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Groundwater Recharge Estimation in Pompon Sub-Basin, Densu Basin, Ghana

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Abstract: ***Drinking water has become a challenge for many urban and rural folks in Ghana. In the Pompon River Basin which forms part of the Densu Basin, most inhabitants depend on boreholes for their domestic water supply. In addition, there had been large scale production of sachet and bottle mineral water by several companies within the basin. Despite the use of groundwater for industrial and domestic use, no study had gone into the estimation of groundwater recharge of the Pompon Basin. Hydrograph analysis of stream flow measured by a staff gauge installed on a bank of the Pompon Stream was used to derive a second order-rating curve: $Y=3.3x^2-2.4x+0.4$ for the sub-basin. Using the Universal Soil Moisture Budget Method, estimated monthly recharge for 2001 varied from -62.6 mm in January to 81.5 mm in February. Monthly groundwater recharge as percentage of monthly rainfall varied from -62.6 % to 81.1 %. Annual groundwater recharge is approximately 295 mm. Annual groundwater recharge as percentage of annual precipitation stood at 25.6 % approximately. Thus, almost three-quarter of the annual precipitation is lost into other sources such as runoff (3.6 %), evapotranspiration (37.4 %) and soil moisture (34.4 %).***

Keywords: evapotranspiration, precipitation, runoff, soil moisture, and groundwater recharge

1. Introduction

Pompon Basin, one of the sub-basins of the Densu River Basin had in recent time undergone dramatic change due to anthropogenic activities over the past five decades. Existing forest vegetation is gradually giving way to savanna vegetation due to extensive lumbering of timber resources and the clearing of land for the cultivation of cash crops such as cocoa, cassava, cocoyam and maize. Most inhabitants depend on borehole for their domestic water supply. The ever-increasing population has made some inhabitant to provide water by means of boreholes for domestic water supply. The freshness of the groundwater which in most cases do not need treatment for domestic water usage coupled with large scale production of sachet and bottle water companies makes it imperative to determine the amount of rainfall that goes to replenish the groundwater regime of the area. Estimation of groundwater recharge in the sub-basin is therefore necessary for long-term effective management of the groundwater resources within the basin.

Based on conceptual models, several methods had been developed for estimation of groundwater recharge. The water balance methods, Darcian's approaches, empirical methods, and tracer techniques are some of the few methods that are used for groundwater recharge estimation. Each of these methods has their merits and demerits. Measurement of groundwater recharge using the conceptual models depend on the techniques to employed, the parameters to be measured, the instruments to be used, the hydrogeological conditions, and the hydrogeological conditions of the area. Lerner et al (1990) indicated that for a method to be considered suitable for estimation of groundwater recharge, it must reveal whether a conceptual model is correct or not, its data should not be too difficult to measure, and the available data should be measurable over a long period of time. Several studies had compared various recharge techniques (Flint et al, 2002) and the factors that determine the selection of appropriate techniques for quantifying groundwater recharge (Scanlon et al, 2002). While Solomon and Sudicky (1991) used isotopic method to determine groundwater recharge, Edmunds et al (2002) used the universal mass balance method and the change in chlorine concentration in groundwater to determine groundwater recharge. Others, like Walker et al (2002) reviewed modeling and other techniques for the estimation of groundwater recharge.

In Ghana, researches into groundwater recharge studies are few. In Nabogo River Basin of northern Ghana, groundwater recharge estimates using Chloride Mass Balance and Water Table Fluctuation Methods stood as 37.66 mm / year (4 % of annual precipitation) and 10-143 mm / year (1-13 % of annual precipitation) respectively (Krautstrunk, 2012). In Ejisu-Juaben District of Ghana, estimated groundwater recharge rate was 1874 mm / year which represent 7 % to 9 % of annual precipitation (Anornu et al, 2009). In the Densu Basin, the use of numerical modeling of unsaturated water flow and isotopic studies put groundwater recharge rates at 94 mm / year to 182 mm / year (plus or minus 7 % max.) while the use of peak shift method provided rates of 110 mm / year –250 mm / year (plus or minus 30 % max.), Adomako et al (2010). In Southern Ghana, numerical groundwater flow model used to characterize crystalline basement rocks indicated recharge rates between 0.25 % and 9.1 % of total annual precipitation, and that with reduced recharge of 30 %, the current increase in abstraction rate can be sustained up to 150 % (Yidana et al., 2013). In the Pompon Sub-basin, there had been ever-increasing abstraction of water for domestic purposes and industrial use by several dotted mineral water producing companies without regard to estimate the groundwater recharge within the sun-basin. Hence the need to estimate the groundwater recharge within the sub-basin cannot be over emphasized.

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2. The Study Area

The Pompon sub-basin area lays in the southeastern part of the Densu Basin. It is located (Fig.1.0) within the Akwapim South District of Eastern Region, Ghana. It is bounded between latitudes 5.83333˚N and 5.92833˚N and longitudes 0.21500˚W and 0.35666˚W. It covers approximately 78Km^2. The topography is slightly undulating to fairly gentle. Highest point is 229m above sea level while lowest point is 198m below sea level. The sub-basin falls within the Forest Vegetation but clearing of land for various activities is gradually paving the way from the past forest vegetation to closely Savanna Vegetation. Temperature varies from 23.9˚C to 28.5˚C. The highest temperature occurs in February while the coolest month occurs in August. The dry and wet seasons are the two main seasons that occur in the area. The dry season starts in November and ends in February with February being the period with the highest temperature. The wet season is in two folds. A major rainy season starts in March and ends in July with peak rainy season in June. The minor rainy season starts in August and ends in late September or early October (Dickson and Benneh, 1988).From January to December 2001, rainfall measurements at Buokurom Hydrometric Station varied from 1mm to 188mm with an average of 96.1mm approximately. Geologically, the sub-basin is within the Basin-type Granitoids which forms part of the Birimian Supergroup of the Paleoproterozoic Era (Kesse, 1985). Boreholes logs and road cuts within the basin confirmed that rocks in the area are made up of granite. Drilled boreholes logs shows that depth to boreholes within the area varied from 38m to 45m; aquifer zones varied from 25m to 35m. Water quality results for six wells within the area shows that the quality for boreholes meets the World Health Organization's standard (WHO, 2011). The Pompon River, one of the ephemeral streams that drains the Densu Basin, is dendritic in nature and occasionally overflows it banks near Buokurom during the peak of the rainy season.

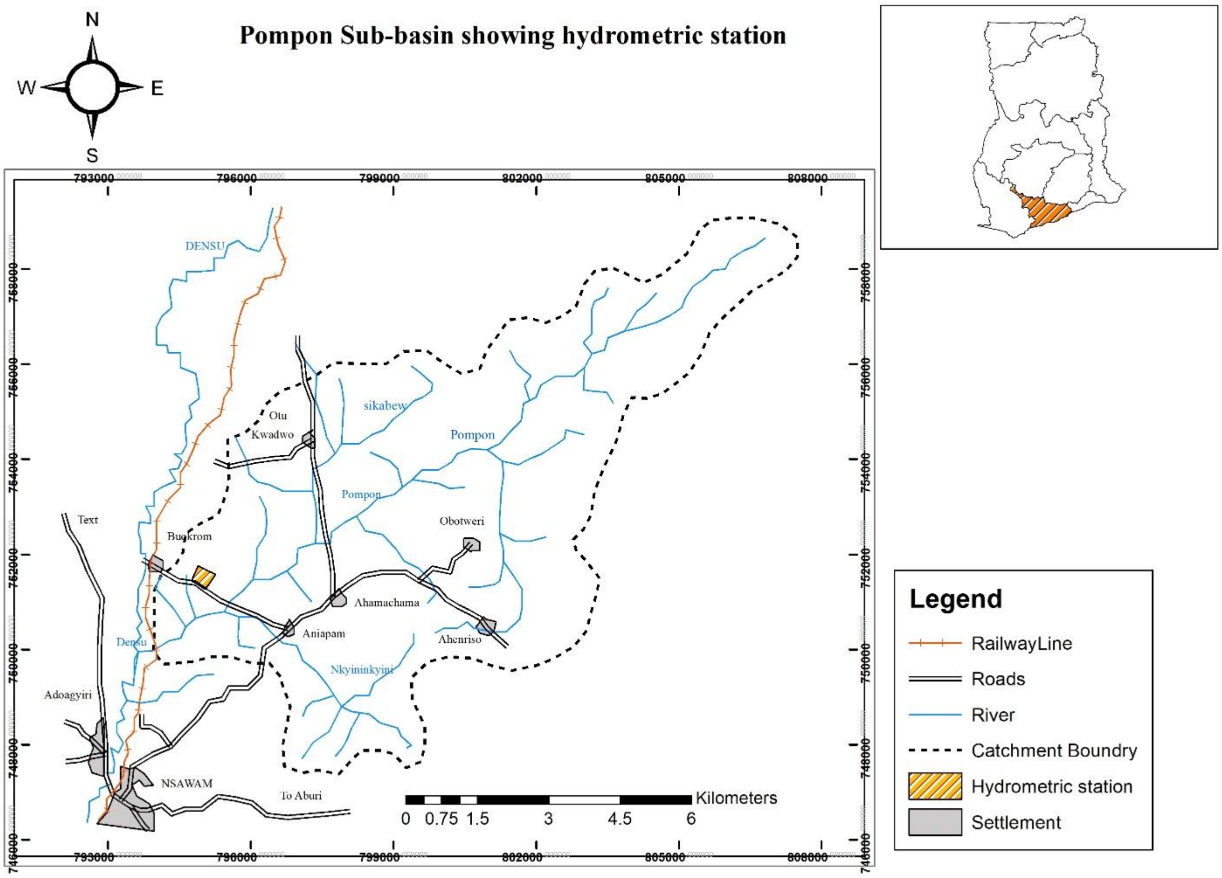

Figure 1.0: Map showing Pompon Sub-basin as part of Akwapim South Municipal of Ghana

3. Method and Instruments Used

Several methods exist for groundwater recharge estimation. However, the Universal Soil Moisture Budget Method was used for this study because rainfall, the main inputs for groundwater recharge can be measured. In addition, all the parameters that does not recharge the groundwater regime such as capillary water, runoff, soil moisture, evaporation, evapotranspiration can be measured using appropriate instruments and the data can be collected over a long time. Also, hydrometric parameters such as daily temperature, net solar radiation, wind speed, relative humidity, and other parameters that go into estimation of evaporation and evapotranspiration can readily be obtained and can be measured over long period of time. Furthermore, the data can be put into Microsoft excel making it easy for analysis of large data without much difficulty. The choice of this method for estimating recharge was also based on the available instruments at hand besides the fact that the method has high accuracies for measuring recharge in humid climates (Gupta and Gupta, 1992).

3.1 Precipitation, Runoff and Soil Moisture

Monthly rainfall was obtained by means of tilting bucket connected to data logger. Runoff was determined from stream flow measurements of staff gauge installed on upper section of the Pompon stream. The stream flow measurements were obtained over two-year period (2000 – 2002). The runoff was obtained from hydrograph analysis of a staff gauge installed on one section of the stream and was used to produce a second order rating curve for the sub-basin. The monthly staff gauge readings were used to determine the stream monthly discharges for the period, 2001. The ratio of the monthly discharge to the area of the basin gives the monthly runoff for the basin. Soil moisture measurements at the hydrometric station were obtained every fortnight for the one-year period (December 2001to December 2002) at 0.3m 0.6m and 0.9m depths using Nuclear Neutron Probe. The percentage (%) reading of soil moisture was converted per unit length of soil mass for the determination of change in soil moisture at specific depth. For this study, change in soil moisture at 0.6m below ground level was used.

3.2 Evaporation and Evapotranspiration

Evapotranspiration, defined as the loss of water from land, plants and water surfaces into the atmosphere was determined on monthly basis using the Combined Aerodynamic and Energy Balance Equation. This is because it is the most accurate when all required data are available, well suited for application for small areas with detailed climatic data (Chow et al, 1988).In this study, three main assumptions were used for the determination of monthly evapotranspiration. A seasonal coefficient for crop development was taken as 0.7, a psychometric constant (albedo of water) was taken as 0.05 and roughness of the grass at the hydrometric station was taken as 0.3cm.

By using the various relations below, Et for specific months were obtained.

Also evapotranspiration, Et is given as:

$$Et = fE \qquad \ldots\ldots\ldots\ldots\ldots (1)$$

where E is evaporation, and f is the seasonal coefficient for crop development taken as 0.7 for areas within the tropics (Gupta and Gupta, 1992).

Also, the Combine Aerodynamic and Energy Balance estimating of Et is given by:

$$Et = \{ (\Delta Er/ (\Delta + \gamma)\}+Ea\, \gamma / (\Delta + \gamma)\} \text{ (mm/day) and } \gamma = 66.8 \text{ (Pa/}^0\text{C)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

In this case, r is psychometric constant, or the Albedo of water taken as 0.05 for this study.

Also, $Ea = 0.35\ (0.5 + \mu 2/100)\ (es - ea)$ = drying capacity of air,

Δ = Change in saturated vapor pressure with respect to temperature,

$\Delta = de_s/d_T = 4098e_s/ (273.3 +T)$, $e_s = e^{\{ (1727T/ (273.3 + T) \}}$
$= (e_s\, e_d)/ (Ts -Td) = (e_a -e_d)/ (Ta-Td)$

Also, e_a is saturated vapor pressure at air temperature Ta and e_d is saturated vapor pressure at air temperature Td.

$$\text{Furthermore, } Er=0.0353Rn \qquad \ldots\ldots\ldots\ldots (3).$$

In this case, Rn is the net radiations in W/m^2.

$$\text{Also, } Ea=B\ (e_S - e_a)\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4),$$

where $B=0.102U_2 / [\ln (Z_2/Z_0)]$ and U_2 is wind speed (m/s) measured at height Z_2 (cm) and Z_0 is roughness height of the area. For grass, it varied from 0.1cm to 2.0cm (Chow et al, 1988). A value of 0.3cm was used for this analysis. Also, $_{eS} = 611e^{(17.27T/237.3+T)}$ (Pa), T=air temperature (^{0}C), $e_a = Rhe_S$ (Pa) in which Rh is the relative humidity ($0 \leq Rh \leq 1$).

Microsoft Excel Version 2008was used to analyze the hydrometric parameters (temperature, wind speed, net solar radiation, humidity, vapour pressures) downloaded from data logger to obtained evaporation and consequently evapotranspiration for the study area.

3.3 Estimation of Groundwater Recharge

In general, the Universal Soil Moisture Method for measuring groundwater recharge is given by the equation:

$$P=Rf+ Sm +Gr+ Et \qquad \ldots\ldots\ldots (5),$$

where P, Rf, Sm, Gr and Et represents rainfall, runoff, soil moisture, groundwater recharge and evapotranspiration respectively. The various parameters were obtained by various instruments, data loggers installed at the hydrometric station as well as the staff gauge installed on the Pompon Stream near Buokrom.Finally, using the universal mass energy equation of a given controlled volume, the groundwater recharge of the sub-basin can be obtained from the relation:

$$Gr = P- Rf-Et -Sm.$$

4. Results and Discussions

Hydrograph analysis of measurements obtained from a staff gauge installed on a section of the Pompon Stream near Buokurom was used to derive a second order rating curve (Fig. 2.0) given as:

$$Y = 3.3x^2-2.4x +0.4 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (6).$$

In this case, Y represents discharge in m^3/h and x represents gauge height in metres. During the measurement of stream flow, a peak discharge of 7.78m^3/h corresponds to a gauge height of 1.63m. The least discharge flow 0.056m^3/h also corresponds to a gauge height of 0.36m.

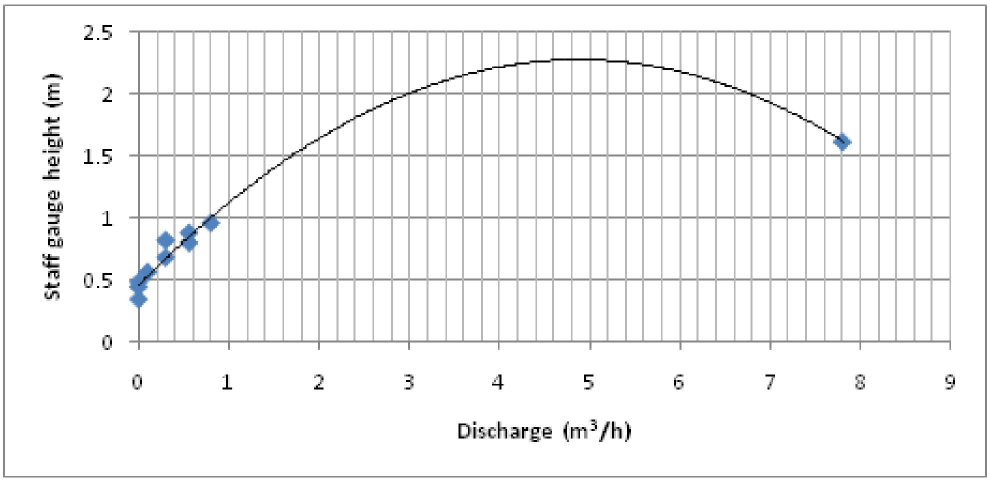

Figure 2.0: Second order rating curve of Pompon Basin

Results of monthly rainfall, runoff, change in soil moisture, evapotranspiration and groundwater recharge for 2001 had been summarized in Table 1.0.

Table 1.0: Summary of Estimated Parameters for Determining Groundwater Recharge in Pompon Basin

Month	Precipitation (mm)	Runoff (mm)	Change in soil moisture (mm)	Evapotranspiration (mm)	Groundwater recharge (mm)
January	1.0	0.00	56.7	6.52	-62.6
February	109.0	0.00	15.4	5.21	88.4
March	81.0	0.00	8.2	43.3	39.5
April	161.0	0.00	41.4	52.1	67.5
May	137.0	1.36	39.3	67.8	28.6
June	188.0	25.4	28.9	84.2	49.5
July	75.0	9.09	31.6	29.5	4.85
August	20.0	0.00	10.3	5.11	4.56
September	97.0	0.00	56.7	23.9	16.4
October	144.0	0.576	47.9	51.1	49.6
November	83.0	4.82	26.2	45.9	6.04
December	57.0	0.00	21.91	17.8	17.3
Total	1153.0	41.2	395.0	432.0	295.0

Minimum rainfall of 1mm occurred in January, 2001 while maximum rainfall of 188mm occurred in June; annual rainfall was 1153mm as against 41.2mm runoff; least change in soil moisture of 8.2mm occurred in March and the maximum of 56.7mm occurred in January, the least evapotranspiration 5.1mm occurred in February while the highest 84.2mm occurred in June. The least groundwater recharge is -62.6mm in January and highest of 88.4mm in February. In June, when the peak of rain occurred, monthly recharge stood at 49.5mm, about twice the monthly mean recharge of 24.6mm for the year. There was no direct relationship between monthly precipitation and monthly recharge (Fig.3.0).

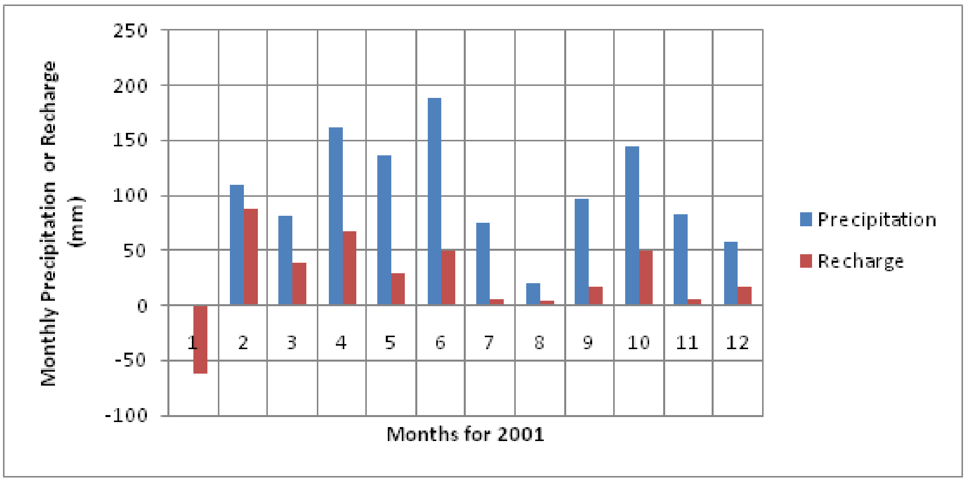

Figure 3.0: Monthly precipitation compared with monthly groundwater recharge for 2001

With the exception of February, there were months of high precipitation and corresponding months of low recharge. Most often, months of high recharge had proceeding months of high rainfall and months of low recharge had preceding months of low rainfall. With the exception of July and August, months of high recharge were followed by months of low recharge and the vice versa. The different stages of advancing wetting fronts within the subsurface regime contributed to these phenomena. Where advancing wetting front was close to the surface, the rate of infiltration became low leading to a low recharge rate. On the other hand, where the advancing wetting front was at greater depth, there was corresponding increase in infiltration leading to higher recharge. Monthly groundwater recharge as percentage of monthly rainfall varied from -62.6% to 81.1% (Table 2.0).

Table 2.0: Estimated monthly recharge as percentage of monthly precipitation for 2001

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug	Sep	Oct	Nov	Dec
Rainfall	1.0	109	81.0	161.0	137	188	75.0	20.0	97.0	144.0	83.0	57.0
Recharge	-62.61	88.39	39.5	67.54	28.57	49.5	4.85	4.56	16.4	49.64	6.044	17.29
R/P *100	-62.6	81.1	48.7	41.9	20.8	26.5	6.4	22.8	16.9	34.4	7.2	30.3

The recharge value of -62.6% suggests that infiltrated water at the subsurface was heavily depleted by evapotranspiration in January. The dry northeast trade wind (Harmattan), which affects the entire country from mid-November to early February might be a contributing factor responsible for this phenomenon. Mid- February represents the highest month of recharge which may be due to low or absence of wetting front within the subsurface regime. Annual groundwater recharge was 295 mm/year. Annual groundwater recharge as percentage of annual precipitation stood at 25.6% approximately. Thus, a little more than a quarter of annual precipitation goes into recharge of aquifers. Almost three-quarter of the annual precipitation is lost into other sources such as runoff, evapotranspiration and soil moisture. Approximately, 37.5%, 34.3% and 3.6% of annual precipitation is lost to evapotranspiration, soil moisture and runoff respectively.

5. Conclusions

Estimated evapotranspiration varied from 5.11mm in August to 84.2mm in June with mean of 36mm; soil moisture measured varied from 8.2mm (March) to 56.7mm (January and September) with 32.9mm approximately as average. Peak runoff of 25.4mm was experienced in June coinciding with month of highest rainfall. Mean runoff was 3.4mm approximately and no runoff was recorded from January to April and from August to September. Monthly recharge for 2001 varied from -62.6mm in January to 81.5mm in February. Monthly groundwater recharge as percentage of monthly rainfall varied from -62.6% to 81.1%. Annual groundwaters recharge for 2001is 295 mm/ year. This is far more than the amount indicated by (Adomako et al, 2010). Annual groundwater recharge as percentage of annual precipitation stood at 25.6% approximately. Almost three-quarter of the annual precipitation was lost to other sources such as runoff, evapotranspiration and soil moisture. Approximately, 37.5%, 34.3% and 3.6% of annual precipitation is lost to evapotranspiration, soil moisture and runoff respectively. With continuous loss of vegetation cover due to anthropogenic activities in the area, ever-increasing use of groundwater for domestic and industrial purposes, there is a likelihood of continuous fall in groundwater table giving rise to undesirable environmental consequences. Thus, there is the need to research into a balance between groundwater recharge and domestic and industrial groundwater use in the sub-basin in order to find a sustainable management of the resource.

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