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Estimation of Groundwater Recharge in Oil Producing Areas of the Niger Delta Basin of Nigeria: Using Soil Moisture Deficit Technique

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Abstract. The study was undertaken to predict natural and incidental groundwater recharge using the moisture deficit technique. It evaluates the rate of contaminants inflow into the phreatic aquifers of the Niger Delta Basin. The computer model used basic hydrological and agro-meteorological input parameters such as rainfall, potential evapo-transpiration, runoff coefficient, weighted root constant and oil and gas exploration/production spill data of 3 years to estimate the incidents of recharge on daily bases. The model was applied to selected four non-overlapping potential spill sites within the onshore area based on available data and geology/soil types. The study indicated that the daily natural recharge ranged from zero to 120 mm. Average monthly and annual natural recharge varied from zero to 585mm, and from 1416 to 2044 mm, respectively. The study established recharge coefficients of 0.143 to 0.365 for the area, with 95% confidence limit. Extensive tests determined that the model results are the most sensitive to variations in rainfall, evaporation and spill data. The estimated recharge coefficients were in agreement with the earlier reported range of 0.08 to 0.30.

Keywords: groundwater recharge, Niger delta, soil moisture deficit, oil exploration impact

Introduction

Groundwater recharge is that amount of surface water which reaches the permanent water table either by direct contact in the riparian zone or by down ward percolation through the over lying zone of aeration (Rushton and Ward, 1979). It is this quantity that may, in the long term, be available for abstraction and which is, therefore, of prime importance in the assessment of any groundwater contamination/pollution. Recharge is either natural (mainly through direct infiltration of rainfall into permeable soils and from surface flow), or it can be enhanced by contour ploughing, building dams, ponds, diversion channels and wells. It can also be incidental through irrigation, wastewater disposal, leaking pipes or clearance of deep-rooted vegetation.

The Niger delta basin is situated on the continental margin of the Gulf of Guinea and Bight of Biafra in equatorial West Africa. It lies between latitude 4 ° and 6 ° N, and longitude 5 ° and 8 ° E (Fig. 1). The region has great potential for present and future large-scale economic development due to bountiful natural resources such as hydrocarbon reserves, farmlands, water and fishery resources (Newton, 2005; Olowo, 2005; Reijers *et al.*, 1997). In spite of huge oil and gas revenue from the area, low quality of life indices indicate poor infrastructure development, health care delivery and lack of basic amenities especially potable water (SPDC, 2002; Obasanjo, 2001; Onosode, 2001). In addition to the reported low development indicators (World Bank Report, 2003), integrity of the groundwater, which is the only source of potable water supply, is threatened by the activities of oil exploration and production operation in the area (Ndubuisi *et al.*, 2005; Araque, 2001; Garland *et al.*, 1988). Large number of small spills occur daily (Abam, 2001; Adejuyigbe, 2000; Singh *et al.*, 1995). Over 70% of the rural communities in the oil producing area of the Niger delta rely upon untreated groundwater supply from shallow hand dug wells and springs for their daily needs (Abah, 2004; SPDC, 2002; Environmental Care Ltd, 2000; Singh *et al.*, 1995; Uma, 1989). These wells tap groundwater from the phreatic aquifers in the superficial deposits of the Delta Plain (Ohagi and Akujieze, 1989; Uma, 1989).

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The results of the above socioeconomic and poor environmental management include bitterness and growing agitation for resource control. This has lead to disruption of production, hostage taking, sabotage at oil facilities and instability. The instability in the area sometimes also affects the global crude oil price and the national economic development (Newton, 2005; Olowo, 2005; SPDC, 2002; Araque, 2001).

Previous studies of the regional geology of the Niger delta has established four distinct geological formations with ages ranging from Palaeocene to Oligocene times (SPDC, 2002; Reijers *et al.*, 1997). A summary of the characteristics of these formations is presented in Table 1.

Ohagi and Akujieze (1989) further classified the superficial deposits into coastal plain sands (found in Kokori), Sambreioro-Warri delta plain at Utorogu, alluvial Ogwashi-Asaba unit found in and around Egbema and Ameki unit in Obigbo areas (Fig. 1).

A review of major relevant environmental impact assessment (EIA), post impact assessment and other study reports for the area revealed lack of studies on groundwater recharge and models for predicting chemical movement through soil (SPDC, 2002). The reports exhibit strong inclination to aspects of pollution that can easily be seen or observed by the affected communities such as surface water, soil, fishery and forestry. Previous studies of recharge into the phreatic aquifers of the on shore areas are lacking. Accurate prediction of pollution impact requires an understanding of recharge into the aquifer system.

Table 1. Characteristics of the geological formation

Formation	Age	Type of sediment	Maximum thickness (m)
Superficial deposits	Quaternary to recent	Coarse layered sand and silt	500
Benin	Tertiary (Oligocene)	Massive continental fluvial sand and gravel inter-collations	2000
Agbada	Tertiary (Eocene)	Shallow marine deposits	1000
Akata	Tertiary (Palaeocene to Recent)	Deep marine pro-delta unit: shale, silt and clays	6000

Sources: Reijers *et al.* (1997), SPDC (2002)

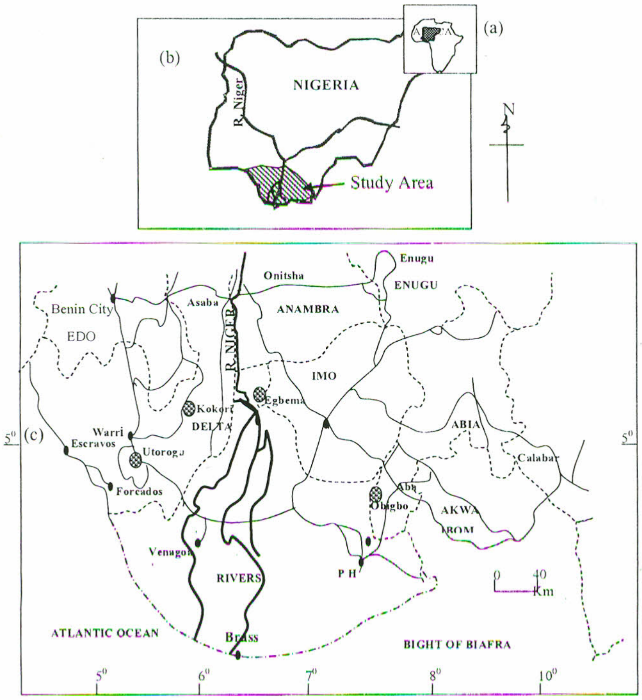

Fig. 1. (a) Map of Africa showing the position of Nigeria; (▰)
(b) Position of Niger delta in Nigeria;
(c) Location of study sites in Niger Delta (⊗);

Assessment of recharge is the first step towards development and application of chemical transportation model for the area. It will also serve as a basis for simulation, prediction, decision and ultimately policy formulation. This is because recharge is one of the key parameters for evaluating the rate of contaminant inflow (Jury, 1986a, 1986b). The main objective of this paper is to provide an estimate of the amount of natural and incidental recharge.

Materials and Methods

The data was obtained through primary as well as secondary sources and collected during October 2001 to January 2004. The data through field visits included daily rainfall and evaporation, type of vegetation cover, sources of domestic water supply, and oil/gas exploration and production facilities considered to be potential source of incidental recharge in the area.

The studied sites were relatively flat, located in agricultural rural environment near major oil and gas exploration and production (OGEP) facilities with potential for large and repeated spill, leaks or discharges. Such sites are liable to creat long-term environment problem and associated health hazards (Singh *et al.*, 1995; DPR, 1991).

The sites were accessable on shore upland and in an unconfined aquifer environment had adequate relevant amount of input data for the model.

The selected four non-overlapping sites included two from the eastern zone and two from the western zone of the Niger delta namely Egbema, Kokori, Obigbo and Utorogu.

After studying various methods for estimating recharge such as lysimeter, radioactive tracers, soil moisture balance, and ARGOSS guidelines (Lawrence *et al.*, 2001), the soil moisture deficit (SMD) model was adopted and applied to the selected sites; it has the advantage of being able to predict different scenarios without involving tedious and time consuming experimentation (Ikem *et al.*, 2002).

Preference was given to computation of hydrological input from those parameters, which require a minimum of the commonly available agrometeorological/hydrological data over a more complex and sophisticated model with comparable accuracy of prediction (Fapohunda and Ude, 1992; Duru; 1984).

In SMD model, recharge was calculated as the balance remaining after deduction of direct surface runoff (RO) and evapo-transpiration (PE) from precipitation (P1).

$$\Delta S = P1 - PE - RO \qquad (1)$$

where:

ΔS = change in storage
P1 = precipitation (mm)
PE = potential evapo-transpiration (mm)
RO = runoff (mm)

Negative value of ÄS represents decrease in soil moisture and positive value indicates potential recharge.

Basically computation of recharge is carried out on a one-day time step. In the process possibility of recharge depends on the SMD. This can assume four states, as follows:

A: SMD = 0
B: $0 \leq$ SMD $\leq$ RC
C: RC $\leq$ SMD < D
D: SMD = D

where:

RC = root constant,
D = maximum soil moisture deficit.

A computer programme developed by Ndubuisi (2005), as suggested by Odigie and Anyaeche (1991) and Rushton and Ward (1979), was used to estimates recharge for the area.

Some assumptions made in the application of the method were as follows:

(i) Water (or incidental discharge) movement through the soil was assumed to be according to the piston - flow model (Athavale *et al.*, 1980).
(ii) Precipitation is represented by rainfall data only as other forms of precipitation are negligible in the area.
(iii) Soil properties were assumed to be uniform as primary vertical soil heterogeneity is negligible (Elkateb *et al.*, 2003; Lawrence *et al.*, 2001).
(iv) Recharge was assumed to be only direct, hence recharge from seepage via river- aquifer interaction was not included.

Model parameters and input data. The parameters for computation of maximum soil moisture deficit (D) were obtained from the Federal Department of Agriculture and Land Resources. Recharge calculation was started at the beginning of January each year when the initial moisture deficit was taken as maximum.

The runoff coefficients (CI) were adopted from Sonuga (1990) which varied from 0.05 for 2001 to 0.20 for 2003 to reflect the variation of the data within the study area. The rainfall (P1) and evaporation (PE) records for the period 2001-2003 were obtained from the Nigerian Meteorological Agency. Oil exploration and production discharge (P2) was based on data from SPDC, Warri office. From this incidental data recharge, during both dry and rainy seasons of the year, could be assessed. The values were introduced during the months of January, April, July and October each year. A value of 15% was used to represent direct contribution to recharge rapid percolation (Tanaka *et al.*, 1996).

Computer simulation trials were performed using 3 years data (2001-2003) for the selected sites. The daily recharge estimates obtained from application of the SMD model was summarized into monthly and annual values.

The results were checked by sensitivity analysis, all potential errors including inherent errors in the input data and model parameters for eliminating uncertainties (Howard and Lloyd, 1979).

The computer programme was run daily and the parameters examined included the potential evapotranspiration (PE), rainfall (P1), weighted root constant (WRC), weighted soil moisture deficit (WD), runoff coefficient (CI) and slope of the drying curve (F).

The model estimate (mm) was compared to new estimates obtained by varying each parameter .The percentage variation of these new estimates from the model estimates were used to compute their sensitivity ratio as follows:

$$S_R = \frac{E_N - E_M}{E_M \times V_P} \times 100 \qquad (2)$$

where:

S_R = sensitivity ratio
E_N = new estimate
E_M = model estimate
V_P = percentage variation which ranged from $\pm$ 10 to $\pm$ 50.

The sensitivity levels are grouped as follows:

High: $/S_R/ \geq 1.0$ (significant)
Moderate: $0.5 \leq /S_R/ \geq 1.0$
Low: $0.1 \leq /S_R/ \leq 0.5$
Nil: $/S_R/ < 0.1$

Results and Discussion

The results indicate that the daily natural recharge RECH (I) for the period of this investigation ranged from zero to 120 mm and incidence of daily recharge occurred in 60% of the rainfall days. The number of days of recharge ranged from one in April to 21 in August. The maximum daily value occurred during the months of May to October, except for incidental recharge.

The monthly recharge in Egbema (Fig. 2a) ranged from the maximum value of 400 mm in September 2001 to zero in all the months of January to March and December for the period 2001- 2003. In Obigbo (Fig. 2b), the range is from zero to a maximum of 409 mm in August, 2002. The results for Utorogu ranged from zero to 539 mm in July 2002 (Fig. 2d). A maximum value of 585 mm was obtained for Kokori, which occurred in October 2002 (Fig. 2c). Thus, the investigation has shown that maximum natural direct recharge occurs between the months of July to October in the area.

These monthly values were also found to be about 26 to 49% of the rainfall (P1) in the area with an average of 35%, which can be regarded as the natural recharge coefficient for the area (Williamson and Lawrence, 1980). The coefficients ranged from zero to 0.11 in Egbema, 0.25 to 0.30 at Utorogu, 0.14 to 0.20 at Obigbo and zero to 0.11 at Kokori. The average recharge coefficient was 0.14± 0.016 at 95% confidence limit. Natural recharge occurs during the months corresponding to the peak of the rainy season, July to October (Fig. 2a-d) with zero recharge values. The low input of such periods resulted in a high SMD, which could not be compensated by the next day's, or next month's rainfall/discharge in excess of evaporative demands.

The maximum natural recharge of 400 mm for the month of September 2003 in Egbema, could be the result of the amount of P1 in excess of the PE/AE during the preceding month (August). Thus most of the P1 in excess of AE and runoff (RO) demands in September went into groundwater of the phreatic aquifers in the area as storage (S). Since the Storage values was high, the lower P1 of the next month (October) gave a high recharge. This can also be an indication of the period of potential contamination of the groundwater. Same is the trend of monthly recharge for the years 2001-2003. Similarly, the monthly spill data for January 2001 in Egbema was enough to offset the SMD and to produce incidental recharge of 11mm in 2001 and 9 mm in 2002. However, the SMD for the subsequent months (February to April) could not be satisfied till the month of May. This explained the zero recharge values for preceding months (Feb-April, 2001).

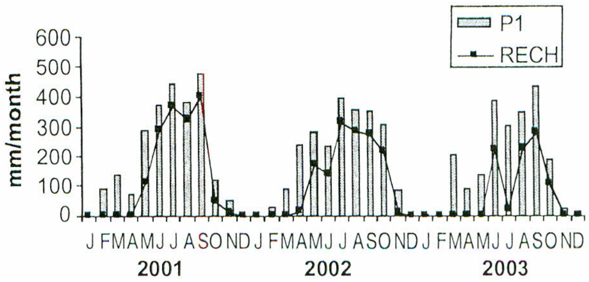

Fig. 2a. Variation of recharge with rainfall for Egbema.

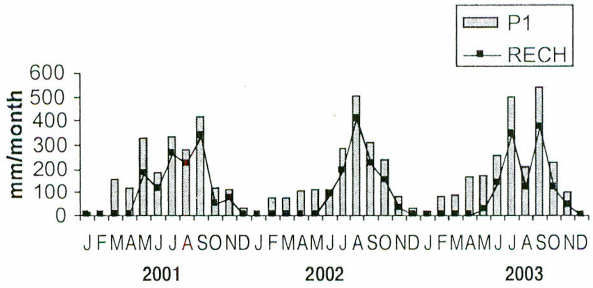

Fig. 2b. Variation of recharge with rainfall for Obigbo.

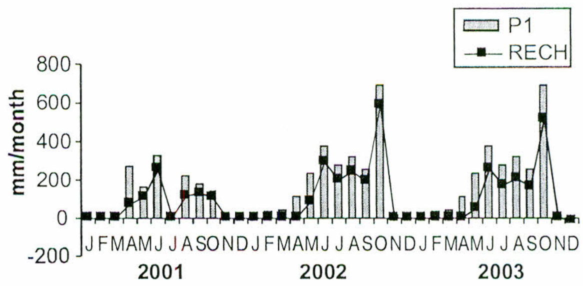

Fig. 2c. Variation of recharge with rainfall for Kikori.

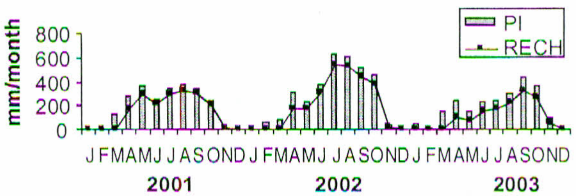

Fig. 2d. Variation of recharge with rainfall for Utorogu.

A summary of the estimated annual recharge (TRECH) from the model results is presented in Table 2. The mean annual natural recharge (NRE) ranged from 1252 mm in Kokori to 1802 mm for Utorogu site, with a mean of 1451mm for the four selected sites in the Niger delta basin.

The existence of a natural divide provided by the River Niger has lead to the classification of E and P activities in the Niger delta into East and West (Fig. 1) divisions. The mean values obtained could therefore be classified into 1375 mm for the Eastern (Egbema and Obigbo), and 1527 mm for the Western division (Kokori and Utorogu). These results show that

Table 2. Summary of predicted annual recharge (mm)

Site	2001	2002	2003	Total (E)	Mean	R/P1	Type	Total×10^4m^3
Egbema 1	1539.70	1423.12	1015.96	3978.8	1326.26	0.57	NRE	1.33
Egbema 2	1628.90	1510.44	1108.82	4248.2	1416.05		NRE/IRE	1.42
Egbema 3	1693.59	1558.58	1120.66	4372.8	1457.6		NRE/IRE	1.46
Obigbo 1	1243.04	1879.17	1148.78	4271.0	1423.66	0.57	NRE	1.42
Obigbo 2	1331.24	1981.0	1648.89	4961.11	1653.70		NRE/IRE	1.65
Obigbo 3	1403.54	2032.64	1290.23	4726.41	1575.47		NRE/IRE	1.58
Utorogu 1	1528.84	2537.82	1340.34	5407.0	1802.53	0.67	NRE	1.80
Utorogu 2	1962.44	2681.15	1487.00	6130.67	2043.56		NRE/IRE	2.04
Utorogu 3	2004.2	2692.77	1472.38	6169.35	2056.45		NRE/IR	2.06
Kokori 1	786.76	1596.63	1372.19	3755.58	1251.86	0.62	NRE	1.25
Kokori 2	933.85	2199.10	1900.90	5033.85	1677.95		NRE/IRE	1.68
Kokori 3	913.5	1718.49	1476.22	4108.21	1369.40		NRE/IRE	1.37

NRE = natural recharge; IRE = incidental recharge; R/P1 = recharge/rain fall

Western zone has possibly more recharge value than the Eastern. Similarly, the mean annual recharge for the four model sites ranges from 1416 to 2044 mm with an average of 1698 mm. Again, the mean for the Western sites (1867 mm) is higher than the mean for the Eastern sites.

It was further observed that mean annual recharge TRECH for Egbema and Kokori, in the Northern part of the study area, was lower than those for Obigbo and Utorogu, located in the South. Obigbo and Utorogu, being close to the Atlantic Ocean, equator and onshore swamps, have more rainfall incidents and amount/magnitude, less PE and less SMD. Since RECH (I) is the main source of potential contaminants inflow into the shallow rural wells, these sites are likely to experience greater contamination relative to other sites subject to other model factors remaining constant. This agrees with earlier studies of Ndubuisi *et al.* (2005), Abare (2003) and Uma (1989). Variation in the model result can be explained by the differences in rainfall distribution and the SMD.

Total annual input of natural recharge to the phreatic groundwater reserve of the study area is evaluated by multiplying the recharge area with the mean annual value for the aquifer (Athavale *et al.*, 1980); total natural recharge per hectare thus ranges from 1.25 x 10^4m^3 for Kokori to 1.80 x 10^4 m^3 for Utorogu. The mean natural recharge for the four stations is 1.45 x 10^4m^3/year. Combined natural and incidental recharge (NRE and IRE) ranges from 1.4 x 10^4m^3 in Egbema to 2.04 x 10^4m^3 is Utorogu with an average of 1.69 x 10^4m^3 for the four sites, (Table 2). The distribution and variation of these total volumes of infiltration follows the same pattern as the mean annual recharge (TRECH).

There is no doubt that the gradual decline in groundwater quality in the area reported in literature by Abah (2004), Environmental Care Ltd. (2000), SPDC (2000), Uma, (1989), resulted from contamination via recharge; a quantitative estimate has been provided by the study. In particular, recharge coefficent was found to be about 0.14 to 0.36 in the area at 95% confidence limit. Therefore, for every 1000 m^3/d of uncontained discharge within the area, at least 143 m^3 will infiltrate to enrich the water wells. This indicates that shallow groundwater in the area should be protected from pollution through recharge. Spacifically, this can be achieved by adequate and proper treatment of wastes to eliminate or minimize effluent pollutant concentration. This should be followed by reguler monitoring of the discharge to ensure compliance to limits.

Generally, the sensitivity ratio (S_R) was found to range from 0.11 to 0.79 during the months of May to October (2001-2003) due to relatively low PE values in the Niger delta environment during this period. Since, the variation of evaporation has moderate effect on the recharge results, input data source should be as reliable as possible.

Variations in the rainfall and incidental inflow by 10 to 50% produced high sensitivity ratio level (S_R> 1.0) in the monthly results. This indicates that the model is highly sensitive to variation in these parameters. It also gave the highest values of S_R which means that the model is the most sensitive to these inputs. This agrees with the sensitivity results reported by Odigie and Anyaeche (1991) and Howard and Lloyd (1979). The S_R values show that up to 50% variation in the slope of the drying curve (F) has zero to low effect on the model results.

Root constant (RC) determines the rate of evaporation. Reduction in RC leads to a reduction in the AAE and a consequent increase in recharge. The sensitivity tests showed that up to 50% modification does not lead to under estimation or over estimation of the monthly estimate from the model. Few moderate to high S_R values were recorded for the month of May, which is regarded as a transition month between the dry season and the growing season or onset of recharge. This may indicate that these input parameters may become significant at high % variations such as 3000 (Howard and Lloyd, 1979). The variation of runoff coefficient (CI) gave low sensitivity ratio levels indicating that the estimates are slightly sensitive to variation in CI. The effect was found to be more pronounced during the onset of RECH (I).

Comparison of sensivity ratios showed that the model results are highly sensitive to variations in rainfall and incidental discharge (PI), moderate to PE and CI, low to RC and D, and zero to CI and the slope of drying curve (F). The influence of variation in the parameter is more significant during the onset of farming season (April-May) which also corresponds with the onset of recharge

The result shows that the range of recharge coefficients of about 0.14-0.35 compares favourably with 0.08-0.3 given by Odigie and Anyaeche *et al.* (1991), Odigie and Olu (1985) and Athavale (1980). Thus, the predicted natural and potential incidental recharge is consistent and reliable.

Conclusion

A prediction of the groundwater recharge in selected onshore sites of the Niger delta basin of Nigeria has indicated that the average of recharge to the phreatic aquifers of the basin between 2001 and 2003, was about 1451mm/year (1.45×10^4 m^3/ hectare/year). The daily recharge values ranged from zero to 120mm at different geological sites within the basin. The recharge incidents occured in about 60% of the daily rainfall cases. The recharge coefficient ranged between 0.143 ± 0.016 to 0.36 ± 0.012 at 95% confidence limit.

It is revealed that the recharge estimates are the most sensitive to rainfall and incidental discharges. The effect was more in the early part of the rainy season than the later part. The recharge coefficients were found to be in good agreement with those reported by other researchers.

This work has provided an estimate of groundwater recharge, which could be useful in prediction of contaminant infiltration into shallow rural wells in the area. However, much work is required to be done in this area, especially in the field of environmental hydrology. More studies are suggested to provide groundwater flow models and also recharge through river-aquifer interaction. This will assist in future design of groundwater assessment and management strategies.

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