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Groundwater Recharge Estimation From Modified Soil Moisture Balance Approach at the University Of Ibadan, Ibadan, Nigeria.

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ABSTRACT

Amount of water that may be extracted from an aquifer without depletion is primarily dependent on recharge. Thus, a quantitative evaluation of spatial and temporal groundwater recharge distribution is a pre-requisite for operating groundwater resource system in an optimal manner. A step-by step procedure of National Resources Conservation Services (NRCS) was used to estimate groundwater recharge based upon modified soil moisture balance approach at the University of Ibadan which covers about 1032 hectares of land. The methodology incorporates the theory of NRCS method of finding storage index. Water recharges were highest in sandy clay loam (59.0% Sand, 11.4% Silt, 29.6% Clay) between 113.1-122.5cm/hr, followed by sandy clay (58.1% sand, 8.9% silt, 33.0% clay) with values between 41.6-55.3cm/hr and sandy clay (56.8% sand, 7.5% silt, 35.7% clay) between 38.4-47.9cm/hr. This methodology gives better estimates of groundwater recharge because it takes into consideration climatic data, land use pattern and soil properties of study location. However, conventional methods of precipitation minus evapotranspiration minus runoff, is subjective to measurement errors and the method of calculating groundwater recharge by multiplying a constant specific yield value by the water table rise over a certain time interval may also be erroneous, especially in shallow aquifers.

Keywords: Groundwater, Recharge, Storage index, Infiltration, Moisture balance.

INTRODUCTION

Groundwater recharge is the rate of replenishment of an aquifer with water from land surface. Groundwater recharge varies with time, region and location. The rate of aquifer recharge is one of the most difficult factors to measure in the evaluation of groundwater resources (Moon *et. al.*, 2004). The main techniques used to estimate groundwater recharge rates are the Darcian approach, the soil water balance approach and the groundwater level fluctuation approach. Estimation of recharge, by whatever method is normally subject to large uncertainties and errors (Kumar, 1999)

Groundwater loss due to evaporation occurs in areas with shallow groundwater and loss due to transpiration by plants have a significant effect on the water balance in dry land as plant may draw water not only from unsaturated zone but also from the deeper saturated zone. (Klock and Udluft, 2002)

Component of soil water budget model includes; Precipitation, Runoff, Evapotranspiration, Soil moisture storage and Infiltration. The infiltration rate can be estimated through the use of cylindrical infiltrometer. The cylindrical infiltrometer could be single cylinder or double. The double cylinder is an improvement on the single cylinder to control the lateral seepage to reduce the error of non-uniform infiltration.

Objective of the study was to estimate groundwater recharge in the University of Ibadan using evapotranspiration data. Estimation of groundwater recharge using evapotranspiration data is important in order to determine the amount of water loss in the water budget model which reduces groundwater recharge and also to know the rate at which groundwater could be discharged to augment other sources of water supply during vulnerable seasons. Estimation of groundwater recharge also helps to determine the number of wells needed for water supply per day and the spacing of the wells so that the well draw-down of one over another do not affect its recharge

Several methods of estimating groundwater recharge have been deduced by different researchers, so as to maintain a balance in groundwater management (De Silva, 1998 Kumar, 1999; Moon *et. al.*, 2004; Shukla and Jaber, 2005 Moon *et. al.*, 2004; Shukla and Jaber, 2005). Underground aquifers are supplemented from sources other than rainfall such as seepage from canals and field channels, ponds, tanks, influent drainage from rivers, deep percolation from irrigated fields etc. Precipitated water must filter down through the vadose zone to reach the zone of saturation, where groundwater flow occurs (Anon, 2005). Groundwater recharge rate is the most important parameter required in the successful development of groundwater resources, as often, it is this rate that can safely be abstracted as safe yield from wells and boreholes.

The main techniques used to estimate groundwater recharge rates are the Darcian approach, the soil water balance approach and the groundwater level fluctuation approach. Estimation of recharge, by whatever method, is normally subject to large uncertainties and errors (Kumar, 1999). Some researchers came out with a Lumped model to predict the recharge behaviour of aquifer as the difference between the total input and output. Doll et al (2003) estimated annual groundwater recharge by the hydrological model Water Gap Global Hydrological Model (WGHM) based on time series of monthly climate variables as well as soil and land cover characteristics. Groundwater recharge is then calculated as a fraction of the total runoff using data on relief, soil texture, geology and glaciers.

Groundwater recharge is likely to vary even over a short distance as variation in climate, soil, and vegetation parameters can significantly affect the rates of recharge (Cook et al, 1989). Beekman (2005) observed that groundwater recharge is small in semi-arid regions due to low rainfall.

The rate of groundwater recharge increases with increase in rainfall. Furthermore, reduction in rainfall may be accompanied by reduced cloud and hence increase in solar radiation and reduced relative humidity (Hess, 1998; Hulmes, 1996). The effect of these would be to increase potential evapotranspiration and therefore exacerbate the impacts of reduced rainfall on the soil water balance.

MATERIALS AND METHODS

The research was conducted in the University of Ibadan which lies on 30 52' 30" E and 70 26' 30"N. Ibadan is located at the edge of tropical rainforest vegetation region of Nigeria at an altitude of about 206.68m above mean sea level. The University covers about 1031.95 hectares of land and was divided into three study areas based on the land use patterns viz: Bello Hall (Location 1), Independence Hall (Location 2), and Abadina Village (Location 3).

The locations are of gentle slope with fine-textured sandy soils. The study was carried out at a distance of 50-80m, which falls within the radius of influence of the well at each location. Part of location 1 was cultivated to maize and the rest was grown with grasses as at the time of the experimentation; Location 2 and 3 were covered with grasses. Infiltration rates, Precipitation, and Evapotranspiration were measured at the locations. Monthly data of 5 years previous rainfall, evaporation, minimum and maximum temperatures for Ibadan were obtained from the Institute of Agricultural Research and Training (IAR&T), old meteorological station Samonda and International Institute of Tropical Agriculture (IITA) Ibadan for comparison with University of Ibadan weather station data obtained from Geography Department, to have a better estimate of maximum infiltration.

Double ring infiltrometer method was used to determine the infiltration rate. The cylinders were installed about 100mm deep into the soil with the remaining 150mm exposed. Water was added to the inner cylinder from a graduated container. The soil surface inside the instrument was covered with jute and the water was poured on it. This was to prevent pudding and sealing of the soil surface as water was added. The jute was then removed after three quarter of the desired water has been filled and the water level in the inner cylinder was read. The outer cylinder, which is the buffer, was also filled to the same height to reduce the lateral seepage of water from the inner cylinder. Each experiment was conducted for 150 minutes (experimentation shows that infiltration becomes negligible after 120 minutes) and the water level noted at every 5 minutes. The values from each was recorded and plotted against elapsed time.

Groundwater Recharge Parameters

The soil water balance model can be represented as

$$G_r = P - Ea + \Delta S - R \ldots\ldots\ldots\ldots(1)$$

(Bekesi and McConchie, 1999)

Where, G_r = Recharge

P = Precipitation

E_a = Actual Evapotranspiration

ΔS = Change in soil water storage and

R = Runoff

To estimate groundwater recharge using this approach, daily rainfall, 5-week antecedent rainfall and Potential Evaporation were obtained from the University weather station using self-recording rain gauge and pan evaporimeter. Soil moisture contents were determined using the core method; the core consists of a hollow cylindrical material of 62mm diameter and 62mm height. Soil samples were taken from successive depth increments and the core was hammered by hitting the plank place on the core without disturbing the soil. Core soil samples were weighed before drying in the oven at 105^{0}C for about 24 hours until a constant oven dried weight of the soil were recorded. For soil moisture at saturation, the base of the samples were covered with cloth and the samples soaked in water bath (height of water in the bath should not be more than the core) for 24 hours so that water would completely fill the pores. The core was then placed in oven and dried at 105^{0}C to a constant weight. Porosity was calculated as the ratio of volume of pore spaces in the soil sample to the volume of core. Maximum amount of water a saturated soil can hold when all pore are filled with water is the water holding capacity and is computed as the difference between the weight of saturated soil and weight of oven-dried soil. In determining the field capacity after saturating the soil in water bath for 24 hours, the top of the core is covered with cellophane to prevent evaporation and then placed in the funnel to drain gravity water for 3 days. The sample was weighed after 3 days drainage. The ratio of weight of water at field capacity to oven-dried weight of soil gave the field capacity. Permanent wilting point was assumed to be half of field capacity since its laboratory determination is tedious and subjective, depending on the growth stage of vegetation planted. Hydraulic conductivity was determined by collecting undisturbed soil sample in a core and inverting a conical flask filled with water and corked with small delivery tube into the core. The soil core was placed in a funnel over a calibrated beaker. The soil core was filled with water to a known height and the refill water in the conical flask maintained the water head. Water collected in the beaker was recorded every 5 minutes until it reached equilibrium. Hydraulic conductivity was calculated using the Darcy's law (Freeze and Cherry, 1979). Saturated hydraulic conductivity was determined by the same process but the soil was saturated for 24 hours. Land use map and practice of study location was obtained from area map of the University of Ibadan. Crop coefficient (K_c) was obtained from the FAO Irrigation and Drainage paper 56 (Allen et. al., 1998).

Ground Water Recharge was determined by the following step-by-step procedure:

1. Determination of hydrologic soil groups
2. The antecedent moisture condition (AMC) from 5 –weeks antecedent rainfall
3. Plotting of Thiessen polygon areas of hydrologic soil groups and super imposing on land use map
4. Runoff Curve Number from National Resources Conservation Service (NRCS) method.
5. Initialize the cumulative recharge;

$$Q_{rc} = 0$$

6. Determination of storage index; $S_{(t-\Delta t)} = {}^{25400}/_{CN} - 254$
7. Comparison of total rainfall $P_{(t)}$ during time (t-Δt) to t with $0.2 \times S_{(t-\Delta t)}$ and estimation of initial abstraction (I_a) as follows;

$I_{a(t)} = 0.2 \times S_{(t-\Delta t)}$ if $P_{(t)} > 0.2 \times S_{(t-\Delta t)}$ ..(2)

$I_{a(t)} = P_{(t)}$ if $P_{(t)} < 0.2 \times S_{(t-\Delta t)}$ ....(3)

8. Initial water content of the soil (O_i) and water content at saturation (O_s) deduced from laboratory determination of porosity.
9. Estimation of infiltrated water (Q_i) during the current time step
10. Estimation of root zone soil moisture (O_i) and ground water recharge, $Q_r(t)$ in time step t, where O_f is final root zone moisture content after time (t) as follows;
11. If $(O_f - O_i)D_o < Q_i(t)$. Then $O_i(t) = O_f$ ......(4)

and $Q_r(t) = Q_i(t) - (O_f - O_i)D_o$................(5)

If $(O_f - O_i)D_o > Q_i(t)$

$$O(t) = \left(\frac{Q(t)}{Do} + \left(1 - \frac{KcEp(t)Oi}{2Do(Of-Ow)}\right) + \left(\frac{KcEp(t)Ow}{Do(Of-Ow)}\right)\right)\left(1 + \left(\frac{KcEp(t)}{Do(Of-Ow)}\right)\right) \quad (6)$$

$Q_r(t) = 0$

12. Determination of the cumulative groundwater recharge, $Qrc(t) = Qrc(t-\Delta t) + Qr(t)$..(7)
13. Estimation of evaporation loss from upper reservoir, $E_u(t)$ and transpiration loss from lower reservoir, $E_l(t)$ as:

$E_u(t) = E_p(t)$ if $P(t) > 0$ and $E_p(t) < I_a(t)$ ......(8)

$E_u(t) = I_a(t)$ if $P(t) > 0$ and $E_p(t) < I_a(t)$ ....(9)

$E_u(t) = E_p(t)$ if $P(t) = 0$ and $E_p(t) < I_a(t-\Delta t) - E_u(t-\Delta t)$.....................(10)

$E_u(t) = I_a(t-\Delta t) - E_u(t-\Delta t)$ if $P(t) = 0$ and $E_p(t) > I_a(t-\Delta t) - E_u(t-\Delta t))$.......................................(11)

$E_l(t) = K_c E_p(t)\left(\frac{O(t) - O_w}{O_f - O_w}\right)$ if $O(t) > Ow$...(12)

$E_l(t) = 0$ if $O(t) < Ow$.....................(13)

Where, $K_t\left(\frac{\theta(t)-\theta_w}{\theta_f-\theta_w}\right)$ is the coefficient for converting Pan Evaporation to Transpiration.

14. Updating storage index as;

$S(t) = S(t-\Delta t) + E_u(t) + E_l(t) - (Q_i(t) - Q_r(t))$......(14)

Where E_a (Actual Evapotranspiration) = $E_u(t) + E_l(t)$

RESULTS AND DISCUSSIONS

Water infiltrated greatest in Location 1 Sandy clay loam (59.0% sand, 11.4% silt, and 29.6% clay) and least in the Location 3 Sandy clay (58.1% sand, 8.9% silt, and 33% clay). Comparing Location 2 Sandy clay (56.7% sand, 7.5% silt, and 35.7% clay) and Location 3, water initially infiltrated at a higher rate in Location 2 until 95th minute when the infiltration rate dropped below that of Location 3, this may be due to panning of soil surface at Location 3 resulting from traffic over the surface, leading to low initial infiltration (Fig 1). Figure 2 showed that aquifer recharges highest in Location 1 and lowest in Location 3. However when the rate of infiltration was steady for the three locations, the recharge tends to be lowest in Location 2 (Fig 1). Figure 3 also indicated that there was a decrease in infiltration rate with time as the soil moisture increases, while accumulated infiltration increases.

With reference to field experiment on the 27th June 2005, 5-day antecedent rainfall was taken on the 22nd June and antecedent moisture condition was found to be 46.2mm. This was done during growing season of maize, which proved to fall under AMC group II from 5-Day Antecedent Rainfall according to USDA Natural Resources Conservation Service; 1972 (Mockus, 2005). Having known the hydrologic soil group, the Runoff Curve-Number was determined by plotting the Thiessen polygon areas of hydrological soil groups and superimposes the Curve Number on the land use map. It was found that location 1 has 2% row crop land use, 6% of road, and 92% for house stead. Location 2 has 5% row crop land use, 10% was covered by road, and 85% as house stead. Location 3 has 5% row crop land use, 4% to wood of good condition, 6% to road and right-of-way, 3% to pasture and 82% of house stead.

The recharge rate and the accumulated groundwater recharge were shown in figures 4 & 5. The result was obtained using step-by-step procedure in the methodology, with the aid of FORTRAN 90. Figure 5 showed that water accumulated at Location 1 more than the other two locations because of its least-clay percentage, thereby giving more room for infiltration.

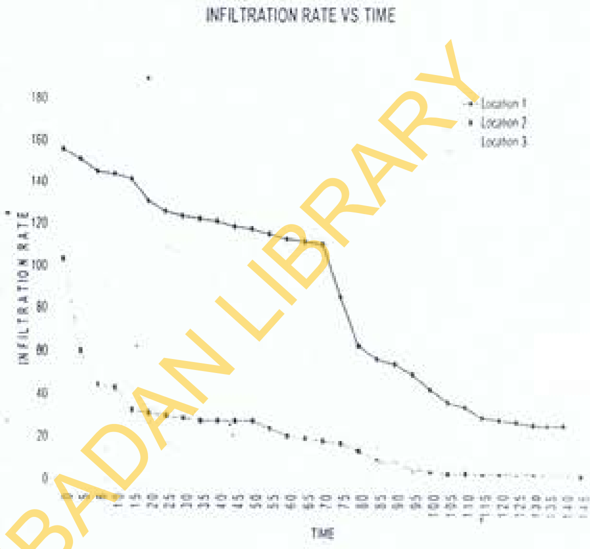

Figure 1: Infiltration rate at different locations

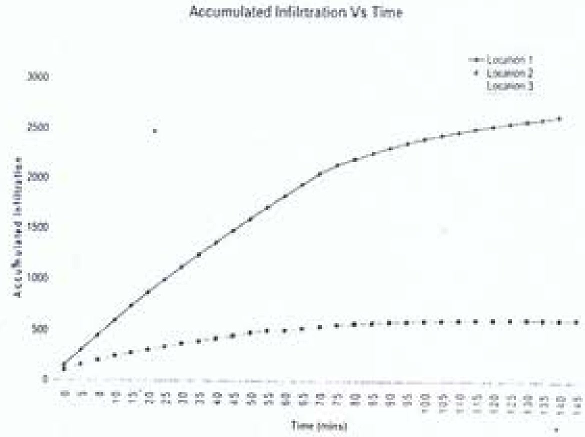

Figure 2: Accumulated Infiltration Capacity

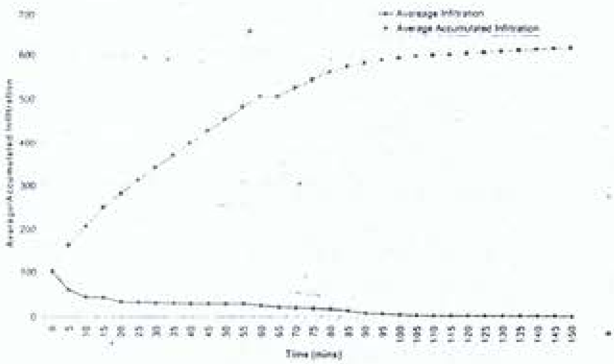

Figure 3: Average and Accumulated Infiltration

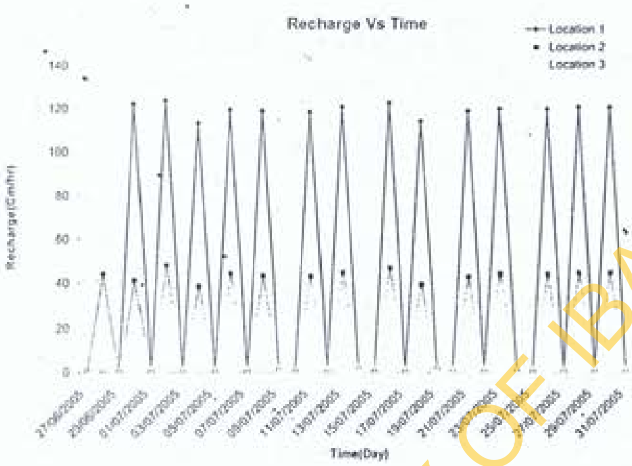

Figure 4: Groundwater Recharge

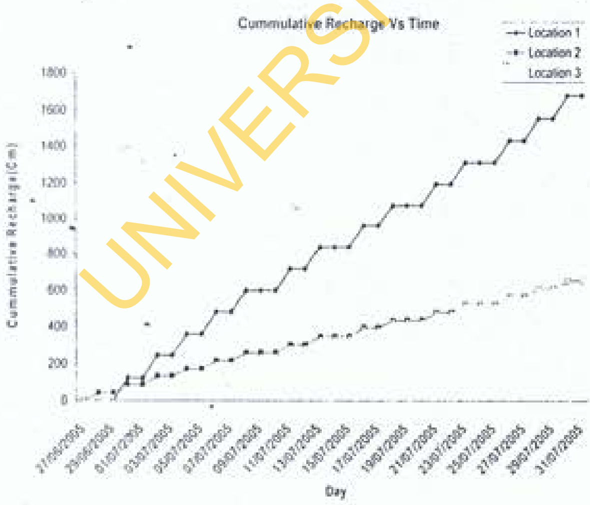

Figure 5: Cumulative Recharge at the Three Locations

Michael (1998) noted that large pores induce aeration and infiltration, medium size-pores facilitate capillary conductivity and small pores induce greater water holding capacity. This was observed in Location 1 with largest pore space, highest accumulated infiltration and the lowest moisture content, while the sandy clay of larger quantity of clay with smaller pores has the lowest accumulated infiltration and the highest moisture content. It is expected that, the highest runoff will occur in clay soil because of its low infiltration capacity, while sandy clay loam has the lowest runoff.

CONCLUSION

A methodology with systematic procedure to estimate the groundwater recharge based on modified soil moisture balance approach was applied. This methodology gives better estimates of groundwater recharge. However, the reliability of groundwater recharge estimated was improved by monitoring aquifer behaviour from observation wells on each of the three locations on a continuous daily basis. Water depths monitored at these observation wells between 7-7.30am showed that rate of water abstraction from these wells were lower than average recharge rate of 70cm/hr as a result of no noticeable well drawdown.

The application of several independent groundwater recharge estimation methods can complement one another and is likely to improve our knowledge of aquifer recharge, provided that an adequate hydro-geologic database and soil characteristics exist.

RECOMMENDATION

Based on results of this study at the University of Ibadan; water recharges averagely at 70cm/hr, and the entire area of study area is 1031.935 hectares, the average volume of 7,220,105.22m^3 of water recharges per day. Hence, pumping should not exceed this recharge volume.

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