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Characterization of Potential Direct Recharge in the Gold Mining District of South-Western Ghana Using the Hydrus-1D Computer Code

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Abstract

The mean annual potential recharge rate to the ground water system in the Tarkwa gold mining district of South Western Ghana, has been estimated for the period 1977 to 2001 by analyzing precipitation recharge in response to rainfall pattern and distribution for the four main soil types; Huni, Tarkwa Phyllite, Banket and Kawere. Using the Hydrus-1D infiltration computer code model, simulation results of recharge-precipitation exhibited a linear relationship, and gave correlation coefficient values R^2 ranging from 0.39 to 0.55 for the four soil types and 0.72 for the composite soil. Variability of annual recharge was assigned to various reasons, including the variation in the weather pattern (rainfall, temperature, evapotranspiration etc), topography and hydraulic properties of the aquifer system. The potential direct recharge rate was estimated to range from 269 mm/yr to 611 mm/yr, with an average value of 385 mm/yr. This is as a result of infiltration of about 18% to 36% (average 27%) of the mean annual precipitation. The high average value of 385 mm/yr is reasonable on the basis that it represents the potential maximum value of the actual recharge value of 299±72 mm/yr.

Keywords: characterization, potential recharge, unsaturated zone, gold mining, Hydrus 1D computer software, Ghana.

1. Introduction

Gold dominates the mining sector in Ghana, with prospective gold deposits localized in three regions namely; Western, Ashanti and Brong-Ahafo. The Western and Ashanti regions have varying years and indelible experiences of gold mining, whilst communities in the Brong-Ahafo region are yet to experience the full scale negative effects of surface mining. The Tarkwa area in the Wassa West District of South Western Ghana, where this study was conducted, is said to have the single largest concentration of mines and mining companies on the African continent, with about one-third of the total land area under concession for mining (Akabzaa & Darimani, 2001). Siegel (1997) has noted that, developing a mine-plan of operations, operational procedures, hydrological control structures and other best management practices to prevent negative environmental impacts require accurate knowledge of the variables associated with hydrological conditions at the mine. The most important being the proper characterization of baseline hydrogeological conditions, with groundwater recharge being paramount, so that the extent of impacts to hydrologic and other related resources can be minimized or avoided. Pressure on groundwater resources resulting from mine dewartering has been identified among others to be the single major mining impact in the study area and this has necessitated the need to provide more accurate recharge estimates for various tools that can assess the sustainability of long-term water use.

In this work, we have used the Hydrus-1D computer software package (Šimunek et al., 2005) to estimate the mean annual potential recharge rate by analyzing the variability of precipitation recharge for the various soil types (Huni, Tarkwa Phyllite, Banket and Kawere) in the unsaturated zone, in response to rainfall and evapotranspiration. This software was chosen because of its advantage of dealing with hydrological complexities and the derivation and estimation of water budgets and fluxes (Hernandez et al., 2003; Simunek & van Genuchten, 1999; Shah et al., 2007). Neuman et al. (1974) observed that most studies that use unsaturated zone models to estimate groundwater recharge normally assumed the unit gradient flow at the lower boundary, with the bottom water flux taken to be equal to the potential groundwater recharge (Nolan et al., 2003, 2007; Small, 2005; & Keese et al., 2005). Potential recharge is defined as the likely recharge in cases where the water table is deep enough, such that it no longer has influence on the recharge rate. This is interpreted to mean that the recharge process can be estimated assuming that the flow in the unsaturated zone is freely draining. This rate is effectively a maximum rate, as in some cases the inability of groundwater to flow away fast enough will mean that recharge will be rejected.

Previous studies (Kuma & Younger, 2000; Kortatsi, 2004) contend that vertical groundwater recharge from precipitation and evapotranspiration are the main components of the water cycle in the study area, with the unsaturated zone playing an important role. Using the water budget method, Kuma (2007) estimated a recharge rate of (299±72) mm/yr for the study area. According to these researchers, the humid climate of Tarkwa district is characterized by a surplus of precipitation over soil evaporation and plant transpiration, with no distinct monsoon. As a result, precipitation is the primary source of recharge, whereas seepage from other surface bodies, watercourses, terrain depressions, fractures, and diversion from denser soil contribute indirectly with a trivial volume, especially in the environments of new surface mine development. Once infiltration is reduced by evapotranspiration, the rest of the moisture percolates down through the vadose zone to the water table as a potential recharge to the groundwater. The shallow areas, however, allow for some moisture to be driven back by a capillary rise in response to evapotranspiration demand

2. Research Materials

2.1 Hydrus-1D computer Code

The vertical movement of water in the unsaturated zone of HYDRUS-1D Computer code (Šimunek et al., 2005) is described by the Richard's equation whose one-dimensional mixed form is given in equation (1) as:

$$\frac{\partial\theta(z,t)}{\partial t} = \frac{\partial}{\partial z}\left\{K(\theta)\left[\frac{\partial h(\theta)}{\partial z} + 1\right]\right\} - S \tag{1}$$

This is subject to the initial and boundary conditions given in equation (2) as:

$$\frac{\partial h}{\partial z}(L,t) = 0 \qquad \text{or} \qquad h(L,t) = h_L(t) \tag{2}$$

where the parameters are defined by van Genuchten & Mualem, (1980).

Hydrus-1D (Šimunek et al., 2005) solves the Richard's equation by establishing relationships between soil water retention θ(h) and the unsaturated hydraulic conductivity K(h) which are nonlinear functions of pressure head (h) and water content, respectively. However, Hydrus-1D (Šimunek et al., 2005) permits the use of four alternative analytical models for determining soil hydraulic properties (Brooks & Corey, 1964; van Genuchten & Mualem, 1980; Vogel & Císlerová, 1988; Kosugi, 1996; Durner, 1994). In this study, in modelling the unsaturated flow, the van Genuchten & Mualem, (1980) analytical model as expressed in equation (3) was used to describe the soil-water retention parameters.

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m} for\ h \leq 0 \\ \theta_s \qquad\qquad\qquad for\ h \geq 0 \end{cases} \tag{3}$$

The relationships between water retention and pressure head as expressed in equation (3) have five parameters that define the shape of the function; $\boldsymbol{\theta_s}$ saturated porosity of the soil, $\boldsymbol{\theta_r}$ residual moisture content, $\mathbf{K_s}$ saturated hydraulic conductivity, $\boldsymbol{\alpha}$ inverse of the air entry value (or bubbling potential), and **n** pore size distribution index. The required input data includes model parameters, geometry of the system, boundary conditions and initial conditions for transient flow simulation. The dimensions of the problem domain are defined via the geometry parameters while the physical properties of the system under consideration are described via the physical parameters. The unsaturated zone includes the soil water characteristic, θ(h) and hydraulic conductivity, K(h).

2.2 Study Area Description

Recharge is a region-specific property and therefore the study was concentrated at the Tarkwa mining district of South Western Ghana. The study area is located in the Ankobra Basin, which is bordered to the west by the Ankobra River that flows towards the south, and the north and south by the Huni and Bonsa Rivers, respectively. The area is highly dissected and has moderate relief with a general decrease in elevation southwards (Kuma, 2007). The main types of soil in the area are the forest oxysols in the south and the forest ochrosol-oxysol in the north (Asklund

& Eldvall, 2005), and consists mostly of silty-sands with minor patches of laterite (mainly on the hilly areas) and underlain by the Banket Series and Tarkwa Phyllite rocks (Kuma & Younger, 2001; Kortatsi, 2004).

3. Research Method

3.1 Numerical Model Design Using Hydrus-1D Computer Code

The annual potential recharge rate was forecasted through the modelling of the soil system. The basic approach was to perform numerical simulation on a conceptual one-dimensional column from the surface to the water table by using the following data.

3.1.1 Meteorological data

The meteorological data from 1977 to 2001 of South Western Ghana used for this study was obtained from the Ghana Meteorological Service weather station at Tarkwa. This was statistically processed and analyzed, and appropriate graphs presented as shown in Figure 1 (a composite graph showing the daily and monthly variations in precipitation and evapotranspiration). The analyzed data was used as input for the Hydrus-1D Computer code (Šimunek et al., 2005) and the modelling of bottom fluxes in the estimation of the potential recharge.

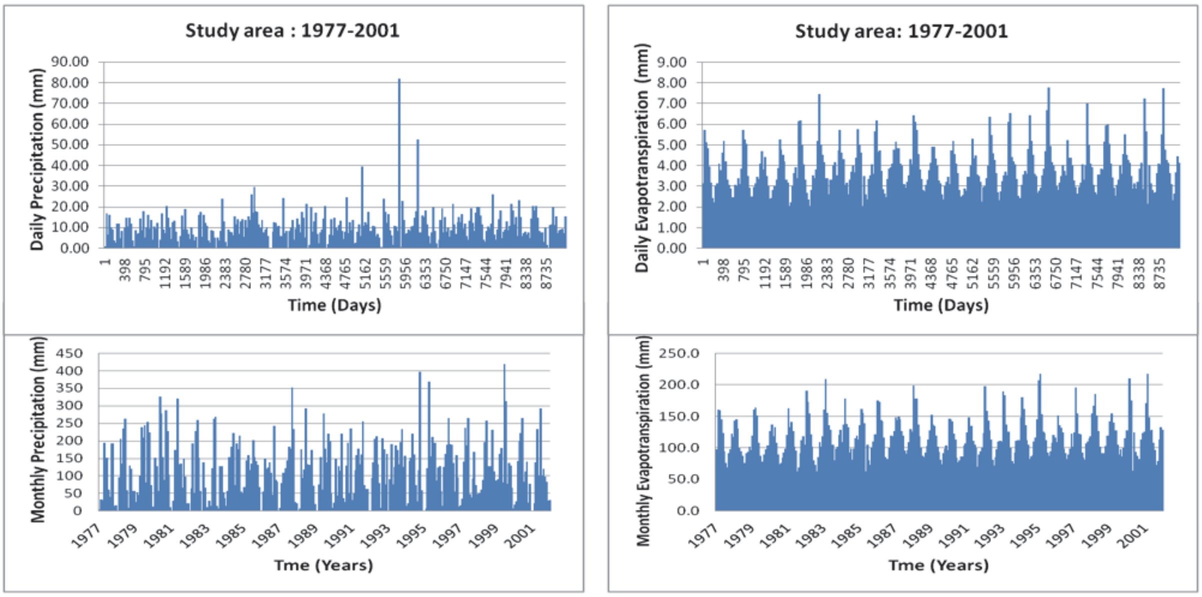


Figure 1. Precipitation and Potential Evapotranspiration rates of South Western Ghana averaged over the period 1977-2001

Table 1. Estimated Van Genuchten hydraulic parameters using Rosetta model (Schaap et al., 2001)

Soil Type	Soil Texture	Hydraulic parameters Bd (gmm^{-3})	θr (m^3m^{-3})	θs (mm^{-3})	α (mm^{-1})	N (-)	Ks (mm/d)	L (-)
Huni	Silty Sand	26.5	0.0414	0.3889	0.00208	1.4186	336	0.5
Tarkwa Phyllite	Laterite	27.4	0.0537	0.3789	0.00313	1.394	320	0.5
Banket	Silty Sand Laterite	26.7	0.0404	0.3854	0.00372	1.4556	530	0.5
Kawere	Silty Sand	26.5	0.0485	0.3935	0.00114	1.4856	177	0.5

Bd=bulk density; θr = residual soil water content; θs=saturated soil water content; Ks=saturated hydraulic conductivity; α, N and L are empirical coefficients that determine the shape of the hydraulic functions

3.1.2 Soil Hydraulic Properties Data

Soil properties representing the four main soil types (Huni, Tarkwa Phyllite, Banket and Kawere) were determined for each of the profile components in describing the soil profile using the results of infiltration tests technique used by Kuma and Younger (2001). The soil hydraulic parameters, as presented in Table 1, were estimated using the pedo-transfer function model, Rosetta (Schaap et al., 2001). This model predicts the hydraulic parameters from soil texture and related data as implemented in Hydrus-1D (Šimunek et al., 2005). The van Genuchten parameters were estimated using Rosetta (Schaap et al., 2001), based on the soils data collected by Carsel and Parrish (1988).

3.1.3 Setting the Initial and Boundary Conditions

In this study the threshold value of pressure head, hcrit, was assumed to be minus 1000000 mm. However, because the surface soil remained relatively wet due to regular precipitation and remained above the hcrit threshold, the simulation results obtained were insensitive to this parameter value when specified in the range minus 1500000 mm to minus 1000000 mm as observed in a previous study (Simunek et al., 2005).

The upper boundary condition was specified as an atmospheric boundary condition with surface runoff. Implementation of the atmospheric boundary condition requires specifying daily precipitation and evapotranspiration rates, therefore, a twenty-five year daily time steps series (01/01/1977 to 31/12/2001) of precipitation and potential evapotranspiration was defined in excel format, as presented for the first month of the first year in Table 2. This was repeated for the rest of the years and were input into the Hydrus-1D computer code (Šimunek et al., 2005).

Table 2. Time variable atmospheric Boundary Conditions of daily precipitation (Precip) and evapotranspiration (EvapoT) rates for the period 01/01/1977 - 31/01/1977

Time Series	Time (days)	EvapT (mm/m)	No. of Days	Precip. (mm/m)	Rain days	Precip (mm/d)	Precip/sp (mm/d)	EvapT (mm/d)	hcritA
1	01/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
2	02/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
3	03/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
4	04/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
5	05/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
6	06/01/1977	97.9	31	3.6	5	0.72	0.72	3.16	100000
7	07/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
8	08/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
9	09/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
10	10/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
11	11/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
12	12/01/1977	97.9	31	3.6	5	0.72	0.72	3.16	100000
13	13/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
14	14/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
15	15/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
16	16/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
17	17/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
18	18/01/1977	97.9	31	3.6	5	0.72	0.72	3.16	100000
19	19/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
20	20/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
21	21/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
22	22/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
23	23/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
24	24/01/1977	97.9	31	3.6	5	0.72	0.72	3.16	100000
25	25/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
26	26/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
27	27/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
28	28/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
29	29/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000
30	30/01/1977	97.9	31	3.6	5	0.72	0.72	3.16	100000
31	31/01/1977	97.9	31	3.6	5	0.72	0.00	3.16	100000

3.1.4 Numerical Simulations on the Conceptual One-Dimensional Column

The time series data of precipitation and evaporation was introduced to the surface of the model grid system as a source term. When the top layer becomes saturated as a result of heavy downpour, precipitation rate exceeds infiltration rate. Precipitation then begins to accumulate in the surface and the ponded water is assumed to be immediately removed by runoff whiles the model automatically converts the pressure head of the top layer to zero. Then, the bottom water flux was assumed to be equal to the potential groundwater recharge which was calculated for the various soil types as indicated in Table 3.

In order to get the resulting solutions to produce the same initial cyclic pattern, the initial conditions of the model have to be generated by running a certain period of preliminary cyclic simulation earlier to the time of interest. A three-year preliminary simulations were therefore performed by a multiple-year precipitation and evapotranspiration sequence having a cyclic pattern of the first-year (Y1) meteo sequence such that Y2=Y3. Figure 2 shows the temporal changes of water fluxes at the bottom of the lower boundary showing the cyclic pattern of the peaks representing Y1, Y1, Y1, Y2, Y3, Y4, Y5.

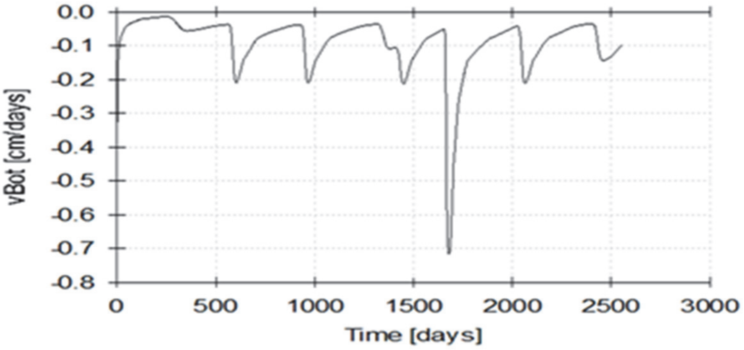


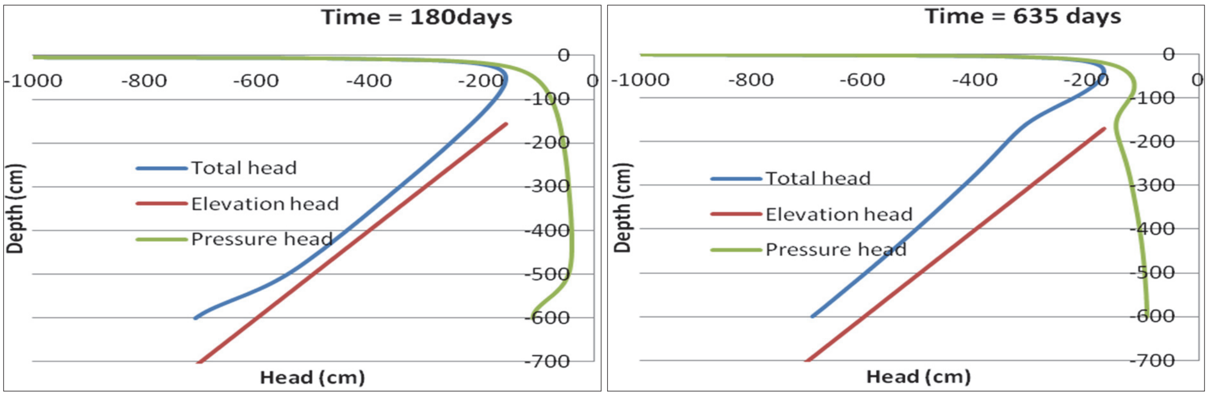
Figure 2. Temporal changes of water fluxes at the bottom of the lower boundary

4. Results and Discussion

4.1 Water Infiltrations in the Unsaturated Zone

The bottom water flux of the infiltration model was taken to be equal to the potential groundwater recharge. Figure 3 is a composite graph showing breakthrough plots of the elevation, pressure and the total head in order to check whether the system was behaving properly, and in particular, whether the flow had reached the base of the model. The first 180 days was taken by the system's initial conditions to adjust to the temporal changes. The system became stable by 635 days, i.e. within the three years, year 1 cycling, with infiltration reaching the water table.

Figure 4 shows plots of temporal changes in actual and cumulative water fluxes and pressure heads across the upper and the lower boundaries of the infiltration model. The cumulative bottom flux was used in the calculations of the potential recharge estimates to the groundwater system for the period 1977 to 2001.



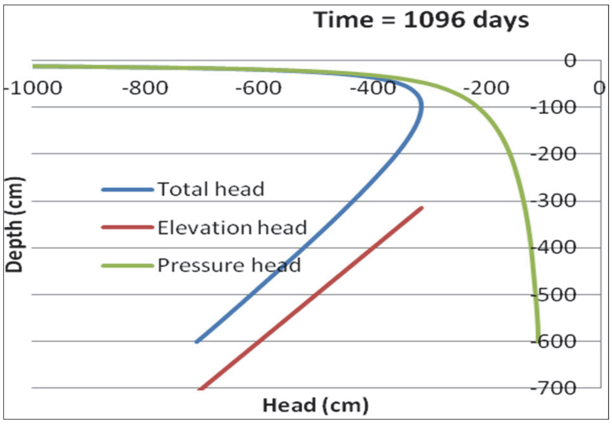


Figure 3. Water infiltrations in the unsaturated zone showing the elevation head, pressure head and the total head for the periods 180 days, 635 days and 1096 days

Table 3 shows the data summary of the entire results of the potential recharge estimates to the ground water system of the various soil types for the period 1977 to 2001. The annual percentage contribution of precipitation to recharge was also calculated. A preliminary investigation into the relationship between precipitation and recharge indicated that there was significant variation in the data and might have resulted from a number of reasons, most notably, different antecedent conditions. Depending on the soil types, the average potential annual recharge rates ranged from 355 mm/yr to 411 mm/yr, corresponding to 25.4% to 29.4% of the annual precipitation for the entire period of 25 years, respectively.

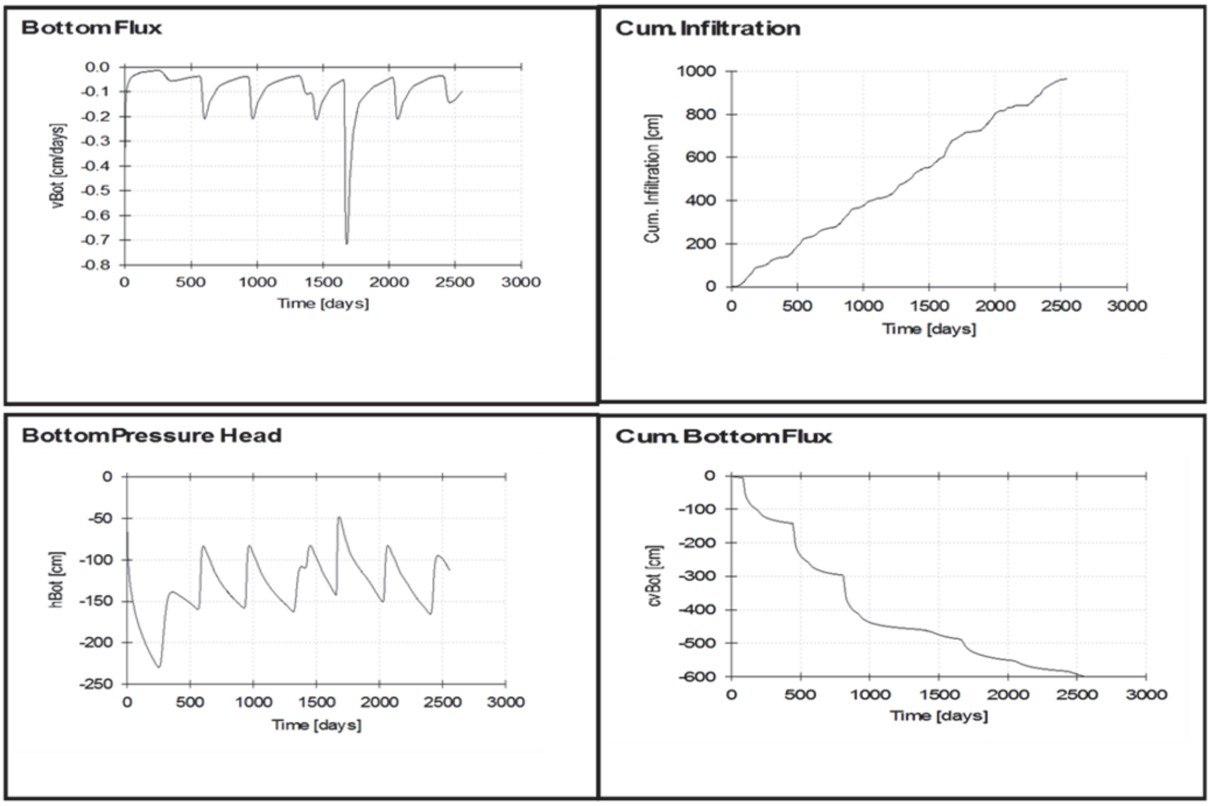


Figure 4. Graphs of temporal changes in actual and cumulative water fluxes and pressure heads across the upper and lower boundaries

Table 3. Predicted potential recharge values of Tarkwa District in South Western Ghana for a range of rainfall distribution spanning for the period 1977-2001

Time (Years)	Precip. (mm/yr)	Annual recharge (mm/yr)									
		Soil 1 Banket	% Precip	Soil 2 Huni	% Precip	Soil 3 Kawere	% Precip	Soil 4 Tarkwa	% Precip	Study Area	% of Ann. precip
1977	1085	223	21	192	18	165	15	217	20	199	18
1978	1383	516	37	459	33	403	29	511	37	472	34
1979	1554	530	34	506	33	480	31	558	36	519	33
1980	1827	796	44	763	42	821	45	730	40	778	43
1981	1216	450	37	434	36	341	28	471	39	424	35
1982	1225	405	33	375	31	350	29	398	33	382	31
1983	1071	269	25	242	23	221	21	265	25	249	23
1984	1459	246	17	215	15	185	13	249	17	224	15
1985	1385	380	27	364	26	338	24	375	27	364	26
1986	1158	232	20	216	19	215	19	218	19	220	19
1987	1507	379	25	423	28	381	25	479	32	416	28
1988	1255	351	28	231	18	204	16	231	18	254	20
1989	1368	440	32	415	30	375	27	466	34	424	31
1990	1351	290	21	265	20	273	20	261	19	272	20
1991	1284	426	33	367	29	302	24	419	33	379	29
1992	1502	279	19	260	17	257	17	281	19	269	18
1993	1692	489	29	435	26	380	22	486	29	448	26
1994	1389	447	32	426	31	411	30	470	34	439	32
1995	1594	594	37	555	35	527	33	559	35	559	35
1996	1598	453	28	436	27	422	26	448	28	440	28
1997	1352	428	32	394	29	372	28	417	31	403	30
1998	1429	181	13	172	12	171	12	191	13	179	13
1999	1686	721	43	680	40	640	38	403	24	611	36
2000	1320	469	36	440	33	414	31	460	35	446	34
2001	1253	270	22	235	19	222	18	263	21	247	20
Mean	1398	411		380		355		393		385	27%

Figures 5 and 6 are double y-axis graphs (combo graphs) that show the effect of rainfall pattern and distribution on the potential infiltration recharge over the period 1977 to 2001, for the entire study area and for the four main soil types, respectively. Although, there is variation in precipitation recharge to the groundwater system in the study area, generally, the plots look similar, which is an indication that there isn't much difference in precipitation recharge for the soil types. High recharge rates were observed from 1977 to 1984 and remained almost in a dynamic equilibrium from 1984 to 2001, with the exception of 1998, where a minimum rate was observed over the entire period. This is due to the corresponding variations in rainfall pattern and distribution in the area.

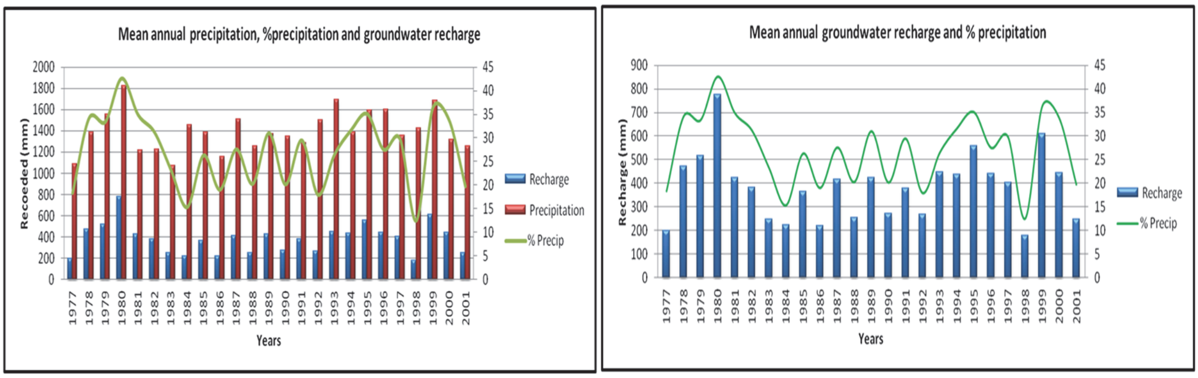


Figure 5. Data summary of mean annual precipitation, percentage of precipitation and groundwater recharge in Tarkwa District of South Western Ghana

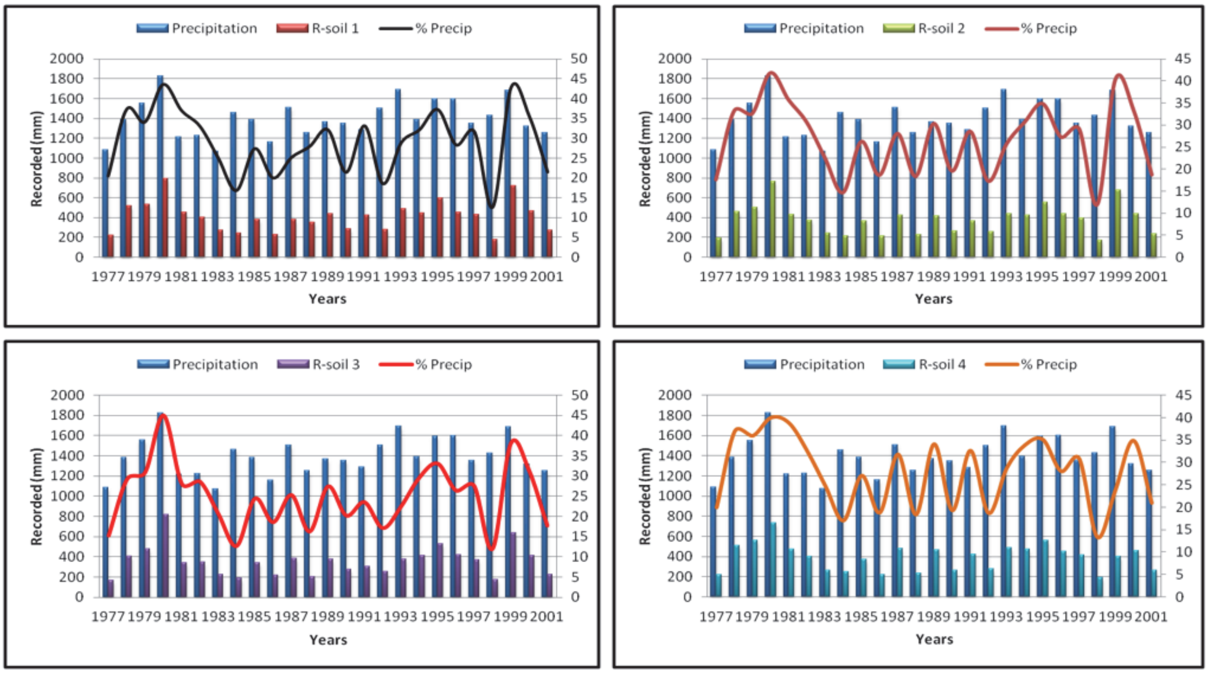


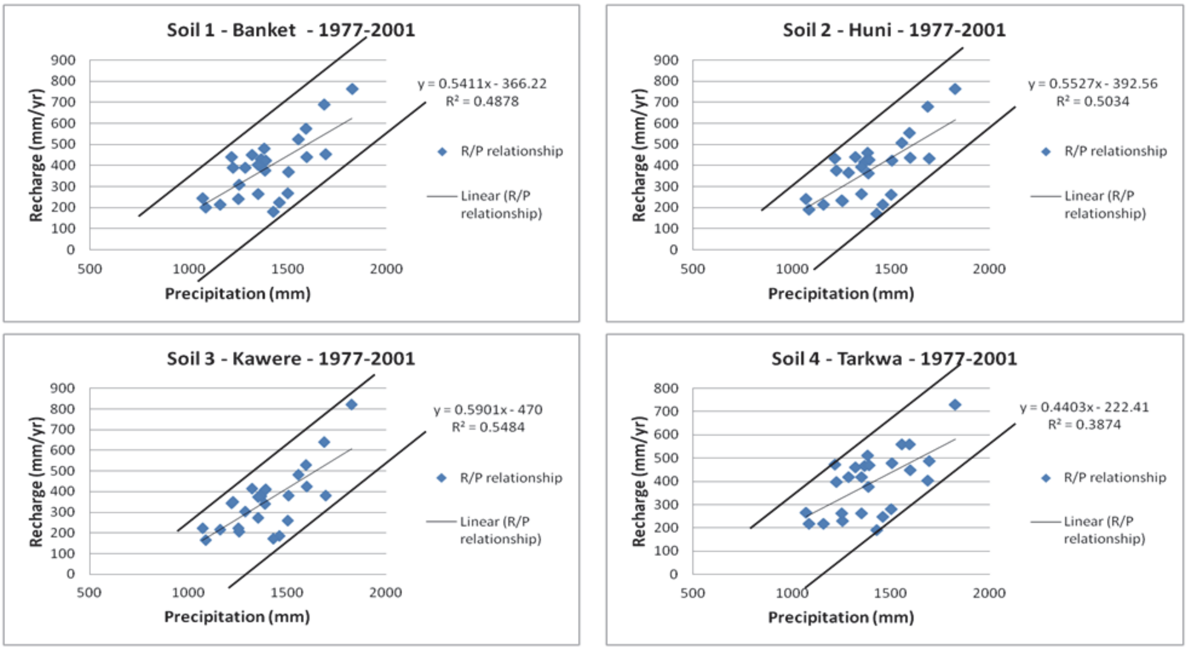
Figure 6. Mean annual precipitation, % of precipitation and groundwater recharge of soil type 1 (R-soil 1), (R-soil 2), (R-soil 3), and (R-soil 4) in Tarkwa District of South West of Ghana

Overall, the results suggest a strong relationship between the annual rainfall and observed recharge. To further investigate this relationship an attempt was made to relate the dependent parameter (recharge) to the independent parameter using a linear regression analysis expressed in equation (4) as:

$$R = mP + C \tag{4}$$

where R is the annual recharge rate (mm), P is the annual precipitation (mm), and m and C are calibration coefficients.

Figure 7 is a composite graph showing the linear variation between the annual recharge and precipitation for the four main soil types in the area, and that of the study area. The calculated R^2 values, which are the standard coefficient of determination or correlation, indicate the strength of the relationships.



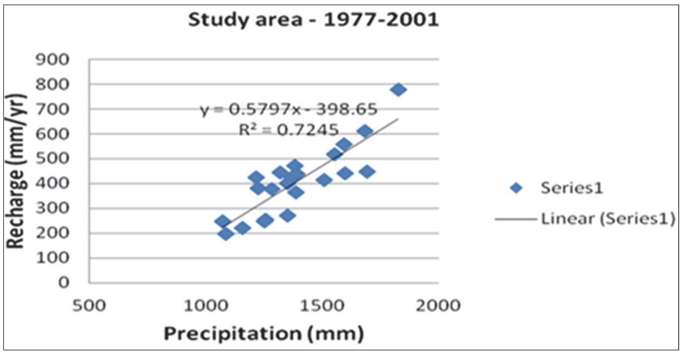


Figure 7. Variations of mean annual recharge with precipitation rate for the four main soil types and their composite, showing the R^2 values

Results of the linear regression analysis are tabulated in Table 4 for the entire study area and the four soil types. The results show R^2 value of 0.7245 for the study area, while that for the four soil types ranged from 0.3874 to 0.5484. The negative intercept value *c* indicates the existence of a threshold rainfall needed for recharge to occur. This threshold is quite large, ranging between -222 and -470, and therefore making %P less meaningless when taken into consideration the low correlation between recharge and precipitation. The high value of *c* may be that the relationship is not really linear, and therefore no need to extrapolate to P values below the lowest, as seen in the data set.

Table 4. Linear regression analysis of recharge-precipitation relationships of the study area for the period, 1977-2001

Soil Type	Mean annual recharge R	Mean annual precipitation P	% of Ann. Precip.	m	c	R^2
Soil 1- Banket	411	1398	29.40	0.54	-346	0.47
Soil 2 - Huni	380	1398	27.18	0.55	-393	0.50
Soil 3- Kawere	355	1398	25.39	0.59	-470	0.55
Soil 4 -Tarkwa	393	1398	28.11	0.44	-222	0.39
Study Area	406	1398	29.04	0.58	-399	0.72

5. Conclusions

Using the Hydrus-1D Computer code infiltration model, the mean potential annual recharge to the groundwater system in the Tarkwa District of South Western Ghana has been estimated for the period 1977 to 2001. The recharge estimation was conducted by analyzing precipitation recharge for the four main soil types Huni, Tarkwa Phyllite, Banket and Kawere; in response to rainfall pattern and distribution within the study area. Simulation results establishing a recharge-precipitation relation, when a linear relationship was used, gave correlation coefficient values R^2 ranging from 0.39 and 0.55 for the four soil types and 0.72 for the entire study area. The variability of annual recharge in the area may be assigned to various reasons, including the variation in weather pattern (e.g. rainfall, temperature, and evapotranspiration), topography and hydraulic properties of the aquifer system. The potential direct recharge rate was estimated to range from 269 mm/yr to 611 mm/yr, with an average value of 385 mm/yr. This is as a result of infiltration of about 18% to 36% (average 27%) of the mean annual precipitation. The high average value of 385 mm/yr is reasonable on the basis that it represents the potential maximum value of the actual recharge value of 299±72 mm/yr as reported by Kuma (2007).

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