Groundwater recharge assessment in northern Ghana using soil moisture balance and chloride mass balance

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ABSTRACT
Two groundwater recharge assessment methods were applied in northern Ghana as part of a regional hydrogeological synthesis supporting groundwater resource development and management. Recharge was first estimated through a soil moisture balance that suggests a single recharge period mainly controlled by the intensity and duration of rainfall and for which recharge ranges from 12-268 mm/y. Groundwater recharge was also estimated through the chloride mass balance (CMB) method using rainfall samples and pore water from soil samples collected in sixteen unsaturated-zone profiles. CMB recharge estimates range from 11-73 mm/y and reflect variations in local conditions.

RÉSUMÉ
Deux méthodes d'estimation de la recharge ont été utilisées dans le nord du Ghana dans le cadre d'une synthèse hydrogéologique régionale supportant le développement et la gestion des ressources en eau souterraine. La recharge a d'abord été estimée par bilan hydrologique suggérant une période de recharge principalement contrôlée par l'intensité et la durée des précipitations pour laquelle la plage de recharge est de 12-268 mm/an. La recharge a également été estimée par bilan de masse des chlorures à l'aide d'échantillons de précipitations et d'eau interstitielle provenant d'échantillons de sol. Ces estimés de recharge varient entre 11-73 mm/an et reflètent des conditions locales variables.

1 INTRODUCTION

While groundwater recharge is one of the most important parameters required to support sustainable management of groundwater resources, it is one of the most difficult to evaluate accurately, due to the numerous factors involved in recharge processes. Various methods exist to estimate recharge, each with their own advantages and limitations. Reviews of methods applicable to semi-arid and arid environments state the importance of using a variety of independent techniques, as they can complement each other in terms of time and space scales (Scanlon *et al.*, 2006; Kinzelbach *et al.*, 2002; Simmers *et al.*, 1988).

In northern Ghana, a few local studies have provided estimates of recharge (Martin, 2006; Pelig-Ba, 2004) but regional recharge has not been investigated so far. Two recharge estimation methods, the soil moisture balance and the chloride mass balance have thus been implemented as part of a larger project.

1.1 HAP brief description

The Hydrogeological Assessment Project (HAP) of the Northern Regions of Ghana aims at collecting and analysing scientific data on groundwater to improve groundwater resource management and development in the three northern regions of Ghana. As part of its main objectives, the HAP was expected to provide key information on groundwater quantity for groundwater resources planning in northern Ghana.

1.2 Purpose and scope

This study mainly aims at providing a reliable range of regional recharge estimates in northern Ghana to support future sustainable groundwater development and its management. The soil moisture balance (SMB) method was first implemented to provide first order estimates as it required readily available climate data. Local direct recharge was later evaluated with the unsaturated zone chloride mass balance (CMB) method. The latter method was chosen to provide independent estimates as it has been widely used in semi-arid regions and is relatively low-cost and easy to implement. To complement local estimates derived from the unsaturated zone and allow a better assessment of spatial variability of recharge, the saturated zone CMB method is also being implemented through shallow groundwater sampling from 50 hand dug wells. The latter work is still on-going and will thus not be discussed in this paper.

After presenting northern Ghana hydrogeological contexts, this paper describes the methodology and discusses results of the two recharge estimation methods implemented to date (SMB and unsaturated zone CMB). Results are compared with regards to the limitations of each method in order to guide future work related to groundwater recharge. Since saturated zone CMB results were not available at the time of writing, spatial variation of recharge is only briefly discussed.

2 DESCRIPTION OF STUDY AREA

2.1 Physical setting

The study area roughly consists of the upper half of Ghana and is approximately bounded by latitudes 7°58'N and 11°11'N and longitudes 2°57'W and 0°34'E (figure 1). It covers 97 704 km^2 and comprises the three northern regions of Ghana, namely the Upper East Region, Upper West Region and Northern Region.

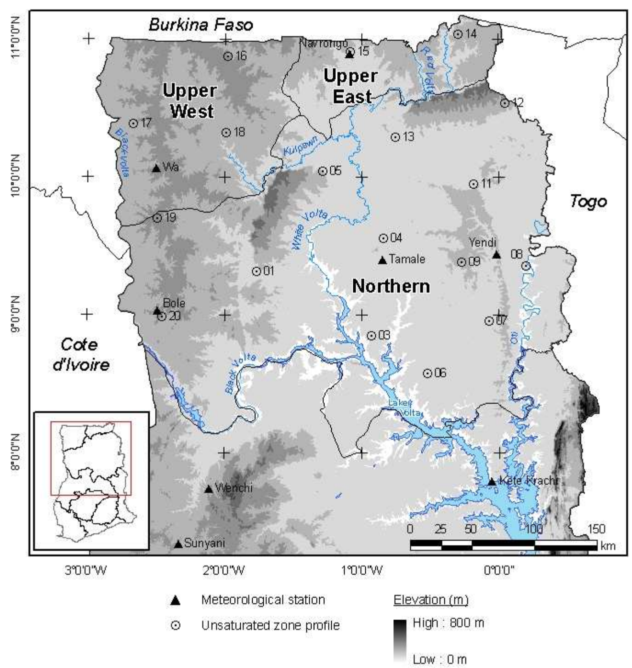

Figure 1 – Topography of northern Ghana; meteorological stations and unsaturated zone profiles are also indicated.

The whole country is generally classified as lowland, with less than 10 % of the country above 300 m elevation. In the north of the country the highest areas (average ~ 500 m) are located around the Gambaga and Damongo scarps. The lowest areas are found in the middle of the Voltaian Sedimentary Basin, around Tamale (figure 1). The whole study area is drained by the Volta River system which comprise the Red, Black and White Volta Rivers as well as the Oti River. High seasonal flow variation is observed in the northern regions where many streams and rivers are intermittent.

2.2 Climate

The climate in the north of the country is generally considered semi-arid with only one rainy season (~ late May to October) and temperatures commonly range from 20 °C to 35 °C. Average annual rainfall for the 1971-2007 period ranges from 735 mm in the extreme north to approximately 1 240 mm in the south-eastern portion of the study area. The dry season is generally longer and more intense with increasing latitude.

2.3 Geological and hydrogeological settings

At the regional scale, two major hydrogeological contexts can be distinguished in northern Ghana on the basis of geology: the Voltaian Sedimentary Basin (VSB) and the Precambrian Basement. The latter mainly consists of rocks of Proterozoic age which have been folded, metamorphosed and intruded by granitoids during and after their emplacement. Groundwater occurrence and flow in this context are mainly controlled by secondary porosity as a result of chemical weathering, faulting and fracturing. The VSB, which developed in a gentle synform depression of the West African Craton, contains a thick succession (up to 700 m) of relatively non deformed Neoproterozoic to Palaeozoic consolidated sedimentary rocks (mainly sandstone, shale, mudstone, conglomerate and limestone). Groundwater in the VSB mainly occurs and flows in fracture zones, and along bedding planes for some areas, since the primary porosity of these rocks has often been destroyed through consolidation and cementation. Most formations in northern Ghana are overlain by a weathered layer (regolith) varying in thickness, texture and composition. Available borehole data reveals a regolith thickness ranging from 2-46 m with an average 24.5 m for the Precambrian Basement and from 3-48 m with an average 17.3 m for the VSB. Infiltration would both occur by diffuse (direct) recharge and localized (indirect) recharge (e.g. from streams, accumulated run-off in depressions, preferential flow through fractures …). Their relative importance would vary according to different factors (weathering, geology, geomorph. …) but previous studies in similar contexts (Martin, 2006; Sukhija *et al.*, 2003) suggest that localized recharge would predominate.

The main aquifer system in the Precambrian basement usually consists of the lower part of the weathered layer (regolith aquifer) and the upper part of bedrock (fractured rock aquifer), which complement each other in terms of permeability and storage. The upper, less permeable, part of the regolith can act as a semi-confining layer because of its higher secondary clay content. The continuity of aquifers would vary laterally with geomorphology, degree/connectivity of fractures and variability of the hydraulic link between fractured bedrock and regolith. It would thus be possible to encounter local flow systems of limited area, especially for the regolith.

In the Voltaian Sedimentary Basin, the regolith is reported to be often unsaturated and would thus only locally provide minor groundwater (Acheampong and Hess, 1998). The productive aquifer thus generally consists of the fractured bedrock. Fracture zones are generally developed at depths greater than 20 m below ground surface (Acheampong, 1996). While required yields for rural supplies are obtained above 100 m depth, production potential from deeper fractures has not been investigated thoroughly. Fracture characteristics such as frequency, aperture and connectivity can substantially vary over small distances, making it difficult to locate laterally extensive aquifers. The low fracturing observed in some VSB rocks would suggest that the importance of localized recharge through preferential pathways would be lower than in the Precambrian Basement.

3 METHODOLOGY

3.1 Soil Moisture Balance

This method estimates groundwater recharge as the residual of all other fluxes that can be measured or estimated more easily. The relation between fluxes is:

$$P = Q + ET + R + \Delta S \quad [1]$$

where P is rainfall, Q surface run-off, ET evapotranspiration, R groundwater recharge and ΔS the change in water storage in the saturated and unsaturated zones.

While rainfall was readily available for calculations, run-off and ET had to be estimated. The Penman-Monteith method recommended by the Food and Agriculture Organisation (FAO) was used to estimate potential ET as its validity has been demonstrated in humid and dry climates (Allen et al., 1998). Incomplete streamflow datasets and lack of reliable data on soil texture and crop characteristics in northern Ghana did not allow estimation of reliable run-off values for each meteorological station. A constant run-off coefficient of 12.5 % of annual rainfall was thus derived from previous studies in Ghana (Acheampong, 1996; Andreini *et al.*, 2000; Darko and Krasny, 2003; Friesen *et al.*, 2005; Martin, 2006).

3.1.1 Climate data

Daily climate data was available for eight meteorological stations within or near the northern regions: Navrongo, Wa, Bole, Tamale, Yendi, Kete-Krachi, Wenchi and Sunyani (figure 1). The dataset, which covered the 2000-2005 period, included the following variables: temperature, rainfall, relative humidity, wind speed, sun hours. As some daily values were missing, gap filling was done using measurements from nearest neighbouring stations and monthly average data observed at the gap filled station with a constant ratio correction (Gong, 2004).

3.1.2 SMB model

Various conceptual models have been developed to represent soil water storage in the upper layer of soil. For this study, an improved soil moisture balance model was used (Rushton *et al.*, 2006). This model notably introduces a modification for near surface soil storage of water (NSSS) whose aim is to retain a certain amount of water after a significant rainfall event when soil moisture deficit is greater than the readily available water. This allows a more realistic response by making some water available for evapotranspiration on subsequent days instead of being all allocated to reduce soil moisture deficit. The model also takes into account soil water stress by considering soil moisture distribution in terms of total and readily available water, which allows the adjustment of transpiration and evaporation rates as soil water is depleted. While this model can also take into account the influence of the different characteristics of each crop (i.e. length of crop development stages, crop height, crop distribution & density), the lack of readily available data on crops did not allow such an adjustment.

3.2 Chloride mass balance

The CMB method uses chloride (Cl) as a natural conservative tracer to distinguish downward soil-water flux from evapotranspirative loss as it does not evaporate from soil surface and vegetation does not take up significant quantities. Input of Cl occurs at the soil surface both as dry fallout and rainfall. For this study, it was assumed that Cl remains inert during atmospheric processes and that only solutes deposited during the rainy season (both wet and dry deposition) form the effective solute load for CMB calculations (Edmunds and Gaye 1994). Dry deposition during the dry season is likely to be in a quasi-steady state, in which the amount of dust deposited is equal to that taken up (Edmunds *et al.*, 2002). The application of the CMB method involves the following assumptions (Wood, 1999):

- Flow is 1D, vertically downward, piston-type (i.e. no preferential flow and dispersion & diffusion are negligible compared to vertical convection);
- Cl in pore water originates only from atmospheric Cl flux (i.e. Cl input from run-on/run-off and underlying or adjacent aquifers is unaccounted for);
- Cl is conservative in the system;
- Cl mass flux is in steady state.

Assuming all assumptions are verified, local direct recharge (R) can be expressed by:

$$R = P \cdot Cl_P / Cl_S \quad [2]$$

where P is the average annual rainfall (mm), Cl_S is the average unsaturated zone Cl concentration (mg/L) and Cl_P is the average Cl concentration in rainfall (mg/L). Another approach, using Cl concentrations from the saturated zone instead of the unsaturated zone, allows estimation of spatially average recharge considering both diffuse and localized input. This approach will be used with results from an upcoming shallow groundwater sampling. The CMB method has been used before in West Africa and in other semi-arid regions of the world and a detailed description can found in literature (Allison *et al.*, 1994; Cook *et al.*, 1992; Murphy *et al.*, 1996; Eriksson and Khunakacem, 1969; Wood, 1999).

3.2.1 Rainfall data

Atmospheric Cl deposition was estimated from rainfall samples collected at 8 meteorological stations in northern Ghana. Rainfall events were sampled directly from rain gauges into sterile containers obtained from the lab. Samples were sealed after collection and kept cool until shipment to the SGS Laboratory in Tema (Ghana), where they were analyzed for Cl by colorimetry. Due to project constraints, only major events of the 2007 rainy season were sampled, which represented 39-66 % of annual average rainfall at the stations. Also, nitrate in rainfall was only analyzed for a limited number of samples. However, at the time of writing, rainfall sampling was being pursued for 2008 and 2009, so it will be possible to revisit CMB calculations with more representative Cl and NO_3^- deposition values in the near future.

Daily rainfall amount was available for 2007 at the eight meteorological stations sampled and monthly average rainfall values were also available for 141 stations throughout Ghana for the 1971-2007 period. Consequently, it was possible to interpolate rainfall over the study area and extract estimated annual rainfall values at each profile location.

3.2.2 Unsaturated zone profiles

Soil sampling in the unsaturated zone was carried out during the 2007-2008 dry season using a truck-mounted hollow stem auger. Samples were collected at 0.3 m intervals until the water table was reached or refusal. Core samples recovered with a split-spoon sampler were stored in 250 ml Kilner jars and placed in an ice chest to minimize potential evaporation. All soil samples were sent to the British Geological Survey (BGS) laboratory in Wallingford (UK) for extraction and analysis of pore water. Total moisture content was determined upon reception of samples by loss on drying. Extraction was carried out by elutriation and centrifugation for comparison purposes. Only elutriation results are presented here as samples extracted by centrifugation were still being processed at the time of writing. For elutriated samples, 30 ml of distilled demineralized water was added to 50 g of soil; resulting supernatant was filtered and used for analysis of chloride and nitrate by ion chromatography.

A total of 18 unsaturated zone profiles were drilled in the upper part of the weathered layer (regolith). Their locations are shown in figure 1. Soil sampling proved to be difficult as a duricrust was often encountered at very shallow depth preventing, in some cases, collection of samples below assumed evapotranspirative zone. Consequently, only 12 profiles, ranging from 2.7 m to 6.6 m, were considered for interpretation.

4 RESULTS

4.1 Soil moisture balance

The average annual values obtained for each component of the SMB are summarized in table 1 for all eight stations considered (N.B.: in the table, pET is for potential evapotranspiration and aET is for actual evapotranspiration). Results for two selected stations, Sunyani and Navrongo, are illustrated in figure 2.

Actual evapotranspiration is the dominant component, representing 68-86 % of the average annual rainfall. Groundwater recharge generally occurs near the end of the rainy season, during a relatively short period (i.e. generally less than 1 month, but up to 2-3 months). For stations located in the northern regions, recharge values range from 1.8 % (19 mm) to 15.9 % (205 mm) of average annual rainfall. These results are consistent with values stated in previous studies (Acheampong, 1988; Apambire, 1996; Kwei, 1997; Martin, 2006). For the five stations inside the northern regions, results reveal only one rainy season preceded by high potential evapotranspiration. Within a few weeks of the start of the rainy season, actual evapotranspiration generally increases to reach a high proportion of the potential evapotranspiration and the soil moisture deficit starts to decrease.

The influence of the near surface soil storage of water (NSSS) on actual evapotranspiration rates would generally be minor (i.e. NSSS would generally account for less than 2% of annual aET). Its influence on recharge estimates would however be more significant. Eliminating NSSS from calculations would generally overestimate recharge rates from 4.4% (Kete-Krachi) to 35.9% (Bole) depending on annual rainfall and its distribution. While the use of a constant run-off coefficient may provide a reasonable first order approximation of annual run-off, it does not yield a realistic distribution. One example is that a lower run-off proportion would be expected at the beginning of the rainy season when soil moisture is being replenished but the use of a constant run-off coefficient just follows rainfall values. This limitation is likely to influence the recharge estimate, especially towards the end of the rainy season where the relative proportion of run-off would likely increase.

It can be observed from figure 3 that the occurrence and amount of recharge is notably influenced by the distribution of rainfall events. Rainfall events at the Sunyani station are generally distributed more or less throughout the year as opposed to the Navrongo station where they are more clustered together during the shorter rainy season, thus allowing field capacity to be reached more rapidly. This observation is supported by the relatively good correlation observed between estimated recharge and the amount of rainfall during the rainy season (avg. period of May-Oct. for the northern regions).

Table 1 – Summary of soil moisture balance results for the 2000-2005 period (mm of water and % of rainfall)

Station	**Navrongo**		**Wa**		**Tamale**		**Yendi**		**Bole**		**Kete-Krachi**		**Sunyani**		**Wenchi**	
Region	Upper East		Upper West		Northern		Northern		Northern		Volta		Brong-Ahafo		Brong-Ahafo	
Units	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)
pET	1968	-	1767	-	1944	-	1642	-	1670	-	1582	-	1551	-	1472	-
P	963	100	1040	100	1040	100	1291	100	1157	100	1353	100	1197	100	1258	100
Q	120	12.5	130	12.5	130	12.5	161	12.5	145	12.5	169	13	150	13	157	13
aET	758	78.7	891	85.7	862	82.9	919	71.2	970	83.9	915	68	1006	84	1071	85
R	84	8.8	19	1.8	48	4.6	205	15.9	36	3.1	268	20	34	3	12	1

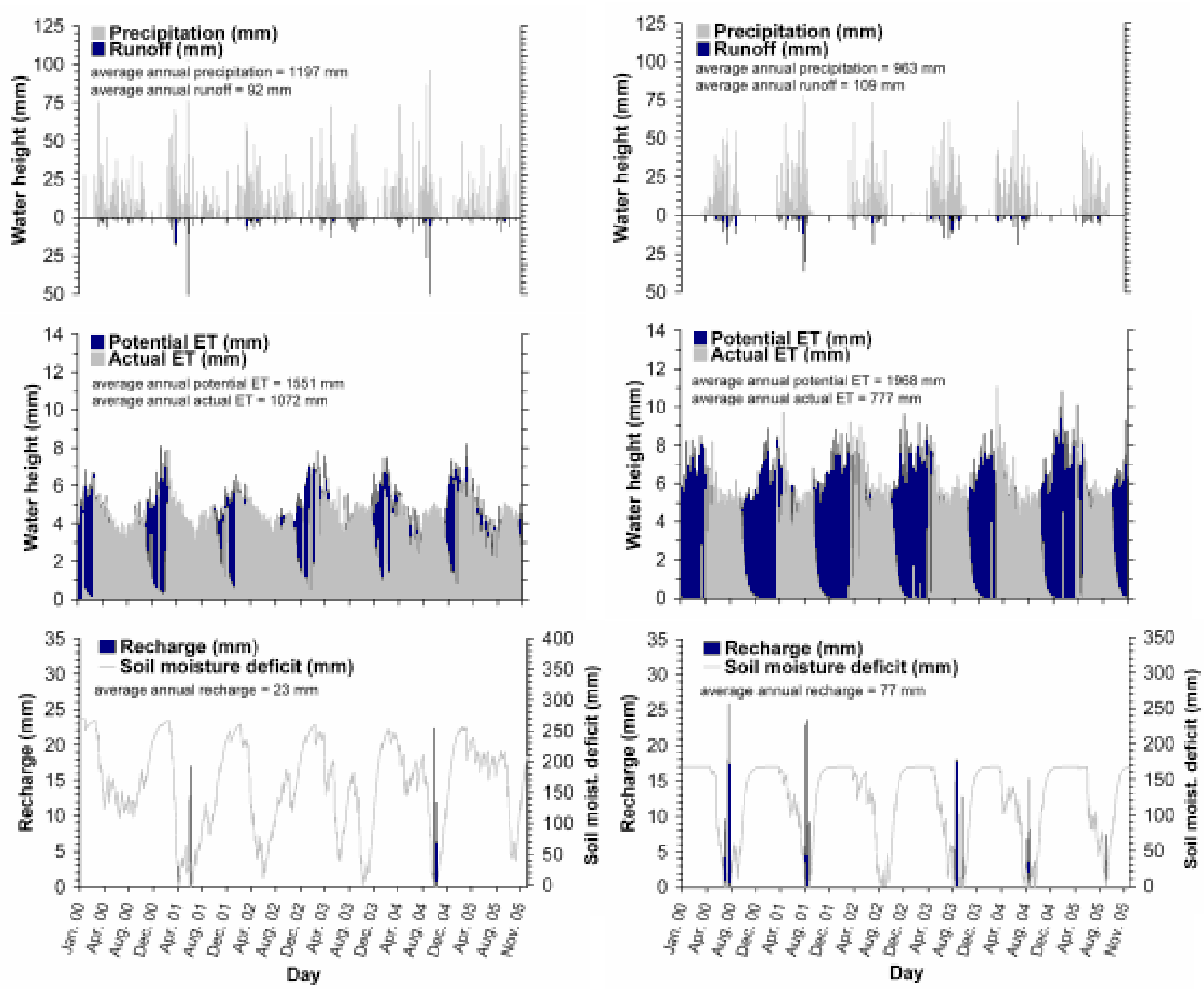

Figure 2 – Daily soil moisture balance for the Sunyani (right) and Navrongo (left) stations for the 2000-2005 period

4.2 Chloride mass balance

4.2.1 Rainfall inputs

Weighted average Cl values were calculated from analysis results with the following relation:

$$\text{Weighted } Cl_{P\ total} = \Sigma\,(Cl_{P\ event})P_{event})/P_{total} \qquad [3]$$

where $Cl_{P\ event}$ is the Cl conc. measured for the individual event (mg/L), P_{event} is the precipitation of the individual event (mm) and P_{total} is the total sampled rainfall for the rainy season (mm). A summary of weighted average Cl values in rainfall is provided in table 2 for each station considered. The regional weighted average Cl value used for calculations is 0.39 mg/L.

Results generally show a more or less constant accumulation of Cl throughout the rainy season. Only the Wa station exhibits a higher accumulation rate starting around mid-season. The reason for this behavior is not well understood but the extension of the rainfall sampling program for 2008 and 2009 will allow verification whether or not this increase is recurrent.

Table 2 – Weighted average chloride values for 2007 rainfall at selected stations

Station	Annual rainfall (mm)	Annual rainfall sampled (%)	Weighted avg. Cl (mg/L)
Bole	950.2	52.6 %	0.33
Kete-Krachi	1149.6	46.8 %	0.30
Navrongo	1203.8	66.5 %	0.48
Sunyani	1297.2	40.9 %	0.27
Tamale	1046.5	50.5 %	0.46
Wa	996.7	38.7 %	0.58
Wenchi	1217.3	48.4 %	0.44
Yendi	1157.7	53.6 %	0.24
Average	-	-	0.39

Results for the few samples analyzed for nitrate range from undetected to 0.49 mg/L, with a regional average of 0.28 mg/L. As the number of samples analyzed for NO_3^- is relatively low, reliable comparison analysis with Cl values was not possible. Future rainfall sampling will however include analysis for NO_3^- for all samples.

4.2.2 Unsaturated zone profiles

Average recharge values for the 12 profiles considered for interpretation were estimated with equation 2 using the regional weighted average Cl value stated in table 2. Results are summarized in table 3 and figure 3 presents an example of unsaturated zone profile for location CMB4. The average Cl concentrations in profiles range from 5.4 to 38.7 mg/L for samples collected below the evapotranspirative zone. Assuming run-off is negligible, this would translate into an estimated recharge range of 1.0 % (11 mm) to 7.2 % (73 mm) of average annual rainfall. Typically, recharge estimates would be slightly higher in the Precambrian Basement than in the Voltaian Sedimentary Basin. This could imply that the upper layer of the regolith in the Precambrian Basement comprises more permeable material than in the VSB. Nitrate concentrations show much more variation, ranging from 1.1 to 78.5 mg/L. They however mimic Cl concentrations for most profiles which could be seen as qualitative validation of Cl's conservative nature. For some profiles, nitrate concentrations however tend to decrease with depth, which could suggest a higher input of nitrate in recent years. As there is no historic record of NO_3^- concentrations in rainfall, it is however difficult to determine if the origin of the additional NO_3^- input (i.e. rainfall or anthropogenic or other). High nitrate values can however partly be explained by the nitrogen fixation by vegetation in soils (Edmunds *et al.*, 2002).

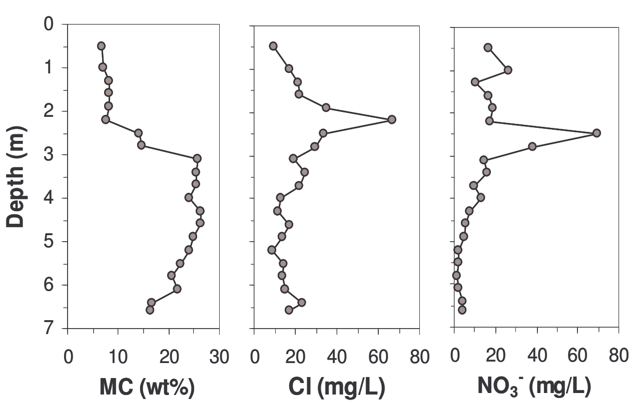

Figure 3- Unsaturated zone profile CMB4 showing moisture content and Cl & NO_3^- in pore water

Moisture contents vary from approximately 2-25 %wt with an average around 8.7 %wt. They would be slightly higher in the VSB (9.5 %wt) than in the Precambrian Basement (7.6 %wt), suggesting a weathered layer with a finer soil texture on average in the VSB. Moisture contents obtained also suggest that the evapotranspirative zone would range from 0.9-3.1 m in thickness. Some profiles reveal a high Cl concentration, in this zone, which would likely be caused by enrichment of Cl by evapotranspiration (Sukhija *et al.*, 2003). Such a feature has also been associated near surface mineralization that is released through elutriation (Gaye and Edmunds, 1996). As figure 3 shows, profiles can also exhibit relatively large fluctuations of Cl concentrations with depth. These probably reflect the combined effects of Cl concentration variations and of rainfall amount and intensity fluctuations. Analysis of temporal variations of recharge with respect to climatic variations has however not been completed at this point, so that correlation of these fluctuations with rainfall input will not be discussed here.

5 DISCUSSION

5.1 Estimation method comparison

Recharge estimates from the 12 CMB profiles considered for interpretation are generally lower than those obtained from the SMB. Average annual rainfall values used for the SMB (daily data for 2000-2005) are generally higher than the average annual rainfall values used for the CMB (monthly data for 1971-2007) which could partly explain the observed differences. The estimated recharge range for the unsaturated zone CMB is 11 mm to 73 mm while it is of 19 mm to 205 mm for the SMB. For most of the meteorological stations inside the study area (Tamale, Bole, Navrongo, Wa), there is a relatively good correlation between recharges estimates of both methods but for Yendi, there is a significant difference. Possible causes for this difference have not been investigated yet.

According to Rushton *et al.* (2006), the SMB method would only be able to indicate if recharge occurs but would not provide precise numerical estimates. Assuming all assumptions are verified for the CMB, this would suggest that the unsaturated zone CMB method would provide more accurate recharge estimates. However, since previous work suggests that localized recharge is a major part of overall recharge in similar contexts, both methods would underestimate recharge. As mentioned before, upcoming work will thus focus on the saturated zone CMB method in order to provide estimates including both diffuse and localized recharge.

5.2 Spatial variations of recharge

The general spatial trend of recharge estimates obtained from the SMB indicates that values would increase from West to East, due to rainfall distribution rather than total rainfall amount. While this is consistent with recharge estimates stated in previous studies, results from the unsaturated zone CMB do not allow additional verification of this trend. Lack of spatial trend in unsaturated zone recharge estimates could be explained by the variability of unsaturated zone conditions locally (i.e. differences in soil type, depth, vegetation, slope ...). Again, the upcoming sampling and analysis of shallow groundwater for chloride is expected to provide a better assessment of spatial variability of recharge in northern Ghana.

Table 3 – Summary results for unsaturated zone profiles in northern Ghana

Profile ID	Hydrogeological context	Sampling date	Profile depth (m)	Est. annual rainfall (mm)	Avg. pore water Cl (mg/L)	Est. annual recharge (mm)
CMB01	Voltaian Sed. Basin	2008-01-30	4.2	1052	9.9	41
CMB04	Voltaian Sed. Basin	2007-12-13	6.6	1034	16.6	24
CMB05	Voltaian Sed. Basin	2008-02-07	4.8	1002	5.4	73
CMB07	Voltaian Sed. Basin	2008-01-17	2.9	1184	14.2	32
CMB12	Voltaian Sed. Basin	2008-01-09	3	980	20.4	19
CMB13	Voltaian Sed. Basin	2008-01-10	3.9	979	13.2	29
CMB14	Precambrian Basement	2008-02-10	2.7	922	6.2	57
CMB15	Precambrian Basement	2008-02-08	5.7	938	7.5	49
CMB16	Precambrian Basement	2008-02-04	3	974	13.0	29
CMB17	Precambrian Basement	2008-02-02	3.3	1016	5.5	72
CMB18	Precambrian Basement	2008-02-03	4.2	1016	12.2	32
CMB19	Precambrian Basement	2008-02-01	2.7	1052	38.7	11

5.3 Limitations and problems encountered

For the SMB, the main limitation is that it relies on the subtraction of large quantities (ET and P) to estimate a small quantity (recharge). The uncertainty associated to estimates thus greatly depends on the relative magnitude of these inputs. Two other important sources of error have also been identified. The first concerns the quality and time period covered by the climate dataset. For some meteorological stations, data gaps had to be filled with an independent estimation method, thus introducing possible errors. Also, daily climate data used to compute the SMB were only available for the 2000-2005 period. The availability of a dataset covering a longer period would also have helped reduce uncertainty in recharge estimates. The second source of error identified relates to the estimation of SMB inputs for which measured data was unavailable or unreliable. Evapotranspiration was estimated with a recognized method for which measured inputs (e.g. wind, relative humidity …) were available. However, run-off, which was approximated with a constant coefficient, could represent a significant source of error. Reliable and complete run-off datasets for a few gauging stations would ideally be required in order to obtain more accurate run-off estimates.

The assumptions required by unsaturated zone CMB method are often difficult to verify and may thus constitute sources of error. The first assumption, considering that infiltration occurs as piston-flow, introduces uncertainty as previous work suggests that preferential flow would represent a large portion of total recharge. Since CMB recharge estimates thus possibly underestimate the overall value of recharge, they should be considered only as reliable conservative estimates (i.e. minimal values). The importance of localized recharge will however be assessed in upcoming work so that these estimates will be further analyzed. The assumption concerning the origin of Cl may also contribute to errors in recharge estimate as the Cl data for rainfall was only available for a short period. Consequently, there is a large uncertainty for Cl in rainfall, which obviously translates into large uncertainty in recharge. As only major events were sampled, the values presented in table 2 are likely to be underestimated (by at least 10-15 %, if Cl detection limit is used for minor non sampled events). However, comparison of Cl concentration values obtained here with those of another study available for northern Ghana (Martin, 2006) reveals Cl concentrations of similar magnitude, which would suggest that Cl values estimated here are representative. To minimize the error associated to Cl flux from run-on/runoff, profiles were carefully sited in the field to avoid locations with steep slopes or depressions. Still, the assumption that no run-on/run-off occurs could induce an error assumed to be in the order of 10 %.

6 CONCLUSION

Groundwater recharge estimated with the soil moisture balance yielded results ranging from 12 to 268 mm for the eight meteorological stations considered. These values, which would generally increase from West to East, would be mainly controlled by the distribution of rainfall events throughout the year. The estimates obtained through the chloride mass balance for twelve unsaturated zone profiles range from 11 to 73 mm. The latter values were estimated using a weighted average Cl in rainfall of 0.39 mg/L. While the latter values would be realistic according to previous studies, a large uncertainty remains as only one year of data was used to derive the weighted average Cl in rainfall. The rainfall sampling program is scheduled to continue for 2008 and 2009 so that it will be possible to revisit these values in a near future.

Comparison of results for the two methods reveals lower values for the CMB method. A good correlation between the two methods is however observed for most meteorological stations. A more detailed assessment of spatial variability of recharge is being carried out through the sampling and analysis of shallow groundwater from hand dug wells. The data obtained from this work will also help determine the importance of localized recharge versus diffuse recharge in northern Ghana.

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