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An Estimate of Groundwater Recharge in the Nabogo River Basin, Ghana Using Water Table Fluctuation Method and Chloride Mass Balance

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AN ESTIMATE OF GROUNDWATER RECHARGE IN THE NABOGO RIVER BASIN, GHANA USING WATER TABLE FLUCTUATION METHOD AND CHLORIDE MASS BALANCE

By

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Abstract

The Cambrian-Precambrian fractured sandstone aquifer in the Nabogo River Basin in the Sahelian Northern Region in Ghana is one of the most important sources for fresh water supply for the local rural communities there. Recent population growth and commercial agricultural interests in this region could have an impact on this critical water resource. Groundwater recharge estimates are determined in this study using the Water Table Fluctuation Method and Chloride Mass Balance and can be applied to future sustainability studies of the region's water resources. Recharge estimates of the Water Table Fluctuation Method are in a range of 10-143 mm/yr or 1-13% of annual rainfall. Chloride Mass Balance groundwater recharge estimates show an annual recharge of 37.06 mm/yr. or 4% of annual precipitation. Recharge source is determined to be from local meteoric waters using stable isotopic analysis of Oxygen ($\delta^{18}O$) and Deuterium (δD). The limitations, advantages and disadvantages of these methods are discussed in this study as well as the possibilities for future research.

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1.1 Chapter One - Introduction

Groundwater recharge estimates are an important tool for managing water resources, but are not frequently adopted in developing nations due to lack of financing and interest in areas with limited commercial resources. The Nabogo River Basin in Northern Ghana illustrates this condition as it does not have a large economic base, or offer commercially viable mining opportunities like many other regions in Ghana. However, there is a recent population boom in the nearby capital of the Northern Region, Tamale, and subsequent interest in commercial agriculture in the surrounding areas. This interest in commercial agriculture has the potential to impact local groundwater resources that are crucial to sustaining life for local communities. Groundwater recharge estimates can be used to help determine the sustainability of agricultural expansion initiatives and are especially important in regions that are expected to support a rapidly increasing population.

The recharge estimates completed for this study are within the Nabogo River Basin. The Nabogo River Basin is part of the White Volta sub-basin of the Volta River basin that drains over 400,000 km^2 of the West African countries of Ghana (42%), Burkina Faso (43%), Mali, Benin, Côte d'Ivoire and Togo (Van de Giesen et al. 2001)(Fig. 1). The Nabogo River Basin is situated in Northern Ghana between latitudes 9.92 °N to 9.95 °N and longitudes 0.25 °W to 0.82 °W, and the Nabogo River (Fig.2) drains approximately 3,600 km^2 (Lutz et al. 2007). The reliance on groundwater supplies for rural Ghanaian communities is based largely on two main factors; that groundwater is a feasible potable water source via hand dug wells or boreholes, and it is also the most economically viable (Gyau-Boakye 1999).

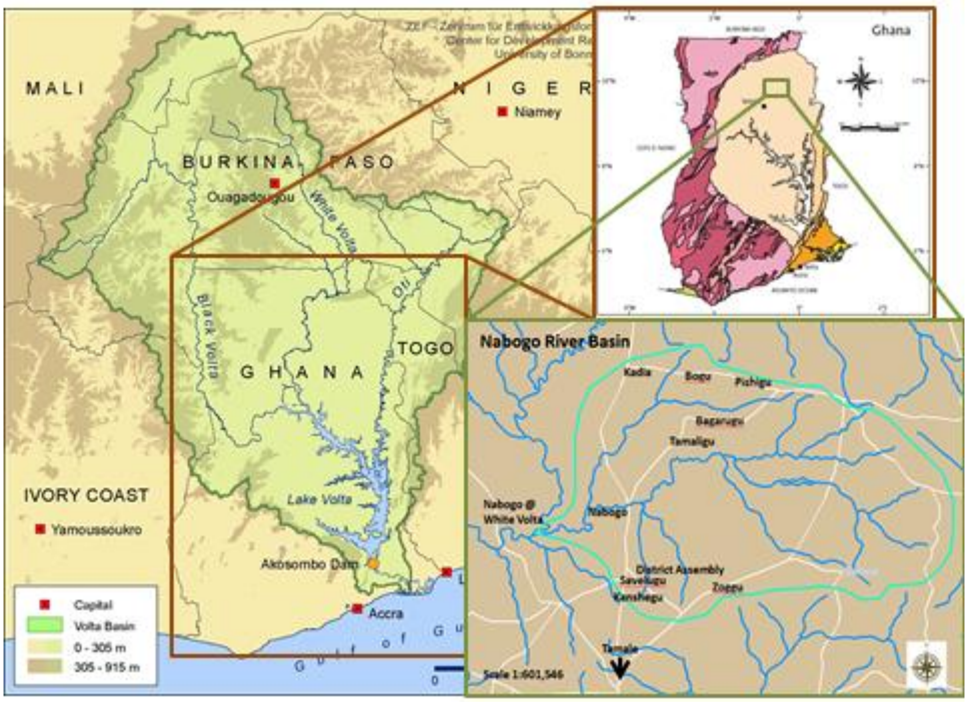

Figure 1. The Volta River Basin drainage in West Africa, expanded drainage in Ghana, and expanded Nabogo River Basin. (Schlüter 2008; www.glowa-volta.de). The inset geological map is expanded in Fig. 5.

Figure 2. Map of Voltaian River System within Ghana

Rural communities account for about 68% of the population of Ghana (Gyau-Boakye 2001) making the reliance on groundwater one of the most important issues for the country. It has been estimated that the cost of potable surface water for communities with less than 5,000 inhabitants can cost approximately twice that of water obtained from aquifers (Bannerman 1975). This fact places a high demand on hand pump wells.

There are several factors affecting the condition of the groundwater system in the Nabogo Basin. Within the last 30 years wells with mechanized pumps have been introduced, increasing demand on the groundwater supply due to the additional use of these unconfined aquifers as a source of water for domestic use and irrigation. In Northern Ghana the dry season can be especially harsh and the importance of a sustainable groundwater supply is crucial to daily life. In response to these issues, the Ghana Water Resource Commission has completed an unpublished Hydrological Assessment Project (HAP) study for the Northern Region of Ghana that includes large scale regional recharge estimates (Carrier et al. 2011), and reports that the region surrounding the Nabogo River Basin has the lowest borehole production in the Northern Region.

Little is known or published regarding the physical hydrological parameters of the Nabogo River Basin. A lack of commercial mining and other commercial industries in this region has contributed to the limited economic incentives for groundwater research in the area. Thus, quantifiable parameters that are needed to conduct a water mass balance, that could contribute to further sustainability studies in this region, are limited.

Sustainability of water resources in this area is crucial to sustaining the lives of the communities in this region. The purpose of this study is to develop an improved groundwater recharge estimate for the Nabogo River Basin that can be used and adapted for better water management in the future. Contributing to this effort, the objective of this study is to determine better defined, basin specific groundwater recharge estimates determined using the Water Table Fluctuation Method (WTFM) (Healey and Cook 2002; Abdalla 2009; Bazuhair and Wood 1996), and tracer methods such as the Chloride Mass Balance (CMB) method (Ting et al. 1998). In this study, these two methods are used independently to provide groundwater recharge estimates

(Healey and Cook 2002). Environmental tracers, such as chloride, have been widely used successfully in dry regions (Allison et al. 1994). The WTFM can determine recharge by examining the troughs and peaks of water levels in monitoring wells (Leduc et al. 1997; Sibanda et al. 2009), more specifically from four monitoring wells in the Nabogo River Basin made available by World Vision Internationals Ghana Rural Water Project (GRWP) and The Desert Research Institute (DRI) in Reno, NV. A comparison of these two methods is used to provide a recharge estimate which can be applied in future sustainability calculations. As an ancillary tool, stable isotopes of Oxygen ($\delta^{18}O$) and Deuterium (δD) are used to determine whether groundwater is generally meteoric in origin or fossil water.

The recharge estimates generated using these methods will contribute to larger, future studies of the groundwater system in Northern Ghana. A comparison of these two methods is used to provide a recharge estimate that may be used in future water balance studies and, it is anticipated, ultimately help determine sustainability of water resources in the area.

1.2 Climate

The climate in Northern Ghana is determined by similar factors that drive climate in the Sahelian region. Average annual precipitation for Tamale based on a 29 year historical data set from the Regional Meteorological Survey of Ghana is 1083 mm/yr. Potential Evaporation (PET) based on the Penman-Monteith and Thorthwaithe methods for Tamale are 1,839 mm/yr (+/- 127) and 2161 mm/yr (+/- 253) respectively (Carrier et al. 2011) and can be defined under the Köppen Classification as arid to semiarid as PET exceeds annual precipitation. The climate in Northern Ghana is characterized by low latitude and semiarid conditions and is driven by three air masses: the Southwest Monsoon, the Northeast Trade Winds and the Equatorial Easterly (Hess 2011). As the moist Southwest Monsoon encounters the dry Tropical Continental Air Mass, together they form the Inter Tropical Convergence Zone (ITCZ) (Gyau-Boakye 2001). The ITCZ is the driving force of the wet and dry seasons in Ghana. The rainy season in Northern Ghana falls from April through October, with approximately half of the annual precipitation recorded during four months (typically late June to late September) of that period (Fig.3). During the dry season that falls between November and March, very little or no rainfall is recorded (Gyau-Boakye 2001). The Harmattan winds (Thiessen 1991) that travel northeast to southwest from November through March produce an enrichment of $\delta^{18}O$ and are shown in Fig. 4 (Pelig-Ba 2009.)

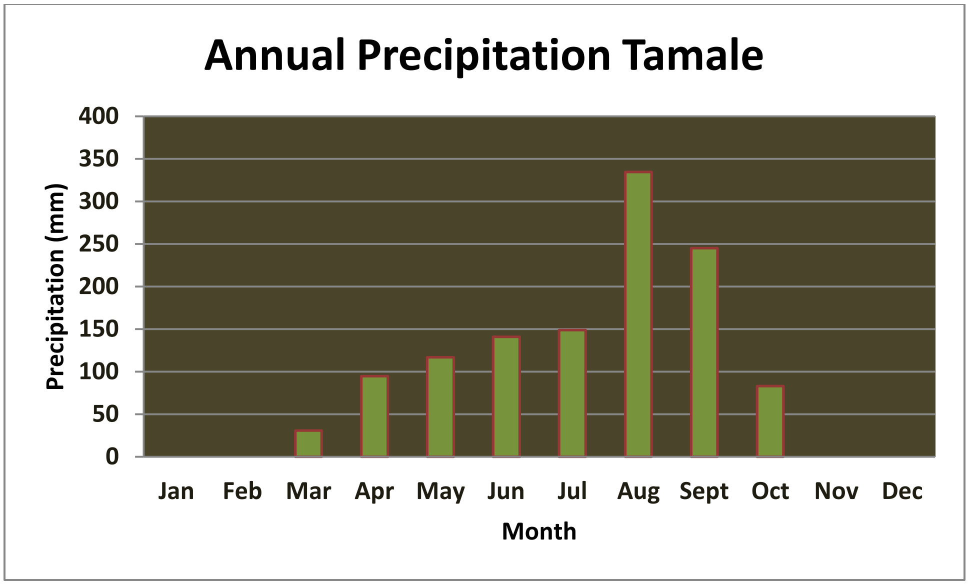

Figure 3. Monthly precipitation (mm) hydrograph for Tamale, Northern Region, Ghana. (The Ghana Regional Meteorological Survey 2011).

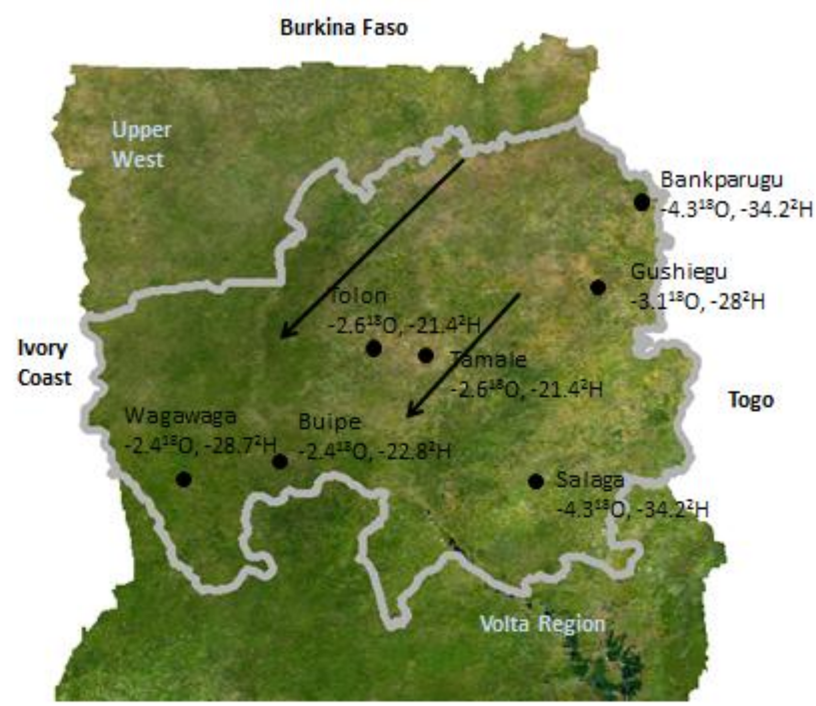

Figure 4. Stable Isotopic Oxygen ($\delta^{18}O$) and Deuterium (δD) values in Northern Ghana showing isotopic enrichment (18O) trend (after Pelig-Ba 2009).

1.3 Physical Geography and Land Use

The physical geography of the Nabogo River Basin is fairly homogenous and can be described by a few factors. The basin is categorized by the Ghana Water Resource Commission (Carrier et al. 2011) as Guinea Savannah, typified by the grasses and trees that are characteristic of this classification. However, there have been some introduced agricultural vegetative influences such as rice, cotton, maize, bean, mango and shea production. Much of the land use is pastoral grazing land used by the nomadic *Fulani* (shepherds) that are common to the North of Ghana and West Africa.

1.4 Geology

Surface geology in the Nabogo Basin is represented by two subgroups (the Oti Pendjari and the Obosum, deposited between 635 million years ago (Ma) and 542 Ma) of the Precambrian and Cambrian Voltaian Supergroup (Fig.5, Fig.6). The Voltaian Supergroup is made up of three subgroups, Kwahu-Morago, Oti-Pendjari, and Obosum, (oldest to youngest) separated by unconformities. The onset of deposition of the Voltaian Supergroup follows the unconformity between the underlying Eburnean Plutonic Suite (marked at 1000 Ma) and the Kwahu-‘Morago” Group member of the Voltaian Supergroup. The sediments deposited at this time were within the passive margin that occurred as the result of regional subsidence within the Rodinia Supercontinent (Duodu 2009). Although none of the formations found in the Kwahu-‘Morago’ Group are found as surface geology within the Nabogo Basin, these formations can be found as underlying permeable layers of the aquifer system. The Kwahu-Murago

Group has a probable thickness range of 6-47.9 meters and an average thickness of 20.3 meters (Carrier et al. 2011). The upper end of this group was uplifted and subjected to a period of erosion lasting approximately 300 million years.

Regional subsidence resumed in the area at approximately 635 Ma marking the bottom end of the Oti-Pendjari Group. This group has a thickness range of 3-45 meters and an average thickness of 17 meters (Carrier et al. 2011). This depositional period coincided with the Marinoan global glaciation event (Duodu 2009) approximately 635-620 Ma. Localized alkaline volcanism took place during this period as a result of the intracontinental rift zone marking the Panafrican deformed margin in the Voltaian Supergroup (Duodu 2009). Although these volcanic deposits are not represented in the surface geology of the basin, they can be expected to be found in the underlying layers, as well as on the surface as detritus from surrounding areas to the north. The northern portion of the basin is largely represented by one formation of the Oti-Pendjari Group, (Bimbila Formation) formed between 540Ma and 620Ma and is described by the Geologic Map of Ghana as “Mudstone and siltstone, weakly micaceous with thin beds of arkosic, lithic sandstone”. Rift-related volcanism was terminated by the Panafrican orogenic belt which uplifted and deformed parts of the foreland basin creating basins where marine deposition occurred. This marked the end of the deposition of this group and marked the unconformity between the Oti-Pendjari Group and the Obosum Group. This final, overlying group (Obosum) can be characterized by non-marine clastic sedimentation following the unconformity. The basins in this group were fed by “westerly-flowing, high energy depositional systems, such as alluvial fans and braided rivers emanating from a mountain front of considerable relief" (Duodu 2009). The surface geology of the southern portion of the Nabogo Basin is largely represented by the "undifferentiated Obosum Group" characterized by the Geological Map of Ghana as: mudstone, siltstone, sandstone. The thickness range of the Obosum group is from 2.9 – 51.9 meters with an average thickness of 17.5 meters (Carrier et al. 2011).

According to the Geologic Map of Ghana, a later Phanerozoic phase of deformation associated with the breakup of Gondwana and the opening of the Atlantic Ocean resulted in the faults and fractures that are characteristic of the aquifer system found in the Nabogo Basin. Additional weathering of the Voltaian Supergroup created regolith that makes up aquifer material in the Nabogo Basin. The Voltaian Regolith has been recorded by the Ghana Water Resource Commission of Ghana (Carrier et al. 2011) as having a probable thickness range of 3-29 meters.

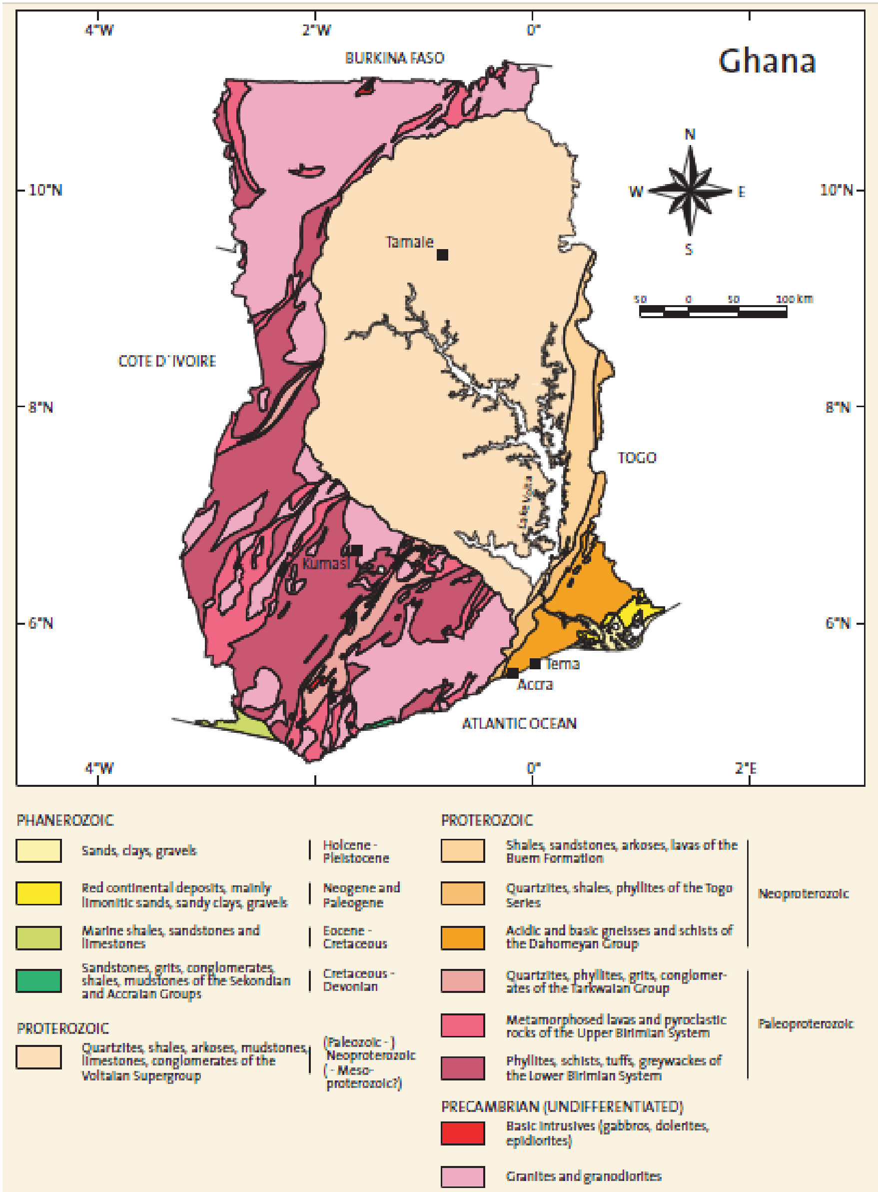

Figure 5. Geologic Map of Ghana (Schlüter 2008).

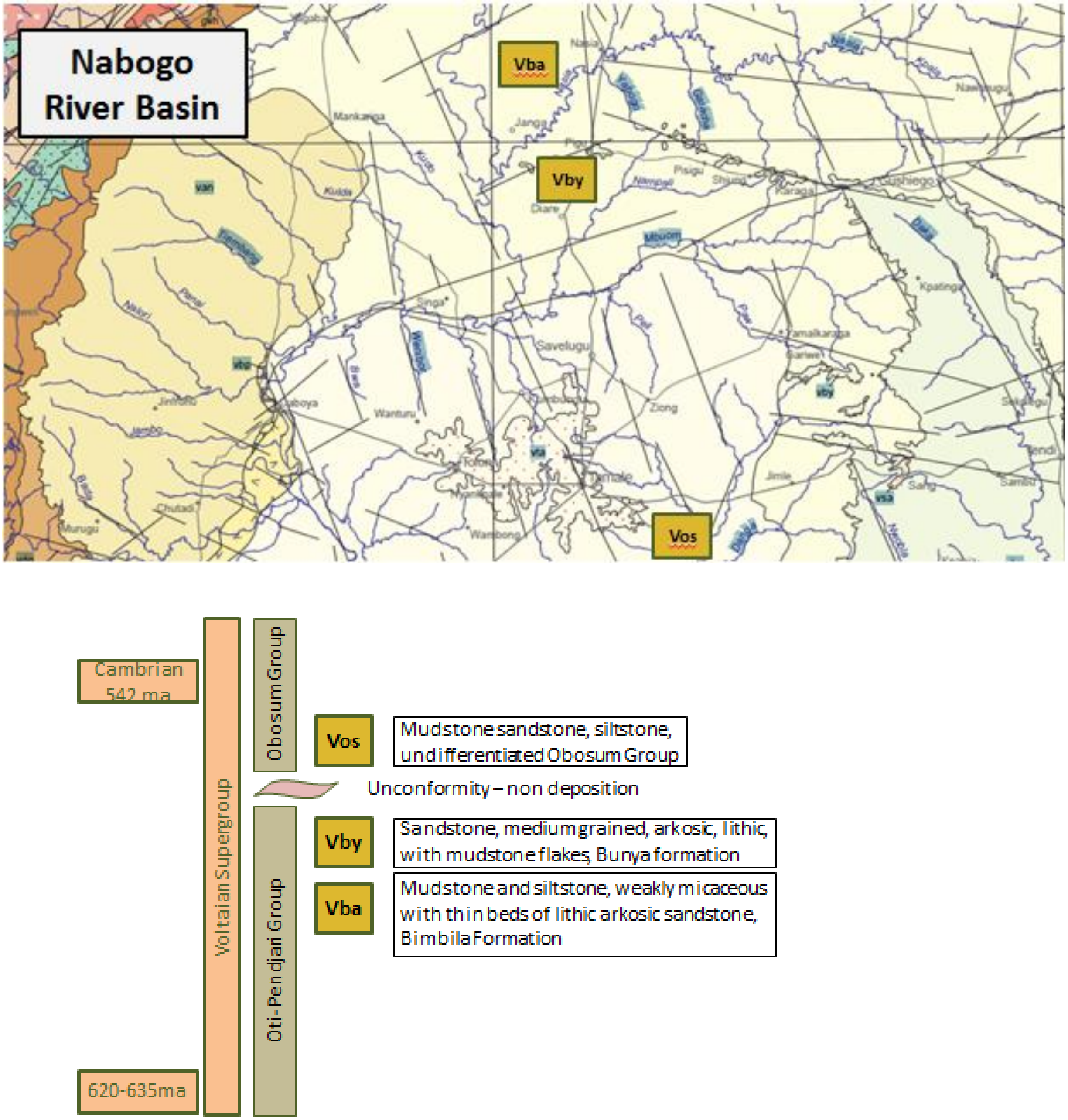

Figure 6. Lithology of Nabogo Basin, formations shown represent surface geology found in the Nabogo River Basin (after Duodu 2009).

1.5 Hydrogeology

Although the aquifers in the Nabogo River Basin have some uniform characteristics of the parent geologic material, the fractured nature of the formation can make determining parameters challenging. The characteristics and nature of the aquifer are described in this section and the majority of information is taken from the HAP report authored by the Water Resource Commission (2011) and Carrier et al. (2011). The regolith thickness of the Voltaian Sedimentary Basin falls between a range of 3 to 49 meters in thickness. Static water levels vary from 2.9- 32.48 in the region (Carrier et al. 2005). The aquifer falls within the Obosum Group and the Oti-Pendjari Group of the Voltaian Sedimentary Basin and is defined by depth as follows:

- < 5m to surface – Normally unsaturated, may contain a possible perched aquifer in some areas
- 2-15m - Normally unsaturated zone that can act as a leaky semi-confining layer depending on parent rock and groundwater level.
- 10-80m - Leaky low grade metamorphic sandstone fractured aquifer (highly variable productive zone depending on lithology, weathering, depth and structure).

The lower portion of this range is made up of the Oti-Pendjari and Obosum groups that have been weathered and fractured that make up the aquifer (variably productive, mostly associated with sub-vertical fractures).

Although the aquifer in the Nabogo River Basin is unconfined, the presence of clay rich plinthosols, that form near river banks as the rise and fall of water level changes from the rainy to dry seasons, act as a semi-confining layer, retarding infiltration in the areas where present.

The Ghana Water Resource Commission (Carrier et al. 2011) has documented 7874 boreholes located in the Northern Region of Ghana. Out of this total, 1908 were technically unproductive, (dry, low flow, or briny), and 5966 were successful. Although this represents a success rate of almost 78%, the success rate seems to be higher in the Upper West and the Upper East regions of Northern Ghana. Borehole success rate in the Savelugu/Nanton and Karaga Districts that lie in the Nabogo River Basin is closer to about 30% based on data from the HAP report.

Based on borehole geologic information from the HAP database (Carrier et al. 2011), the aquifer ranges in thickness and in depth. The static water level lies in the upper weathered layers of the Obosum Group in the elevation range between approximately 115 meters above sea level (m.a.s.l.) and 170 m.a.s.l. The regolith thickness of the Voltaian Sedimentary Basin ranges between 3 and 49 meters in thickness (Carrier et al. 2011).

As mentioned in the previous section borehole success rate in the Nabogo Basin falls between <20% - 40% (Carrier et al. 2011). This poor efficiency of borehole production in the basin is the result of the complicated lithology (fractures and low grade metamorphism retarding lateral flow, hard pan soil retarding infiltration, and the presence of briny wells that have been categorized in the technically unproductive category).

Recharge to the aquifer system occurs from the infiltration of precipitation through fractures in bedrock and from weathered sandstones and soils (Gyau-Boake 2001; Thiessen et al. 1991).

2.1 Chapter Two - Methodology

2.2 Field Methods

The findings of this research were a result of field sampling of groundwater, surface water and precipitation for chloride concentration and stable isotopes of oxygen $\delta^{18}O$ and hydrogen δD, collected data from previous research in this region, and from the use of historical data collected from DRI for stable isotopes and water level, from the Ghana Water resource Commission and Ghana Regional Meteorological Survey for precipitation and streamflow discharge. Surface water, ground water and precipitation samples were collected in, and around the Nabogo Basin from November 2011 to June 2012 at locations shown in Fig. 7. All samples were collected and analyzed according to standard methods as much as possible and more details are available in Appendix A. Surface water samples were collected from the bankside of the river, while borehole water samples were collected after pumping three volumes of the borehole. Precipitation was sampled from triple rinsed (with water from precipitation) buckets taken from direct precipitation (not from an overhang). Samples not analyzed in the field (titration for chloride) were placed in a cooler and frozen until laboratory analysis for chloride was done at the Desert Research Institute (DRI) in Reno, Nevada, using an Ion Chromatograph and EPA Method 300 with an accuracy within 1%. Field titration of chloride was also done at sampling locations using a Hach hand held Titrator. Details of DRI laboratory procedure and calibration of the Hach Titrator can be found in more detail in Appendix B. Although titration values were collected, they were not used in the CMB calculations, as the results from laboratory analysis were considered more accurate and consistent. Tables of lab results for chloride concentration and from field titration are detailed in Appendix C.

Field data for the WTFM was collected by four Schlumberger Mini Diver pressure transducer data loggers at monitoring wells located at different points in the basin. Accuracy of the loggers is ±0.5 cm pressure head. The monitoring wells also served as boreholes that were in regular use by their surrounding community. The loggers were deployed in March 2009 and collected groundwater levels hourly until May, 2012. One pressure transducer data logger was stationed at the GRWP base to monitor the air pressure for barometric compensation. Additional data were collected from the Ghana Water Resource Commission, the Ghana Meteorological Survey, and GRWP.

As the monitoring wells were being pumped for regular household use, anthropogenic effects on the water levels in those monitoring wells was considered. Diurnal fluctuation of water level for each monitoring well was plotted for the dry season and the rainy season at each monitoring well to determine if recovery of water level was rapid or slow. The plots are discussed in the results section and in Appendix D. These plots show rapid recovery and the highest recovered water levels shown at the 4:00 a.m. time step. This time step (4:00 a.m.) was chosen to be the most representative of the natural groundwater level and was used to generate the seasonal hydrograph for each monitoring well. Monthly averages were computed from the 4:00 a.m. values to represent seasonal water level fluctuation at each borehole. The anthropogenic effects were considered to be minimal as recovery is rapid after pumping (4-6 hours on average) and is constant throughout the year. The anthropogenic effects were also considered to be minimal as the daily fluctuations are, on average,2% of the seasonal water lever fluctuation

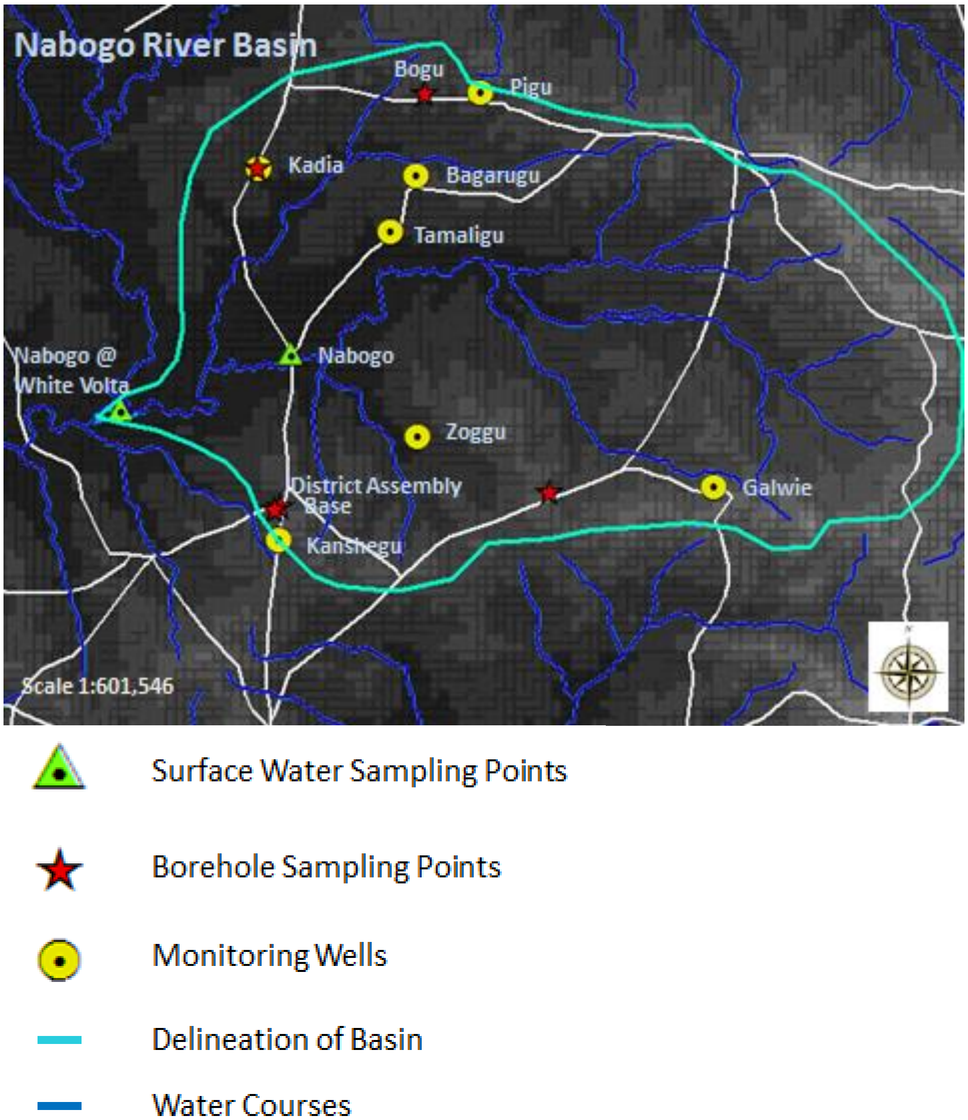

Figure 7. Distribution map of sampling and data collection points in the Nabogo River Basin.

2.3 Water Table Fluctuation Method

The Water Table Fluctuation Method is applied as a tool for estimating groundwater recharge in this study. This method can be used on a small scale, over periods of a single rainfall event, and large scale, over seasonal periods (Risser et al. 2009; Sibanda et al. 2009; Healey and Cook 2002; Sophocleous 1991). This method assumes that the aquifer is unconfined, and that recharge is occurring locally from precipitation, which is already known (Lutz, personal communication 2011; Pelig-Ba, 2009; Acheampong and Hess 2000) and further confirmed by stable isotopic analysis conducted in this research, and that water that reaches the aquifer (water level monitored within the borehole) goes immediately into storage (Healey and Cook 2002). Assumptions are also made about the parameter specific yield and are discussed further in this section.

In the WTFM, recharge of groundwater from precipitation can be estimated in unconfined aquifers by modeling the fluctuation in water levels over a defined period of time and is defined in Equation 1 as (Healey and Cook 2002):

Equation 1:

$$Q = S_y \frac{\Delta \mathrm{h}}{\Delta t}$$

Where:

(Q)= Recharge from precipitation (mm/yr)

(S_y) = Specific Yield

(Δh) = Annual rise in Water Table (mm)

(Δt) = Period of time of Annual Rise (yr)

Specific yield is a storage term, independent of time that accounts for the volume of water that will be released from a saturated aquifer per unit of falling water table (Sophocleous 1991; Healey and Cook 2002), it is a unitless parameter that accounts for the physical hydrologic properties of the aquifer. Generally, in fractured rock aquifers, specific yield values can change as the degree and connectivity to fractures decreases with depth (Cunningham and Daniel 2001), this trend is shown in Figure 8.

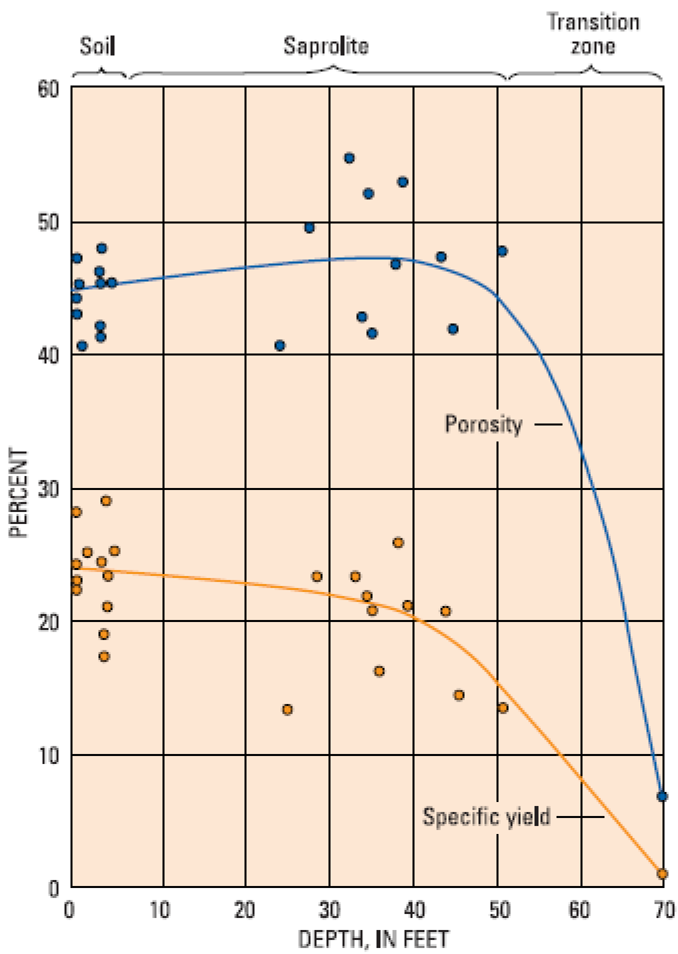

Figure 8. Porosoty and specific yield trend lines in a fracured rock aquifer, demonstarting a change in specific yield at different depths as the connectivity and degree of fractures decreases (Cunningham and Daniel 2001).

As mentioned above specific yield (S_y) values for this basin have not been determined (Oboubie et al. 2012), so estimated values for specific yield were chosen based on the assumptions that specific yield varies in the aquifer(Cunningham and Daniel 2001) and that the aquifer is unconfined. To account for the range in specific yield assumed in the fractured rock aquifer, values from specific yield were selected from literature review that would generate a low end recharge estimation and a high end recharge estimation. The values of .001, .005, .002, and .008 for specific yield were selected from analog sites in Zimbabwe and Australia with similar climates and fractured aquifers to represent the low end estimation representing the "semi-confined" portions of the watershed effected by plinthosols (Sibanda et al. 2009; Cook 2003) and the values .05 and .08 from a recent study in the White Volta River Basin (Oboubie et al 2012 after Sinha and Sharma 1988) to represent the high end of the estimation, and are summarized in Table 1.

Selected Values for Specific Yield (Sy)			
	Low end recharge estimation values		High end recharge estimation values
Source	Sibanda et al. 2009	Cook 2003	Oboubie et al. 2012 after Sinha and Sharma 1988
Sy	0.002	0.001	0.05
	0.008	0.005	0.08
Region	Zimbabwe	Australia	Ghana

Table 1. Sources of values used for specific yield (S_y) and their regional context. (Cook 2003; Sibanda et. al. 2009).

Water table fluctuations occur seasonally in response to climatic effects (precipitation) and daily in response to short term effects (pumping). These short term effects were examined by observing recovery rates after pumping and are detailed in the results section. The values for Δh in this formula are calcuated by measuring distances between peaks and troughs in water head levels annually (Δt) at monitoring wells. These values are selected from annual hydrographs produced by pressure data recovered from the Schlumberger pressure transducers collected at the five monitoring wells.

2.4 Chloride Mass Balance

The chloride mass balance (CMB) methodology is adaptable for recharge estimates for this river basin based on several assumptions. The CMB method assumes that there is a balance of meteorically derived chloride within the hydrologic cycle (Eriksson and Khunakasem 1969; Dettinger 1989). Chloride is chosen as the environmental tracer due to its natural abundance and stability throughout the phases of the hydrologic cycle (Huang and Pang 2011). It is also selected as a tool for measuring recharge due to its suitability to arid regions and its ability to reflect long-term average tracer (chloride) inputs that can be found in the saturated zone (Sami and Hughes 1996; Allison et al. 1994). It is commonly used in Northern Ghana to estimate groundwater recharge and is the common method chosen by the Ghana Water Resource Commission (Carrier et al. 2011; Bazuhair and Wood 1996). A precipitation-based model is chosen over a soil pore water-based model based on the assumptions that virtually all chloride reaches the groundwater table, concentrations found in recharging meteoric water can be compared to the concentrations found in groundwater to determine recharge (Sami et. al. 1996), other major chloride sources are not present, and that the surface area of the basin is properly delineated (Dettinger 1989).

The formula used for CMB method in this study given in equation 2. Equation 2 is derived from Dettinger (1989)(Eq.2a) based on the assumptions that chloride found in the water table is derived from precipitation, and that dry fall of chloride, or chlorides derived from sea spray, is negligible due to the considerable distance from the coast.

Equation 2a:

$$PC_p=RC_r + SC_s + ETC_{et}$$

Where:

(P) = Precipitation in recharge area (m^3/month)

(R) = Recharge (m^3/month)

(S) = Surface runoff (m^3/month)

(ET) = Evapotranspiration (m^3/month)

(C_r) = Chloride concentration in recharge (R) includes chloride in surface runoff that eventually contributes to recharge (mg/L)

(C_s) = Chloride concentration in surface runoff (S), includes chloride in rejected groundwater discharge within the recharge area that contributes to surface runoff (mg/L)

(C_p) = Chloride concentration in precipitation (P), includes both wet fall and dry fall (mg/L)

(C_{et}) = Chloride concentration in ET, where (C_{et}) = 0(mg/L)

These terms can be rearranged to solve for recharge to be written as:

Equation 2b:

$$\mathrm{R} = P\frac{(C_p)}{(C_r)} - S\frac{(\mathrm{C}_s)}{(\mathrm{C}_r)},$$

This formula does not account for ET, based on an assumption that chlorides do not travel through the hydrologic cycle in evaporation or transpiration, and ETC_{et} can be neglected.

These terms are further rearranged as:

Equation 2. Chloride Mass Balance

$$Q = (PAC_P - qC_s)/C_{GW}$$

(Q) – Recharge (m^3/mo)

(P) – Precipitation (m/mo)

(A) – Surface area of basin (m^2)

(q) – Surface discharge (m^3/mo)

(C_p) – Chloride concentration in precipitation (mg/L)

(C_s) – Chloride concentration in surface water (mg/L)

(C_{GW}) – Chloride concentration in groundwater (mg/L)

This formula accounts for the areal extent of the basin (m^2) delineated in ArcGIS (Fig. 7), and does not account for ET originally used by Dettinger (1989).

Using the field aqueous chloride concentration data collected, Microsoft Office Excel 2007 (Excel) is used to compute monthly recharge values, the 12 monthly values were summed to compute the annual recharge.

The monitoring wells used for sampling groundwater for chloride concentration for the CMB were selected from the availability of boreholes drilled by GRWP. When possible, boreholes were simultaneously used to collect data for the WTFM via pressure transduscers/data loggers and for CMB method via monthly sampling. A total of seven boreholes were chosen throughout the Nabogo River Basin and are shown in Fig. 7. All boreholes sampled for chloride were being utilized in the villages located near them. The wells and their locations are summarized in Table 2.

Name	Type	N	W	WTFM	CMB
Kadia	Well	09^{o} 54.172'	000^{o} 51.127'	X	X
Pishigu	Well	09^{o} 58.233'	000^{o}39.337'		X
Galwie	Well	09^{o} 37.334'	000^{o}26.913'		X
Tamaligu	Well	09^{o} 50.855'	000^{o} 44.075'		X
Bagurugu	Well	09^{o} 53.799'	000^{o} 42.736'		X
Zoggu	Well	09^{o} 40.010'	000^{o} 42.736'		X
Kanshegu	Well	09^{o} 34.494'	000^{o} 50.038'		X
Nabogo	River	09^{o} 44.415'	000^{o} 49.426'		X
White Volta	River	09^{o} 41.417'	000^{o} 58.488'		X

Table 2. Summary of sampling locations used in this study

2.5 Stable Isotopes δ^{18}O and δD

Stable isotopes can be used as environmental tracers to determine the relative source of groundwater recharge (Dincer et al. 1974). As meteorically derived water travels horizontally from the oceans via evaporation and wind transport, the stable isotopic signature will become increasingly enriched in 18O (Craig 1961; Clark and Fritz 1997; Dincer et al. 1974). Craig (1961) developed the Global Meteoric Water Line (GMWL) which represents the Isotopic composition of $\delta^{18}O$ and δD for ocean water and can be used as a reference for locally collected precipitation and groundwater. Samples that plot along the local meteoric water line (LMWL), are evidence that groundwater recharge in the Nabogo Basin is derived from regional meteoric waters.

Water samples were collected during the same sampling period for the stable isotopes $\delta^{18}O$ and δD and were used to confirm that groundwater is being recharged locally from meteoric waters, and not from a distant source. Sampling methods are detailed in Appendix A. Isotope samples were analyzed at the stable isotope laboratory in the Geology Department of the University of Nevada Reno, and the methodology used is detailed in Appendix B. The results of laboratory analysis were plotted and compared with regional historical aqueous isotopic composition data collected by Pelig-Ba (2009) and from unpublished data provided by DRI (Dr. Lutz personal communication 2011). The results of these plots were used to show evidence that groundwater is recharging locally from precipitation. The regression lines $\delta D = 6.95^{18}O - 0.20$ for precipitation and $\delta D = 5.68\ \delta^{18}O - 7.29$ for groundwater and precipitation were plotted based on the Pelig-Ba (2009) data, the regression line $\delta D = 7.2\ \delta^{18}O + 7.6$ represents the Local Meteoric Water Line (LMWL) based on groundwater and precipitation values from DRI, and the regression lines $\delta D = 5.35\ \delta^{18}O + 6.67$ for precipitation, and $\delta D = 6.58\ \delta^{18}O + 3.05$ for groundwater represent the precipitation and groundwater isotopic data collected in the Nabogo Basin during the sampling period specifically for this study.

3.1 Chapter Three - Results

The results of the recharge estimates for WTFM and CMB, as well as $\delta^{18}O$ and δD sampling analysis are discussed in this section. The raw data used in calculations can be accessed at https://sites.google.com/site/mkrautstrunkdata/videos/home and are available on CD at the University of Nevada, Las Vegas Graduate College .

3.2 Water Table Fluctuation Method (WTFM)

Plots were created for each monitoring sell showing the diurnal water level fluctuation during the rainy and dry season for each monitoring well and can be found in Appendix D. Representative plots for diurnal water level fluctuation are shown below in Tables 9 and 10 for Bogo and Base monitoring wells. The plots show rapid recovery of water levels (406 hours) after pumping and highest recovery of water levels at 4:00 a.m.

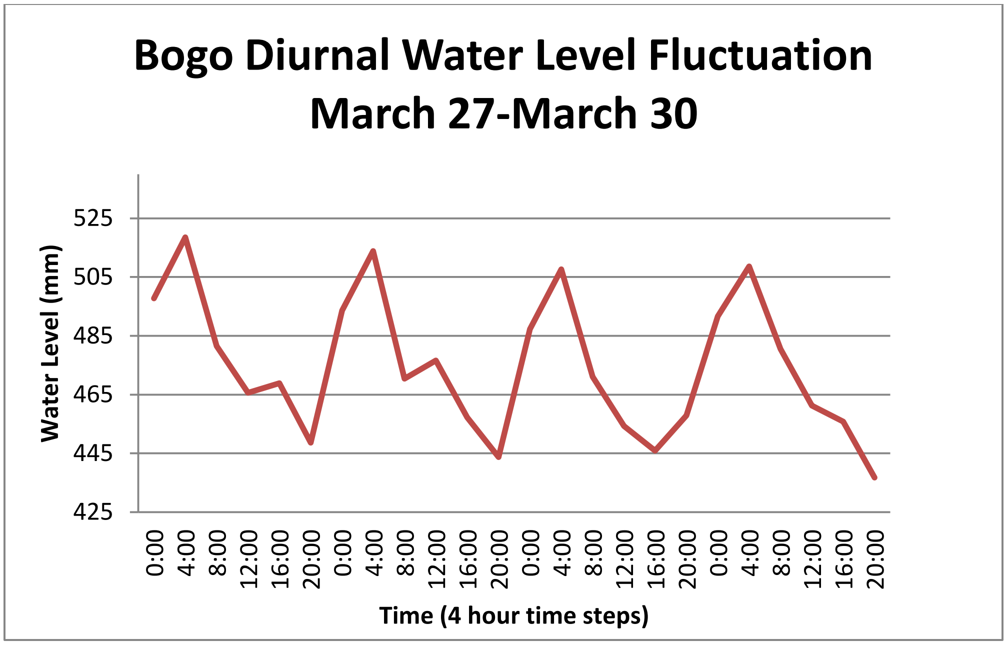

Figure 9. Diurnal water level fluctuation plot for the monitoring well at Bogo showing rapid recovery rate of water level and the highest recovery point at 4:00 a.m.

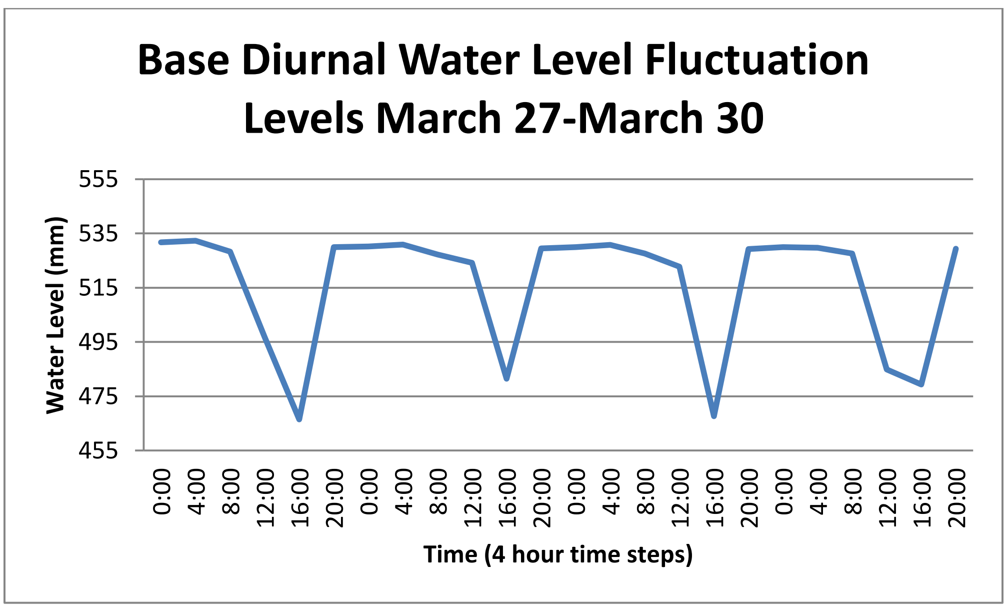

Figure 10. Diurnal water level fluctuation plot for the monitoring well at Base showing rapid recovery rate of water level and the highest recovery point at 4:00 a.m.

Representative plots of monthly groundwater level measurements from Kadia, District Assembly, Bogo, and Base are shown in Figures 11-14. These plots were used to calculate Δh and Δt from Eq.1. Δh was calculated as the height between the peak and the antecedent recession curve.

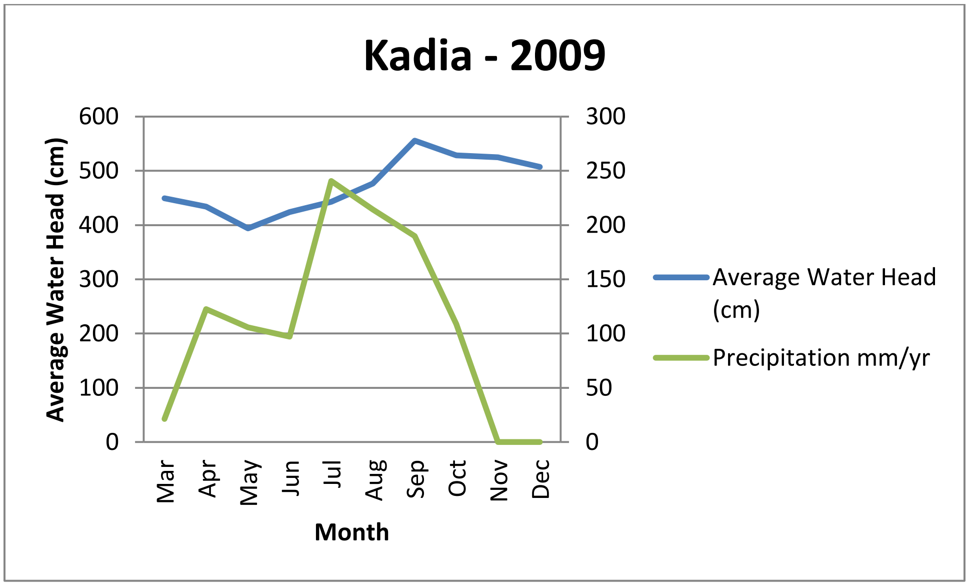

Figure 11. Kadia hydrograph including average water head (cm) and precipitation (mm/yr).

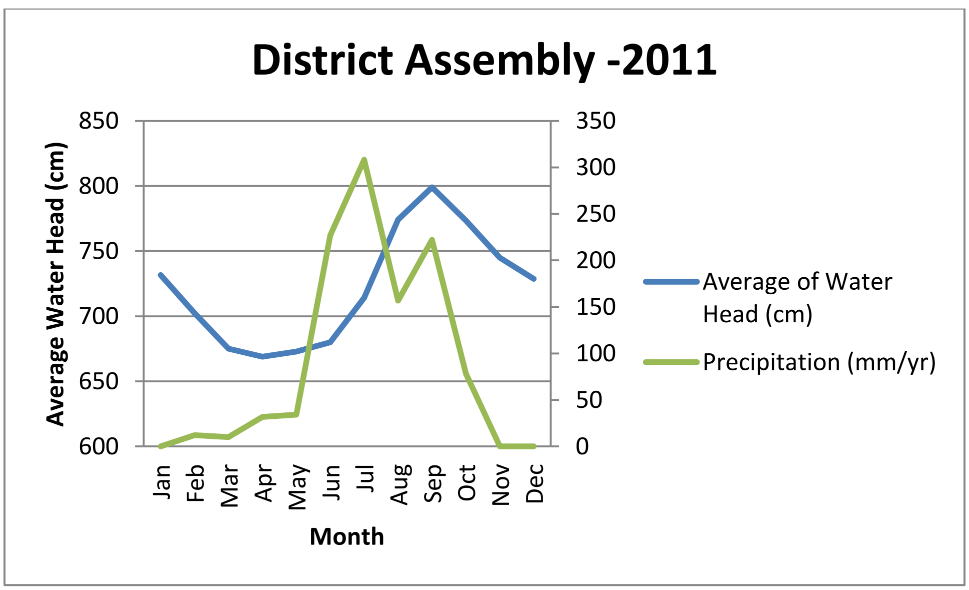

Figure 12. Distric Assembly hydrograph including average water head (cm) and precipitation (mm/yr).

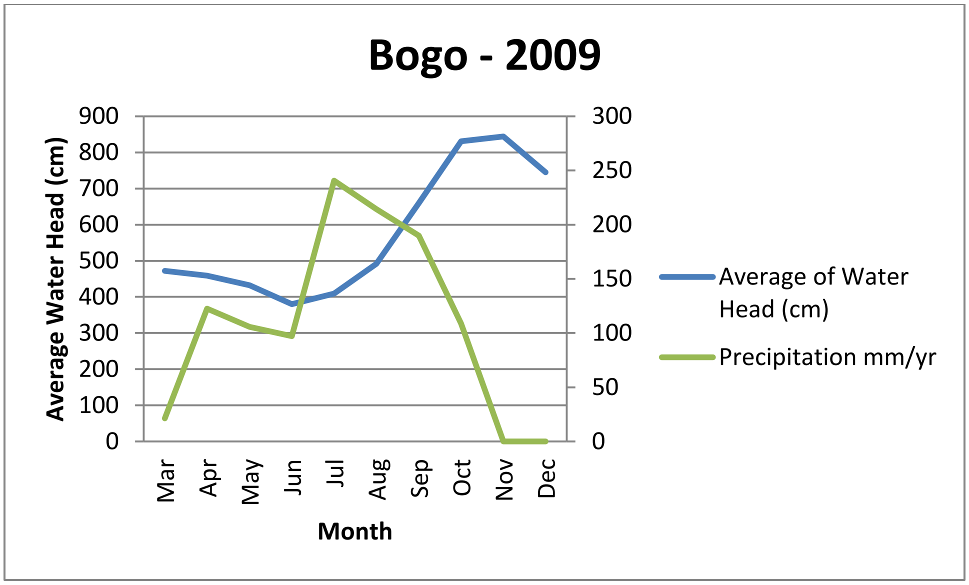

Figure 13. Bogo hydrograph including average water head (cm) and precipitation (mm/yr).

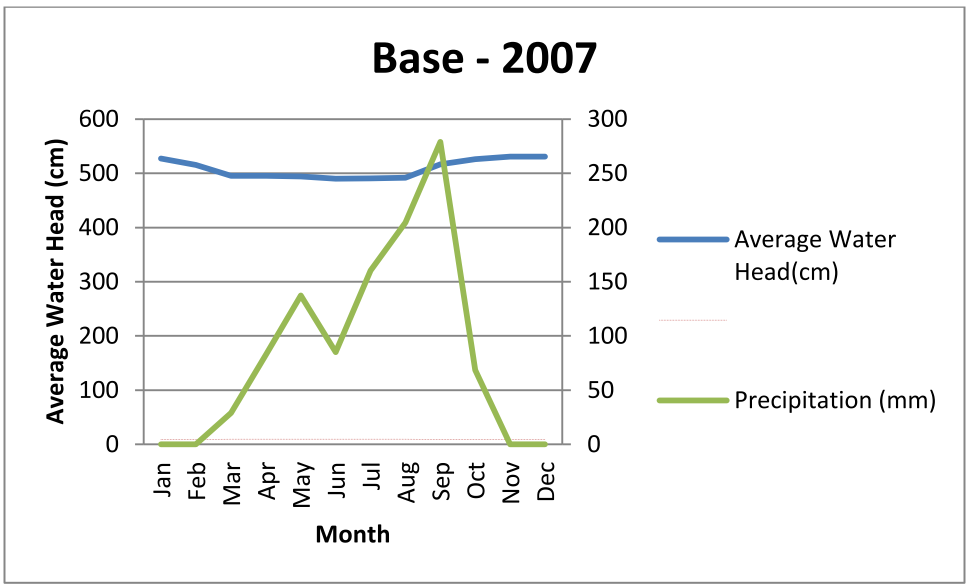

Figure 14. Bogo hydrograph including average water head (cm) and precipitation (mm/yr).

The change between the peaks and troughs in the water head were calculated at each borehole and were then calculated as a portion of the year and used for the (Δt) value in Eq.1. The range of specific yield values chosen is due largely to the varied nature of the fractured rock sandstone and variance in pumping rates (Carrier et al. 2007; Cunningham and Daniel 2001) from well to well. As discussed in methodology values for specific yield in this area are not defined (Oboubie et al. 2012; personal communication with the Ghana Water Resource Commission 2011; personal communication with The Ghana Rural Water Project 2011) and is one of the most challenging parameters in this region.

The water level fluctuation data used from the monitoring wells at Kadia, District Assembly, Bogo, and Base were used as inputs in Excel using Eq. 1. Ranges and averages were computed for each monitoring well to estimate a low end of groundwater recharge and a high end of groundwater recharge, and in addition, an overall average for the basin was included and the results are discussed in this section. The four monitoring wells showed a small variation in lag time in a range from 6-7 months (Table 3).

	Lag from peak to trough (Δt) for Eq.1			
	District Assembly	Bogo	Kadia	Base
Peak to Trough (Δt)(months)	6	7	6	6

Table 3. Calculated Time from peak to trough (Δt) (months) for Eq. 1 for the monitoring wells used in WTFM calculation.

Results of the recharge estimate based on the Water Table Fluctuation Method (WTFM) and the Chloride Mass Balance (CMB) method are shown in the tables below. Tables 4-8 show the groundwater recharge values computed for the WTFM, based on different rates of specific yield (S_y) and using water level fluctuation data available from each of the four monitoring wells chosen. Table 9 shows the results from the CMB and Table 10 displays a comparison of the two methods. Due to malfunction in the data loggers recording record, certain wells had a gap in the historical record for water level fluctuation data, varying from days to months in a row. Water level fluctuation data from the pressure transducers were only used for the years with complete annual data sets and were applied to Eq.1. The results are listed below in each monitoring well's respective tables (Tables 4-7).

Kadia						
Low End Estimation				**High End Estimation**		
Year	S_y	Q (mm/yr)	Q(%)	S_y	Q (mm/yr)	Q(%)
2007	0.001	1.74	>1	0.05	87.24	9
2009	0.001	1.50	>1	0.05	75.00	7
2006	0.001	1.61	>1	0.05	80.72	7
2007	0.002	3.49	>1	0.08	139.58	14
2009	0.002	3.00	>1	0.08	119.99	11
2006	0.002	3.23	>1	0.08	129.15	12
2007	0.005	8.72	1			
2009	0.005	7.50	1			
2006	0.005	8.07	1			
2007	0.008	13.96	1			
2009	0.008	12.00	1			
2006	0.008	12.92				
Distribution		**1.7-12.9**	**>1-1**		**75-129.15**	**7-14**
Range		**12.46**	**1**		**64.58**	**7**
Average		**6.48**	**1**		**105.28**	**10**

Table 4. Results of WTFM at Kadia monitoring well for 2006, 2007 and 2009, each year shows values of specific yield (S_y) used for the high end estimation and the low end estimation and the resulting values for groundwater recharge Q(mm/yr) and as a percentage of that year's annual precipitation Q(%P).

Table 4 lists the recharge values produced from the WTFM for the monitoring well located in Kadia. Three years, 2006, 2007 and 2009, were selected from the available water level information based upon complete data sets. Recharge values were calculated using selected values of specific yield (S_y), as well as water level values and historical precipitation depths. The lower end recharge estimate for Kadia shows an average of 6 mm/yr, or 1% of annual precipitation. The high end of the estimate generated in Equation 1 shows an average of 105 mm/yr, or 10% of annual precipitation.

District Assembly						
Low End Estimation				**High End Estimation**		
Year	S_y	Q (mm/yr)	Q(%)P	S_y	Q (mm/yr)	Q(%)P
2009	0.001	4.32	>1	0.05	215.99	20
2011	0.001	1.30	>1	0.05	65.04	6
2009	0.002	8.64	1	0.08	345.58	31
2011	0.002	2.60	>1	0.08	104.06	10
2009	0.005	43.20	4			
2011	0.005	13.01	1			
2009	0.008	34.56	3			
2011	0.008	10.41	1			
Distribution		**1.3-41.9**	**>1-4**		**65-345.5**	**6-30**
Range		**41.90**	**4**		**280.55**	**25**
Average		**14.75**	**1**		**182.67**	**17**

Table 5. Results of WTFM at District Assembly monitoring well for 2009 and 2011, each year shows values of specific yield (S_y) representing the low end groundwater recharge estimate and the high end groundwater recharge estimate (Q) in mm/yr and as a percentage of annual precipitation (%)(P).

Table 5 lists the values produced from the WTFM as computed in by equation 1. Two years, 2009 and 2011, were selected as water level fluctuation data sets from the available water level measurements based upon their completion of recorded data (not effected by equipment malfunction). The water levels, as well as the selected range of specific yield (S_y) values, and historical precipitation amounts were used to calculate groundwater recharge. The lower end recharge estimate for the the District Assembly shows an average of 15 mm/yr, or 1% of annual precipitation. The high end of the estimate generated in Equation 1 shows an average of 183 mm/yr, or 17% of annual precipitation.

Bogo						
Low End Estimation				**High End Estimation**		
Year	S_y	Q (mm/yr)	Q(%)	S_y	Q (mm/yr)	Q(%)
2009	0.001	4.64	>1	0.05	232.04	20
2011	0.001	3.38	>1	0.05	168.77	16
2009	0.002	9.28	1	0.08	371.27	34
2011	0.002	6.75	1	0.08	270.04	25
2009	0.005	23.20	2			
2011	0.005	16.88	2			
2009	0.008	37.13	3			
2011	0.008	27.00	2			
Distribution		**3.4-37.1**	**>1-3**		**168.8-202.5**	**20-34**
Range		**33.75**	**3**		**202.50**	**18**
Average		**16.03**	**1**		**260.53**	**24**

Table 6. Results of WTFM at Bogo monitoring well for 2009 and 2011, each year shows the values of specific yield (S_y) used for the high end estimation and the low end estimation and the resulting values for groundwater recharge Q(mm/yr) and as a percentage of that year's annual precipitation Q(%P).

The results from the WTFM shown in Table 6 are computed from transducer/data logger sets from 2009 and 2011 and from precipitation values collected from the Ghana Regional Meteorological Survey.

The water levels, as well as the selected range of specific yield (S_y) values, and historical precipitation amounts were used to calculate groundwater recharge. The lower end recharge estimate for the Bogo shows an average of 16 mm/yr, or 1% of annual precipitation. The high end of the estimate generated in Equation 1 shows an average of 261 mm/yr, or 24% of annual precipitation.

Base						
Low End Estimation				**High End Estimation**		
Year	S_y	Q (mm/yr)	Q(%)	S_y	Q (mm/yr)	Q(%)
2007	0.001	0.19	>1	0.05	9.44	1
2009	0.001	0.41	>1	0.05	20.51	2
2006	0.001	0.41	>1	0.05	20.40	2
2007	0.002	0.38	>1	0.08	15.10	2
2009	0.002	0.82	>1	0.08	32.82	3
2006	0.002	0.82	>1	0.08	32.64	3
2007	0.005	0.94	>1			
2009	0.005	2.05	>1			
2006	0.005	2.04	>1			
2007	0.008	1.51	>1			
2009	0.008	3.28	>1			
2006	0.008	3.26	>1			
Distribution		**0.19-3.28**	>1		**9.4-32.8**	**1-3**
Range		**3.09**	**>1**		**23.38**	**2**
Average		**1.34**	**>!**		**21.82**	**2**

Table 7. Results of WTFM at Base monitoring well for 2006, 2007 and 2009, each year shows values of specific yield (S_y)) used for the high end estimation and the low end estimation and the resulting values for groundwater recharge Q(mm/yr) and as a percentage of that year's annual precipitation Q(%P).

Table 7 lists the values produced from the WTFM as computed by equation 1 for the monitoring well located at Base. Three years, 2006, 2007 and 2009, were selected from the available water level records, based upon complete data sets. Once again, recharge values were calculated using selected values of specific yield (S_y), as well as water level values and historical precipitation depths. The lower end recharge estimate for Bogo shows an average of 1.4 mm/yr, or >1% of annual precipitation. The high end of the estimate generated in Equation 1 shows an average of 22 mm/yr, or 2% of annual precipitation.

The monitoring well at Base has a much lower calculated recharge rate than the other three monitoring wells, this is considered in more detail in Table 8.

A summary of ranges and averages of the lower end and higher end recharge estimates in the Nabogo Basin are shown in Tables 8 and 9. Five years of water level data from the monitoring wells were considered for these ranges and averages, and the results are based on the selected values of specific yield from analog sites (Table 1).

Low End Recharge Estimation - WTFM Nabogo River Basin					
	District Assembly	Kadia	Bogo	Base	Overall
Distribution (Q)(mm/yr)	1.3-41.9	3.4-37.1	1.7-12.9	0.19-3.28	0.19-37.1
Distribution (Q)(%)(P)	>1-4	>1-3	>1-1	>1->1	>1-4
Range(Q)(mm/yr)	41.90	33.75	12.46	3.09	38.80
Range(Q)(%)(P)	4	3	1	>1	4
Average (Q)(mm/yr)	14.75	16.03	6.48	1.34	9.65
Average (Q) (%)(P)	1	1	1	>1	1

Table 8. The low end groundwater recharge estimate using equation 1, based on the specific yield values .001, .005, .002, and .008 for all monitoring wells in the Nabogo River Basin. The results shown for recharge (Q) by distribution, range and averages at each monitoring well in mm/yr and as a percentage of annual precipitation (%)(P).

High End Recharge Estimation - WTFM Nabogo River Basin					
	District Assembly	Kadia	Bogo	Base	Overall
Distribution (Q)(mm/yr)	65-345.5	168.8-202.5	75-129.15	9.4-32.8	9.4-202.5
Distribution (Q)(%)(P)	6-30	20-30	7-14	1-3	1-7
Range(Q)(mm/yr)	280.55	202.50	64.58	23.38	257.17
Range(Q)(%)(P)	0.25	0.18	0.07	0.02	0.23
Average (Q)(mm/yr)	182.67	260.53	105.28	21.82	142.57
Average (Q) (%)(P)	17	24	10	2	13

Table 9. The high end groundwater recharge estimate using equation 1, based on the specific yield values .05 and .08 for all monitoring wells in the Nabogo River Basin. The results shown for recharge (Q) by distribution, range and averages at each monitoring well in mm/yr and as a percentage of annual precipitation (%)(P).

The overall estimate for the Nabogo River Basin for groundwater recharge using equation 1 and the specific yield values for the lower end recharge estimates show an annual recharge average of 10mm/yr, or 1%of annual precipitation. The estimates for the representing the higher end estimation show an average annual recharge of 143 mm/yr, or 13% of annual precipitation. This shows a range from 10-143mm/yr, or 1-13% of annual precipitation for recharge generated using the WTFM.

The recharge estimates for the monitoring well at Base are lower than the estimates shown for the monitoring wells at the District Assembly, Bogo and Kadia, this is expanded on in the discussion section.

3.3 Chloride Mass Balance (CMB) Method

Groundwater recharge estimates based on the chloride mass balance method are shown below in Table 10, the values computed are based on Eq.2. The CMB method is commonly used in Northern Ghana to estimate groundwater recharge and is the method chosen by the Ghana Water Resource Commission (Carrier et al. 2011; Bazuhair and Wood 1996). Using the chloride concentration data, Excel is used to compute monthly recharge values, and the 12 monthly values were summed to compute estimated annual recharge.

Water samples were taken monthly at wells and rivers throughout the sampling period. Laboratory results were used in the CMB for the exception of some outlier data from Kadia and Galwie that fell outside of the standard deviation of chloride that was representative of the respective monitoring wells. The major tributary of the basin was accessible at several points and sampled mainly at the bridge crossing in Nabogo (N 09^{o} 44.415' W 000^{o} 49.426') and at the tributary at the White Volta River (N 09^{o} 41.417' W 000^{o} 58.488'). The chloride concentration values were used in Eq.2 to make monthly calculations of estimated groundwater recharge. For months lacking data, substitutions were made by estimating values using the following methods; for chloride concentration in surface water and in groundwater, values that follow the seasonal trend of increasing and decreasing chloride concentrations were used, for chloride concentration in precipitation averages were calculated from collected samples as there was limited range in all collected values. Area was calculated in ArcGIS as 3600Km^2 (Lutz et al. 2007) and used in all calculations. Precipitation values were used from a 29 year historical data set from the Ghana Regional Meteorological Survey, and streamflow discharge values were used from an average of discharge values at the Nabogo River gauging station located at the bridge at Nabogo Village supplied from the Ghana Water

Resource Commission database that spans 29 years (1962-1991). All units were converted to meters, months, and mg/L for the calculations.

2011-2012 Chloride Mass Balance - Nabogo River Basin						
Month	P (m/mo)	C_p (mg/L)	q (m/mo)	C_s (mg/L)	C_{gw} (mg/L)	Q (m/mo)
Nov 2011	0.00	0.4	1.04E+04	1	13.1	0.00
Dec 2011	0.00	0.4	5.72E+03	1.4	8.6	0.00
Jan 2012	0.00	0.4	7.05E+03	1.4	8.6	0.00
Feb 2012	0.01	0.2	4.45E+03	1.6	3.8	5.13E-04
Mar 2012	0.03	0.4	2.48E+03	2.7	5.5	2.23E-03
Apr 2012	0.08	0.5	4.40E+03	1.3	9.1	4.45E-03
May 2012	0.12	0.23	1.29E+04	2.5	7.75	3.65E-03
Jun 2012	0.15	0.4	5.64E+04	3.1	11.83	4.98E-03
Jul 2012	0.17	0.4	2.08E+05	3.5	12	5.74E-03
Aug 2012	0.20	0.4	6.56E+05	2.9	12.5	6.35E-03
Sep 2012	0.21	0.4	2.19E+06	2	13	6.49E-03
Oct 2012	0.09	0.4	8.77E+05	1.2	13.5	2.66E-03
Results	**P (m/yr)**	**1.07**			**Q (m/yr)**	**0.04**
	P (mm/yr)	**1068.82**			**Q (mm/yr)**	**37.06**
					Q (%/)(P/yr)	**3**

Table 10. Groundwater recharge estimates from the CMB in Nabogo River Basin based on data from precipitation (P(mm/yr)), chloride in precipitation (C_p (mg/L)), streamflow discharge (q) (m/mo)), chloride in surface water (C_s (mg/L)), and chloride in groundwater (C_{gw} (mg/L)). Recharge values (Q(m/mo)) are shown for each month and are summed for an annual total expressed in m/yr, and mm/yr and as a percentage of annual precipitation (Q(%P/yr).

Streamflow discharge values (q) are averages from a 29 year data set for the Nabogo River at the stream gauge located in the village of Nabogo and are used in Eq.2 to calculate estimated groundwater recharge (Table 10). The purpose of this study is to determine an estimate average annual recharge, however, the rainfall for the 2011-2012 sampling period was below average. The justification for q values is explained further in the discussion section.

WTFM – CMB Comparison		
	WTFM	CMB
(Q)(mm/yr)	10-143	37.06
(Q) (%)(P)	1-13	3.5

Table 11. Final recharge estimates of the WTFM method and CMB method.

The WTFM computed a range of recharge estimates based on a four year period of water level fluctuation and a range of specific yield values that are representative of the fractured and varied nature of the aquifer. The values presented are representative of the high and low end of expected groundwater recharge in the Nabogo River Basin (10-143 mm/yr, or from 1-13 % of annual precipitation). The CMB method represents the estimated groundwater recharge over a one year period (37 mm/yr, or 4% of annual precipitation).

3.4 Stable Isotopes

Stable isotopic samples were collected for oxygen ($\delta^{18}O$) and deuterium (δD) for both groundwater in the Nabogo River Basin and for precipitation and are shown in Table 12.

Stable Isotopes $\delta^{18}O$ and δD		
Location	$\delta^{18}O$ (‰ VSMOW)	δD (‰VSMOW)
Bagarugu GW March 9, 2012	-4.6	-27
Bagarugu GW May 1, 2012	-4.7	-28
Tamaligu GW March 9, 2012	-4.7	-28
Tamaligu GW May 1, 2012	-4.8	-28
Tamale (P) April 1, 2012	0.4	9
Tamale (P) May 25, 2012	-4.8	-19

Table 12. Stable Isotopes oxygen ($\delta^{18}O$) and deuterium (δD) values sampled between March 2012 and May 2012 in the Nabogo river basin from groundwater (GW) and precipitation (P).

Scatter plots were made for the data collected within the sampling period and from regional historical data (Pelig-Ba 2009; personal communication DRI 2011) and are shown in Fig 15.

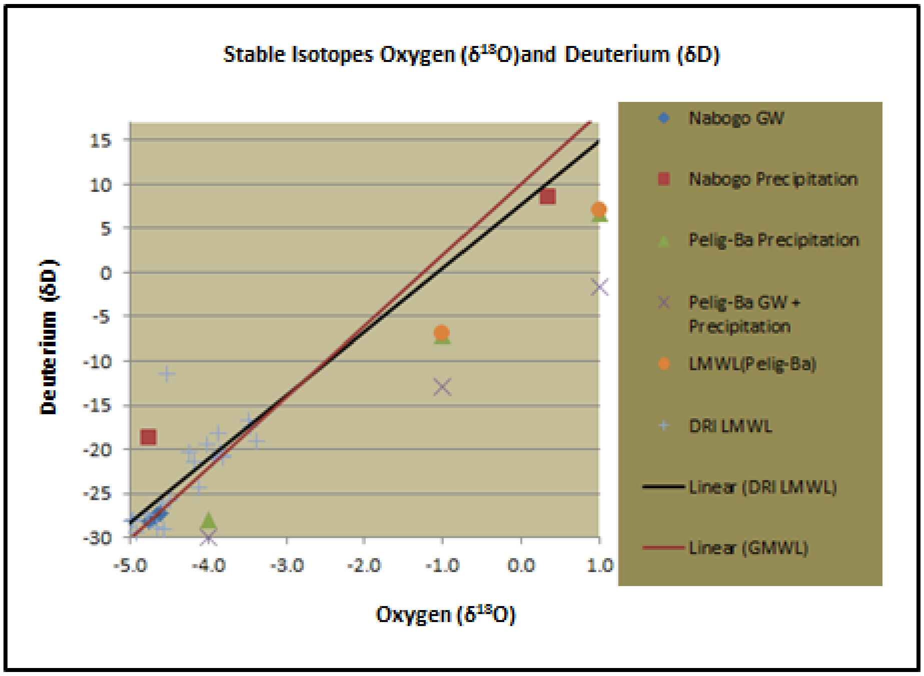

Figure 15. (after Pelig-Ba 2009) Stable isotopes oxygen ($\delta^{18}O$) and deuterium (δD) for Nabogo River Basin.

Figure. 15 shows the plot of the samples collected for stable isotopes $\delta^{18}O$ and δD collected from groundwater and precipitation during the sampling period as well as data collected by Pelig-Ba (2009), from unpublished data from DRI (personal communication with Dr. Lutz 2011) collected in 2002-2003 and from groundwater and precipitation values collected during the sampling period in the Nabogo Basin. All precipitation samples collected during the sampling period are from Tamale rain events, approximately 15 km from the border of the basin. The Global Meteoric Water Line (GMWL)(Craig 1961) is shown in black and the Local Meteoric Water Line (LMWL) based on water samples taken in the research sampling period and unpublished $\delta^{18}O$ and δD values from DRI is shown in red.

4.1 Chapter 4 - Discussion:

Groundwater recharge in the Nabogo River Basin is affected by physical properties of the basin as well as cultural factors. Physical properties that are a factor include geology, which determines the parameters used in hydrologic equations (transmisivity, storativity, and specific yield, among others), and surficial conditions such as vegetation type and density, topography, and climate. Cultural, or community practices such as water use (the extent of water extracted from boreholes), and land use also have an effect on groundwater recharge. These factors and others are discussed below in regards to the calculations made in this study for estimating groundwater recharge using WTFM and CMB methods. The groundwater recharge estimates calculated using the two methodologies produced similar, though not identical, results.

4.2 Groundwater Recharge Estimates Using the Water Table Fluctuation Method

Groundwater recharge estimates derived from WTFM are based on hydrographic analysis of water fluctuation level data collected over a four year period (2006-2009) from monitoring wells in the Nabogo River Basin. In this case, the peak and trough values were selected from annual hydrographs for each monitoring well. The peaks and troughs represent the seasonal change in water level and the anthropogenic effects of pumping were considered when plotting the hydrographs as shown in the results section. The major peaks and throughs were assumed to represent the major annual change in water tables and therefore, because of the major seasonal shift in rainfall and infiltrating water each year, the calculated recharge from this method was taken to be annual recharge.

The recharge estimate based on the WTFM averages point source monitoring well water head levels in response to local precipitation events and the estimates are based on percentages of annual rainfall. Physical conditions of the Nabogo Basin regarding these calculations are discussed in the following section.

The four monitoring wells chosen for WTFM all share similarities in their hydrographs with the exception of Base. The plots of the seasonal and diurnal water level fluctuations at Base are not as high as the monitoring wells at Kadia, Bogo and The District Assembly as shown in Appendix D. Though the reason for this variation is not known, it is expected to be largely attributed to the fact that the Base monitoring well was the only monitoring well not in regular use by a neighboring community, though it was in use by the staff at GRWP. This variation could also be attributed to their respective distance and connectivity to fractures in the aquifer and subsequent specific yield values. Because the reason for the differences in the Base hydrograph are not precisely known, the recharge estimate was computed using all monitoring wells, including Base. However, if the reason for the difference in hydrographs is attributed to the effects of pumping on the water level data, then the values calculated for the Base monitoring well would more accurately represent groundwater recharge, and the estimates shown in this study could be considered an overestimation.

The groundwater recharge estimate for the Nabogo River Basin generated by WTFM is based on groundwater recharge estimates generated at four monitoring wells created by the water level fluctuation data available for each monitoring well. The variations shown between these four point source estimates are within an annual range of 17 mm of groundwater recharge. This represents an average of 1.5% of annual rainfall over a four year period (2006-2009). This range can be attributed several factors. The variation of hydrogeologic parameters such as connectivity to and degree of fractures in the aquifer at each locale, well integrity (based on community maintenance and the age of the borehole), and the frequency of pumping by surrounding communities can all attribute to the outcome of groundwater recharge estimates using WTFM. Well integrity can vary from borehole to borehole based on the duration of time the borehole is in use, the frequency of use, the quality of construction and other factors that are difficult to quantify. Although these factors can impact the water level data collected at each borehole, the impact is considered negligible. The frequency and duration of pumping at each borehole can also have an impact on water level readings, but is considered minimal for both frequency and duration based on field observations (they are used for household use and not commercially). Maximum diurnal water level fluctuations (which recover daily) are typically 2-3 % of seasonal fluctuations and diurnal impacts are considered low and within acceptable limits.

The hydrogeological parameters of the basin are ill defined and quite variable, necessitating the estimation of specific yield values. This aspect has the largest impact on the values calculated for groundwater recharge, as specific yield is a critical parameter in the WTFM equation. Careful consideration was given to the selection of the specific yield values chosen from literature review and are based on sites with similar aquifers and climates, and on recent studies done in the region. This is also accounted for by generating a range of values representing the possible high and low end of groundwater recharge that can be expected in the area.

Table 13 shows specific yield values used in similar aquifer types and was used as a basis of selection for specific yield values in this study. The values .001, .002, .005, .008, .05, and .08 were selected, not only based on their comparable analog sites, but from comparison to many studies that have defined specific yield. Although these vales are more typically used for unconfined aquifer conditions, they were also chosen based on the presence of plinthosols acting as a semi-confining layer in the watershed.

Aquifer type	Research area	Specific Yield	Source
Folded and fractured shales, siltstones and sandstones	Pennsylvania	0.01	Risser et al. 2009
Folded and fractured shales, siltstones and sandstones	Pennsylvania	0.0035-.035	Risser et al. 2009
Cambriam -Precambrian - voltaian sedimentary Basin	White Volta Basin, Ghana	.01-.05	Oboubie et al. 2012 (from Sinha and Sharma 1988)
Hard fractured crystalline rock, granite gneiss basalt	India	.0017, .0015	Marechal et al. 2003)
Fractured granite	India	.014, .0138	Marechal et al. 2006)
Sand, fine to medium	Illinois	0.03	After Prickett 1965
Sand, fine to medium	Illinois	0.01	After Prickett 1965
Sand, medium, silty	Illinois	0.05	After Prickett 1965
Sand, silty to medium	Illinois	0.01	After Prickett 1965
Sand, fine to medium	Illinois	0.01	After Prickett 1965
Sand, fine with clay	Illinois	0.02	After Prickett 1965
Sand, fine with clay	Illinois	0.20	After Prickett 1965
Sand, fine with silt	Illinois	0.02	After Prickett 1965

Table 13. Specific yield values for comparable aquifer types to the Nabogo River Basin.

4.3 Groundwater Recharge Estimates Using Chloride Mass Balance

The seven boreholes utilized for groundwater sampling data for the CMB method share similar physical, topographic, vegetative, and land use characteristics, however, production of water at boreholes varies. Topography throughout the basin is marked by gently rolling hills and slight elevation change, suggesting fairly homogeneous distribution of recharge. Vegetation at each site is characterized by grasses, and thinly populated Baobob and Kapok trees in the surrounding area. The terrain at each borehole is in regular pastoral use by the Fulanis. The Fulanis range freely throughout the region and have not constructed any dams or barriers that could affect the infiltration of precipitation into the aquifer. Overall variations from 2 mg/L to 67 mg/L are shown in the chloride concentrations in groundwater and water production ranges from 10 to 500 liter per minute in the region are reported in the HAP report (2005) demonstrating the variability of geologic conditions. The two most consistent boreholes in both chloride concentration and water production are at Tamaligu (2-5mg/l) and Bagarugu (0.9-2.4 mg/l), located north centrally in the basin, however the central counterpart to these boreholes in the southern central portion of the basin, at Zoggu, shows a steady decrease in water production and a moderate increase in chloride concentration (4-23 mg/l). This trend of decrease in water production, and an increase in chloride concentration is also shown for the borehole in Galwie, though the increase in chloride concentration is more drastic with a range from 6-142mg/L from December to March. Water production remains constant at Pishigu and a moderate increase in chloride concentration from 4-15mg/l is shown throughout the sampling period. The chloride concentration at Kadia is consistently in a higher range (30-90mg/l) than the other boreholes, but water production remains constant. The borehole at Kadia also doubles as an arsenic treatment plant, however, as stated in personal communication with Sampson Tettey at GRWP that the treatment methodology does not contribute to any outside sources for chloride.

Chloride concentration variation throughout the hydrologic cycle is evident from collected data. Concentration in precipitation is relatively constant throughout the sampling period and is within a range from 0.2-0.9mg/l. Seasonal variations are found in the chloride concentration of surface water with a peak in the dry season, and a decrease as the rainy season begins. This trend can be expected as the effects of evaporation on surface waters are intensified in the height of the dry season and this phenomenon is common in arid regions (Huang et al. 2011). All boreholes sampled show a trend (with varying degrees) of increase in chloride concentration from December to June. This increase in chloride concentration follows the decline in water levels shown in the hydrographs. The reason for the increase of chloride concentration coinciding with the decline in water level is not known.

4.4 Comparison of Results

Estimated annual groundwater recharge for the Nabogo River Basin generated across both methods in this study fall between a range of 10 – 143 mm/yr or 1-13% of annual precipitation. These values are compared to the findings of other studies in Ghana and the Volta River Basin here. Groundwater recharge estimates for Ghana and the Volta River Basin found in literature review as well as the relationship between annual rainfall and groundwater recharge in weathered rock are listed below in Table 14 and Fig.16.

Area of study	Recharge (% annual precipitation)	Source
White Volta River Basin	2.5-16.5 %	Oboubie et al. 2012
Volta River Basin,Ghana and Burkina Faso	3.7%	Martin and Van de Giesen, 2005
Upper East - Ghana	4-13 %	Martin, 2006 (cited from Carrier et al., 2005)
Upper East - Ghana	3-4 %	Apambire, 1996 (cited from Carrier et al., 2005)
Upper West - Ghana	2.5%	Bannerman and Ayibotele, 1984 (cited from Carrier et al., 2005)
Eastern Ghana	12.0%	Acheampong, 1996 (cited from Carrier et al., 2005)
Eastern and Central Ghana	3.9%	Darko and Krasny, 2003 (cited from Carrier et al., 2005)
Volta River Basin	5.0%	Friesen et al., 2005 (cited from Carrier et al., 2005)

Table 14. Groundwater recharge estimated for the Volta River Basin and surrounding regions in Ghana.

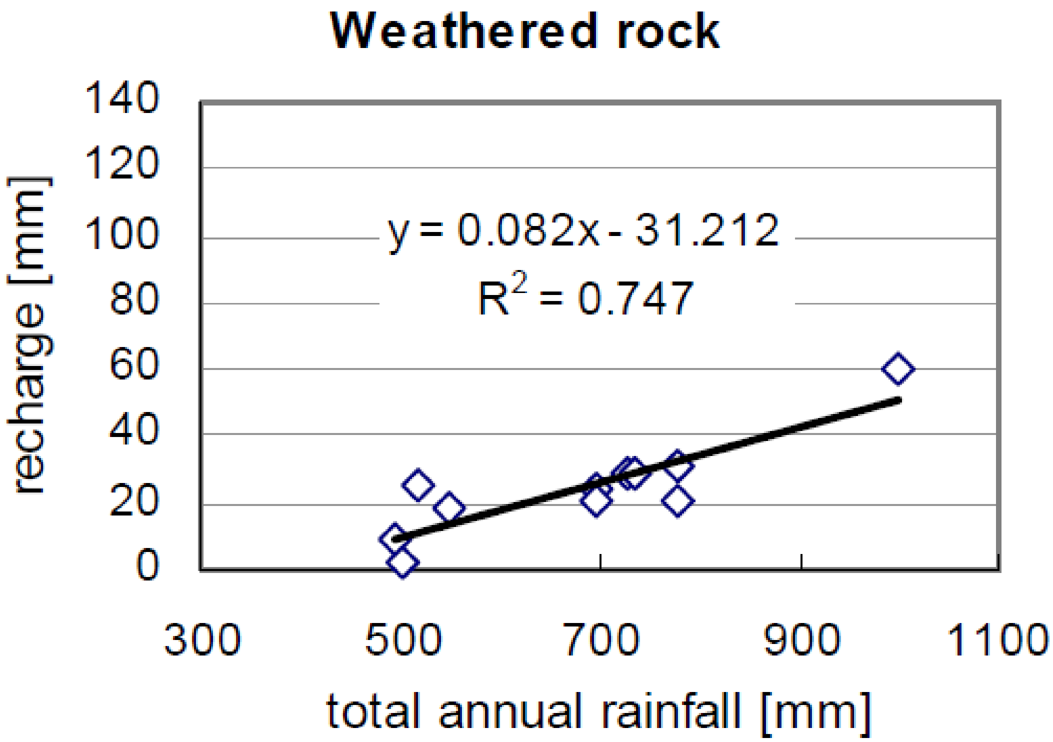

Figure 16. Relationship of groundwater recharge and annual rainfall in weathered rock aquifers. (Martin and Van de Giesen 2005 after IWACO and Dieng 1991; Diluca and Müller 1985; Millville 1991).

The rates in this study, especially those computed by CMB, compare to recharge estimates in the Volta River Basin and in other regions in Ghana and also compare to expected recharge for weathered rock aquifers shown in Fig. 13.

4.5 Differences of methods

The WTFM and CMB are both cost effective ways of determining groundwater recharge, but vary in their methodology. The differences in the groundwater recharge estimate generated by WTFM and the groundwater recharge estimate generated by CMB can be attributed to a number of factors.

The WTFM is a point based method based on the time variance and rise and fall of water level at one single point and can yield different values for each location. The values determined for each point source location can be combined to use as an average to be applied to the entire basin for average annual recharge. The CMB is limited more by time constraints of short (10 months) sampling period, as longer sampling periods (one year to multiple years) are ideal. WTFM is limited largely by the accuracy of physical parameters (specific yield) assumed in the equation. The CMB is a basin wide value derived from sampling surface water, groundwater and precipitation for chloride concentration throughout the basin. The recharge estimate is a value that can be applied to the entire basin and likely has an increasing accuracy with more, representative samples and local estimates. Although limitations are evident for CMB and WTFM methodologies, the methods can be calculated independently and used for comparison.

4.6 Evaluation of Methods and Limiting Factors

The use of WTFM and CMB are cost effective methods for measuring groundwater recharge, however the accuracy of the results is limited by regional and methodological factors discussed in this chapter.

Variations in regional hydrogeologic conditions can limit the confidence of the results of the WTFM recharge estimate such as, composition of local lithology, connectivity and degree of fracture of the aquifer, and can been seen by the subsequent effects on borehole production (productivity of water production). The complexity of the Voltaian Basin is largely due to its slightly metamorphosed and fractured nature. The limited data available on the characteristics of this basin presents a challenge in determining not only parameters for research, but presents a major obstacle to finding productive boreholes, and methods of increasing borehole efficiency.

Limiting factors of the results computed using the WTFM are largely based on the uncertainty of specific yield values assumed for this study. Values were not found in the literature review for the Nabogo Basin and local hydrogeologists report it as being one of the most challenging parameters in the area. The justification for using the chosen specific yield values is based on the assumption that the aquifer is unconfined. Although there are areas delineated in the HAP report as “hard pan soil retarding infiltration”, these semi-retardant layers are found only along the banks of rivers, created as the rise and fall of the water level fluctuates from wet to dry seasons. For this reason, the hard pan soils are not considered a true confining layer to infiltration for the basin. This did, however, have an influence on the values for specific yield chosen, which are closer to typical values used for confined aquifer conditions for the low end estimation than unconfined aquifers, this factor is due largely to the presence of plinthosols that act as a semi-confining layer near in certain areas within the basin. Other factors contributing to the chosen specific yield values are the fractured nature of the rock and its subsequent effect on water production at boreholes, and the lithologic and climatic similarities demonstrated at analog sites, found in literature review, with similar formations located in arid regions. The expected change in specific yield with depth in weathered/fractured aquifers was also considered by selecting a range of values for specific yield. WTFM is also constrained by the number of point source values, in a region with complicated lithology and boreholes that vary in water production (connectivity to fractures) the more point source values used for estimation, the more accurate the results. In this study, four point sources were chosen distributed throughout the basin and are considered to be an acceptable representation of basin characteristics as the recharge estimates generated at each point source fall within one standard deviation of the combined recharge estimates.

Limiting factors using the CMB method are largely due to the 10 month sampling period and in the difficulty of accounting for possible outside sources of chloride that might originate from agriculture or soaps used by community members throughout the basin in hand washing clothes. Literature review did not yield any parameters that would discount these sources. Personal communication with the Ghana Water Resource Commission and research faculty at University of Ghana – Legon commented that these parameters are considered constants in the system and are not accounted for in the formula. Time limitations for sampling only allowed for a 10 month sampling period, however, historical records spanning over 30 years for precipitation and streamflow discharge used in comparison to the data collected during the sampling period and are found to be comparable to collected historical data and are considered an accurate representation for the months not included in the sampling period.

The justification for using an average of streamflow discharge values from the 29 year data set is based on the goal of determining an annual average of groundwater recharge. For comparison, a recharge estimate using Eq 2, assuming the same chloride concentrations from the 2011-2012 sampling period and streamflow values from a year in the historical record with similar precipitation (1990 with 1969.8mm/yr) is shown below in Table 15.

1990 Chloride Mass Balance - Nabogo River Basin						
Month	P (m/m)	C_p (mg/L)	q (m/m)	C_s (mg/L)	C_{gw} (mg/L)	Q (m/mo)
Nov	8.9	0.4	5.70E+03	1	13.1	2.72E-04
Dec	33	0.4	1.30E+03	1.4	8.6	1.53E-03
Jan	0	0.4	5.18E+03	1.4	8.6	-2.34E-07
Feb	91.2	0.2	4.45E+03	1.6	3.8	4.80E-03
Mar	0	0.4	2.48E+03	2.7	5.5	-3.39E-07
Apr	45.9	0.5	4.40E+03	1.3	9.1	2.52E-03
May	130	0.23	1.29E+04	2.5	7.75	3.86E-03
Jun	67.6	0.4	1.04E+03	3.1	11.83	2.29E-03
Jul	97.9	0.4	5.96E+04	3.5	12	3.26E-03
Aug	228.6	0.4	6.94E+05	2.9	12.5	7.27E-03
Sep	311	0.4	2.49E+06	2	13	9.46E-03
Oct	55.7	0.4	6.46E+05	1.2	13.5	1.63E-03
Results					**Q (m/yr)**	**0.04**
	P (mm/yr)	**1068.82**			**Q (mm/yr)**	**36.9**
					Q (%/)(P/yr)	**3**

Table 15. Groundwater recharge estimates from the CMB in Nabogo River Basin based on data from Precipitation (P(mm/yr)), Chloride in precipitation (C_p (mg/L)), Streamflow discharge (q) (m/m)), Chloride in surface water (C_s (mg/L)), and Chloride in groundwater (C_{gw} (mg/L)). Recharge values (Q(m/mo)) are shown for each month and are summed for an annual total expressed in m/yr, mm/yr and as a percentage of annual precipitation (Q(%P/yr).

Table 13 shows the groundwater recharge estimate based on streamflow (q) and precipitation (P(mm/mo)) values from 1990. The difference between the recharge estimate generated by the CMB method during the 2011-2012 sampling period (37.06 mm/yr.) and the 2009 estimate (36.90 mm/yr.) is negligible (0.16mm/yr.) and the averages are considered a representative value for the CMB recharge estimate used in this study.

The use of the CMB method is suited to regions at high chloride concentration in precipitation and low recharge rates due to the analytical errors that are magnified as the limits of the concentration levels are reached (Gee, et. al, 2005). Although chloride concentrations are relatively low, the expected and computed recharge levels are correspondingly low, in part justifying the use of this method.

Chloride concentration data used in this method are based on values collected from seven of the many boreholes located within the Nabogo River Basin that served to represent the basin as a whole. Variation in borehole characteristics, especially water production and concentration of chloride, demonstrate the complexity of lithology within the basin. The similarities shown in the trend of increasing chloride concentration for each borehole from December to June demonstrates their value as a representative sample of basin characteristics.

The lack of a strong economic base associated with commercially viable minerals in this region is one of the main causes of the lack of funding and outside interests, and subsequently the data collected by government and private agencies. This may change as recently, interest in agribusiness has increased in this region and is of new interest to foreign investors for marketable cotton, mango and maize and shea production.

4.7 Stable Isotopes

Stable isotopic analysis of $\delta^{18}O$ and δD show evidence that recharge is occurring locally from meteoric waters. Precipitation samples collected during the sampling period fall along the LMWL with the exception of the rain sample collected on April 1, 2012. This sample is enriched in O18, suggesting evaporation of the raindrop. The monsoonal effect (Risi et al. 2008; Risi et al. 2010) can be used to explain the April 1 rain event. Other precipitation samples fall along the LMWL exhibiting depletion from possible rainout and continental effects. This is consistent with monsoonal moisture patterns in the region bringing moisture from the southwest.

4.8 Further discussion

Interviews with local foreign agriculture development parties reveal a trend in increasing interest in this area for commercial farming, especially for mango plantations, maize, cotton and rice and shea. Recently, a new mango plantation was developed in the basin, and is a popular business venture possibility for local entreprenuers. Within the Nabogo River Basin, there are two mango plantations that extract water directly from the Nabogo River for irrigation. Foreign investors are developing a growing industry in selling agricultural products such as fertilizers and seed to local farmers. There is a factory processing cotton in Tamale, fed by cotton grown commercially in the surrounding area, also being developed with increasing interest from foreign investors. The One Acre Fund has recently built an office in the Northern Region and has stated that crop yield in Northern Ghana is 20% of the yield being produced in neighboring

Burkina Faso, an interesting figure based on the fact that Burkina Faso is more arid than Northern Ghana, and has fewer tributaries to the Volta River. This increasing commercial interest can have an impact on the aquifer if groundwater sources are habitually used to sustain these farms in areas that are not close to the river. A complete water balance for this region is important to determine the sustainability of these practices.

4.9 Future Research

Defining the physical characteristics of this basin will be important to solving water resource issues as well as land use management, especially in response to questions being asked by the One Acre Fund, and by borehole exploration efforts.

A detailed examination of the possible reasons for the crop yield discrepancy between these neighboring countries could be beneficial to decrease the water stresses of this region. Cultural and physical factors should be considered.

DRI is currently training the GRWP in geophysical techniques and the information collected from this practice could help quantify some of the variables in the basin that are currently undefined or vague such as specific yield, transmissivity, storativity and degree of fractures in the aquifer.

5.1 Chapter Five - Conclusions

The importance of managing water resources in developing countries must be given high priority. Groundwater sustainability research in areas that have limited financial resources can be achieved by using low cost and efficient models of estimating recharge such as the Water Table Fluctuation Method and Chloride Mass Balance. As additional stresses are added to local water resources by increasing interest in commercial agriculture, it is important to look at the sustainability of these new environmental practices.

Recharge estimates generated in this study are comparable to estimates generated in the region and are comparable to the expected estimates for fractured rock aquifers. These methods have been rated highly at many sites for accuracy in comparison of other methods and value has been placed on their use as an efficient cost effective tool for estimating recharge (Sibanda et al. 2009). Estimates generated by the CMB method in the Nabogo Basin yielded the average rate of 37.06mm/yr or 3% of annual precipitation and the WTFM yielded a range of 10-143 mm/yr or 1-13 % of annual precipitation.

This study has also shown that there are limitations to using both CMB and WTFM for estimating recharge, specifically when values for specific yield are unknown and time constraints are applied to the sampling period. These margins of error are reduced when using the two methods in conjunction to justify specific yield and reduce the uncertainty associated with using only one method.

Appendix A. Field Sampling Methodology

A.1 Data Logger/Water Level and Pressure Data Collection

A.2 Schlumberger Long term ground Water Monitoring Mini Diver –

Pressure Accuracy +/- 0.5cm/H20

Temperature Accuracy +/- 0.2 ^{o}C

http://www.swstechnology.com/groundwater-monitoring/groundwater-dataloggers/mini-diver

A.3 Field Sampling Methodology

A.3.1 Surface Water

Though many of the smaller tributaries were dry during the sampling period, the major tributary was accessible at several points and was sampled, mainly at the bridge crossing in Nabogo (N 09^{o} 44.415' W 000^{o} 49.426') and at the tributary at the White Volta River (N 09^{o} 41.417' W 000^{o} 58.488'). All surface water samples were collected using nitrile sterile sampling gloves and HDPE sample bottles (30ml) and (10ml) for chloride and stable isotopes, respectively, that were triple rinsed with stream water, before the sample was collected. Theses sample bottles were labeled for location and date and stored in the freezer until they were shipped for laboratory analysis at DRI in Reno. Samples were collected at the same time for stable isotopes in 10ml HDPE bottles ensuring that no head space was left in the sample bottle.

Duplicate samples were taken at some locations as well as split samples. Field titration values for chloride were also obtained using a hand held Hach Titrator, the methodology is described below.

A.3.2 Groundwater-

Through a working relationship with DRI in Reno, and World Vision in Ghana, I was given access to certain wells that they had drilled in the northern region. I chose seven wells that were distributed throughout the basin from the wells that they had available. All the wells sampled were being utilized in the villages located near them. The wells chosen were located in: Kadia (N 09^{o} 54.172' W 000^{o} 51.127') located along the Bolgatonga Road on the northwest edge of the basin, Pishigu (N 09^{o} 58.233' W 000^{o}39.337') on the road heading east to Sung from Pishigu near the Northeastern edge of the basin, Galwie (N 09^{o} 37.334' W 000^{o}26.913') located on the southeastern border of the basin, Tamaligu(N 09^{o} 50.855' W 000^{o} 44.075') and Bagurugu(N 09^{o} 53.799' W 000^{o} 42.736') north centrally located in the basin, Zoggu (N 09^{o} 40.010' W 000^{o} 42.624') south centrally located and Kanshegu (N 09^{o} 34.494' W 000^{o} 50.038') on the western edge. At each borehole, a translator was hired to meet with the assemblyman and chief of each surrounding village to explain the work being done at the borehole and to gain community support. A time was arranged when women in the village normally come to collect water so that sampling of the well would not result in wasting a community resource. After the initial arrangements were made, regular visits to the boreholes were possible. Although some discharge rates were available through World Vision, these rates were considered maximum yield rates, so a known volume rate was chosen as a preferred method. At each borehole, a tape was used to measure the depth of the borehole, the top of the water table was not known, and the assumption was made that the length of the borehole was saturated to calculate the amount to pump to ensure that groundwater was being sampled.

Volume of the Borehole (V) was calculated as:

$$V=\pi r^2 h$$

Where:

$\pi=3.14$

r=.063m {diameter of well is 126mm converted to m by (126mm)(.001)=.126m/2 = .063m}

h=(x)m

Volume (one well volume) converted to Liters : (V)(1000L)

To purge three well volumes (V)(1000)(3)

A known volume bucket was used to count the liters pumped until the desired volume was reached, then sampling procedure began.

A.3.3 Precipitation

Precipitation samples were taken during rain events using plastic buckets placed on an elevated surface to prevent outside sources of chloride from contaminating the sample that may have originated from splashing of nearby surfaces. These buckets were rinsed three times before samples were taken using sterile nitrile gloves. 30ml and 10ml HDPE sample bottles were triple rinsed with this collected water to be processed for chloride and isotopes, respectively. It was ensured that there was no head space in the 10ml sample bottles to be used to analyze for stable isotopes. The 30ml sample bottles were frozen until sent to DRI in Reno for laboratory analysis. The 10 ml sample bottles were kept at room temperature.

A.4 Field Titration

A.4.1 World Vision Lab Feb. 8 2012

A.4.1.1Calibration of Hach Titrator and Hanna Meter

Hanna meter was calibrated for pH only, waiting on solution containers for ppm and EC calibration solutions to calibrate.

A.4.1.2 Calibration of the Hach Digital Titrator

The Mercuric Nitrate Method 8206 was followed using the Hach Digital Titrator Model 16900 Manual, pgs. 67-68.

Summary of the Mercuric Nitrate Method (from Hach Manual)

"When using Mercuric Nitrate Standard Solution, the sample is diluted under acidic conditions in the presence of diphenylcarbazone indicator. Upon addition of a slight excess of mercuric ion, a pink-purple complex is formed with the indicator, signaling the end point." (N $Hg(NO_3)_2$)

Table 1 for Method 8206 is provided to select the correct cartridge for the expected amounts of chloride as well as the corresponding Digit Multiplier.

Range (mg/L as Cl^-)	Sample Volume (ml)	Titration Cartridge (N $Hg(NO_3)_2$)	Digit Multiplier
10-40	100	0.2256	0.1
40-160	25	0.2256	0.4
100-400	100	2.256	1.0
200-800	50	2.256	2.0
500-2000	20	2.256	5.0
1000-4000	10	2.256	10.0
2000-8000	5	2.256	20.0

Appendix A, Accuracy check and Standard Additions in the Hach Manual states: ‘if the actual number of digits required is within 1% of the expected number of digits, the analyst can conclude the answer for the sample is accurate and the reagents, apparatus, and method used are working properly.”

For the calibration of the Hach Titration Unit, a solution was made of 1.5088 g of NH_4Cl dissolved in 100 ml of Deionized water (DI) to achieve 10,000 ppm Cl^-.
1 ml of this solution was then diluted to 100 ml with DI to achieve 100 ppm Cl^-.

Using 100 ml sample volume of 100 ppm Cl^- calibration solution in a 250 ml Erlenmeyer flask a packet of Diphenylcarbazone Powder Pillow was added and swirled to dilution. Using the Hach Digital Titrator, the Hach Digital Titration Cartridge Mercuric Nitrate 2.256 +-0.005 N was inserted as well as a clean delivery tube, which was flushed with titrant so that no air bubbles were present. The counter was reset to zero before drops were added to the Erlenmeyer flask while swirling. Three tests were performed, per Table 1, the Digit Multiplier 1.0 was used yielding the following results

1st test: 94 drops of titrant were added to reach end color X (1.0) = (94 mg/L as Cl^-)

2nd test: 89 drops of titrant were added to reach end color X (1.0) = (89 mg/L as Cl^-)

3rd test: 94 drops of titrant were added to reach end color X (1.0) = (94 mg/L as Cl^-)

Results were averaged to (92.3 mg/L as Cl^-). Although this result is not within the 1% range of the calibration solution (100 mg/L as Cl^-) the results given were uniformly within a 10% range and can be assumed accurate within that range.

Calibration solution of 25ppm Cl^- was mixed by diluting 0.25 ml of the 10,000 ppm Cl^- solution in 100 ml DI. Using 100 ml sample volume of the 25 ppm Cl^- calibration solution in a 250ml Erlenmeyer flask a packet of Diphenylcarbazone Powder Pillow was added and swirled to dilution. Using the Hach Digital Titrator, the Hach Digital Titration Cartridge Mercuric Nitrate 0.2256 +- 0.0010 N was inserted as well as a clean delivery tube, which was flushed with titrant so that no air bubbles were present. The counter was reset to zero before drops were added to the Erlenmeyer flask while swirling. Two tests were performed, per Table 1, the Digit Multiplier 0.1 was used yielding the following results:

1st test: 246 drops of titrant were added to reach the end color X (0.1) = (24.6 mg/L as Cl^-)

2nd test: 244 drops of titrant were added to reach the end color X (0.1) = (24.4 mg/L as Cl^-)

Results were averaged to (24.5 mg/L as Cl^-). Although this result is not within the 1% range of the calibration solution (25 mg/L as Cl^-) the results given were uniformly within a 2% range and can be assumed accurate within that range.

Calibration solution of 10 ppm Cl^- was mixed by diluting 0.1 ml of the 10,000 ppm Cl^- solution in 100 ml DI. Using 100 ml sample volume of the 10 ppm Cl^- calibration solution in a 250 ml Erlenmeyer flask a packet of Diphenylcarbazone Powder Pillow was added and swirled to dilution. Using the Hach Digital Titrator, the Hach Digital Titration Cartridge Mercuric Nitrate 0.2256 +- 0.0010 N was inserted as well as a clean delivery tube, which was flushed with titrant so that no air bubbles were present. The counter was reset to zero before drops were added to the Erlenmeyer flask while swirling. Three tests were performed, per Table 1, the Digit Multiplier 0.1 was used yielding the following results:

1st test: 94 drops of titrant were added to reach end color X (0.1) = (9.4 mg/L as Cl^-)

2nd test: 85 drops of titrant were added to reach end color X (0.1) = (8.5 mg/L as Cl^-)

3rd test: 102 drops of titrant were added to reach end color X (0.1) = (10.2 mg/L as Cl^-)

Results were averaged to (9.4 mg/L as Cl^-). Although this result is not within the 1% range of the calibration solution (10 mg/L as Cl^-) the results given were uniformly within a 6% range and can be assumed accurate within that range.

Calibration solution of 25 ppm Cl^- was mixed by diluting 0.25 ml of the 10,000 ppm Cl^- solution in 100 ml DI. Using 25 ml sample volume of the 25 ppm Cl^- calibration solution diluted to 100 ml with DI in a 250 ml Erlenmeyer flask a packet of Diphenylcarbazone Powder Pillow was added and swirled to dilution. Using the Hach Digital Titrator, the Hach Digital Titration Cartridge Mercuric Nitrate 0.2256 +- 0.0010 N was inserted as well as a clean delivery tube, which was flushed with titrant so that no air bubbles were present. The counter was reset to zero before drops were added to the Erlenmeyer flask while swirling. Two tests were performed, per Table 1, the Digit Multiplier 0.4 was used yielding the following results:

1st test: 65 drops of titrant were added to reach end color X (0.4) = (26 mg/L as Cl^-)

2nd test: 70 drops of titrant were added to reach end color X (0.4) = (28 mg/L as Cl^-)

Results were averaged to (27 mg/L as Cl^-). Although this result is not within the 1% range of the calibration solution (25 mg/L as Cl^-) the results given were uniformly within a 8% range and can be assumed accurate within that range.

Calibration solution of 25 ppm Cl^- was mixed by diluting 0.25 ml of the 10,000 ppm Cl^- solution in 100 ml DI. Using only 50 sample volume of the 25ppm Cl^- calibration solution in a 250 ml Erlenmeyer flask a packet of Diphenylcarbazone Powder Pillow was added and swirled to dilution. Using the Hach Digital Titrator, the Hach Digital Titration Cartridge Mercuric Nitrate 2.256 +-0.005 N was inserted as well as a clean delivery tube, which was flushed with titrant so that no air bubbles were present. The counter was reset to zero before drops were added to the Erlenmeyer flask while swirling. One test was performed, per Table 1, the Digit Multiplier 2.0 was used yielding the following results:

1st test: 28 drops of titrant were added to reach end color X (2) = (56 mg/L as Cl^-)

Results were within a 26 mg/L as Cl^- over 100% range. It is not recommended that this cartridge be used for results expected to be less 40 mg/L as Cl^- .

Overall laboratory tests show that the titrator can be used within an accuracy range of 2-10%, excluding cases where the chloride concentration is low, where the Mercuric Nitrate 2.256 +-0.005 N cartridge should not be used.

Appendix B. Laboratory Methodology

Desert Research Institute, Reno, NV

B.1 Chloride

Chloride analyses were performed at the Desert Research Institute in Reno, NV using a Dionex ICS 2000 Chromatography System with Chromeleon Software Version 6.6 AS14A column and guard Column accuracy is verified as 90-110% (+/-10%) based on calibration tests.

B.2 Stable Isotopes

Stable isotope analyses were performed using a Micromass IsoPrime stable isotope ratio mass spectrometer. Water δD analyses are performed using the method of Morrison et al. (2001). δD results are reported in units of ” vs. VSMOW. An uncertainty of ±1” (1 standard deviation) is recommended. Water δ18O analyses are performed using the CO2 - H2O equilibration method of Epstein and Mayeda (1953). δ18O results are reported in units of ” vs. VSMOW. An uncertainty of ±0.1” (1 standard deviation) is recommended.

B.3 References:

EPA/600/R-93/100 August 1993, *Methods for the determination of Inorganic Substances in Environmental Samples* United States Environmental Protection Agency, Office of Research and Development, Washington, DC 20460, Method 300.0, Determination of Inorganic Anions by Ion Chromatography, Pages 300.0-1 to 300.0-30.

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Appendix C. Chloride Concentration Results
Laboratory Analysis at DRI and Field Titration

C.1 Precipitation

Sample Location	Sample Date	DRI Laboratory (mg/l) EPA 300.0	Field Titration (mg/l) as an average of field tests	Difference between methods (mg/l)
Tamale	20-Feb-12	0.2	3.15	3.0
Tamale	20-Feb-12	7.6	1.4	6.2
Tamale	1-Apr-12	0.9	0.8	0.1
Tamale	2-Apr-12	0.3	0.9	0.6
Tamale	8-Apr-12	0.3	0.9	0.6
Tamale	25-May-12	0.23		
Tamale	25-May-12	0.23		

C.2 Surface Water

Sample Location	Sample Date	DRI Laboratory (mg/l) EPA 300.0	Field Titration (mg/l) as an average of field tests	Difference between methods
Nab v at Nabogo	30-Nov-11	1.0		
WV v number 2	23-Nov-11	1.0		
Gus v	28-Nov-11	0.7		
WV v	29-Nov-11	1.3		
Pis str near stream	23-Nov-11	0.9		
WV v at number 2	20-Dec-11	0.7		
BV v	24-Dec-11	0.2		
Gus sw	28-Dec-11	0.8		
Zog str number 1	17-Dec-11	2.4		
Nab v	31-Dec-11	0.7		
Gal SD	30-Dec-11	1.1		
Nab v at nabogo	20-Dec-11	0.8		
WV v number 1	20-Dec-11	1.4		
Zog str number 2	17-Dec-11	3.6		
Zog str	2-Dec-11	1.8		
Nab V	17-Feb-12	1.6		
WV V	12-Feb-12	1.0		
Nab v at Nabogo	16-Feb-12	1.6		
Nab v at Nabogo	21-Feb-12	2.1	2.1	0.5
Nab v	8-Mar-12	1.5	1.9	0.9

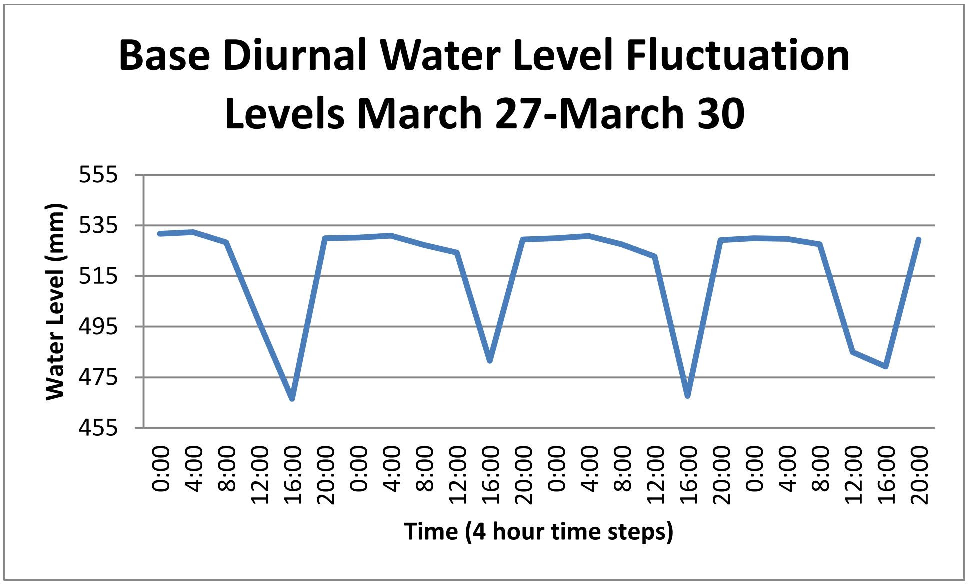
Gal sd	4-Mar-12	2.7	2	0.4
Nab v	9-Mar-12	1.6	3.45	1.4
Gal sd	31-Mar-12	4.9	3.05	1.6
WV v	2-Apr-12	1.4	3.4	0.7
Nab v at Nabogo	10-Apr-12	0.7	3.35	1.8
Nab v at WV	2-Apr-12	1.7		
NR N	1-May-12	3.4	2.1	0.7
NR N	2-May-12	1.6	3.95	3.3
NR N	2-Jun-12	3.1	2.77	1.1

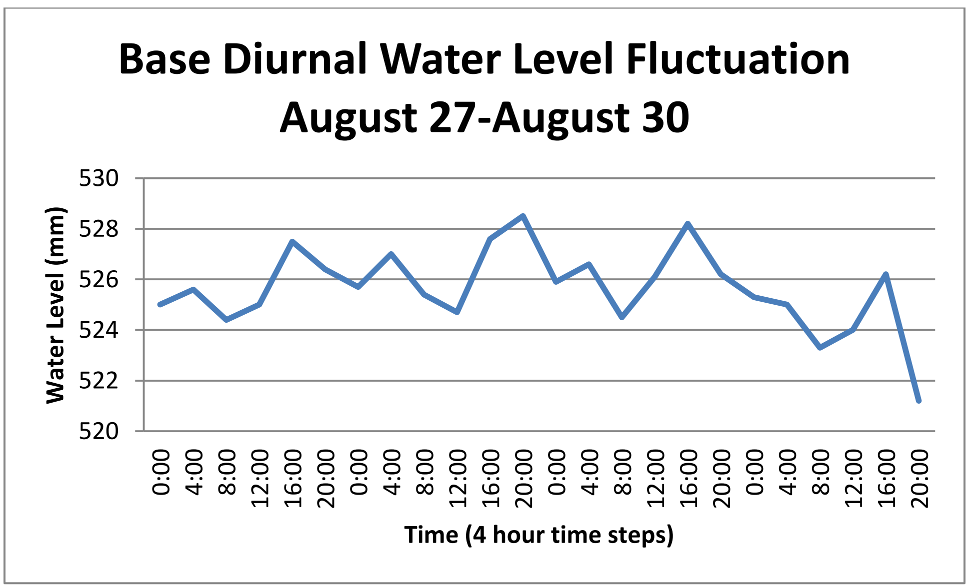
C.3 Groundwater

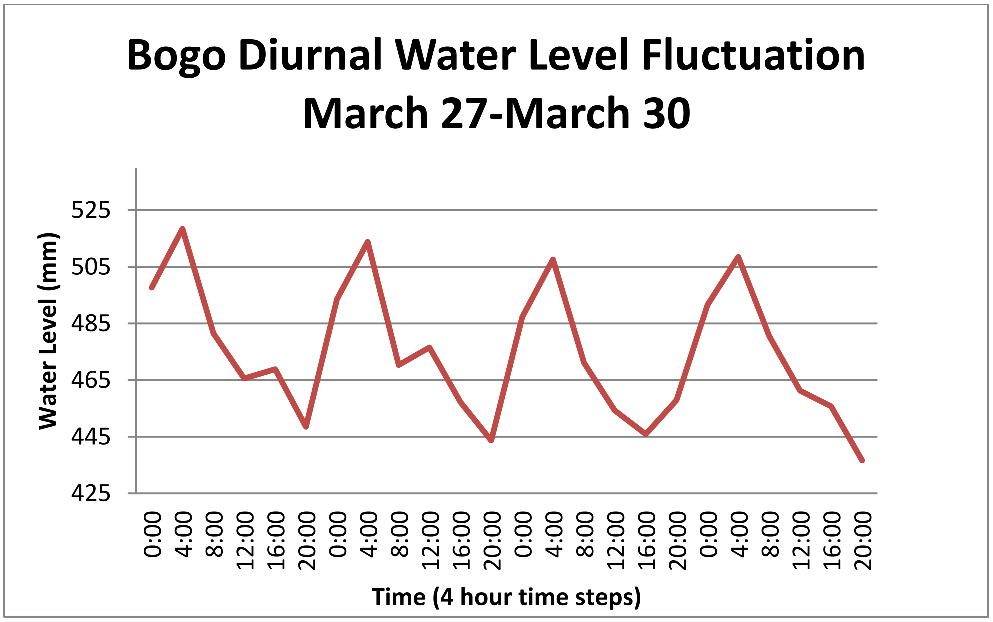
Sample Location	Sample Date	DRI Laboratory (mg/l) EPA 300.0	Field Titration (mg/l) as an average of field tests	Difference between methods
GalGW	31-Mar-12	142	84	58.0
PisGW	11-Feb-12	5.8	9.25	3.5
Bag GW	16-Feb-12	0.9	0.65	0.3
Gal GW	9-Feb-12	9.4	45.5	36.1
Kad GW	11-Feb-12	36.6	45.5	8.9
Zog GW	14-Feb-12	4.0	15.65	11.7
Tam GW	16-Feb-12	2.1	0.75	1.4
Kan GW	14-Feb-12	0.8	2	1.2
Kad GW	28-Dec-11	27.9		
Pis GW	31-Dec-11	4.8		
Gal GW	30-Dec-11	6.7		
Zog GW	17-Dec-11	0.8		
Kan GW	31-Dec-11	1.1		
Bag GW	10-Apr-12	1.4	0.7	0.7
Tam GW	10-Apr-12	4.8	1.4	3.4
Kan GW	2-Apr-12	3.0	2.55	0.5
Kad GW	4-Apr-12	65.0	48.5	16.5
Pis GW	4-Apr-12	15.5	9.15	6.4
Bag GW	9-Mar-12	1.4		
Gal GW	4-Mar-12	62.9	61.25	1.7
Zog GW	5-Mar-12	9.7	16.35	6.7
Kad GW	6-Mar-12	43.2	50	6.8
Kan GW	8-Mar-12	2.0	1.3	0.7
Bag GW	23-Nov-11	1.8	0.75	1.1
Zog GW	2-Dec-11	10.4		
Kad GW	30-Nov-11	94.4		
Gal GW	22-Nov-11	24.4		
Pis GW	6-Mar-12	11.6	10.1	1.5
GAL GW	30-Apr-12	94.5	81	13.5

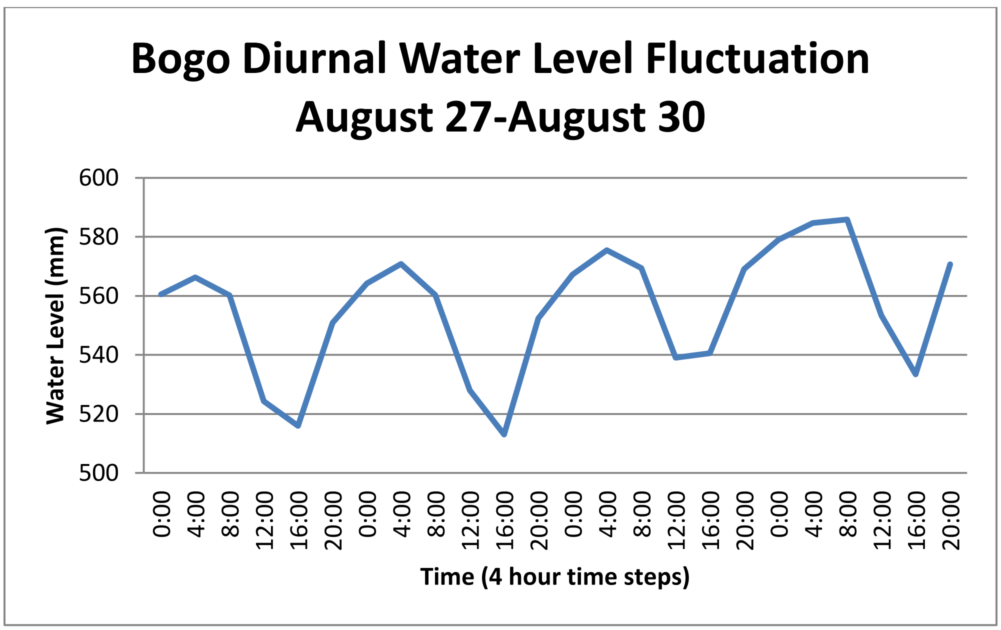
BAG GW	1-May-12	2.2	0.9	1.3
TAM GW	1-May-12	5.0	1.55	3.5
ZOG GW	2-May-12	21.3	18.2	3.1
KAN GW	3-May-12	2.5	1.6	0.9
KAD GW	5-May-12	67.0	46	21.0
BAG GW	2-Jun-12	2.4	7	4.6
KAD GW	3-Jun-12	67.3	50	17.3
PIS GW	3-Jun-12	18.4	15.4	3.0
KAN GW	6-Jun-12	3.2	1.6	1.6
ZOG GW	6-Jun-12	23.3	21	2.3

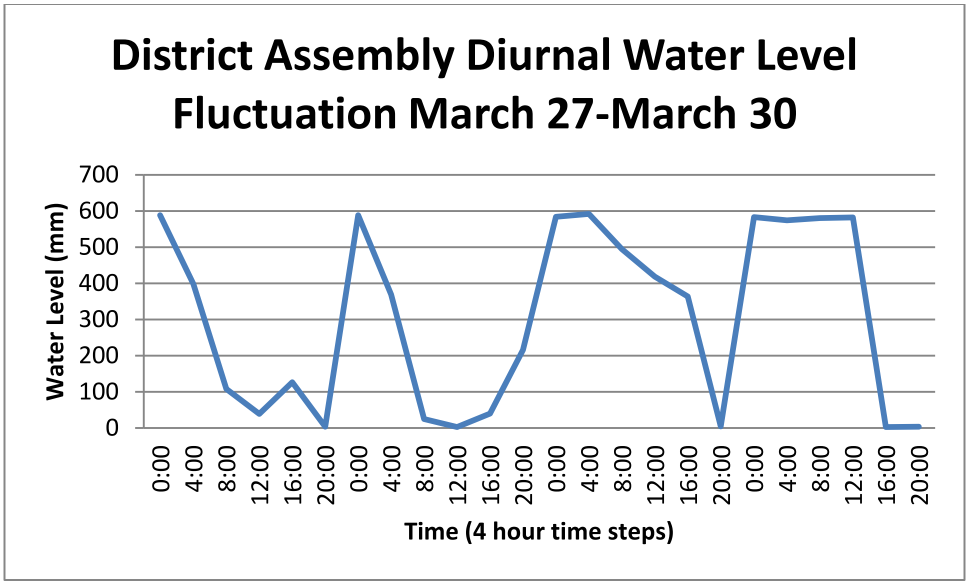
Appendix D. Diurnal Water Level Fluctuation Plots

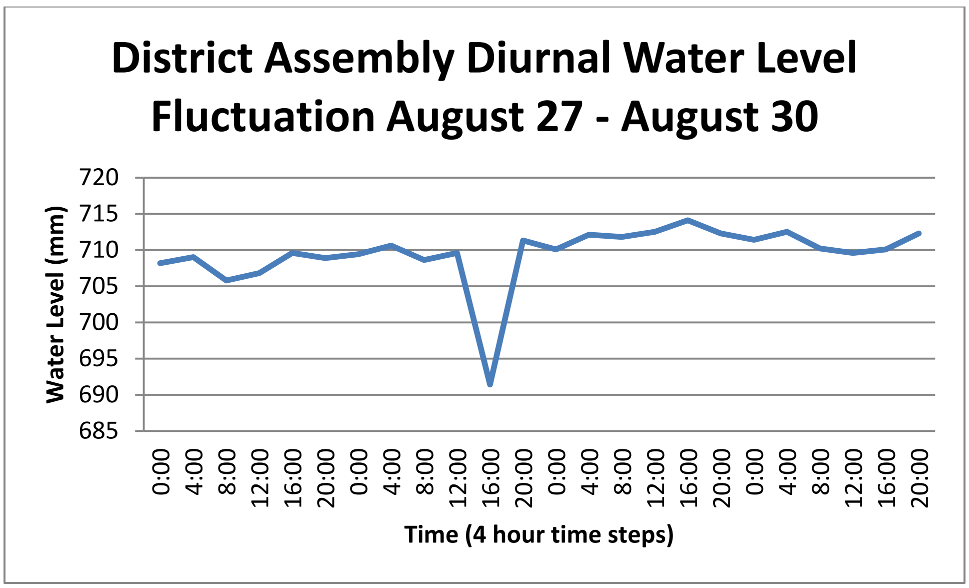


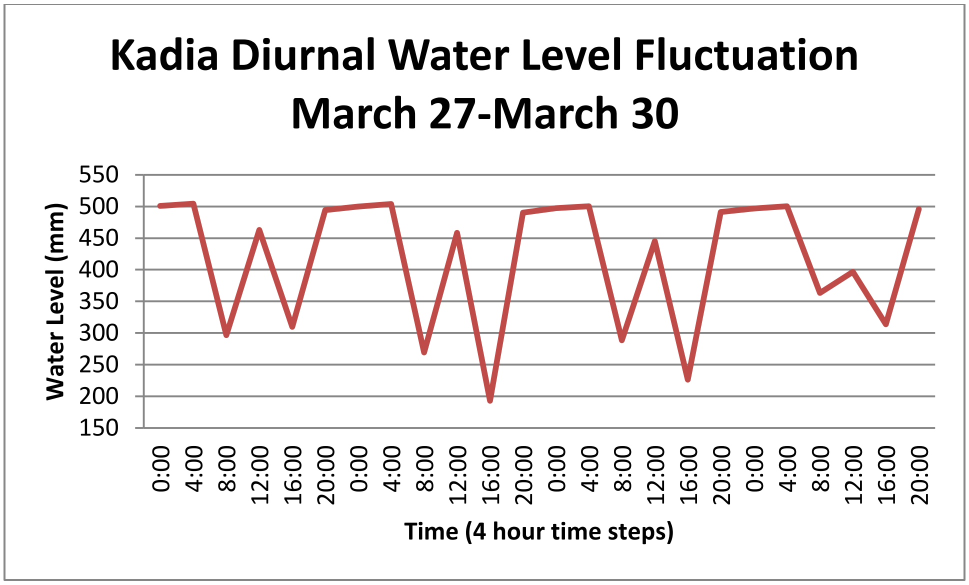


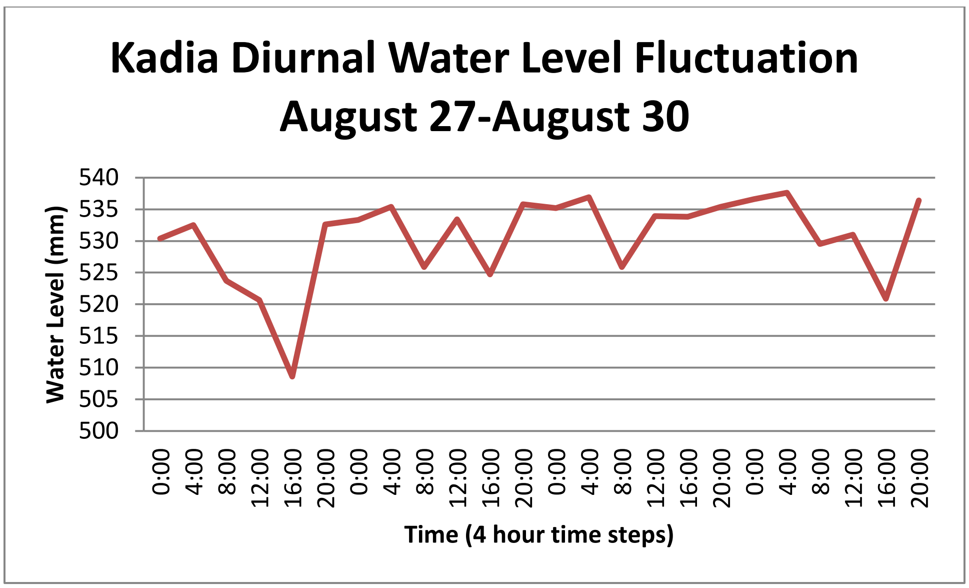

Bogo Diurnal Water Level Fluctuation
March 27-March 30
Water Level (mm)
525
505
485
465
445
425
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
Time (4 hour time steps)


Bogo Diurnal Water Level Fluctuation
August 27-August 30
Water Level (mm)
600
580
560
540
520
500
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
Time (4 hour time steps)


District Assembly Diurnal Water Level Fluctuation March 27-March 30
Water Level (mm)
700
600
500
400
300
200
100
0
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
Time (4 hour time steps)


District Assembly Diurnal Water Level Fluctuation August 27 - August 30
Water Level (mm)
720
715
710
705
700
695
690
685
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
Time (4 hour time steps)


Kadia Diurnal Water Level Fluctuation
March 27-March 30
Water Level (mm)
550
500
450
400
350
300
250
200
150
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
Time (4 hour time steps)


Kadia Diurnal Water Level Fluctuation
August 27-August 30
Water Level (mm)
540
535
530
525
520
515
510
505
500
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
Time (4 hour time steps)

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Education

University of Nevada, Las Vegas — Las Vegas, NV
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Rotary International — Tamale, Ghana
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United States Peace Corps — Rep. of Cape Verde
2006-2008
Environmental Education Volunteer

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Mudlogger

Professional Activities

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Fog harvesting as a potential source of groundwater recharge in the Cape Verde Islands

University of Nevada Las Vegas – Geosymposium
2009
Fog harvesting as a source of artificial recharge in the Cape Verde Islands

Research Interests

My academic research has focused on water resource management solutions for developing nations, and secondarily on artificial and natural recharge of groundwater. I also have an interest in the exploration of economically viable minerals and resources.