GLOBAL JOURNAL OF GEOLOGICAL SCIENCES VOL. 4, NO. 1, 2006: 7 - 19
 ISSN 1596 - 6798

APPLICABILITY OF SOLUTE BALANCE TECHNIQUE IN ESTIMATING RECHARGE: A CASE STUDY OF A PAVED AND NON-PAVED AREA OF THE EASTERN NIGER DELTA, NIGERIA

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(Received 21 April, 2005; Revision Accepted 19 September, 2005)

ABSTRACT

Information on groundwater recharge within a basin is very essential in the management of groundwater resources especially in areas where groundwater forms a major source of freshwater supply and/ or in areas where groundwater supply is susceptible to pollution.

This paper discusses the use of solute balance technique in estimating recharge in a paved and non-paved area. The study area is located in the Eastern Niger Delta which is characterized by humid climate. The subsurface lithologies are fine – coarse grained sands, gravels and clay.

The average annual rainfall for the area for the periods 1985 – 1998 was calculated to be 2235mm. Recharge estimates for the paved zone is between 74mm/yr and 378mm/yr while the non-paved zone is between 279mm/yr and 378mm/yr. These values represent about 13% and 16% of recharge from annual rainfall in the paved and non-paved zones. This implies that only a small proportion of the annual precipitation percolates to the water table. This proportion is much less in the paved zone than in the non-paved zone. However, large quantities of the precipitation run overland to streams, creeks and/or are discharged by the process of evapotranspiration before reaching the aquifer.

Key words: Solute balance, Recharge, Precipitation, Evapotranspiration, Lithology.

INTRODUCTION

Groundwater recharge is water that reaches an aquifer from any direction down, up or laterally (Scanlon, et. al., 2002). Schicht and Walton (1961) define groundwater recharge to include any infiltrating water that reaches the saturated zone and can be written as $R = Q^{gw}_{off} - Q^{gw}_{on} + Q^{bf} + ET^{gw} + \Delta S^{gw}$. However, Hamil and Bell (1986) sees it as that proportion of rainwater that manages to gravitate to the water table. Periodic evaluation of groundwater recharge is important for effective management of groundwater systems and accurate evaluation of water resources. The various types of recharge techniques include groundwater level technique or specific yield, numerical modeling technique, tracer technique, flownet, baseflow separation, solute balance, etc (Scanlon, et. al., 2002). However, these individual techniques have their uncertainties in terms of applicability to certain climatic environment. Table 1 shows techniques for estimating recharge in different climatic environments.

In this study, attempts have been made to estimate recharge into aquifers in a pave and non-paved areas of the Eastern Niger delta by applying the solute balance technique. The results generated from this study will serve as a guide for effective planning and management of water resources in both the study area and related environments.

Table 1: Appropriate techniques for estimating recharge in regions with arid, semi-arid and humid climates

Hydrologic zone	Techniques for Arid and Semi-Arid Climates	Techniques for Humid Climate
Saturated water	Channel water budget. Seepage meters. Heat tracers. Isotopic tracers. Watershed modeling.	Channel water budget. Seepage meters. Baseflow discharge. Isotopic tracers. Watershed modeling.
Unsaturated zone	Lysimeters. Zero-flux plane. Darcy's law Tracers [historical (^{36}Cl, ^{3}H), Environmental (Cl)]. Numerical modeling	Lysimeters. Zero-flux plane. Darcy's law Tracers (applied). Numerical modeling.
Saturated zone	Tracers [historical (CFCs, $^{3}H/^{3}He$), environmental (Cl, ^{14}C)]. Numerical modeling.	Water-table fluctuations. Darcy's law. Tracers [historical (CFCs, $^{3}H/^{3}He$)] Numerical modeling.

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Previous studies that have been carried out in the study area on the aspects of hydrogeochemistry include (Etu-Efeotor, 1981; Etu-Efeotor and Odigi, 1983; Amajor, 1986; Ngah, 2002; Ofoma et. al., 2003). Odigi (1989) used mainly aquifer performance test (APT) and the step drawdown test (SDT) data to determine some hydrogeological parameters in the Eastern Niger Del'a. Etu-Efeotor and Akpokodje (1990) characterized the aquifer systems of the Niger delta area. They observed that the aquifer systems of the Niger delta area is multi layered. However, no known literature on recharge estimates on the Niger Delta area exist, this paper may well serve as a first attempt at quantifying the recharge in the area using the solute balance technique.

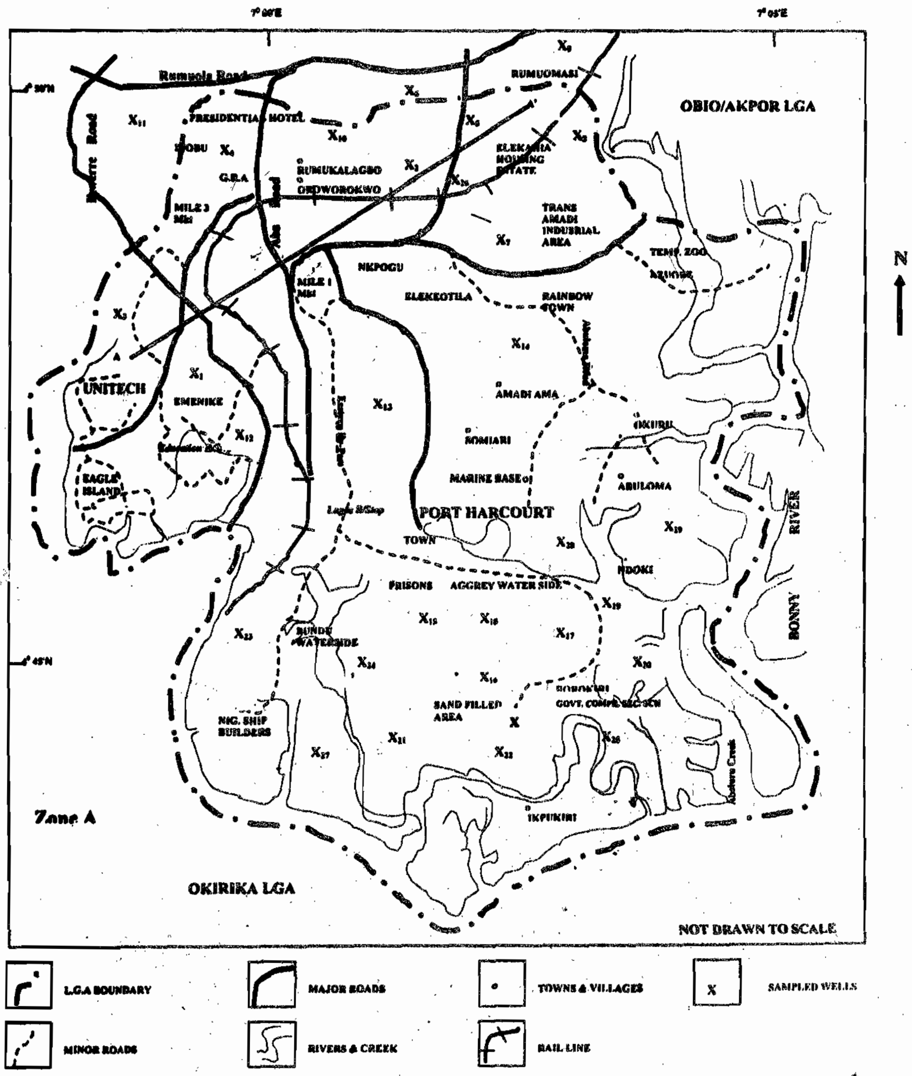
S.UDY AREA DESCRIPTION

The entire study areas lie between latitude $4^0 45'$N and $5^0 00'$N and longitude $6^0 45'$E and $7^0 14'$E. They areas are characterized by humid climate and groundwater reserves are within higher levels or shallow water table. Aquifers are both confined and unconfined. Groundwater abstraction is carried out by using hand pump, submersible pump or hand dug wells with utter disregard to the proper management of this resources. This is partly due to the influx of non-professionals in the planning, exploration, drilling and management of groundwater in the area.

Specific areas have been carved out from the entire study area to represent highly developed and less developed area i.e. Paved Zone 'A' and Non-Paved Zone 'B' (Fig. 1).

PAVED ZONE A

The paved zone 'A' has an estimated area of $87.5km^2$. The zone is carved out from the Port Harcourt city area and tagged paved zone 'A' for this study. It cuts across such areas like Elelewa, Trans Amadi, Rumuodara, Rumuogba, Rumuola, Rumuigbo, Borokiri, etc., accessibility within the zone is either by the numerous tarred or untarred roads and footpaths. This zone is densely populated with a population of about 289,459 people (National Population Commission, 1991 census in Annual Abstract of Statistics, 1999 Edition). This figure by now must have increased beyond the above value. Building/Civil engineering structures in this zone are closely constructed with tarred roads existing at every corner of the city. The major drainages are found within Aba road, Ikwerre road, Aggrey road (Borokiri) and Trans Amadi areas, while minor ones are observed within the layouts. Some of these drainage facilities are lined with concrete slabs at the base while some are not. However, the sides have concrete



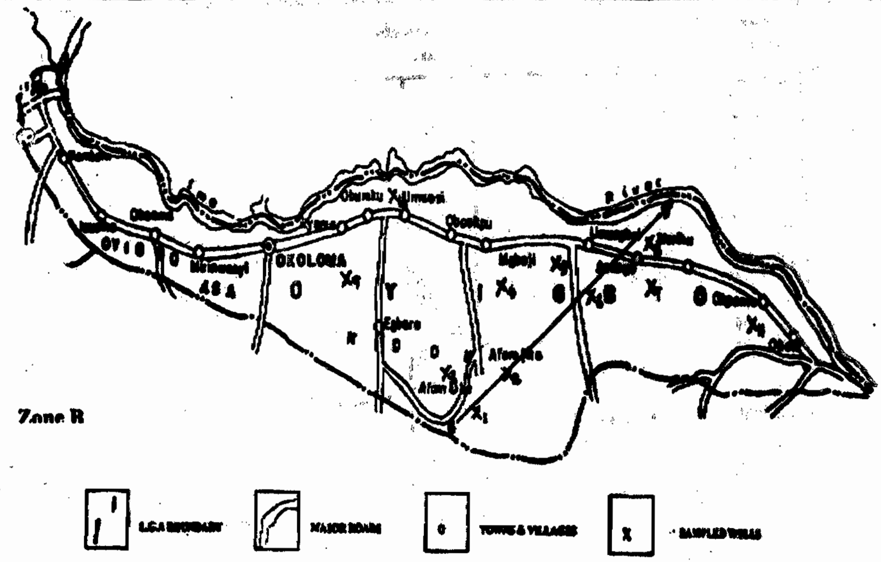
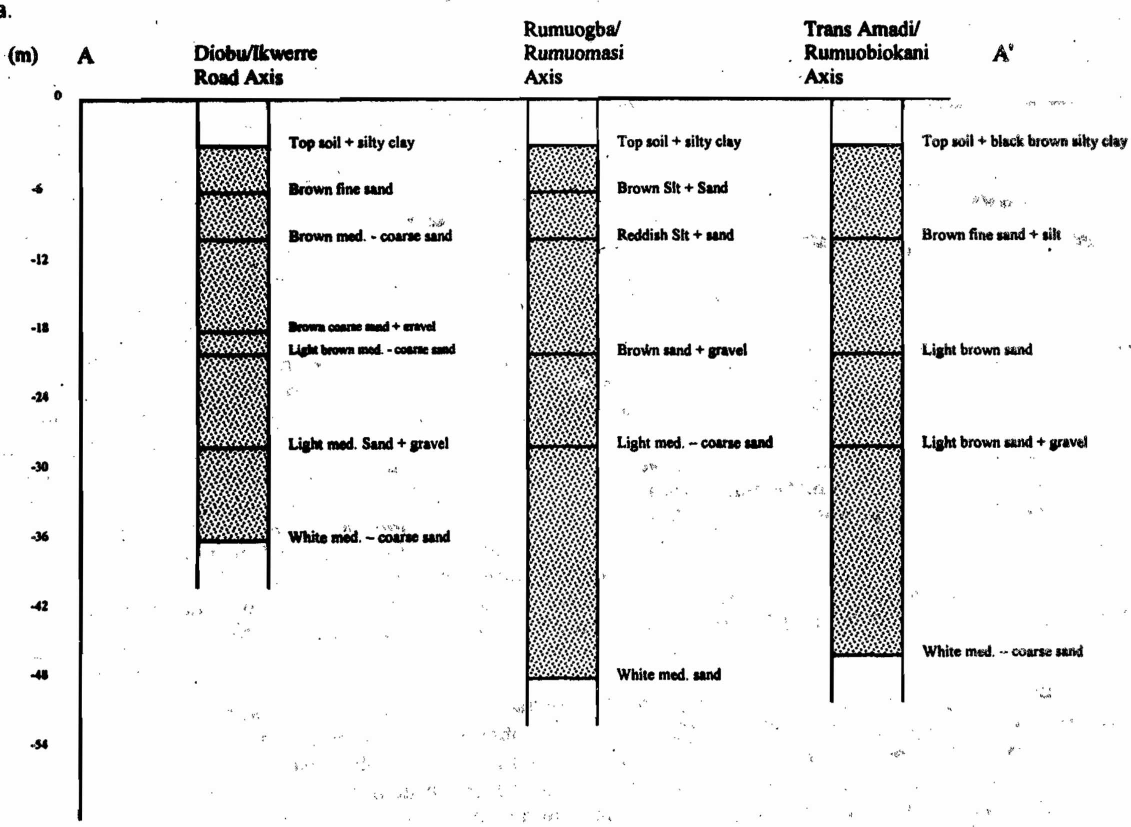


Fig. 1. Map of the study areas showing sampled wells in zones A & B (Paved and Non-paved)

protections. Most of the buildings have concrete cemented surroundings inside their premises. There are no irrigation systems around and vegetation within this zone is quite less. Occasionally, trees like *Musanga cecropioides, Anthocleiso vogelii*, etc are seen at swampy locations and minute quantities of grasses, shrubs or herbaceous plants such as *Dissotis spp., Aspilia africana, Vernonia cinerea*, etc are also seen scattered from place to place and in undeveloped plots of land. Farming is not predominant in this city area and its topography is more or less flat. Precipitation in the area varies from about 2540mm landwards to 5000mm at the coast (Anderson, 1966; Etu-Efeotor, 1981). The highest temperature occurs in February with a mean daily maximum of 90.2^{0}F and the lowest maxima occur in the months of July and August both with a mean daily maximum of 82.2^{0}F. Relative humidity is normally high (Anderson, 1966). So many water boreholes have been drilled in the area and their subsurface lithology logged and described. The subsurface lithologies are sands, which exhibit fining upward sequence, gravels and clay (Fig. 2). The drill depths of the wells are between 33.3m and 51.5m and water table is between 11m and 18m. A typical pathway for precipitation to recharge in an urban area is given in Figure 3. These pathways depend on how highly developed the urban area is and what is obtainable in that area.



Lithologs of the boreholes at different locations for Zones A

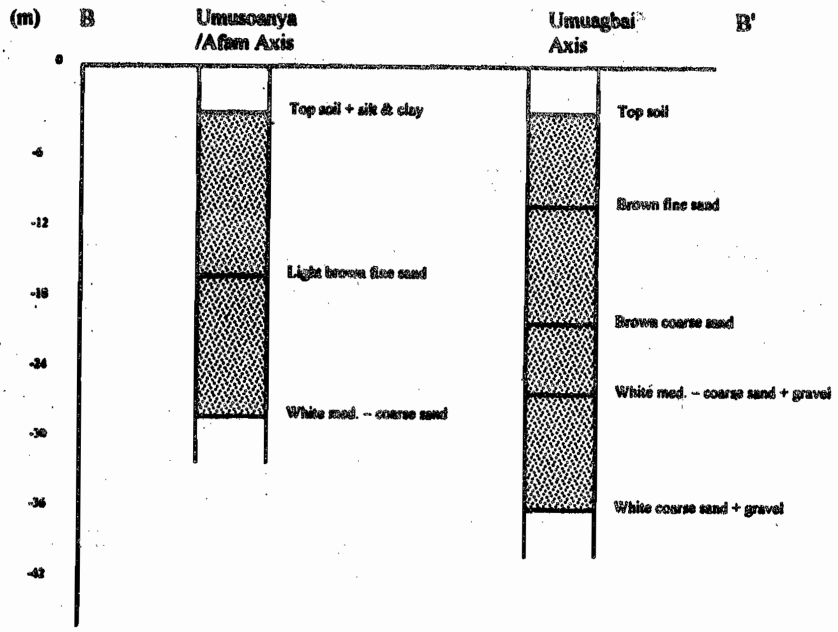


Fig. 2. Lithologs of boreholes at different locations for zones B

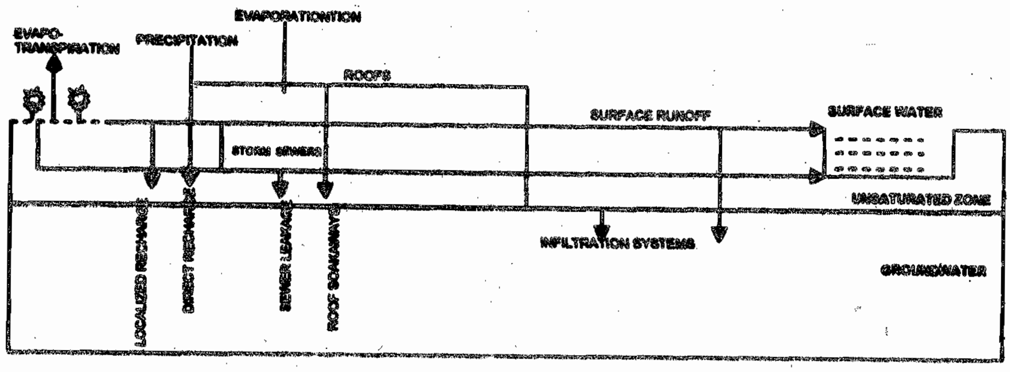


Fig. 3. Pathways for precipitation to recharge Groundwater in urban Areas (Modified from Lerner, 2002)

NON-PAVED ZONE B

This zone cuts across areas like Iriebe, Obigbo, Egberu and Afam. It is located East of Port Harcourt city. 87.5km^2 of area was carved out from this zone and accessibility to and from this area is either by footpaths or minor roads that are not tarred. The major roads are tarred. The area is scarcely populated with estimated population of 9,925 (National Population Commission, 1991 census in Annual Abstract of Statistics, 1999 Edition). Most of the buildings are constructed using mud or cement. Where cement buildings are sited, they are either small bungalows or are several meters apart from each other. Gutter drainage systems are virtually non-existing and vegetation covers are quite much, from large trees to shrubs and grasses. Such swamp forest plants like *Raphia hookeri, Raphia vinifera*, etc., large trees such as *Ceiba pentandra, Irvingia gabonensis* and herbaceous invaders like *Dissotis spp., Aspilia africana* are predominant in this area. Farming and fishing are the predominant occupation of the people in this area several undeveloped hectres of land are cultivated for agricultural purposes. Some of the water wells that were logged at various locations within this zone are shown in Figure 2. Their lithologic description is similar to what is obtained in the paved zone. The total depths of the wells are between 33.3m and 39.4m while the water table is between 10m and 15m.

GEOLOGY

The development of the Niger Delta resulted from the formation of the Benue trough as a failed arm of a rift triple junction associated with the separation of Africa and South American continents and subsequent opening of the South Atlantic (Allen, 1965; Olade, 1975; Evamy et al 1978, Whiteman 1982). The Benue-Abakaliki trough was filled with sediments during the early Cretaceous time, later it underwent folding, faulting and uplift with subsidence of the adjacent Anambra basin to the West and Afikpo syncline to the East during the Santonian. The Proto-Niger Delta ended in the Paleocene time, this initiated the growth of the Niger Delta from Eocene to Recent time (Weber and Daukoru, 1975).

The Niger Delta consists of three diachronous units, namely from bottom, the Akata, Agbada and Benin Formations (Tab.2). The Akata Formation is Eocene – Recent in age and consists of uniform shales that are dark gray to black with sand and silt lenses, they are rich in microfauna, suggesting deposition in shallow marine shelf. Thickness of this Formation is about 600m – 6000m (Weber and Daukoru, 1975).

The Agbada Formation is late Eocene – Recent, with thickness of about 4500m. It consists of shales inter-bedded with fluviatile, coastal and fluvio-marine sands (Weber and Daukoru, 1975).

The Benin Formation, Oligocene to Recent, with a thickness of about 2100m at the basin center consists of coarse – medium grained sandstones, thin shales and gravels (Weber and Daukoru, 1975). The upper section of the Benin Formation which is the quaternary deposits (40 – 150m thick) comprises of rapidly alternating sequences of sand and silt/ clay with the latter becoming increasingly more prominent seawards (Etu-Efeotor and Akpokodje 1990).

Table 2: Geologic units of the Niger delta (After Etu-Efeotor and Akpokodje 1990)

GEOLOGIC UNIT	LITHOLOGY	AGE
❖ Alluvium ❖ Freshwater backswamp, meander belt. ❖ Mangrove and salt water/ backswamps ❖ Active/ abandoned beach ridges ❖ Sombeiro – Warri deltaic plain.	Gravel, Sand, Clay, Silt. Sand, Clay, some Silt, Gravel. Medium – fine grained sands, clay and some silt. Sand, Clay and some Silt. Sand, clay and some silt.	Quaternary.
Benin Formation (Coastal Plain Sands)	Coarse – Meduim sand with clay/ shale interbeds.	Oligocene.
Agbada	Interbedding of sand, shale and silt.	Eocene.
Akata	Shale and Sand.	Paleocene.

METHODOLOGY

Data acquisition was carried out between the months of February 2003 and August 2004. Gathering of data wasn't easy due to the absence of coherent, concise and accurate data system by the appropriate authorities concerned, not only for the study area but the entire country. However, within the limits of what is available attempts were made to process and interpret the available data. Rainfall data was acquired partly from the Niger Delta Basin Development Authority (NDBDA) and the Federal office of Statistics both in Port Harcourt. The data were fairly scanty and in some cases where data is available in one office, may be unavailable in another office that keeps the same data. The chemical analysis of groundwater, rainwater and dry deposition was carried out in Anal concept laboratories Port Harcourt. Subsurface lithologs and core information was obtained from Lithoprobe services Port Harcourt.

Phillips (1994) and Scanlon (2000) expression for estimating recharge is applied

$$D = \frac{PC_P}{C_{UZ}} \quad \text{------------------------------ Equation 1}$$

where: D = Drainage or Recharge.
P = Precipitation or Rainwater and Dry fallout.
C_P = Cl Concentration in Precipitate (mg/l).
C_{uz} = Cl Concentration in drainage water in the unsaturated zone (mg/l).

other expressions such as

$$I = \frac{(PC_O)}{C_S} \quad \text{------------------------------ Equation 2}$$

after Dettinger (1989), and Flint et. al., (2002).
where: I = Average net infiltration (mm/yr).
P = Average annual precipitation (mm/yr).
C_O = Effective average Cl concentration in precipitate (mg/l) including dry fallout.
C_S = Measured Cl concentration in groundwater (mg/l)

as well as Mandel and Shiftan (1981), equation

$$Rg = \frac{P(C_P F_d)}{C_g} \quad \text{-----------Equation 3}$$

where: Rg = Average annual groundwater recharge
P = Average annual rainfall
C_P = Average annual Cl content of rainwater
C_g = Cl content of groundwater.
F_d = Average dry fallout.

were applied. Note that equations (2) and (3) are the same with equation (1); they were merely used to confirm the results of equation (1). The above equations are applied on the basis that chloride and certain other solutes are conservative and non reactive anion in natural waters. Chloride and other unreactive solutes in rainwater usually pass through the soil zone to the water table without change or alteration. Therefore, the ratio of chloride and other unreactive solute concentration in rainwater and in the dry deposition to that in groundwater is then a measure of recharge (Dettinger, 1989; Phillips, 1994; Scanlon, 2000; Shekwolo, 2000).

DISCUSSION OF RESULTS

The estimated average yearly rainfall is 2234.79mm and rainfall event for the period of eleven (11) years (1985 - 1987 and 1991 – 1998) were used for the estimation. Within the coastal areas of the Niger delta, average rainfall is usually between 2450mm and 2500mm while landwards the value decreases (Anderson, 1966; Etu-Efeotor, 1981) this is in agreement with the results of this study. Figures 4 – 7 shows estimated total monthly rainfall event and their mean values per year, while Figure 8(A&B)

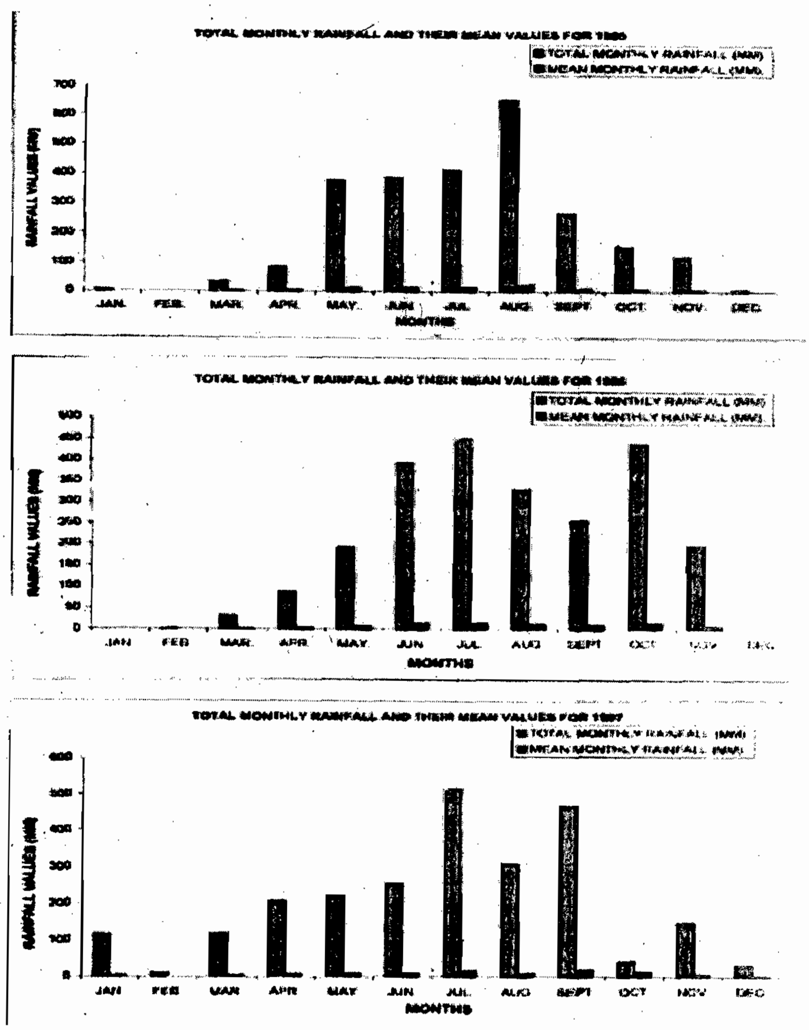


Fig. 4. Total monthly rainfall events and their mean values for the year 1985 - 1987

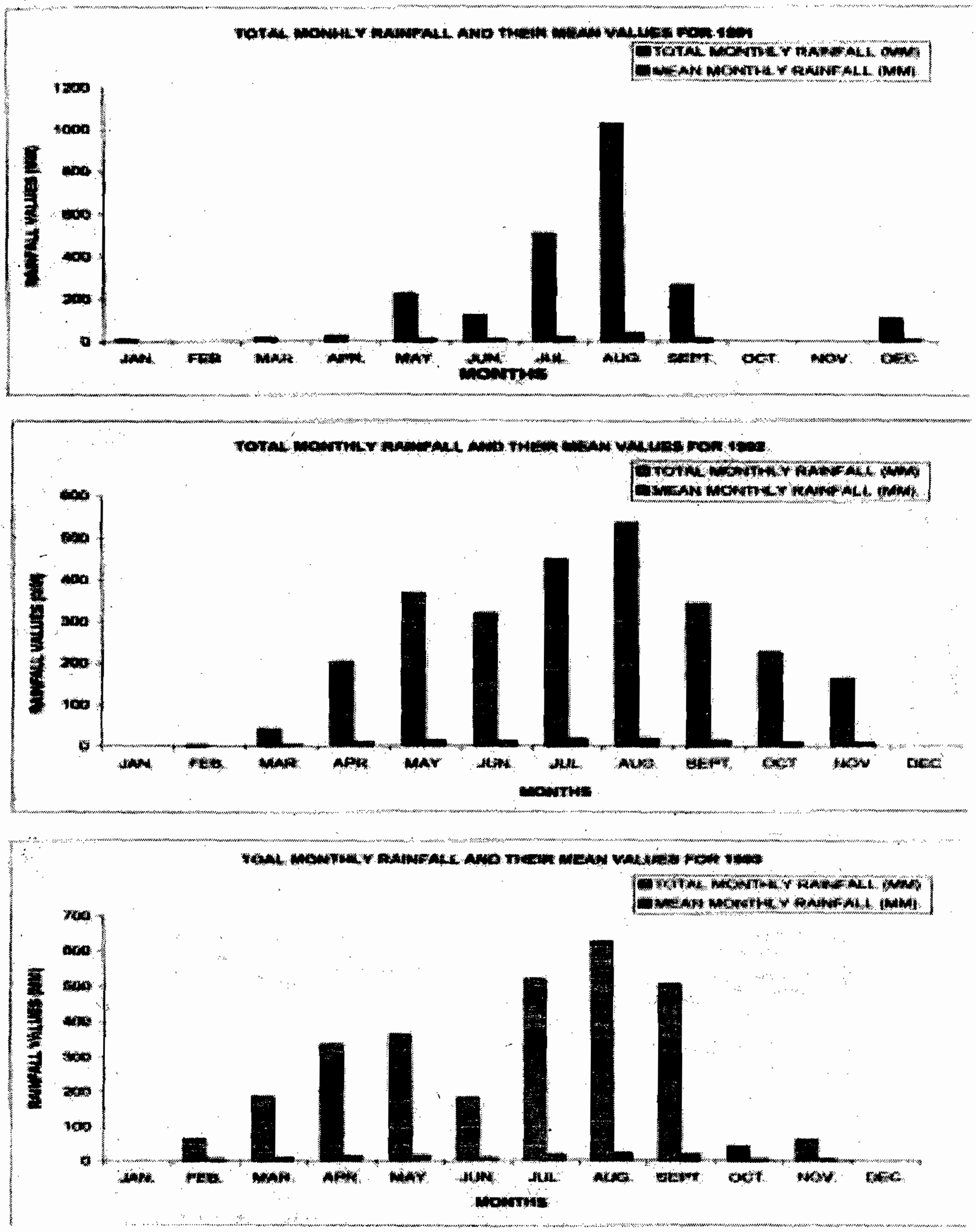


Fig. 5. Total monthly rainfall events and their mean values for the year 1991 - 1993

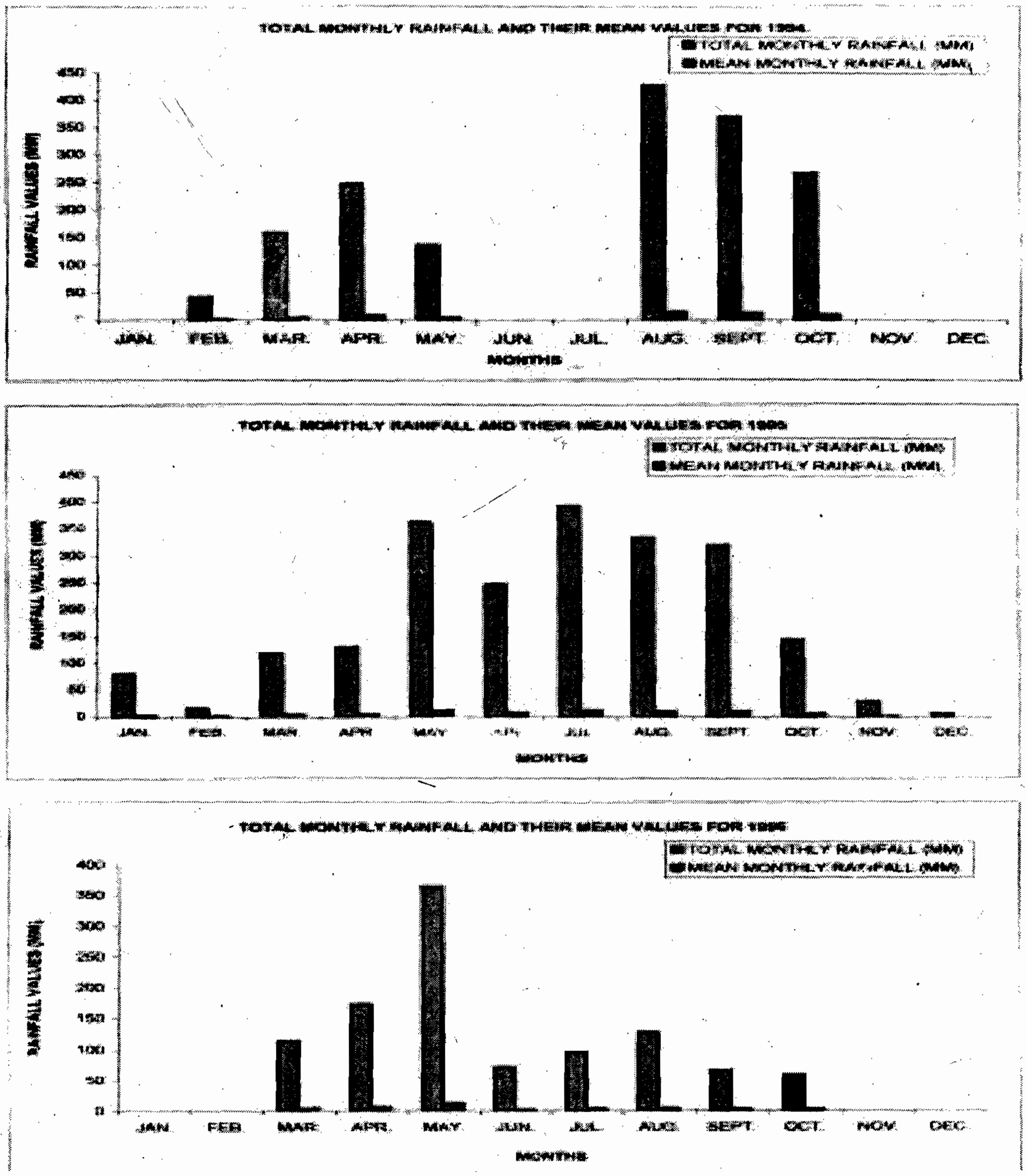
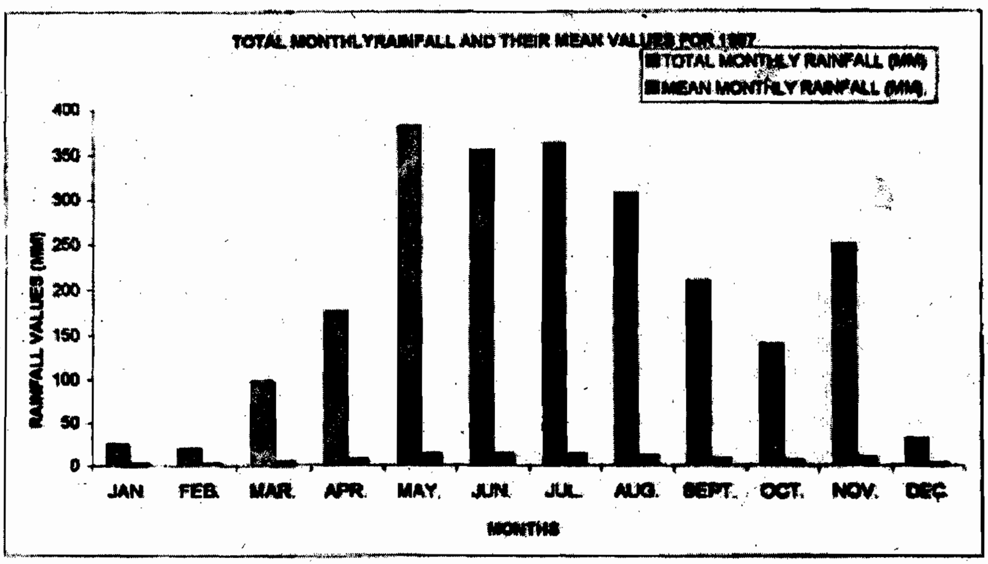


Fig. 6. Total monthly rainfall events and their mean values for the year 1994 - 1996

shows total yearly rainfall event and their mean values. Table 3 is the Average Monthly Rainfall (mm) from 1991 – 1998, while Table 4 is the statistical values of the total yearly rainfall and their mean values for a period of 11years. The wettest months are June, July, August and September. May and October are on the average slightly less wet relative to the wettest months. The driest months are December, January and February, but this does not remove the possibility of at least an inch of rainfall in any of the dry months (Tab. 3). Highest rainfall event occurred between 1992 and 1993 while the lowest rainfall event is observed in 1996 (Fig. 8B).



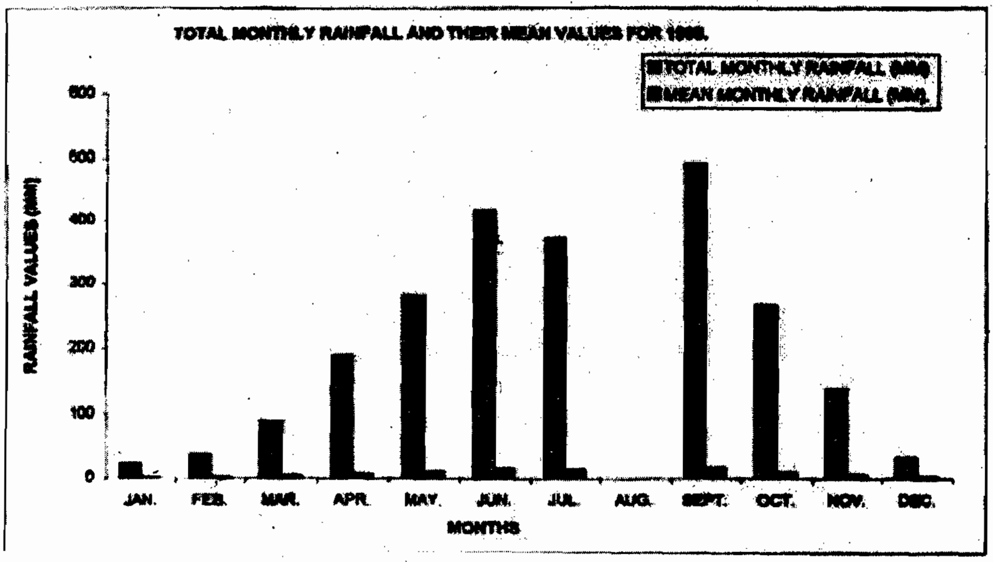


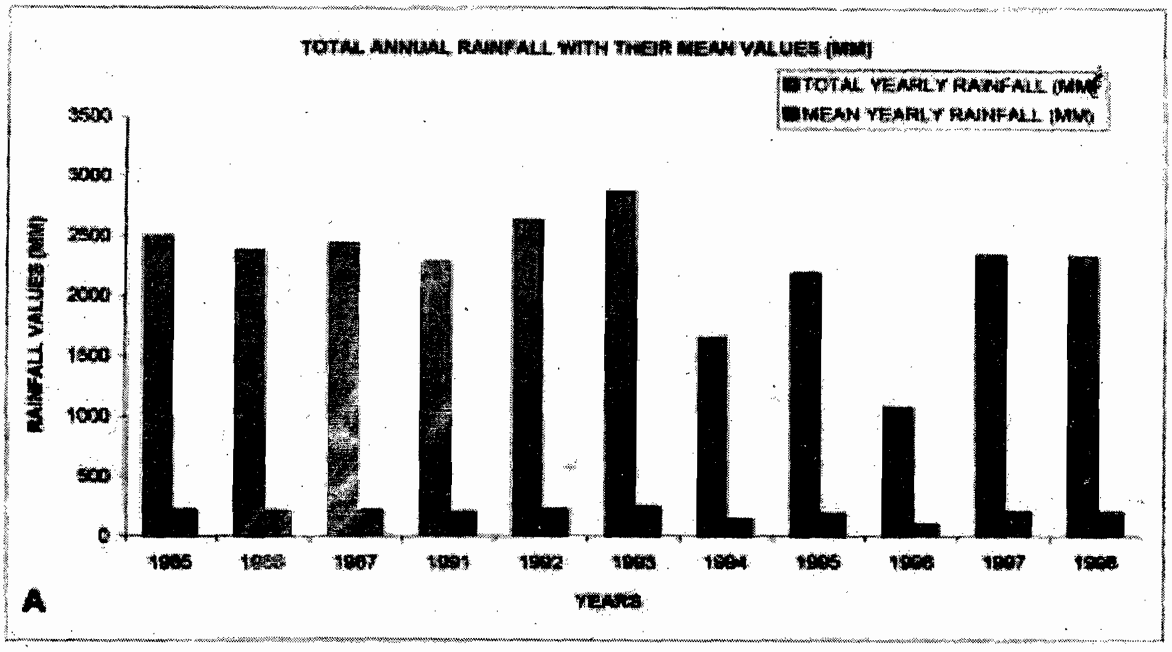
Fig. 7. Total monthly rainfall events and their mean values for the year 1997 - 1998

Table 3: Average Monthly Rainfall (mm) from 1991 – 1998

AVERAGE MONTHLY RAINFALL (mm) FROM 1991 - 1998	
MONTH	AVERAGE
JANUARY	16.19
FEBRUARY	21.75
MARCH	101.29
APRIL	184.16
MAY	308.55
JUNE	212.79
JULY	335.95
AUGUST	421.88
SEPTEMBER	319.26
OCTOBER	141.79
NOVEMBER	79.01
DECEMBER	21.48

Table 4: Statistical values of the total yearly rainfall and their mean for eleven (11) years

Year	Total yearly rainfall (mm)	Mean Yearly Rainfall (mm)
1985	2483.33	206.94
1986	2362.68	196.89
1987	2424.00	202.00
1991	2275.4	189.62
1992	2628.6	219.05
1993	2862.9	238.58
1994	1644.8	137.07
1995	2178.3	181.53
1996	1065.9	88.83
1997	2334.8	194.57
1998	2322.00	193.5



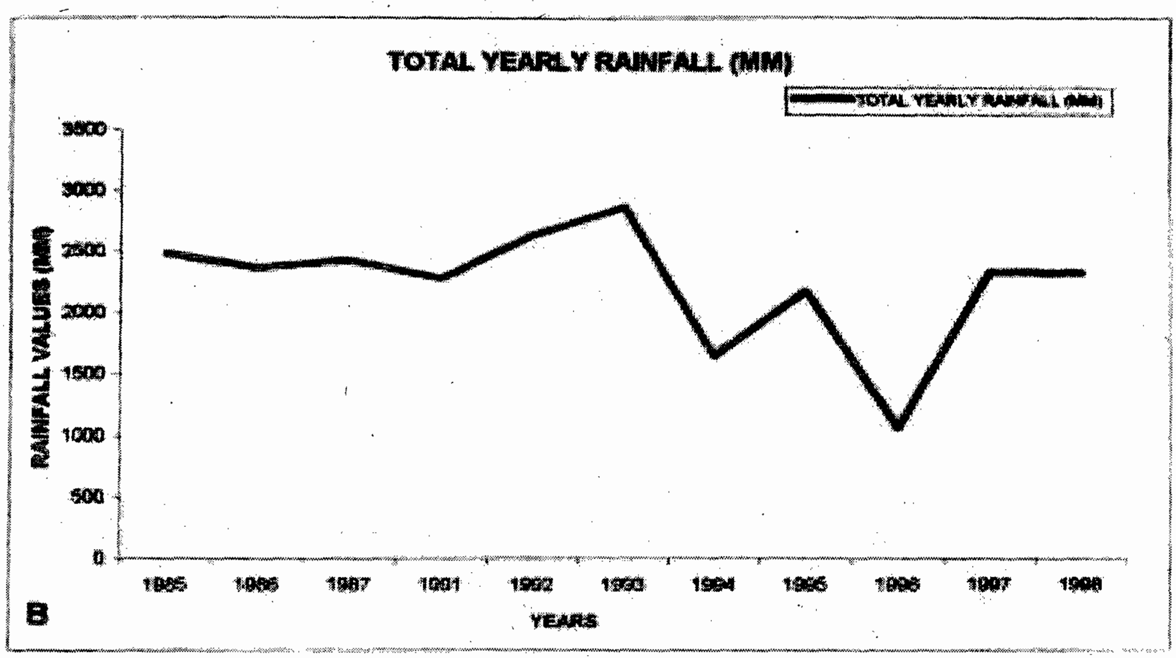


Fig. 8. Total yearly rainfall events and their mean values (A & B) from 1985 – 1987 and from 1991 - 1998

Chloride quantities in groundwater were higher than those from rainwater and the vary from place to place, this may be as a result of sampling on different days or the presence of materials multiplying the solute from the surface or subsurface since multiple sources may exist for most potential solutes (Lerner, 2002). Chloride quantities in rainwater may have been derived from ocean water (Shekwolo 2000) and it is fairly high, probably due to the nearness of the study area to where the solute is derived. The chloride quantities in rainwater from the paved and non-paved zones were quite similar. The origin of the chloride satisfies the required condition for the use of this technique for recharge estimation. The results of recharge for Paved Zone 'A' varied between 73.5mm/yr and 377.9mm/yr while the Non-Paved Zone 'B' is between 278.5mm/yr and 377.9mm/yr (Tab. 5), this does not mean they were no lesser values than this, only frequently occurring values were selected. These results represent about 13% to 16% of recharge from annual rainfall for both the paved and non-paved zones. This implies that only a small proportion of the annual rainfall percolates to the water table, while a greater percentage of the precipitation may probably run overland to streams, creeks or is discharged by the process of evapotranspiration before reaching the aquifer. These values probably might be correct since the chloride values in groundwater vary considerably across the sampled water wells within the zones.

Table 5. Some results of the chloride balance technique carried out in this study.

PAVED ZONE A

Nos.	Rainfall (mm/yr)	Chloride in rainfall (mg/l)	Chloride in dry fallout (mg/l)	Chloride in groundwater (mg/l)	Recharge estimates (mm/yr)
1	2234.79	7.40	0.32	46	115
2	2234.79	7.40	0.32	72	73.5
3	2234.79	7.40	0.32	28	188.9
4	2234.79	7.40	0.32	14	377.9

NON-PAVED ZONE B

Nos.	Rainfall (mm/yr)	Chloride in rainfall (mg/l)	Chloride in dry fallout (mg/l)	Chloride in groundwater (mg/l)	Recharge estimates (mm/yr)
1	2234.79	7.40	0.32	19	278.5
2	2234.79	7.40	0.32	16	330.7
3	2234.79	7.40	0.32	14	377[illegible]
4	2234.79	7.40	0.32	17	311.3
5	2234.79	7.40	0.32	15	352.8

Shallow water table and gaining streams are some of the characteristics of humid regions. Groundwater is usually discharged through evapotranspiration and baseflow to streams (Scanlon et al., 2002). Diffuse recharge is dominant and recharge rates in humid regions are often limited by the ability of aquifer to store and transmit water which may sometimes be affected by the subsurface geology.

Natural recharge is typically about 30 – 50% of precipitation in temperate humid climates, 10% - 20% in Mediterranean type climates and about 0 – 2% in dry climates (Bouwer, 1989; Tyler et. al., 1996). Recharge is generally great in non-vegetated than in vegetated regions (Gee et al., 1994). It is also greater in areas of annual crops and grasses than in areas of trees and shrubs (Prych 1998).

They may be uncertainties in the results obtained for this technique, due to (a) the use of only one technique in the estimation, this is understandable because of the paucity of data. (b) Limited amount of data used. (c) Uncertainty in the values of the airborne chloride, due to the fact that a few years sampling might not be totally representative of the average of a large number of years. (d) The assumption that a particular research area is properly studied cannot be objectively proven. (e) Possibilities exist that some chlorides or salts collected on plastic sheets for dry fallout analysis can be blown away from natural.surfaces.

Despite these shortcomings in the use of this technique in estimating recharge, it is still satisfactory to use the technique due to its suitability, easy application with minute effort and it may further serve as an independent check on estimates derived by other techniques.

SUMMARY AND CONCLUSION

Studies on recharge may provide information on water resource assessment and overall management of groundwater system. The solute balance technique can be used in association with other recharge techniques in quantifying recharge. However, recharge techniques based on surface water and unsaturated zone data provides estimates of potential recharge, whereas those based on groundwater data may provide estimates of actual recharge.

The estimated average yearly rainfall is 2234.79mm. The highest rainfall event occurred between 1992 and 1993 while the lowest rainfall event was in 1996. Recharge estimates in this study is between 74 and 352mm/yr for the paved zone and between 279 and 378mm/yr for the non-paved zone. In carrying out studies on recharge using the solute balance technique, the following information are very vital. They are knowledge of the topography/geomorphology, vegetation/climate, volume of rainfall, surface/subsurface geology e.g. lithology, water table, etc., types of pavement cover, level of development of the area e.g. civil engineering designs, etc., types of water channels e.g. drainages, storm sewers or waste sewers, presence of irrigation systems, etc. However, the above factors have been discussed in detail in this study.

Data management systems e.g. data acquisition and storage on climate, hydrology, geology, drainage, etc should be encouraged by the Federal, State and Local authorities.

This study may provide a foundation on which further investigations can be carried out, and also serve as a complimentary set for other techniques. Finally, the uncertainties associated with this technique and in did other techniques in the estimation of recharge requires the need to apply several recharge techniques to effectively estimate recharge in the study area or related environments.

ACKNOWLEDGEMENT

The Authors are grateful to the Niger Delta Basin Development Authority (NDBDA), Rivers State Water Board and the Federal Office of Statistics all in Port Harcourt for making available requisite data for this study, although some were scanty. We also express our gratitude to members of staff of Anal concept Laboratories Port Harcourt for analyses of samples and Lithoprobe Services, Port Harcourt for providing some Borehole lithologs as well as rainfall data. For those who made inputs and prove read the manuscript we say thank you.

REFERENCES

Allen, J. R. L., 1965. Late quaternary Niger delta and adjacent areas. AAPG bull. 49: 547 – 600.

Amajor, L. C., 1986. Geochemical characteristics of groundwater in Port Harcourt and its environs. Proc. Intl. Symp. on groundwater resources in Nigeria, Lagos, Pp. 358 – 375.

Anderson, B., 1966. Reports on the soils of the Niger delta special area. Niger delta development board (unpubli), Pp. 1 - 46.

Annual Abstract of Statistics (1999 edition). Federal Office of Statistics Abuja, Nigeria. 498p.

Bouwer, H. 1989. Estimating and enhancing groundwater recharge. In M. L. Sharma (Editor) Groundwater recharge. Balkema, Rotterdam, Pp.1 – 10.

Dettinger, M. D., 1989. Reconnaissance estimates of natural recharge to desert basins in Nevada, USA, by using chloride balance calculations. Hydrogeol. Jour. 106: 55 – 78.

Etu-Efeotor, J. O., 1981. Preliminary hydrogeochemical investigation of subsurface waters in parts of the Niger delta. Jour. Min. Geol. 18(1): 103 – 105.

Etu-Efeotor, J. O., and Odigi, M. I., 1983. Water supply problem in the Eastern Niger delta. Jour. Min. Geol. 20 (1 & 2): 183 – 195.

Etu-Efeotor, J. O., and Akpokodje, E. G., 1990. Aquifer systems of the Niger delta. Jour. Min. Geol. 26 (2): 279 – 284.

Evamy, B. D., Haremboure, J., Kamerling, P. Knaap, W. A., Molloy, F. A. and Rowlands, P. H., 1978. Hydrocarbon habitat of Tertiary Niger delta. AAPG Bulletin, V.62: 1 – 39.

Flint, A. L., Flint, L. E., KwickliS, E. M., Fabryka-Matin, J. T., and Bodvarsson, G. S., 2002. Estimating Recharge at Yucca mountain, Nevada, USA: Comparison of methods. Hydrogeol. Jour. 10 (1): 180 – 204.

Gee G. W., Wierenga P. J., Andraski, B. J., Young, M. H., Fayer, M. J., and Rockhold, M. L., 1994. Variations in water balance and recharge potential at three Western Desert sites. Soil Sci. Soc. Am. J. 58: 63 – 71.

Hamil, L., and Bell, F. G., 1986. Groundwater resources development. John Wiley & sons, 133 – 210 Pp.

Lerner, D. N., 2002. Identifying and quantifying urban recharge: A review. Hydrogeol. Jour. 10 (1): 143 – 152.

Mandel, A. and Shiftah, Z. L., 1981. Groundwater Resources: investigation and Development. Academic press, N.Y., 269 Pp.

Ngah, S. A., 2002. Patterns of groundwater chemistry in parts of the Niger delta. 38th Annual Intl. Confr. Nig. Min. & Geosci. Society. Abstr., 39 Pp.

Odigi, M. I., 1989. Evaluating groundwater supply in Eastern Niger Delta, Nigeria. Jour. Min. Geol. 25 (1 & 2): 159 – 164.

Ofoma, A. E., Omologbe, D., and Aigberua, P., 2003. Hydrochemical investigation of groundwater from some parts of Port Harcourt city area, East of the Niger delta. 39th Annual Intl. Confr. Nig. Min. & Geosci. Society. Abstr., 12 Pp.

Olade, M. A., 1975, Evolution of Nigeria's Benue trough (Aulacogen); a tectonic model: Geol. Mag. Vol. 112, p.575-583.

Phillips, F. M., 1994. Environmental tracers for water movement in desert soils of the American Southwest. Soil Sci. Soc. Am. J., 58: 14 – 24.

Prych, E. A., 1998. Using chloride and chlorine-36 as soil – water tracers to estimate deep percolation at selected locations on the U.S department of energy Hanford site, Washington. U.S Geol. Surv. Water – Supply Pap 2481: 67.

Scanlon, B. R., 2000. Uncertainties in estimating water fluxes and residence times using environmental tracers in an arid unsaturated zone. Water Resources Res., 36: 395 – 409.

Scanlon, B. R., Hearly R. W., and Cook, P. G., 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrgeol. Jour. 10 (1): 18 – 39.

hicht, R. J., and Walton, W. C., 1961. Hydrologic budgets for three small watersheds in Illinois. 111 State Water Surv. Rep invest., Pp.40 : 40.

›kwolo, P. D., 2000. Applying limited data to estimate Groundwater Recharge in the Bida Basin, Central Nigeria. Jour. Min. Geol. 36(1): 93 –104.

Tyler, S. W., Chapman J. B., Hammermeister D. P., Blout D. O., Miller J. J., Sully M. J., and Ginanni J. M., 1996. Soil-water flux in the southern great basin, United States: temporal and spatial variations over the last 120,000 years. Water resources Res 32 (6): 1481-1499.

Weber, K. J., and Daukoru, E. M., 1975. Petroleum Geological Aspects of the Niger delta. Proc. 9th World Petr. Confr., 2: 209 – 222.

Whiteman, A. J., 1982. Nigeria: Its petroleum geology, resources and potential. Graham and Trotman, London, 1&2: 394 Pp.