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HYDROGRAPH ANALYSIS FOR GROUNDWATER RECHARGE IN THE PHREATIC BASEMENT AQUIFER OF THE OPEKI RIVER BASIN, SOUTHWESTERN NIGERIA

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ABSTRACT

Using hydrograph analysis, the estimation of groundwater recharge to the phreatic basement aquifer of the Opeki drainage basin in southwestern Nigeria, with an approximate land area of 980 km^2, indicates an annual value of between 29.23 x 10^6 m^3 and 259.09 x 10^6 m^3 , with an average of 134.45 x 10^6 m^3 (i.e.137 mm). The recharge is between 3 and 20% of the total annual precipitation and the baseflow ranges from 6 - 47% of the total annual stream flow with a mean annual runoff (MAR) of 708 mm. The dependence of baseflow on the amount of groundwater recharge is evidenced by a high correlation coefficient of 0.98 and the positive influence of precipitation on baseflow and groundwater recharge, are provided by correlation coefficients of 0.6 and 0.7 respectively. The significant amount of recharge in the study area provides evidence of the considerable amount of groundwater in storage in the basement areas of southwestern Nigeria and on which effective water resources planning and development can be based.

Key words: Groundwater recharge, baseflow, hydrograph analysis, basement aquifers, southwestern Nigeria.

INTRODUCTION

Groundwater recharge is a component of the hydrologic cycle as also precipitation, evapotranspiration, surface-runoff, interception and groundwater flow. It takes place through infiltration of water, part of which gets to the water table, results in the increase of groundwater storage and contributes to groundwater flow. When groundwater flow intercepts a stream channel, discharge to stream (known as baseflow) occurs and constitutes part of the stream hydrograph along with direct run-off. Separation of the total stream flow into surface and subsurface components is possible (WMO, 1974; UNESCO, 1972) and necessary in investigations concerned with the water balance of catchments and the relationship between surface water and groundwater. Such investigations enable the determination, not only of the groundwater contribution to the total stream flow, but also of the groundwater resources of the catchment. These are vital in the face of the prevalent exploitation of groundwater in Nigeria, which has raised concerns about its sustainability and the need for reliable estimates of groundwater

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recharge, as well as efficient planning, development and management of water resources (Goni *et al*., 2005; Goni, 2006). Groundwater development in Nigeria has increased tremendously over the last decade and many governmental and non-governmental organizations seek to improve the critically limited access to potable water, especially in the rural areas, through the construction of water wells. It is estimated that over 75% of the population in Nigeria rely on groundwater for domestic consumption only (Goni, 2006).

The evaluation of groundwater recharge is commonly done by the consideration of the difference between rainfall and evapotranspiration estimates, taking into account any surface –runoff (Ogunkoya 2000; Sjodin *et al*., 2001). In this study, evaluation of groundwater recharge of the Opeki drainage basin (catchment) in southwestern Nigeria is carried out through the analyses of the stream hydrographs and recession equation of the Opeki River.

Study area

Location

The Opeki catchment is well disposed to this kind of analysis as it is a medium to large catchment with a land area of about 980 km^2. It lies entirely within one climatic environment and a consistent geological environment of the Basement Complex of Southwestern Nigeria. Hence, it can provide insight into the nature of groundwater recharge in the basement areas of southwestern Nigeria in general. The attraction of the catchment is further enhanced by the fact that its discharge is gauged just as it discharges into the Ogun River at Abidogun (Fig 1). Opeki catchment is located in Oyo State, Nigeria and has Opeki as its major river. It lies between longitudes 3^{o}15' and 3^{o}30'E and between latitudes 7^o 20' and 7^o 54'N (Fig. 1). Located on Opeki river is an earth dam of a capacity of 2.6 MCM meant to act as a source of water supply to Igbo-Ora and environs.

Physiography and Geology

The Opeki catchment falls within the humid tropical climate with distinct wet and dry seansons. The wet season, which is usually double peaked, starts in March and lasts till November. The average annual rainfall calculated for Abeokuta (the Headquarters of Ogun-Osun River Basin Development Authority) which is located at about 10 km south of Opeki catchment, between 1988 and 1997(the period on which this study is based), is 1196 mm. The basin lies within the savanna environment, although the southern half of it lies within the fringes of the forest zone of southwestern Nigeria. Its vegetation consists of tall grasses in addition to trees with long tap roots, which ensure access to water during the dry season when the water table drops and the grasses wither and die. However, along the water courses, darker and denser vegetation occur throughout the year. The population is mainly rural and the dominant land use is arable agriculture in the wet season. The crops are mainly maize, cassava and yams

The catchment rises to an altitude of about 460m above sea level in the northern part of the basin around Awaiye and slopes southwards to about 135m above sea level at Abidogun, at the mouth of the catchment. The axial length of the basin is about

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73km and its form factor and basin circularity ratio are 0.2 and 0.8 respectively, indicating a long and narrow basin (Horton, 1932). The drainage pattern in the catchment is dendritic and a drainage density of 1.97 km^{-1} for the basin indicates an excellent drainage.Within the catchment are mainly the gneisses complex and minor occurrence of the Older Granites. Occurring in the upper half of the basin are the variably migmatized undifferentiated biotite- and biotite - hornblend gneiss with intercalated amphibolite and in the lower half, the schists, amphibolites, pegmatites and coarse porphyritic biotite and biotite- muscovite granite (Jones and Hockey, 1964).

MATERIALS AND METHODS

The daily discharge records of Opeki River for nine years, between 1988 and 1997, form the basis of this study. The records were collected from the Ogun-Oshun River Basin Development Authority, the Federal Agency responsible for the water resources development of parts of southwestern Nigeria in which Opeki catchment lies. The daily discharge values were obtained from daily stage measurements by using the rating curve for Opeki River. The rating curve was calibrated using the Valeport Baystroke BFM002 current flow meter with standard system comprising both wading and suspension sets. The nine years are the periods on which continuous records, appropriate for this kind of study, are available. The reliability of this analysis is naturally dependent on the accuracy of the data used. The data was consequently subjected to reliability analysis by determining coefficient alpha (using SPSS 11.0 for Windows), which is a measure of the internal consistency of the data based on the average inter-item correlation. The value obtained is 0.7, which indicates high consistency of the data.

The hydrograph of baseflow may be represented by (WMO, 1974; Korkmaz, 1990):

$$Q_t = Q_o e^{-at} \quad (1)$$

where Q_o and Q_t are the discharge at the beginning of the measurement period and at time t respectively, and a is the coefficient of recession or discharge coefficient

If the discharge is from a linear reservoir (as assumed in this study) where the discharge Q is proportional to the storage V, with Q = aV, then, on converting the measurements in seconds to days

$$V = \frac{86400Q}{\alpha} \quad (2)$$

where: V= storage capacity or dynamic reserve (m^3)

Q= groundwater discharge m^3 day^{-1}

a= coefficient of recession or discharge coefficient (day^{-1})

In logarithmic form to base 10, the exponential formula (Equation 1) is transformed into:

$$\log Q_t = \log Q_o - 0.4343at \quad (3)$$

The discharge coefficient is obtained directly from equation (3) via

$$a = \frac{(\log Q_0 - \log Q_t)}{0.434t} \quad (4)$$

Q_o and Q_t are obtained from the recession limb of the hydrograph for each hydrologic year from 1988 to 1997, while t is the time interval between the two. Q_o is chosen to correspond with the beginning of recession when the falloff in stream flow is consistent while Q_t corresponds to the end of the recession. This ensures that the analyses cover the periods when the stream flow is sustained predominantly by baseflow.

Equation (2) applies at each instant so that if Q in Equation (2) is taken as Q_t of Equation (1), then

$$V = (86400\ Q_o/a)\exp(-at) \qquad (5)$$

For a given time period, $\Delta t = (t_o - t_m)$, quantitative data about the dynamic reserve at the end of the period (t_m) may be calculated from the following equation (Korkmaz, 1990):

$$V_m = V_o + R - Q \qquad (6)$$

where: V_m = dynamic reserve at the end of the period, t_m (m^3)

V_o= dynamic reserve at the beginning of the period, t_o (m^3)

R= groundwater recharge volume during the time period Δt (m^3)

Q= groundwater discharge volume during the time period Δt (m^3)

The difference between the dynamic reserve (V_m) at the end of a chosen water year (t_m) and the dynamic reserve at the beginning of the water year (t_o) is the dynamic reserve change (ΔV). The volume of groundwater recharge during the water year is determined from

$$R = Q \pm \Delta V \qquad (7)$$

where: R= groundwater recharge volume during the water year (m^3)

Q= groundwater discharge volume during the water year (m^3);

ΔV= dynamic reserve change during the water year (m^3)

In this analysis, the water year is taken as beginning in March when the rainy season usually starts as observed from the precipitation data. The groundwater discharge (baseflow) volume during the water year is obtained by separating the hydrograph of the total monthly flow of Opeki River into surface (direct runoff) and subsurface (baseflow) components using the simplest and most common method of hydrograph separation (WMO, 1974; Linsley *et al.*, 1982; Bras, 1990; Watson and Burnett, 1995). This is done by extending the baseflow recession curve that existed prior to the influence of the storm to a point directly under the storm peak (Fig 2). A straight line in then drawn to join the point to the point of greatest curvature on the recession limb of the hydrograph. The area under the curve above the line represents the surface component while the area below the line represents the subsurface component.

The precipitation data employed in this study was that obtained from the Ogun-Oshun River Basin Development Authority Headquarters in Abeokuta, 10 km south of Abidogun where the gauging station on Opeki River is located. In order to appreciate the estimated amounts of baseflow, direct runoff and groundwater recharge, these values are compared with the average annual total runoff and precipitation.

RESULTS AND DISCUSSION

Monthly Discharge

The average monthly discharges of the Opeki River for the water year 1988-1997 are presented in Table 1. The discharges are largest between August and October, a result of the combined delayed effect of the two parts in which the wet season can be divided, viz. one part occurring between March and July and the other between September and November.

Discharge Coefficient

The results of the computation of the discharge coefficient for each hydrologic year between 1988 and 1997 by means of Equation (4) are presented in Table 2. The discharge coefficient ranges between 0.01518 - 0.03677 day^{-1} with an average of 0.02436 day^{-1}. A comparable value of (0.022day^{-1}) has been reported for the Ogun River gauged at Olokemeji (Gauff Consult. Nig. Ltd, 1995) located in the same environment as Abidogun, where the gauge on the Opeki River is located. Similarly, discharge coefficient values of between (0.02 – 0.03 day^{-1}) have been reported for Osun River at Esa Odo, also in southwestern (Nigeria (Gauff Consult. Nig. Ltd, 1995).

Dynamic Reserve, Baseflow and Groundwater Recharge

The average monthly data of the Opeki River in March of each year between 1988 and 1997 are given in Table 3, along with the results of the computation of the dynamic reserves at the beginning and end of each hydrologic year by means of Equation (2). The parameters used for this calculation are the discharge (Q_o and Q_m) at the beginning and end of each hydrologic year based on the discharge measurements of Opeki River and the average discharge coefficient of 0.02436 day^{-1}. Presented also in Table 3 are the dynamic reserve changes, the discharge data of the phreatic aquifers in Opeki catchment and the results of the computation of the recharge by means of Equation (7). The dynamic reserve change, hence the change in storage, during the period 1988-1997 is zero. This value is the difference between the total recharge volume and the total discharge volume for the same period. A zero dynamic reserve change obtained for Opeki catchnment supports the fact that over a long period of time, the average annual value of groundwater discharge is equal to the value of recharge to the groundwater reservoir (UNESCO; 1972). The average annual recharge volume from 1988 – 1997 in Table 3 is 134.37 x 10^6 m^3 (Table 3). This is the mean annual replenishment of groundwater in the study area. If this is taken as being indicative of the groundwater replenishment in the basement complex areas of southwestern Nigeria, which has an approximate area of 129 820 km^2, especially in the light of the similarities of the discharge coefficients of the Opeki catchment with Ogun and Oshun drainage basins, then an approximate amount of 1.78 x 10^{10} m^3 may be going to replenish groundwater annually in the phreatic aquifer of the basement areas of southwestern Nigeria.

In spite of the fact that there is a balance between the discharge and recharge volumes for the total period of study between 1988 and 1997, this balance is actually reached twice between 1988 and 1992 and between 1992 and 1997, with a value of 34.19 x 10^6 and 19.55 x 10^6 m^3 , respectively. Whether the conditions of

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reaching equilibrium every four and five years (i.e., cyclic) are characteristic of Opeki catchment may require the analyses of pre-1988 and post-1997 data (which are presently not available) and the monitoring of the water level for a long period of time. A correlation coefficient of 0.7 and 0.6 between precipitation and discharge and between precipitation and recharge respectively, indicate that precipitation influences the amount of groundwater discharge and recharge. Groundwater can constitute a range of between 3 and 20% of the annual precipitation with a mean of about 11%. Baseflow is influenced by the amount of groundwater recharge, indicating that the more the recharge, the more the baseflow. The influence is evidenced by a high correlation coefficient of 0.98. The amount of annual baseflow contributed to annual total runoff can be as significant as 40% with a mean of 20%.

CONCLUSION

The separation of groundwater component from the stream discharge by analysing stream hydrographs for a period of nine years has made it possible to determine the mean annual replenishment of groundwater resources in the zone of intensive water circulation in Opeki river basin of southwestern Nigeria. The average annual replenishment of groundwater is 134.37 x 10^6 m^3 (137 mm) and the influence of precipitation on groundwater recharge is evident by a correlation coefficient of 0.7. An annual mean of 11% of precipitation is constituted by groundwater recharge. Baseflow and groundwater recharge in Opeki basin correlate well with a coefficient of 0.98 and the average annual amount of baseflow contributed to annual total runoff has a mean of 20 %.

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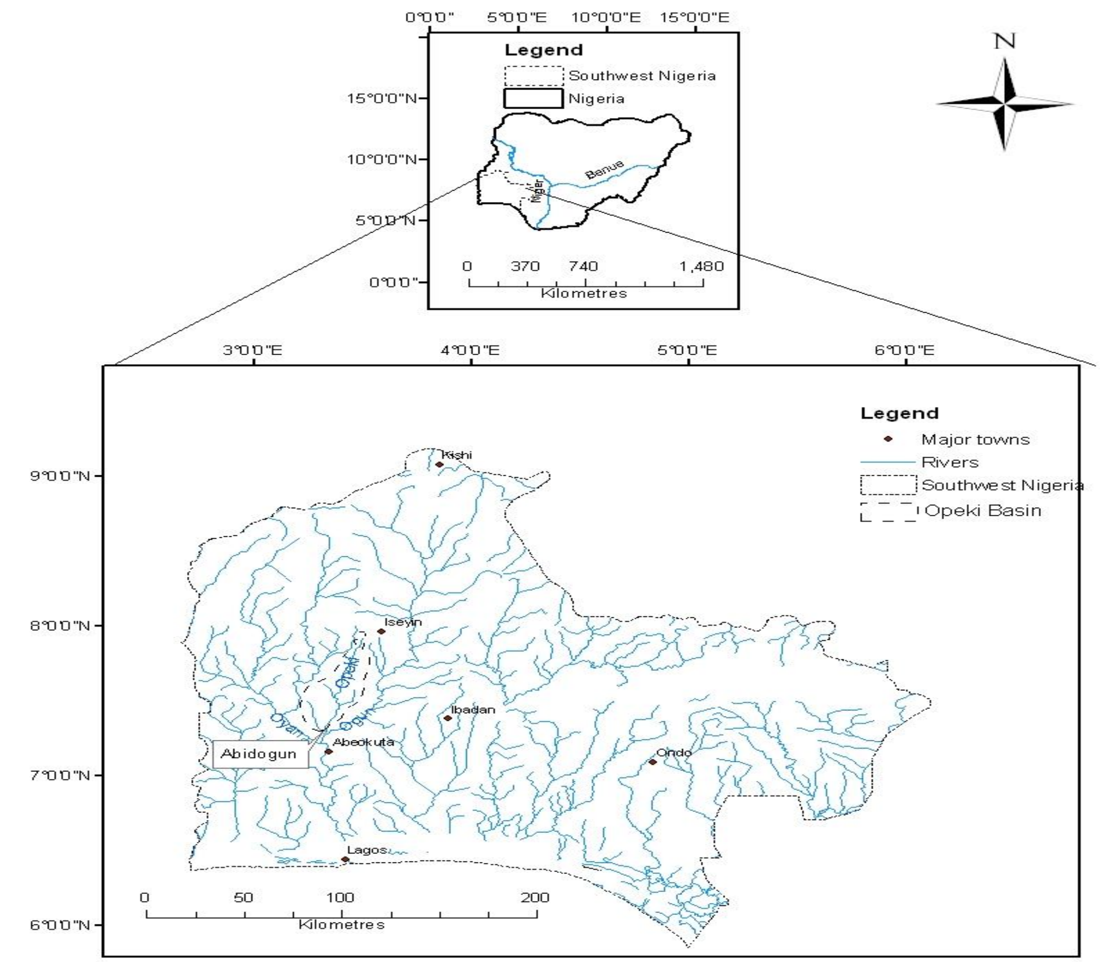

Fig. 1. Location map of Opeki River basin

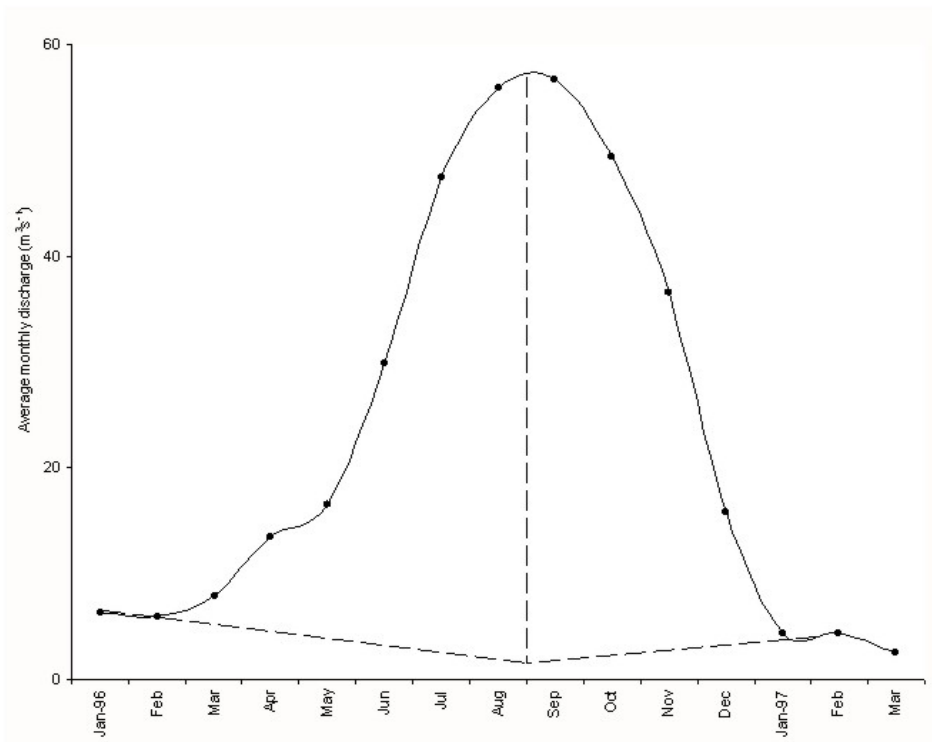

Fig 2: Hydrograph separation technique (Watson and Burnett, 1995)

Table 1: Average Monthly discharge of Opeki River (m^3s^{-1})

Water Year	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
88/89	2.5	2.5	15.63	67.77	54.98	53.36	56.42	9.93	9.83	9.21	8.26	10.59
89/90	17.88	26.81	23.54	46.24	77.81	87.70	63.58	26.79	9.37	12.32	16.42	12.13
90/91	12.24	13.25	14.79	14.66	14.20	19.80	44.42	41.70	16.58	9.83	7.94	8.76
91/92	8.19	2.88	3.58	27.63	99.06	35.64	42.4	7.36	3.62	2.50	2.50	2.50
92/93	2.50	2.90	13.43	28.31	68.97	20.76	64.91	16.74	6.47	4.36	2.50	3.89
93/94	2.93	2.89	4.86	14.65	11.69	25.10	44.14	9.07	44.14	7.06	6.65	3.75
94/95	2.50	2.50	2.50	7.94	8.24	6.51	49.04	37.18	3.57	7.36	6.92	6.73
95/96	11.50	17.87	34.33	49.89	29.35	31.23	65.90	34.87	15.34	6.25	5.97	7.88
96/97	13.39	16.52	29.86	47.47	55.88	56.65	49.43	36.50	15.84	4.28	4.36	2.50

Table 2: Discharge Coefficient Calculation

Water Year	Selected Interval, t (days)	Q0 (m^3s^{-1})	Qt (m^3s^{-1})	Discharge Coefficient, a (day^{-1})
88/89	129	84.9	7.95	0.018358
89/90	118	91.75	8.85	0.019819
90/91	125	51	7.65	0.01517
91/92	92	64.2	2.5	0.03528
92/93	93	76.4	2.4	0.03677
93/94	111	87.2	2.5	0.03417
94/95	19	7.5	5.9	0.01263
95/96	108	86	4.8	0.02671
96/97	158	62.1	2.5	0.02033

Table 3: Hydrographs Analyses

Water Year	March Discharges (m^3s^{-1})		Dynamic Reserve (86400Q/a) ($x10^6m^3$)		Dynamic Reserve Change ($x10^6m^3$)	Baseflow ($x10^6m^3$)	Recharge ($x10^6m^3$)
	Q_0	Q_m	V_0	V_m			
88/89	2.5	10.59	8.87	37.55	28.68	184.68	213.37
89/90	10.59	12.13	37.55	43.05	5.50	125.08	130.58
90/91	12.13	8.76	43.05	31.06	-11.99	271.08	259.09
91/92	8.76	2.50	31.06	8.87	-22.19	69.17	46.98
92/93	2.50	3.89	8.87	13.78	4.91	50.08	54.99
93/94	3.89	3.75	13.78	13.29	-0.49	29.72	29.23
94/95	3.75	6.73	13.29	23.87	10.58	110.64	121.22
95/96	6.73	7.88	23.87	27.93	4.07	198.57	202.64
96/97	7.88	2.50	27.93	8.87	-19.07	170.26	150.19

Table 4: Summary of Results

Water Year	Annual Precipitation (mm)	Groundwater Recharge			Average annual total run-off ($x10^6m^3$)	Direct runoff ($x10^6m^3$)	Baseflow	
		Vol ($x10^6m^3$)	Depth (mm)	% of precipitation			Vol ($x10^6m^3$)	% of total runoff
88/89	1576.1	213.37	217.72	13.8	788.40	603.72	184.68	23.4
89/90	1222.6	130.58	133.24	10.9	1105.34	980.26	125.08	11.3
90/91	1336.1	259.09	264.38	19.8	573.32	302.23	271.08	47.3
91/92	1165.2	46.98	47.94	4.1	625.23	536.05	69.17	11.1
92/93	1145.6	55.00	56.12	4.9	619.47	569.39	50.09	8.1
93/94	941.2	29.23	29.83	3.2	464.94	435.22	29.72	6.4
94/95	1030	121.21	123.68	11.9	370.53	259.89	110.64	29.9
95/96	1244	202.64	206.78	16.6	817.58	619.00	198.57	24.3
96/97	1057.8	151.19	155.03	14.7	874.28	704.01	170.26	19.5