affects the hydrogeologic characteristics of the aquifer system [Carrier, 2008]. The UER consists of granites and Precambrian Rocks of the Birrimiam and Tarkwaian series [Boateng, 1959]. The UER is also a part of the Savanna High Plains [Dickson and Benneh, 1995] which are "gently undulating, with broad, poorly drained valleys and extensive flood plains adjacent to the Volta River [Kranjac-Berisaljevic et al., 1998]."

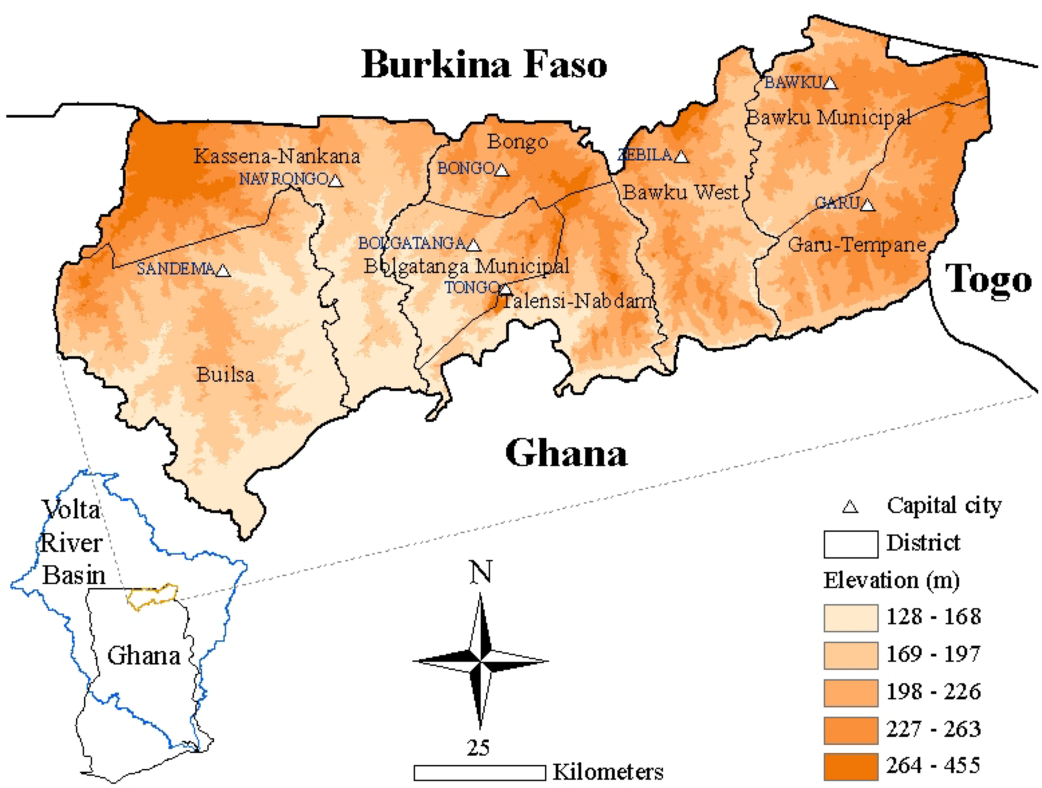

Figure 2. Districts and corresponding capital cities of the UER.

Socioeconomic Attributes

The UER is scarcely populated with close to one million people [Asenso-Okyere et al., 2000] and the population density is 96.5 inhabitants/km^2 [Schmidt-Kallert, 1994]. The population growth was about 1.7% in the period of 1960 to 2000 [Laube et al., 2008]. Ghana Statistical Service [2000] reported that the UER has the largest proportion of poor across the country and the mean annual household income is $1000 which is the second lowest. Agricultural production is the main source of income for most people [Liebe, 2002] and crucial for their food security [Asenso-Okyere et al., 2000]. Therefore, any improvement in agriculture will be accompanied by increased economic development for the region. Education, health, and nutrition in the northern regions are still underdeveloped compared to other regions of Ghana [CIDA, 1999]. The adult literacy rate in Ghana was 65% from 2000 to 2007 compared to 82.4% in South Africa [UNICEF, 2009].

Hydrologic Characteristics

The sub-Saharan West Africa is situated in the savanna zone which is subdivided from north to south into Sahel-, Sudan-, and Guinea-Savanna Zones [Laube et al., 2008]. The UER is located in the area between the southern Sudan Savanna zone and the northern Guinea Savanna zone [Windmeijer and Andriesse, 1993] in which semiarid climatic conditions prevail [Kasei, 1988]. In Navrongo (see Figure 2), the average annual rainfall, potential evapotranspiration, and temperature are 986 mm, 2050 mm, and 28.6°C, respectively [Kranjac-Berisaljevic et al., 1998].

The region has uni-modal rainy season from July to September often characterized by short duration intense rains preceded by heavy storms [Kasei, 1988]. Consequently, rapid runoff is generated into ephemeral and intermittent streams and then captured by artificial dams, primarily used for irrigation. In essence, the retention of runoff into person-made reservoirs contributes significantly to agricultural development, particularly during the prolonged dry season.

The stream network in the Volta River basin including the perennial and intermittent rivers is shown in Figure 1. The four major rivers in the UER are White Volta, Red Volta, Sisili, and Tono River [Liebe, 2002]. The drainage system of the UER is part of the White Volta sub-basin. The sub-basin is named after White Volta because it is the largest river downstream to the other three rivers coming from Burkina Faso. It should be mentioned that the streamflow of White Volta is influenced from the releases of the Bagre Dam in Burkina Faso and thus causing large variation in annual runoff [Ledger, 1964].

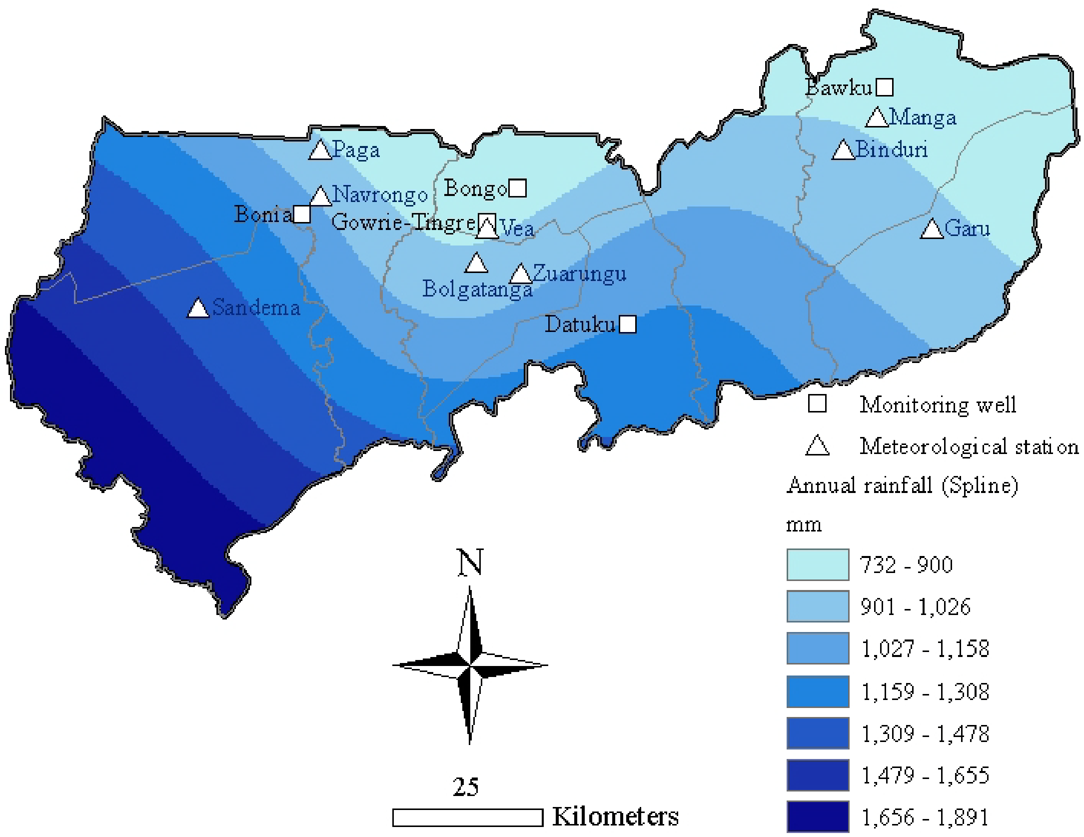

Figure 3. Monitoring wells, meteorological stations, and the annual rainfall pattern in the UER [data from Ayilari-Naa Juati, Director at Ghana Meteorological Agency, personal communication].

DATA AVAILABILITY

Similar to most developing countries, groundwater data are not readily available in Ghana too. Given the data scarcity, detailed hydrologic regional studies are sometime difficult to perform and can be challenging. Most of the hydrologic data in Ghana have been collected through various site-specific and target-oriented projects. Given the limited centralized control in data collection from these projects, most data reside with individuals who have participated in the activities and not with the central government. For this reason, data and information are not readily accessible through a single field visit to the region. However, the Water Resource Commission (WRC) of Ghana is currently establishing a nationwide groundwater database that will be useful in future hydrologic studies. For the purpose of this study, the staff of IWMI provided all available data from IWMI and also coordinated activities to gather data from other state and private sector agencies. It is expected that additional data will be in the coming months.

Meteorological data

Meteorological data from the UER were daily collected by the Ghana Meteorological Agency. The meteorological parameters measured are rainfall, maximum and minimum temperatures, relative humidity at 06:00 and 15:00 hours, sun hours, and wind run. The length of time series depends on the parameter measured and the measurements are not consistent. The meteorological stations are distributed across the UER as shown in Figure 3 and the details of each station are given in Table 1. Rainfall was sporadically measured for all stations except Zuarungu that has the longest time series and Navrongo is the station with the second longest time series. At the Paga station, for instance, measurements are only available for 17 years in the period from 1957 to 1994. Rainfall measurements for Manga and Sandema stations are not available yet.

Table 1. Meteorological stations in the UER [data from Ayilari-Naa Juati, Director, Ghana Meteorological Agency].

Station	Latitude °	Longitude °	Elevation (m)	Average annual rainfall (mm)	Data availability		
					From	To	No. of yrs.
Binduri	10.97	-0.32	202	923.9	1977	2003	19
Bolgatanga	10.80	-0.87	231	929.1	1976	1994	17
Garu	10.85	-0.18	236	929.7	1977	2003	16
Manga	11.02	-0.27	231	-	-	-	-
Navrongo	10.90	-1.10	188	1005.1	1961	2001	41
Paga	10.97	-1.10	224	924.0	1957	1994	17
Sandema	10.73	-1.28	175	-	-	-	-
Vea	10.85	-0.85	201	885.2	1972	2003	23
Zuarungu	10.78	-0.80	215	985.2	1939	2004	65

There are nine meteorological stations in the UER of which five stations measure rainfall, minimum temperature, and maximum temperature. Only three of the nine stations measure rainfall or temperature, while Navrongo was the only station that measured all meteorological parameters mentioned earlier.

Table 2 summarizes the meteorological parameters measured at the Navrongo station. For this station, measurements were significantly interrupted except for rainfall and temperature. For instance, the relative humidity was measured for only seven years from 1987 to 2003 [Ayilari-Naa Juati, Director at Ghana Meteorological Agency, personal communication].

Table 2. Available meteorological data at the Navrongo station [Data from Ayilari-Naa Juati, Director, Ghana Meteorological Agency].

Parameter	Diurnal average	Min.	Max.	Years available
Rainfall (mm) [annual]	1005.1	670.5	1808.2	1961- 2001
Maximum Temperature (°C)	35.0	22.8	44.0	1976 - 2000
Minimum Temperature (°C)	22.8	13.3	31.1	1976 - 2000
Relative Humidity at 06:00 (%)	68.5	3	99	1987 - 2003
Relative Humidity at 15:00 (%)	40.2	4	100	1987 - 2003
Sun Hours (hr)	7.9	0	11.9	1961 - 2000
Wind Run (km/hr)	3.1	0	14.7	1961 - 2000

Since the Navrongo station is the most data intensive station, the seasonal trends of minimum temperature, maximum temperature, and relative humidity at this station are shown in Figure 4. In addition, the seasonal trends of Penman evapotranspiration [Source: Liebe, 2002] and rainfall are also shown in Figure 5. The intra-annual variability of rainfall shows that the wet season prolongs through the summer months. Rainfall is high during these months and the evapotranspiration is low probably due to increased relative humidity. In this humid climate, recharge is most likely high.

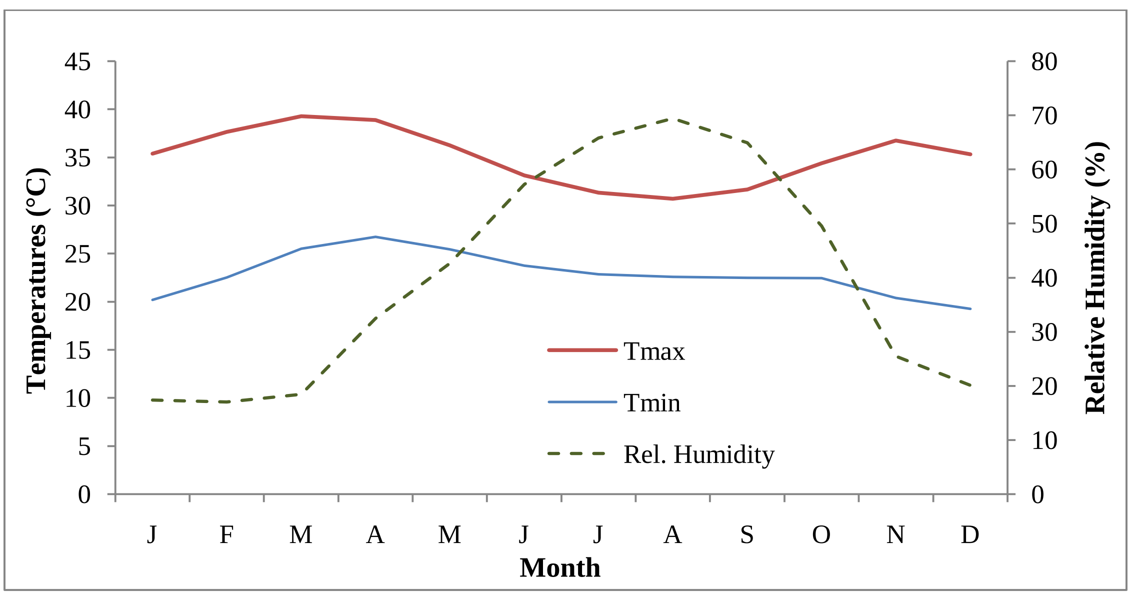

Figure 4. Mean monthly values of minimum temperature, maximum temperature, relative humidity at Navrongo station.

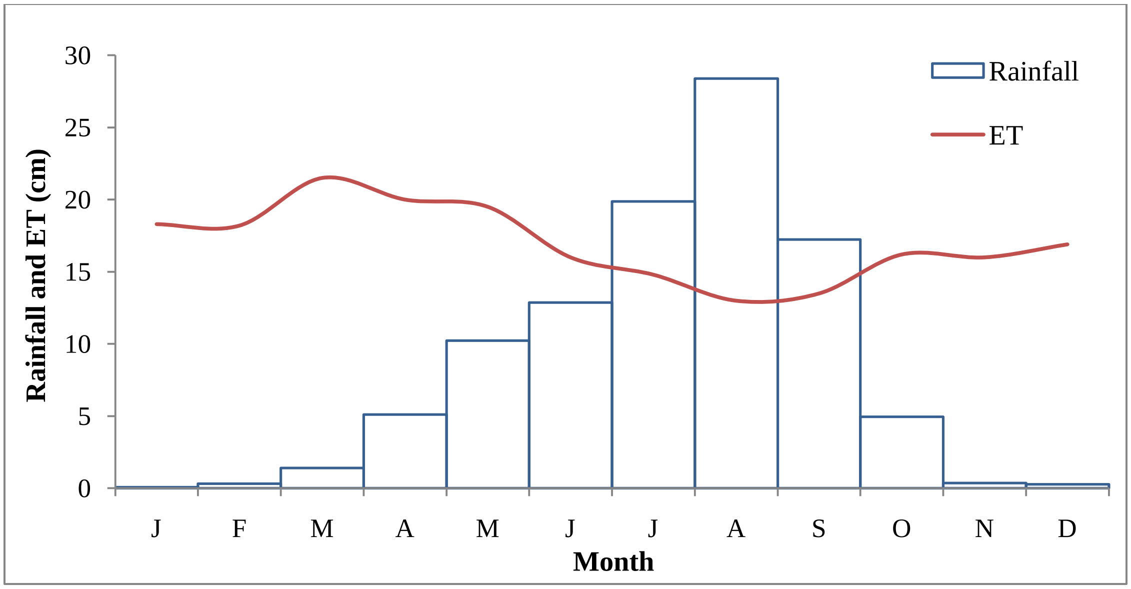

Figure 5 Mean monthly values of Penman evapotranspiration [Source: Liebe, 2002] and rainfall at the Navrongo station.

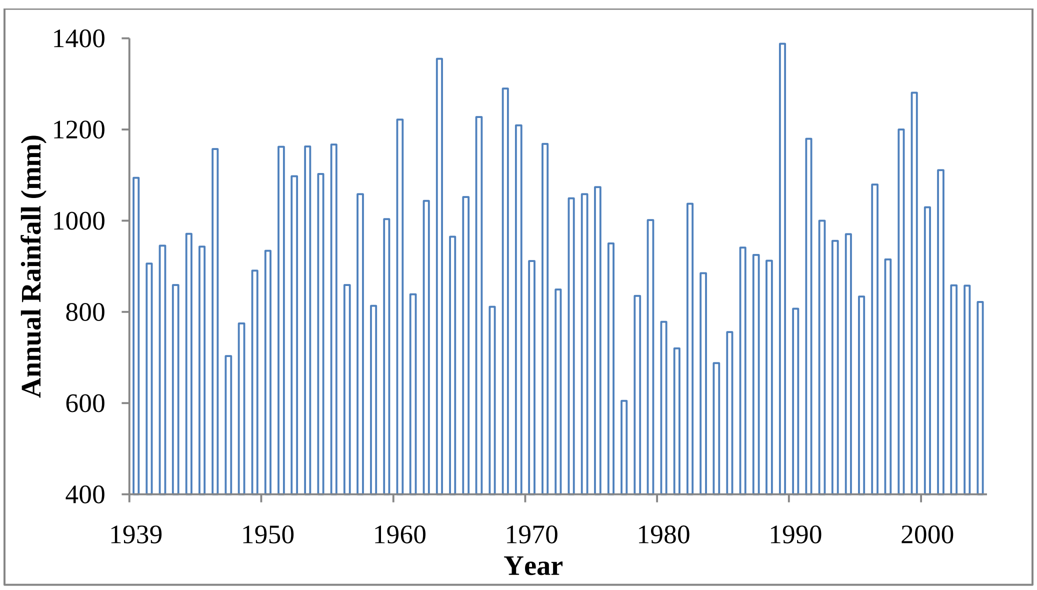

Figure 6. Annual rainfall at the Zuarungu station from 1939 to 2004.

Since the Zuarungu station has the longest continuous rainfall measurements, the annual rainfall data from 1939 to 2004 are shown in Figure 6. The maximum rainfall occurred in 1989 and exceeded 1388 mm while the mean annual rainfall is 985 mm. There is no obvious trend in the annual rainfall data at the Zuarungu station.

Groundwater Data

Groundwater is extracted in northern Ghana using hand dug wells, boreholes, and piped systems (see Figure 7) while actual groundwater extraction is not properly monitored. Martin and van de Giesen [2005] estimated that the groundwater production in the Volta River basin to be around 88 million m^3/yr which is equivalent to less than 5% of the average annual groundwater recharge to the basin. This value suggests that further development of groundwater is possible. Martin and van de Giesen [2005] mentioned that groundwater potential in the region is constrained by availability, accessibility, and economics. The percentage of successful boreholes in the UER is considerably high at 93.8% compared to 60.9% and 90.8% from the northern region and the Upper West region [Carrier, 2008]. The drilling success depends mainly on the yield of the well or the quality of groundwater.

Figure 7. Different methods of groundwater recovery used in the UER; hand dug wells (from left), boreholes, and piped systems.

Groundwater characteristics have been estimated using pump tests from both drawdown and recovery phases of several boreholes in the region. Unfortunately, the aquifer systems in Ghana are not properly identified yet and there is no single geologic map that delineates the aquifer system [Enoch Asari, Groundwater Division, WRC, written communications]. Similarly, the piezometric elevations are not yet properly monitored and established. Nevertheless, some information on properties of aquifers is available and summarized in Table 3 for the two primary geologic formations in the UER. It is noticed that the area is characterized by shallow aquifers with low storativity and moderate specific capacity.

Table 3. Properties of shallow aquifer in the UER.

Property		Precambrian	Voltaian	Reference
Specific capacity (m^3/hr-m)	Range	0.01 – 13.4	0 – 43.2	Carrier (2008)
		0.01 – 21.1		Obuobie (2008)
	Mean	9.3	12.4	Carrier (2008)
Transmissivity (m^2/day)	Range	0.6 - 29.8	0.1 to 40.9	Carrier (2008)
	Mean	7.8	12.1	
Depth to water table (m)	Range	3.0 – 82.5		Obuobie (2008)
	Mean	20.6		
Storativity	Range	0.003 - 0.008		Bannerman and Ayibotele (1984)

In general, groundwater quality in the UER is good but localized groundwater quality problems are present. Some of these concerns include high concentrations of fluoride [Dapaah-Siakwan et al., 2006], manganese, and iron [Carrier et al., 2009]. Carrier [2008] summarized groundwater quality problems in the three northern regions through a broad analysis of different groundwater quality parameters such as fluoride, iron, manganese, pH, nitrate, chloride, and electrical conductivity.

Monitoring of groundwater data started through the Hydrogeological Assessment Project (HAP) in the northern regions of Ghana funded by the Canadian International Development Agency (CIDA) in 2005. A workshop was held in Accra in July of this year to provide an overview of the project and the data collected [see Carrier et al., 2009 and Figure 8]. The HAP project was extended for two more years allowing more wells to be used for better monitoring of the aquifers in northern Ghana and also to develop appropriate groundwater flow models. This project is sponsored by the WRC of Ghana and the Water Research Institute (WRI) is given the responsibility of conducting field work and preparation of datasets.

Figure 8. CIDA workshop held in Accra in July 2009.

As a part of the monitoring effort, water table elevations at the five monitoring wells in the UER were measured every six hours from 2005 to 2008. The monitoring wells are located in Bawku, Bongo, Bonia, Bakutu, and Gowrie-Tingre as shown in Figure 3 and the details of each monitoring well are summarized in Table 4.

Table 4. Details of monitoring wells in the UER [data from William Agyekum, Groundwater Division, WRI].

Well	Latitude °	Longitude °	Elevation (m)	Depth (m)	Yield (L/min)	Data availability	
Bawku	11.06	-0.26	224	3.97	300	Aug-06	Nov-08
Bongo	10.91	-0.81	224	5.72	45	Nov-05	Nov-08
Bonia	10.87	-1.13	179	4.92	175	Nov-05	Nov-08
Datuku	10.71	-0.64	194	2.60	20	Nov-05	Nov-08
Gowrie-Tingre	10.86	-0.85	181	1.50	200	Nov-05	Nov-08

Water table variations for all monitoring wells in the UER are shown in Figure 9. The data are available from November 2005 through November 2008 (except for the Bawku well) and provided by William Agyekum, Groundwater Division of WRI, through personal communication. Continuous measurements are made at Bawku, Bonia, and Gowrie-Tingre monitoring wells, but, the measurements from other two wells were interrupted by instrumental faults and other technical problems.

Water table fluctuations have increasing trends at all monitoring wells. Except the Gowrie-Tingre well, the water levels increased by few meters in all monitoring wells during the last two years. In the meantime, the low coefficients of determination (R^2) do not necessarily indicate a weakness of trends since R^2 determines the linear correlation between two parameters. Due to the seasonal fluctuations in water levels, R^2 would not be statistically significant. Further analysis should be conducted to test these trends and explore the relationship of water levels with both recharge and discharge from the aquifer system.

Monitoring of groundwater started in 2005 and continued until end of 2008. It is anticipated that groundwater levels for 2009 will be available in the coming months. However, daily meteorological data are not available for the recent years as shown earlier. Recent monthly meteorological data are available with CIDA in addition to some daily readings for specific stations. These data will be gathered from the CIDA particularly from Marc-Andre Carrier.

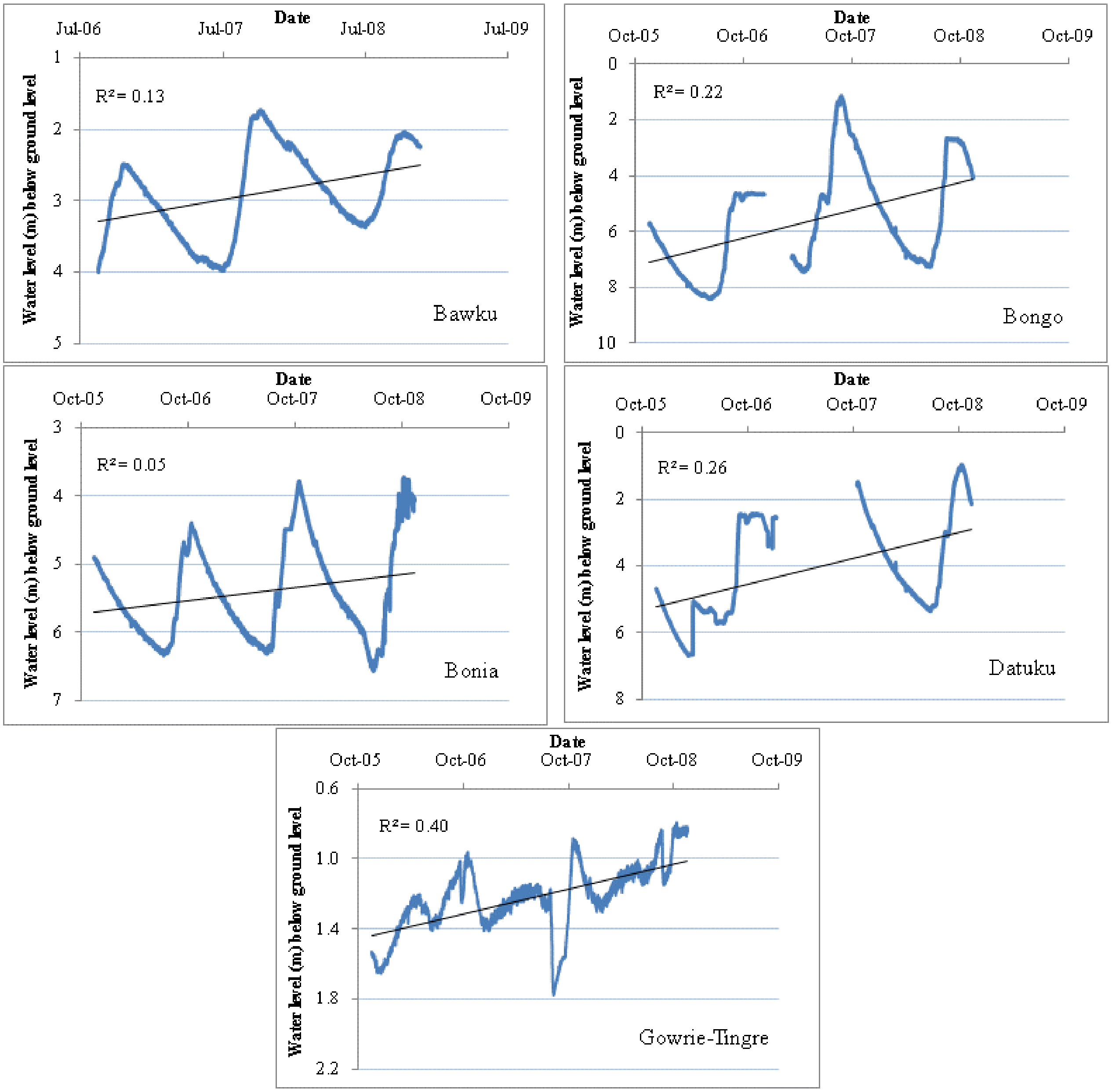

Figure 9. Water table variations at five monitoring wells located in the UER.

Other Relevant Data

In addition to groundwater quantity and quality data, information such as GIS shapefiles of basins, sub-basins, land cover, soil type, and geologic information were also collected during this field trip. Figure 10 shows some of these data related to soil types and land cover collected during the field trip. HAP project has developed a digital library of prior studies conducted and reports related to groundwater resources of northern Ghana that will be useful to the proposed study by USU.

Several recharge estimate studies have been conducted in northern Ghana. These studies used different methods such as chloride mass balance, soil moisture balance, water table fluctuation, and regression analysis to compute recharge as shown in Table 5. We propose to use the results from these studies in the future to compare results and improve the methodology.

Previous studies have estimated groundwater recharge in different areas of northern regions. Most of the studies however have not identified the spatial distribution of recharge adequately. Obuobie [2008] constructed a hydrologic model for the whole White Volta River basin using the Soil and Water Assessment Tool (SWAT) model and found that recharge will increase by 29% in the 2030's as a result of climate change impacts.

Table 5. Recharge estimates from previous studies in north of Ghana.

Region	Annual rainfall (mm)	Estimated Recharge (% of rainfall)	Reference
UER	1232	8	Acheampong (1988)
UER	910 - 1138	4 - 13	Martin (2005); Martin and van de Giesen (2005)
Northern Ghana	1002	5	Friesen et al. (2005)
UER	824 - 1294	7 - 8	Obuobie (2008)
Northern Ghana	990	1.5 - 15.9	Carrier (2008)

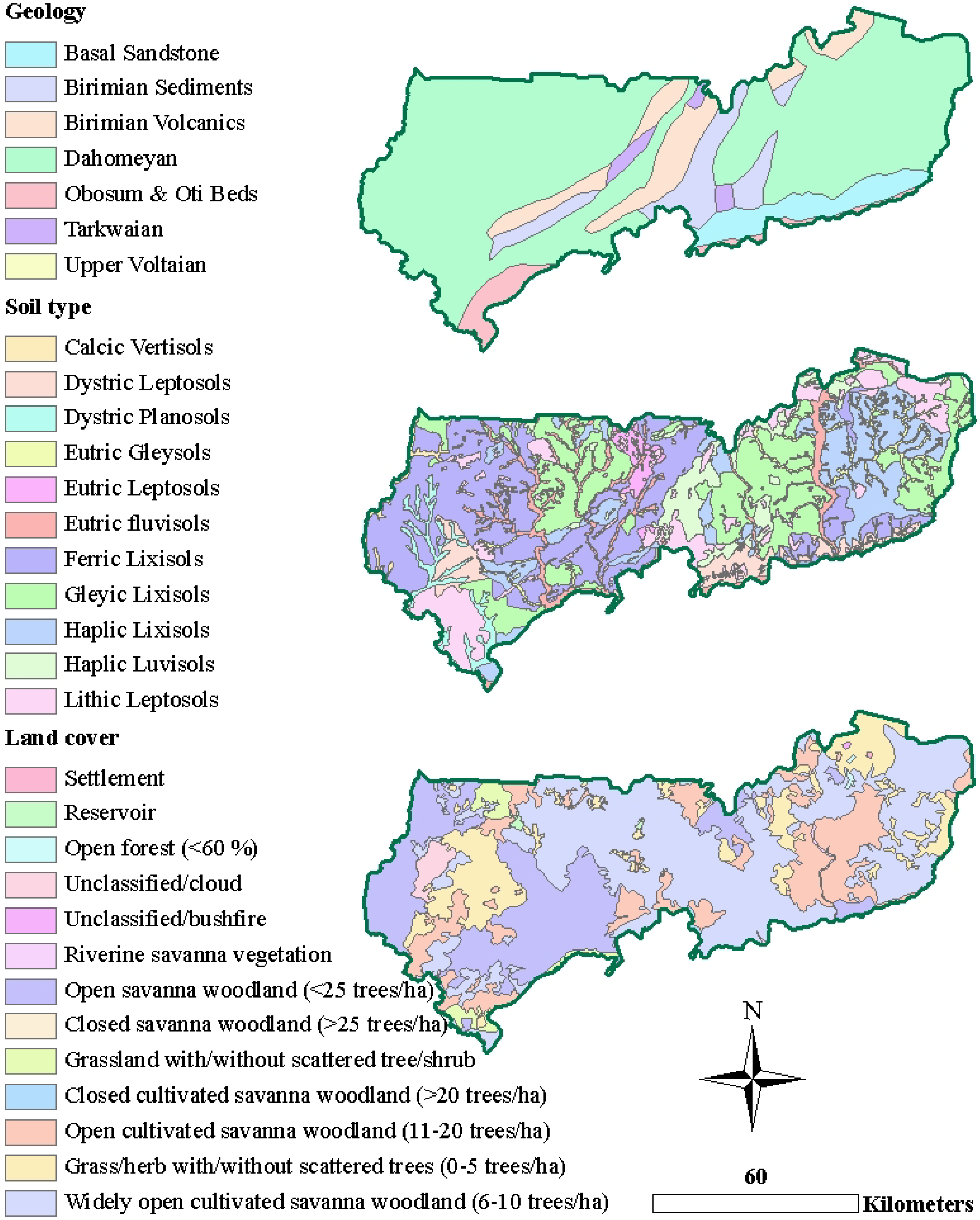

Figure 10. Geology, soil type, and land cover of the UER.

FUTURE RESEARCH NEEDS

This field trip provided the opportunity to discuss various research and monitoring needs related to groundwater resources of the northern regions. These consultations were conducted with personnel from the Government of Ghana, Non-governmental Organizations, and private sector. A list of organizations visited and personnel interviewed as a part of this data gathering effort is listed in Table 6.

Table 6. A list of organizations visited and personnel interviewed during the field trip to Ghana.

Organization	Type	Name	Position
Water Research Commission	Gov	Enoch Asare Aaron B. Aduna Bob Alfa F.Kwadade-Cudjoe	Head of Groundwater Division White Volta Basin Officer Water Resource Engineer Information Technology Specialist
Water Research Institute	Gov	Emmanuel Obuobie Benony K. Kortatsi Patrick A. Mainoo	Research Scientist Principal Research Scientist Research Scientist
Ghana Meteorological Agency	Gov	Ayilari-Naa Juati	Director – Meteorology & Forecasting
Community Water Sanitation Agency	Gov	Wigbert Y. Dogou John G. Aduakye	Regional Director Zonal Hydrogeologist
HYDRO	Gov	Bayor Jude Simons	Regional Hydrologist
University of Ghana	Edu	Bruce Kofi Banoeng-Yakubo	Professor – Hydrogeology
Volta Basin Research	Edu	Benjamin D. Ofori	Research Fellow
University of Development and Science	Edu	Gordana Kraniac-Berisauljovic Thomas Bayorbor	Professor – Water Management Professor – Renewable Resources
University of Cape Coast	Edu	Benjamin Kofi Nyarico	Lecturer – Geography & Regional Planning
IWMI	NGO	Boubacar Barry Gerald Forkuor	Director – West Africa Office GIS and Remote Sensing Specialist
Canadian International Development Agency	NGO	Marc-Andre Carrier	Research Engineer
GLOWA	NGO	Mathias Fosu	Senior Research Scientist
New Energy	NGO	Osman Sahanoon	Research & Development Officre
World Vision Institute	NGO	Sampson Adotey	Head of Operations
UNIHYDRO Group	Prv	Nelson Sekpey Tony Ewusi	Research Engineer Research Engineer

Some of the topics addressed during the consultations were data availability, hydrogeology, groundwater availability and accessibility, groundwater uses, groundwater quality, and vulnerability to contamination. In all these interactions, the importance of estimating recharge to aquifers was highlighted towards identifying the available groundwater resources so that future planning and management could be performed effectively.

As a result of this field trip, the following needs were identified as priorities:

- The spatial distribution of natural recharge to the aquifer system should be studied to determine the available water resources such that groundwater development activities can be better planned.
- Although mapping and monitoring of groundwater resources is essential at present, the interaction of groundwater with population growth, climate change and variability, and urbanization should be carefully studied to understand the broader socioeconomic impacts.
- Efforts should be made to increase the human capacity for future research, and planning and management activities.
- More intensive monitoring and data gathering efforts should be undertaken to understand the groundwater resources in northern Ghana especially geology, aquifer system, and flow patterns.

SUMMARY

The USU field trip conducted in July had three goals; identify a potential study area in northern Ghana for the proposed recharge estimation work, collect available data, and consult stakeholders for their assessment of future needs in data and research. The UER was chosen to be the study area because groundwater in this region is plenty, accessible, and a safe water resource. Information gathered from stakeholders suggests that new research is needed given the expected increasing water demands for domestic, agricultural, and industrial uses.

Similar to any developing country, data availability both quantity and quality is obviously the main constraint for any regional hydrologic study. Groundwater data are limited compared to available meteorological data. More importantly, the aquifer systems are not yet identified not only in the study area but also in the whole country. This data limitation exists for water level data as well. Groundwater monitoring wells were established few years ago through an initiative undertaken by a CIDA project to better understand and manage groundwater resources in northern Ghana. However, these few wells are not adequate for detailed regional studies. In addition, groundwater abstraction data are not available, but this missing information is not critical given the abundance and under utilization of groundwater at the present time. However, the conditions in the future will not be the same given the expected population growth and other demand relevant drivers. Under these constraints, reliable estimate of groundwater recharge becomes imperative and development of the appropriate methodology would be challenging.

This report highlights the major information and data collected during this trip. However, data gathering efforts will continue in the next few months in collaboration with different agencies and personnel. For example, water table elevations for 2009 will be available from WRC or WRI. Meteorological data from 2000 to now is also expected from Ghana Meteorological Agency. It is expected that CIDA has more hydrogeologic data and we will work with CIDA to obtain some of these data. Drs. Boubacar Barry and Emmanuel Obuobie are actively helping to gather information and data relevant to the UER. Therefore, we are optimistic that additional data will be available from these sources in the coming months. While in anticipation of these data, the analytical work will continue at this time.

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REFERENCES

Acheampong, P. K., 1988. Water balance analysis for Ghana. *Geography* 73, 125-131.

Anayah, F., 2006. *An assessment of the nitrate and chloride in the West Bank groundwater resources using GIS.* A MS thesis. An-Najah National University. Nablus. Palestine.

Asenso-Okyere, W. K., Twum-Baah, K. A., Kasanga, A., Anum, and J., Pörtner, C., 2000. *Ghana Living Standards Survey.* Report of the Fourth Round (GLSS 4). Ghana Statistical Service. Accra, Ghana.

Bannerman, R. R. and Ayibotele, N. B., 1984. *Some critical issues with monitoring crystalline rock aquifers for groundwater management in rural areas.* IAHS Publication no. 144, 47-57.

Boateng, E. A., 1959. *A Geography of Ghana.* Cambridge University Press. Cambridge, UK.

Carrier, M.-A., 2008. *Hydrogeological synthesis of Northern Ghana.* A MS thesis. Avant-Garde University, Canada.

Carrier, M.-A., Aubut, R., Lefebvre, R., Racicot, J., Asare, E. B., Fontaine, R., and Rivera, A. 2009. *Interim Hydrogeological Atlas.* Hydrogeological Assessment Project of the Northern Regions of Ghana. Accra, Ghana.

Canadian International Development Agency (CIDA), 1999. Ghana - Building together for a better future. CIDA Africa and Middle East Branch, Ghana programming framework 1999/00 – 2004/05.

Dapaah-Siakwan, S., Agyekum, W., and Darko, P., 2006. *Borehole Drilling and Installation of Divers for Groundwater Monitoring in the White Volta River Basin.* Council for Scientific and Industrial Research (CSIR) Water Research Institute. Accra, Ghana.

Dickson, K. D. and Benneh, G., 1995. *A new Geography of Ghana.* 3rd Revised Edition. Longman. London.

Friesen, J., Andreini, M., Andah, W., Amisigo, B., and Van De Giesen, N., 2005. *Storage capacity and long-term water balance of the Volta Basin, West Africa.* IAHS Publication no. 296, 138-145.

Ghana Statistical Service, 2000. *Poverty trends in Ghana in the 1990's.* Ghana Statistical Service. Accra.

Herrera-Pantoja, M. and Hiscock, K. M., 2008. The effects of climate change on potential groundwater recharge in Great Britain. *Hydrological Processes* 22, 73–86.

IWMI, 2008. *Groundwater in sub-Saharan Africa: Implications for food security and livelihoods.* Draft report. International Water Management Institute. Colombo, Sri Lanka.

Jyrkama, M. I. and Sykes, J. F., 2007. The impact of climate change on spatially varying groundwater recharge in the Grand River watershed, Ontario. *Journal of Hydrology* 338, 237–250.

Kasei, C. N., 1988. The Physical Environment of Semiarid Ghana. In: Unger, P.W., Sneed, T.V., Jordan, W.R., Jensen, R., (eds.) 1988. *Challenges in Dryland Agriculture – A Global Perspective.* Texas Agricultural Experiment Station, pp. 350-354. TAES. Texas.

Kranjac-Berisaljevic, G., Bayorbor, T. B. ,Abdulai, and A. S., Obeng, F. (ed.) 1998. *Rethinking Natural Resource Degradation In Semi-Arid Sub-Saharan Africa: The Case of Semi-Arid Ghana.* Revised January 1999. Available at: http://www.odi.org.uk/rpeg/soil_degradation/ghlit.pdf

Laube, W., Awo, M. and Schraven, B., 2008. *Erratic Rains and Erratic Markets: Environmental change, economic globalisation and the expansion of shallow groundwater irrigation in West Africa.* ZEF Working Paper Series 30. Center for Development Research, University of Bonn.

Ledger, D. C., 1964. *Some Hydrological Characteristics of West African Rivers.* In: Transactions and Papers. Institute of British Geographers. Publication No. 35, pp. 73.90.

Liebe, J., 2002. *Estimation of Water Storage Capacity and Evaporation Losses of Small Reservoirs in the Upper East Region of Ghana.* Diploma thesis, Faculty of Mathematics and Natural Sciences, University of Bonn.

Mainoo, P. A. and Dapaah-Siakwan, S., 2007. *Groundwater Data Inputs To Grid Cells Covering The Three Northern Regions of Ghana (Upper East, Upper West and Northern Regions of Ghana).* Hydrogeological Assessment Project (HAP) of the Northern Regions of Ghana Project CIDA Project 7038883. CSIR Water Research Institute. Ghana.

Martin, N., 2005. *Development of a water balance for the Atankwidi catchment, West Africa – A case study of groundwater recharge in a semi-arid climate.* Doctoral thesis, University of Göttingen.

Martin, N. and van de Giesen, N., 2005. Spatial Distribution of Groundwater Production and Development Potential in the Volta River basin of Ghana and Burkina Faso. *Water International* 30(2), 239–249.

Mygatt, E., 2006. *World's Water Resources Face Mounting Pressure.* Earth Policy Institute. Washington, DC. Available at: http://www.earth-policy.org/index.php?/indicators/C57/

Obuobie, E., 2008. *Estimation of groundwater recharge in the context of future climate change in the White Volta River Basin.* Doctoral thesis. West Africa.

Osei-Asare, Y., 2004. *Household Water Security and Water Demand in the Volta Basin of Ghana.* Doctoral thesis, University of Bonn.

Rosen, S. and Vincent, J. R., 1999. *Household water resources and rural productivity in Sub-Saharan Africa: a review of the evidence.* Development discussion paper No. 673, Harvard Institute for International Development, Harvard University.

Schmidt-Kallert, E., 1994. *Ghana. Geographische Strukturen, Entwicklungen, Probleme.* Perthes Länderprofile. Justus Perthes Verlag. Gotha.

UNICEF, 2009. At a glance: Ghana - Statistics. Available at: http://www.unicef.org/infobycountry/ghana_statistics.html

WHO/UNICEF, 2000. *Global Water Supply and Sanitation Assessment 2000 Report*, New York, Geneva: Joint Monitoring Programme for Water Supply and Sanitation (JMP).

Windmeijer, P. N. and Andriesse, W., (ed.) 1993. *Inland Valleys in West Africa: An Agro-Ecological Characterization of Rice-Growing Environments.* ILRI Publication 52. International Institute for Land Reclamation and Improvement. Wageningen, Netherlands.