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QUANTIFICATION OF GROUNDWATER RECHARGE IN THE RIVER ODA CATCHMENT USING THE WATERTABLE FLUCTUATION METHOD

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Abstract

Quantification of groundwater recharge differs in their methods of estimation and therefore gives variable recharge estimates whenever a groundwater system is evaluated. Quantifying the fraction or the percentage of infiltrated water which reaches the watertable is a key factor in any sustainable planning scheme for groundwater resource management. The watertable fluctuation method was used to evaluate the seasonal and annual variations in water level rise and to estimate the groundwater recharge. The results showed that annual water level rise ranged from 1105-3115 mm in 2009 and from 397-3070 mm in 2010. A range of specific yields have been extracted from the values determined from the soil textural classification triangle. The estimated recharge for the study area ranged from 133-467 mm for the fourteen (14) piezometers installed for the study, representing 9- 31% of the 2009 annual rainfall and 47.6-427.9 mm, in 2010 representing 4-34 % of the annual rainfall. The area-weighted mean recharge was 341 mm in 2009, representing 21 % of the mean annual rainfall and 276 mm in 2010, representing 22 % of the mean annual rainfall. Also results of groundwater recharge rates for three monthly periods show that March-May experienced the highest recharge rate in 2009 and April-June in 2010. The lowest recharge rate was showcased from November-January with 26.4 mm and December-February with 26.9 mm. The recharge rates show that in the drier season around December, irrigation water should be applied based on the cropping season to obtain optimal moisture content and watertable levels.

***Keywords**:* Groundwater, Recharge, Water table Fluctuation, Specific Yield, Irrigation.

Introduction

Farmers along the Oda River in Ejisu-Besease in the Ashanti Region of Ghana practice floodplain cultivation as a form of supplementary irrigation. The Government of Ghana through the Agricultural Sector Rehabilitation Programme of the Ministry of Food and Agriculture (MOFA) and the Crops Research Institute (CRI) are actively encouraging floodplain cultivation, which can be practiced in the dry season using pumped water as a source of irrigation. Groundwater is of prime importance to meet rapidly expanding urban and agricultural demands. Wells were constructed for agricultural crop production in Ghana when MOFA initiated the Valley Bottom Rice Development Project in 1990. The contribution of groundwater in meeting crop water requirements at the Besease valley bottom has not been utilised in recent years. The use of groundwater, however, needs very careful analysis before its application. Therefore, there was the need to quantify the safe yield of the underground aquifer before accessing it for irrigation. Estimation of the rate of groundwater recharge is a basic prerequisite for efficient groundwater resource management (Sophocleous, 1991). This constitutes a major issue in regions with large demands for groundwater supplies, such as in semi-arid areas, where such resources are the key to agricultural development (Merèchal *et al*, 2006).

The determination of groundwater recharge rates is an inherently difficult task because of uncertainties and assumptions associated with the different methods of analysis and because various quantifying methods differ in the type of recharge and the space and time scales represented (Scanlon *et al*. 2002). A multitude of methods have been used to estimate recharge but according to Sophocleous (1991), the main techniques used to estimate groundwater recharge rates can be divided into physical and chemical methods (Allison, 1988; Foster, 1988). These methods produce estimates over various time and space scales and encompass a wide range of complexity and expense. Information on different methods is contained in references such as Simmers (1988, 1997), Sharma (1989), Lerner *et al.* (1990), Scanlon *et al.* (2002) and Merèchal *et al*, (2006). Among the physical methods, the watertable fluctuation technique (WTF) links the change in groundwater storage with resulting watertable fluctuations through the storage parameter (i.e. specific yield in unconfined aquifer). This method is applied likely due to the abundance of available groundwater-level data and the simplicity of estimating recharge rates from temporal fluctuations or spatial patterns of groundwater levels. The primary advantage of this method is ease of use and low cost of application in semiarid areas (Beekman and Xu, 2003). Errors associated with this method relate to ensuring that water-table fluctuations are related to recharge and not to other factors such as pumping, evapotranspiration, changes in atmospheric pressure, and the presence of entrapped air. However, these factors are assumed to be minimal. Groundwater recharge is a critical hydrological parameter that depending on the intended applications may need to be estimated at a variety of spatial and temporal scales (Sophocleous and Perry, 1985; Hendrickx and Walker, 1997). Thus there is the need to develop methods to quantify both the spatial and temporal distribution of groundwater recharge as a component of groundwater budgets. This is due to the fact that, there is a growing concern about the sustainable use and management of groundwater resource. In other words, an understanding of the recharge characteristics of floodplain wetland to rainfall inputs is necessary for viable sustainable floodplain agriculture. For any policy formulation, it is important to assess how sustainable wetland water supply will be able to meet the demand of a unit area of floodplain put under cultivation. This study sought to investigate the recharge to groundwater on the hydrology of the Besease Inland Valley Bottom which is being used for crop production.

Study Area

Besease is a predominantly farming area in the Ejisu Municipal District of the Ashanti Region in Ghana. The site lies within Latitude 1º 15¹ N and 1º 45¹ N and Longitude 6º15¹ W and 7º 00¹ W. The study area covers about 72 ha of the valley bottom lands at Besease (Figure 1). The climate of the study area is mostly related to the semi-humid type. The region is characterised with two distinct seasons, the wet season which begins from April and ends in October while the dry season extends from the month of November to March. The wet seasons can be categorised under two rainy seasons. The major rainy season which ranges from mid-March to July and the minor rainy season starts from September to mid-November. The mean annual rainfall is 1420 mm; mean monthly temperature is 26.5°C, the relative humidity ranges from 64% in January to 84% in August. The average monthly maximum and minimum evapotranspiration (ET_o) for the study area were 127.5 mm and 64.7 mm and has an annual ET_o of 1230 mm. The area is drained by the Oda River which is seasonal and whose basin is about 143 km² (Kankam-Yeboah *et al*, 1997).

The study area is located in the moist semi-deciduous forest zone. Grass species prominently found in the valley bottom are *Santrocema trifolia, Chromolaeve ordorata, Imperata cylindrical, Mimosa pigra,Ceiba patendra, Centrosema pubescens and Mariscus flabelliformis*. Plant species like *Raphia hookeri (Raphia palm), Alstonia boonei, Malotus oppositifolius and Pseudospondias microcarpa* extends along the margins of the Oda River. Soils of the Ejisu-Besease can be found in the soil map of Kumasi area. The study area lies in the Offin soil series which are grey to light brownish grey, poorly drained alluvial sands and clays developed within nearly flat but narrow valley bottoms along streams.The series have very slow internal drainage, very slow runoff, rapid permeability and moderate water holding capacity. The geology of the watershed is relatively heterogeneous and mainly composed of Phyllites, quartzite, shale, Tarkwain and Voltaian-sandstone and limestone. The Phyllites which underlie 59 % of the area consist of upper and lower Birimian rocks. Very few rock outcrops were encountered in the survey as the rocks are deeply weathered. The weathered phyllite is soft and easily broken, recognizable pieces and is typically found at 2-3 m below surface. Soils found within the Oda River catchment are grouped as those derived from granites, sandstones, alluvial materials, greenstone, andesite, schist and amphibolities. Specifically the soils are Orthi-ferric Acrisol, Eutric Fluvisol, Gleyic Arenosols, Eutric Gleysols and Dystri-Haplic Nitisol. The Besease aquifer is composed of heterogeneous sequence of layers which is dominated by sand, clayey sand and silts. The valley bottom is developed by small holder farmers who cultivate rice in the wet season and also grow vegetables like cabbage, lettuce, sweet pepper, cauliflower, cucumber and okra and other cereals like maize in the dry season when the water-table is low.

Materials and Methods

Groundwater Recharge

The watertable Fluctuation method (Meinzer, 1923; Hall and Risser, 1993; Ramussen and Andreasen; 1959; Healy and Cook, 2002; Risser *et al*, 2005 ;) was used for estimating recharge. This method was based on the premise that the rise in groundwater levels in unconfined aquifers was due to recharging water arriving at the water table. Recharge was calculated using the formula:

$R = Sy\frac{dh}{dt} = Sy\frac{\Delta h}{\Delta t}$ Where, R= Recharge (mm/month), Sy= Specific yield, dh or Δh = Change in watertable height (mm), dt or Δt = Time interval (month).

Wetland groundwater level fluctuations was monitored through a network of 14 piezometers installed using a hand auger along a longitudinal and transverse transect at the Besease site as shown in Figure 1. The piezometers consisted of PVC pipes of 7.62 cm diameter screened over the bottom 20 cm with holes of 0.3 cm diameter. The depth of the pipes ranged from 1.8 m to 3 m. Sand was packed around the screens and the rest of the annulus hole was backfilled with auger cuttings and then grout placed on the top to prevent surface water entry. The cup covering the top of the pipes were not hermetically closed to prevent build up of pressure in the piezometer during phases of groundwater rise. Depth to watertable was measured for every two days with greater frequency during rain events by inserting a measuring tape down into the piezometers and observing when it encountered the water surface. The elevations of the piezometers were surveyed to benchmarks to allow adjusting the water levels in the wells to the local datum.

Water Level Rise Estimation

To account for drainage from the watertable that takes place during rises in water levels, water levels rises were generally computed as the difference between the peak of a water level rise and the value of the extrapolated antecedent recession curve at the time of the peak. The recession curve is the trace that the well hydrograph would have followed had there not been any recharge (Delin *et al.,* 2006). There are various approaches for estimating the water level rise.
In this study the rise in water level dh was computed with the graphical approach as the difference between the peak water level during a recharge event and the extrapolated level to which water levels would have declined if the recharge event had not occurred. This was done by visually examining the entire water level records for each piezometer and manually extrapolating the antecedent recession curves. The rise in water level during the recharge period was obtained as the difference between the peak of the rise and the low point of the extrapolated antecedent recession curve at the time of the peak. The extrapolations are represented by the dashed lines in Fig. 2.

Determination of Specific Yield

The specific yield, *Sy*, is the fraction of water that will drain by gravity from a volume of soil or rock. It is defined as the difference between total porosity and the water content at field capacity. According to Martin (2006) the high variability of specific yield even within the same textural class causes the main uncertainty in the determination of recharge rates by means of the watertable fluctuation method. Healy and Cook (2002) list values of *Sy* from different studies. They recommend using the usually smaller *Sy* values determined from pumping tests rather than those determined from laboratory experiments. However, these values also vary over a large range. For fine to medium sand, Healy and Cook (2002) list values for *Sy* ranging from 0.005-0.19. The value depends on the grain size, shape and distribution of pores and compaction of the strata (Gupta and Gupta, 1999 cited in Martin, 2006).

In this study, a soil profile was constructed by pushing core samplers of 8.3 cm diameter and 10 cm long into the ground till it hit the watertable. The centre point of piezometers P13-P4, P11-P14, P1-P2, and P7-P8 were sited for the profiling. The content of the core samplers were packaged and sent to the laboratory for soil physical analysis. The soil textures for all the layers were determined using the hydrometer method. Johnson (1967) developed a relation between particle size and specific yield from a soil classification triangle. The results of percent sand, silt and clay obtained from the soil analysis were used to determine the specific yield from the soil textural classification triangle. The specific yield used for the recharge estimation is a parameter which is difficult to estimate accurately. Lerner *et al.* (1990) ascribed standard specific yield values to be taken from literature rather than field test measurements when values from laboratories are unavailable. Owing to that, the values obtained were compared with standard values of soil specific yields from Prickett (1965), Johnson (1967) and Todd (1980) from which a range of specific yield values were used to quantify the annual groundwater recharge at the study site. Bradford and Acreman (2002) list specific yield values for alluvial deposits to range from 1-10% for clay and 10-30% for silty sands.

Results and Discussions

Water Level Rise

When one takes into account all observation piezometers, rise of water level in the study area is almost entirely from the seasonal rainfall, since water level rise occurred mostly in the rainfall period. Though there were some accumulations of recharge in the dry season possibly due to regional flow of groundwater, this was very small.

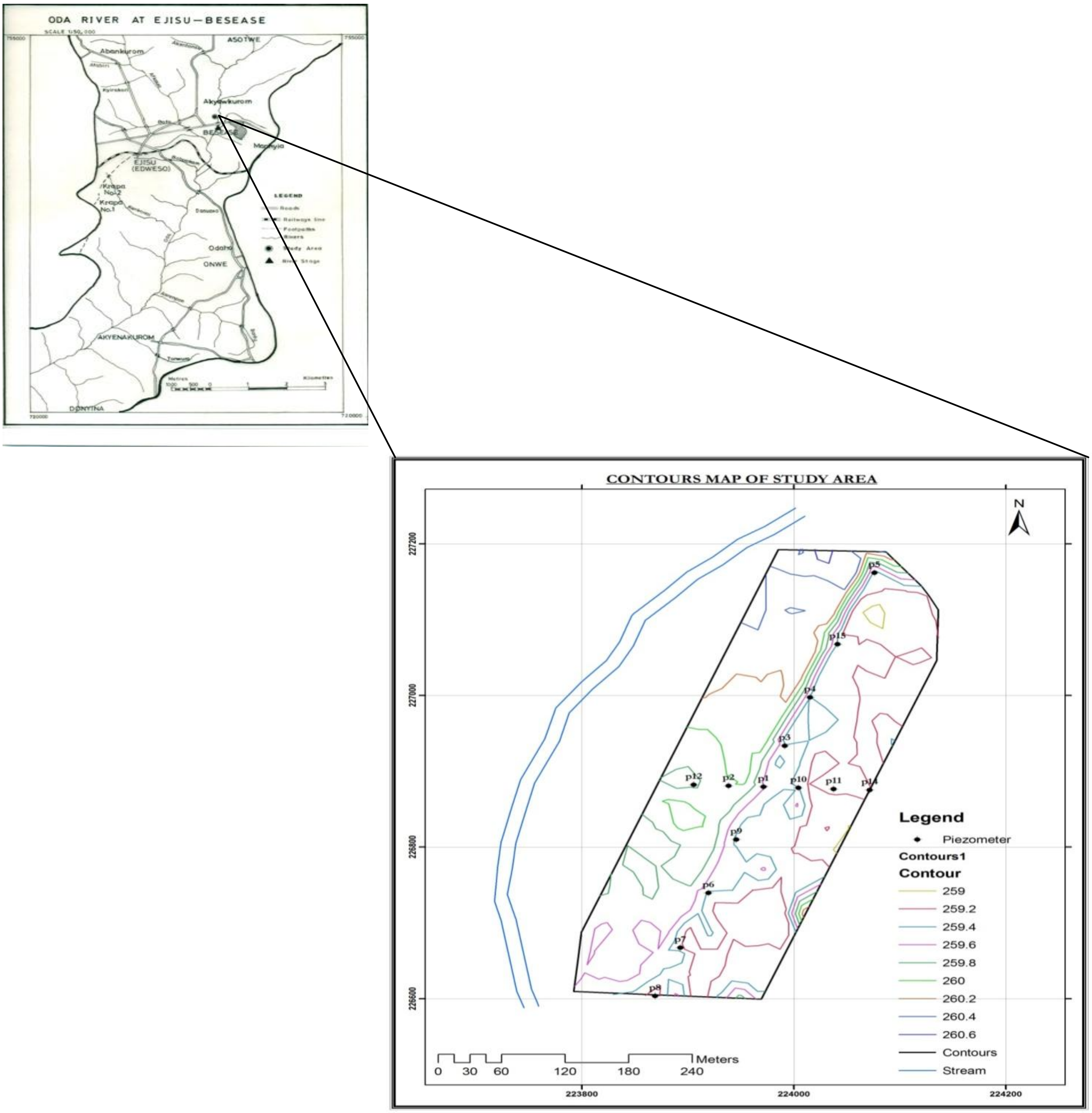

Figure 1 Map of the Besease catchment site showing field piezometric networks

Table 1. Recharge values in the Ejisu-Besease Oda River Basin of Ghana in 2009/2010

Piezometer	Soil Texture	Specific Yield	Year	h(mm)	Recharge (mm)	% of Rainfall
P1	Sandy Loam	0.12 - 0.18	2009	1933	232-348(290)	15-23(19)
	Sandy Loam	0.12 - 0.18	2010	1519	182.3-273.2(227.9)	15-22(19)
P2	Sandy Loam	0.12 - 0.18	2009	3055	366.6-550(458.3)	24-36(30)
	Sandy Loam	0.12 - 0.18	2010	2835	340.2-510.3(425.3)	27-41(34)
P3	Sandy Loam	0.12 - 0.18	2009	2288	247.5-411.8(343.1)	16-27(22)
	Sandy Loam	0.12 - 0.18	2010	1950	234-351(292.5)	19-28(24)
P4	Sandy Loam	0.12 - 0.18	2009	1624	194.9-292.3(243.6)	13-19(16)
	Sandy Loam	0.12 - 0.18	2010	1464	175.7-263.5(219.6)	14-21(18)
P5	Sandy Loam	0.12 - 0.18	2009	2495	299.4-449.1(374.3)	20-29(25)
	Sandy Loam	0.12 - 0.18	2010	2734	328.1-492.1(410.1)	26-40(33)
P6	Sandy Loam	0.12 - 0.18	2009	3115	373.7-560.6(467.2)	24-37(31)
	Sandy Loam	0.12 - 0.18	2010	2205	264.6-396.9(330.8)	21-32(27)
P7	Silt Loam	0.10 - 0.14	2009	3070	307-429.8 (368.4)	20-28(24)
	Silt Loam	0.10 - 0.14	2010	2853	285.3-399.4(342.4)	23-32(28)
P8	Silt Loam	0.10 - 0.14	2009	2784	278.4-389.8(334.1)	18-25(22)
	Silt Loam	0.10 - 0.14	2010	1623	162.3-227.2(194.8)	13-18(16)
P9	Sandy Loam	0.12 - 0.18	2009	2725	327-490.5(408.8)	21-32(27)
	Sandy Loam	0.12 - 0.18	2010	2223	266.8-400.2(333.5)	21-32(27)
P10	Silt Loam	0.10 - 0.14	2009	2230	223-312.2(267.6)	14 -20(17)
	Silt Loam	0.10 - 0.14	2010	2154	215.4-301.6(258.5)	17-24(21)
P11	Silt Loam	0.10 - 0.14	2009	1105	110.5-154.7(132.6)	7-10(9)
	Silt Loam	0.10 - 0.14	2010	397	39.7-55.6(47.7)	3-5(4)
P12	Sandy Loam	0.12 - 0.18	2009	2995	359.4-539.6(449.3)	23-35(29)
	Sandy Loam	0.12 - 0.18	2010	2435	292.2-438.4(365.3)	23-35(29)
P13	Sandy Loam	0.12 - 0.18	2009	2125	255-382.6(318.8)	17-25(21)
	Sandy Loam	0.12 - 0.18	2010	1636	196.3-294.5(245.4)	16-24(20)
P14	Silt Loam	0.10 - 0.14	2009	2650	265-371(318)	17-24(21)
	Silt Loam	0.10 - 0.14	2010	1421	142.1-198.9(170.5)	11-16(14)

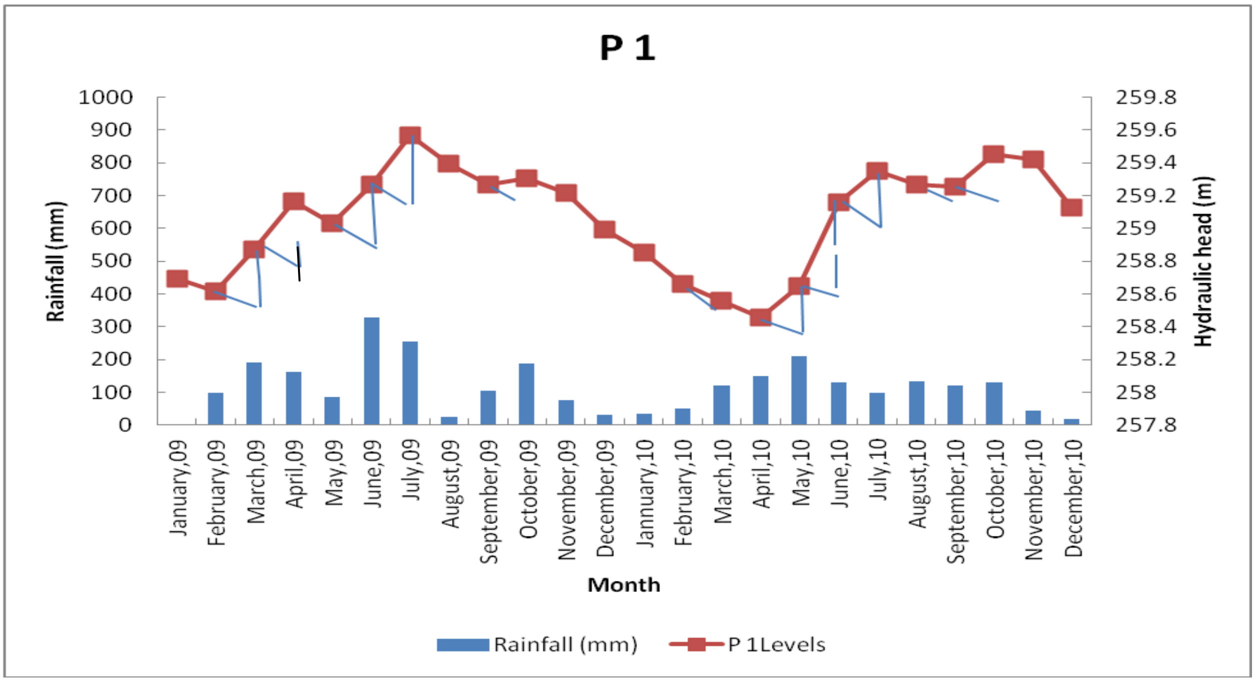

Fig. 2. Graphical Approach for estimating Recharge for P 1

The annual and spatial variations in water level were quite high as shown in the groundwater hydrographs. The total annual water level rise for the piezometric network ranged from 1105-3115 mm for an annual rainfall of 1543.9 mm in 2009 and 397-3070 mm for an annual rainfall of 1247.5 mm in 2010 respectively. The degree to which water levels fluctuate in the piezometers varied considerably within the study area. The variability in water-level rise exhibited by these piezometers was mostly the result of the location of the piezometers. The highest and lowest water level rises in the piezometers were recorded at P 6 and P11 respectively for 2009 and that of 2010 was recorded at P7 and P11 respectively. The water level rise measured at P12 and P2 were rather high and may have been influenced by lateral flow due to its close proximity 33 m and 66 m to the Oda River and P 14 at a low topographic height also experienced a high water level rise.

Groundwater Recharge Estimation

The groundwater recharge rate for each of the observation wells was calculated by multiplying the water level rise with the specific yield values (Table 1). The estimated recharge for the study area ranged from 133-467 mm for the 14 piezometers, representing 9 %-31% of 2009 annual rainfall and 47.7- 427.9 mm in 2010 representing 4-34 % of the annual rainfall. The overall mean groundwater recharge in the Ejisu-Besease Oda River basin of Ghana was estimated to be 316 mm in 2009, representing 22 % of the mean annual rainfall for that year and 238 mm in 2010, representing 21 % of the mean annual rainfall. The difference in the recharge values for the two study years could be attributed to the variability in the annual rainfall distribution and intensity. The recharge estimate obtained in this study is similar to estimates from groundwater studies done elsewhere in the world, using the water table fluctuation method. Sibanda *et al* (2009) estimated the recharge rate of Nyamandhlovu aquifer in Zimbabwe to be 0.4% and 9% of the long term annual precipitation. Also Obuobie (2008) applied the method to the Southern part of the White Volta Basin of Ghana and estimated recharge to range from 28.0-150.0 mm in 2006, representing 3.5-16.5 % of the mean annual rainfall and from 32.0-204.0 mm in 2007, representing 2.5-16.0 % of the mean annual rainfall with a specific yield range of 0.01-0.05. Similarly Sanwidi (2007) used this method for the Kompienga Dam Basin in Burkina Faso near Ghana, and estimated the recharge to be from 5.3-29.4 % of the annual rainfall. Similarly, Martin (2006) applied the method in the Atankwidi catchment, Ghana and estimated the recharge to vary from 1.8-12.5 % of the annual rainfall in 2003 and from 1.4-10.3 % of the annual rainfall in 2004. It can be concluded that differences in estimate of specific yield causes large relative differences in estimated recharge. Cumulative rainfall in January-February 2010 could not recharge the groundwater. This time lag occurred because rainfall takes some time to reach the groundwater table. That implied the rainfall infiltrated to replenish soil moisture deficit.

Recharge rate in the month of March 2009 was very high in all the observational piezometric network. The highest recharge rate of 160 mm occurred in P 14 which is located at a relatively low topographic height (Fig. 1) with a shallower watertable. However, the watertable fluctuation estimated recharge rate increases. One possible reason for this increase in recharge rate may be that it takes proportionately less time for water to travel through a thinner unsaturated zone, thus bringing the water to the saturated zone before it can be transpired by plants. The topographic low height at the site of P 14 coupled with the horizontal movement of subsurface groundwater (West-East) at the location of piezometer 14 gives the field a better point to locate a well to irrigate the field.

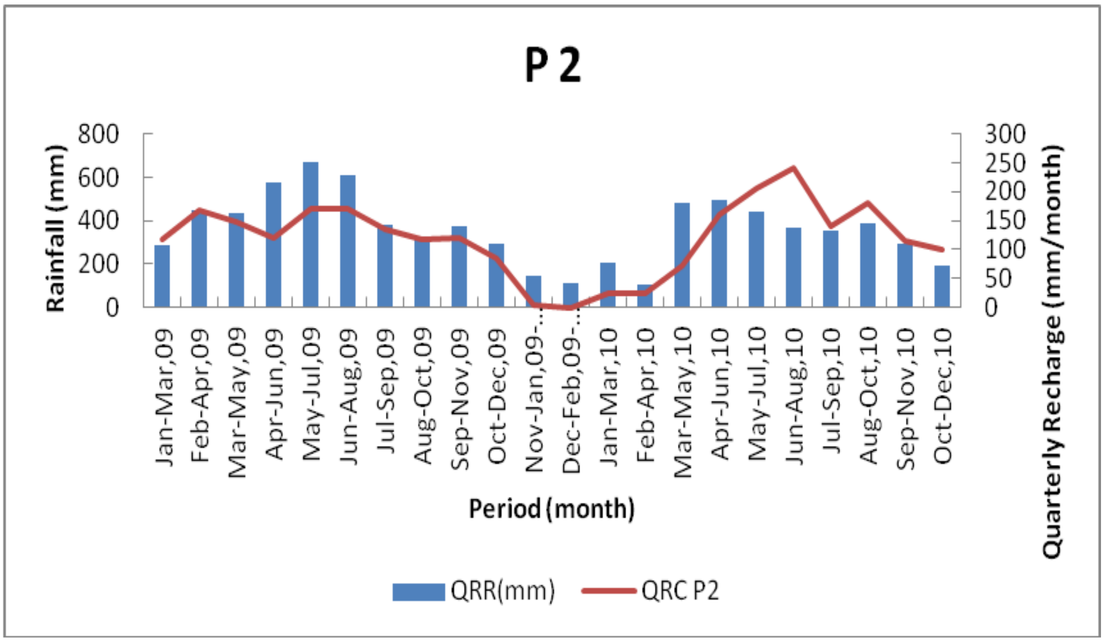

Fig. 3. Quarterly Recharge Estimate for Piezometer 2

Results of groundwater recharge rate (Figure 3, 4, 5 and 6) for three months period showed that March-May experienced a higher average recharge of 179 mm followed by February-April 167 mm and 121 mm of May-July representing 11.6 %, 8.4 % and 7.8 % of annual rainfall of 1543.9 mm for 2009 respectively. The May-July period which experienced a high rainfall but not the highest recharge suggests that water levels were near or at ground surface and so recharge becomes minimal and that was caused by accumulated antecedent high moisture content from the previous quarter and excessive surface water runoff from the Oda River during heavy storms especially in the months of June and

July. For 2010 where recharge was highest in the period of April-June, and May-July shows that substantial rainfall amount were spread over the rainy time periods coupled with intermittent short dry periods in the rainy quarters.

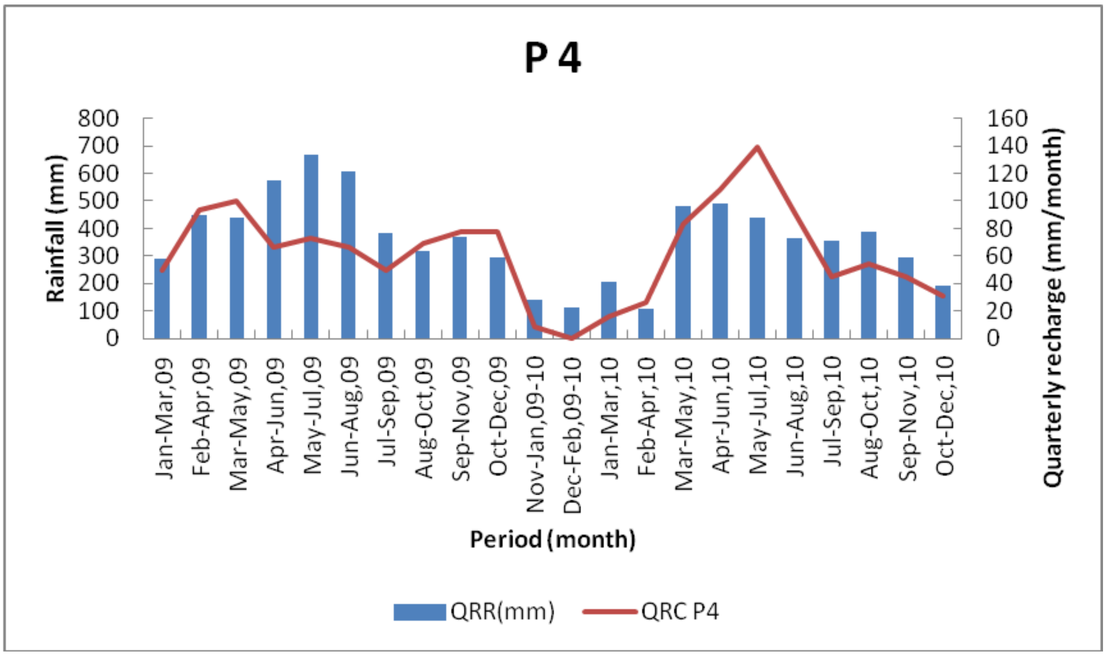

Fig. 4. Quarterly Recharge Estimate for Piezometer 4

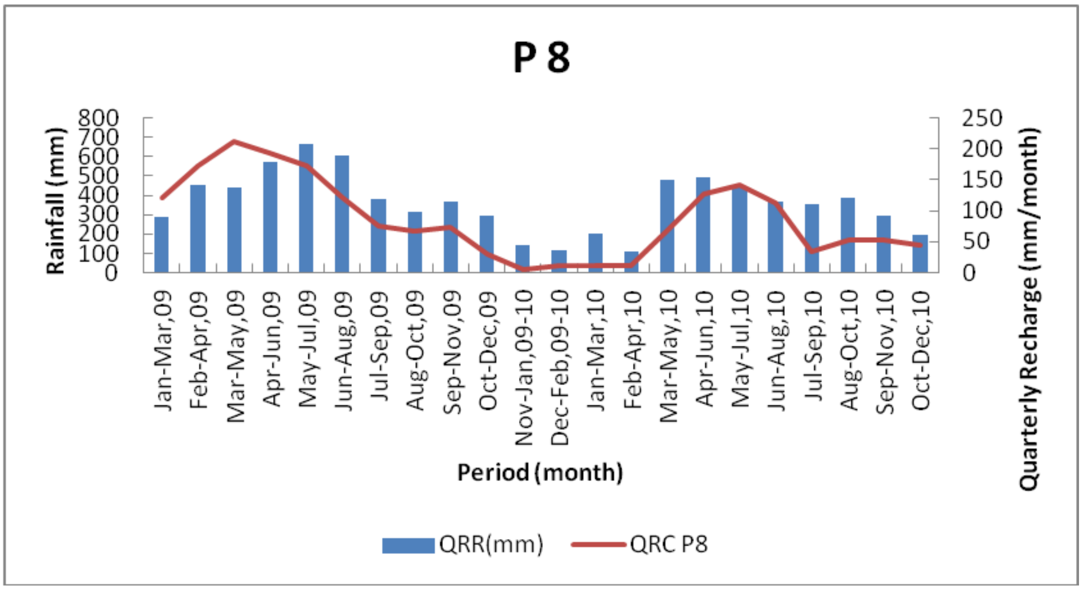

Fig. 5. Quarterly Recharge Estimate for Piezometer 8

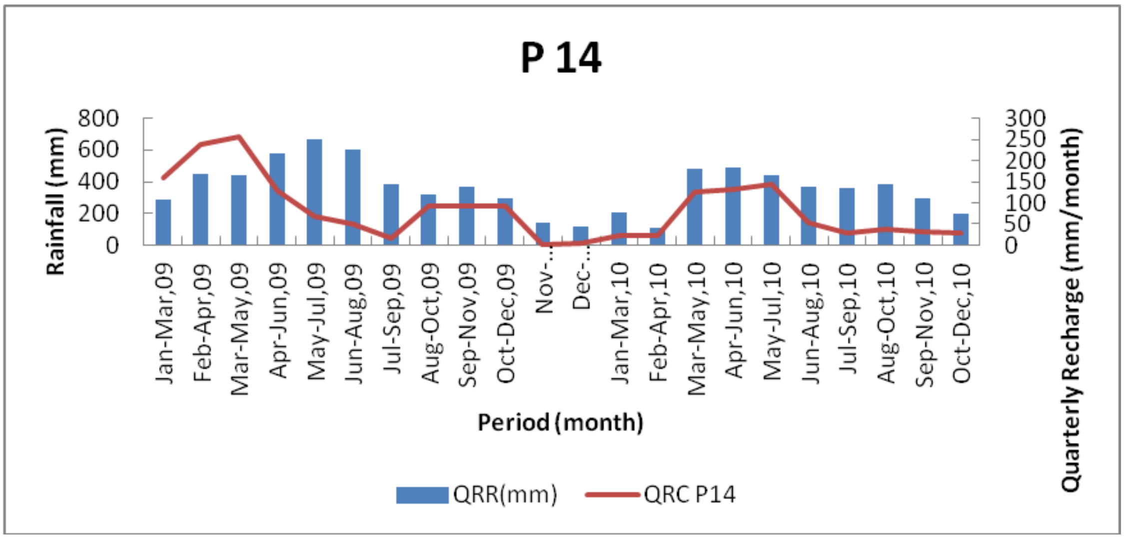

Fig. 6. Quarterly Recharge Estimate for Piezometer 14

It can be inferred that rice which can withstand floodwater ponding could be planted and supported with controlled irrigation and drainage in the catchment. The periods of February-April and March-May 2010 which had appreciable recharge increase indicates that moisture deficit had been replenished and so a higher rise of water level was experienced. This also suggests that high recharge rates lead to lower moisture stress by crops and an occurrence of an optimal watertable height to accommodate crops with differing rooting depths. Therefore there is the need to incorporate cumulative precipitation when accounting for groundwater recharge estimates. The lowest recharge rates were showcased from November-January with 26.4 mm and December-February with 26.9 mm representing 1.7 % of the annual rainfall. This implies, more irrigation water has to be applied to obtain optimal moisture content and watertable levels. Also from the graphs of the quarterly recharge of the four piezometers, it shows that recharge rate was lowest during the dry season followed by the minor rainy season and the highest in the major rainy seasons respectively, indicating a temporal variation of recharge in the seasons (see Figure 3,4,5, and 6). This also suggests that seasonal rainfall causes variation in groundwater recharge.

Conclusions and Recommendations

The water table fluctuation (WTF) method for estimating groundwater recharge requires data of specific yield and changes in the water table over time. It is best applied to systems with shallow water tables that display sharp rises and declines. The method requires no assumption on the mechanisms for water movement through the unsaturated zone hence the presence of preferential flow path does not restrict its use at the research site. The WTF method was applied to the Oda River basin at Besease, Ghana in 2009 and 2010 to quantify groundwater recharge and to analyze the fluctuations in the watertable. Recharge estimation for the study area ranged from 133 mm to 467 mm for the fourteen (14) piezometers, representing 9-31% of 2009 annual rainfall and 47.6-427.9 mm, in 2010 representing 4-34 % of the annual rainfall. Results from the three (3) months successive periods of the study showed that the May-July period in 2009 experienced a minimal recharge because water level were near or at ground surface as a result of high rainfall in the period. The lowest recharge rate in the dry periods of the two study years showed a decrease in groundwater storage which lowered the phreatic water level. It meant that irrigation water should be applied to obtain optimal moisture content and water table levels for effective crop production. Long term data could be collected to validate the study over a longer period.

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