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# A QUANTITATIVE ESTIMATION OF GROUNDWATER RECHARGE IN PART OF THE SOKOTO BASIN, NIGERIA

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*Three basic methods have been quantitatively and comparatively applied to estimate recharge into the groundwater system in the Sokoto Basin. These include empirical (using three simplified equations), hydrochemical (chloride mass balance) and climatic-hydrological methods. The empirical method shows exaggerated values of recharge compared to the chloride and water balance methods. The chloride method shows mean recharge is on the order of 19.6 mm/yr based on an annual rainfall mean of 670 mm from 1916-1993 in the Sokoto area, but suggests that recharge can be highly variable in space and time. For most of the study area the spatial variability of recharge was found to be higher in wetter years than in dry years. Results show recharge around the Wurno and Goronyo areas is <1 % of annual rainfall while for areas outside this region recharge is 3.2 % of annual rainfall. This sharp variation was attributed to local conditions of climate and lithology. The chloride mass balance method appears to be most suitable for estimation of recharge in most of the basin, but is still limited by inadequacy of chloride measurements in rainwater in some areas.*

## INTRODUCTION

The present investigation forms part of a more general evaluation of groundwater and the influence of future exploitation on both surface water and groundwater systems in the Sokoto sedimentary basin, northwestern Nigeria. Over-abstraction of groundwater resources coupled with inadequacies of rainfall and increasing population in northern Nigeria has resulted in the progressive lowering of groundwater levels over the past decade. The recent establishment of more than 50 irrigation schemes in Nigeria have made the situation worse, particularly in the north. Moreover, about 50,000 tubewells have been installed in northern Nigeria for irrigation purposes, mostly in the Fadama areas between 1960 and 1990 (FWRD-JICA, 1990). Since the region consists of a system of multiple aquifers, with confined and unconfined groundwater, it becomes essential to quantify the groundwater resources in this area. Groundwater in the Sokoto Basin exists in a variety of water-bearing formations, including the Gundumi, Rima and Sokoto Groups (Jones, 1948). The exposed formations have a recharge capability of their own which is currently under study. Reliable estimation of the rates of water addition to an aquifer is basic to the assessment of groundwater resources potential so that efficient long-term management schemes can be developed to avoid adverse environmental consequences.

### Location, Geomorphologic and Climatic Setting

The Sokoto Basin lies in northwestern Nigeria between latitudes 10°20’ and 14°00’ N and longitudes 3°30’and 6°58’ E occupying about $6.4 \times 10^4$ km$^2$ of land area (Figure 1). It falls within a region where rainfall distribution is irregular in time and space and characterized by a prolonged dry season and a short rainy season. The Sokoto sedimentary basin in northwestern Nigeria consists predominantly of a gentle undulating plain with an average elevation varying from 250 to 400 m above sea level. This monotonous plain (according to Kogbe, 1979) is occasionally interrupted by steep-sided, flat-topped hills with a low escarpment, called the “Dange Scarp” as the most prominent feature in the basin. The escarpment itself is closely related to the geology of the area and has undergone intensive erosion to the extent that the Dange Scarp is no longer recognizable today (Udoh, 1970).

The climate is semiarid with a zone of savannah-type vegetation as part of the sub-Saharan Sudan belt of West Africa. Rainfall in the Sokoto Basin shows a marked variation, with annual mean precipitation varying from 350 mm (at Kalmalo in the extreme north) to 670 mm (at Sokoto Airport). Rainfall is concentrated in a short wet season, which extends from mid-May to mid-September whilst the dry season (with no single rain) lasts more than 7 months. The yearly variation of rainfall from 1916-1996 at the Sokoto Airport with an annual mean of 670 mm is presented in Figure 2a. The relationship of the annual rainfall with the calculated potential evapotranspiration is illustrated in Figure 2b. Mean annual temperatures are from 21.5 to 34.9°C. The highest temperature occurs between April and July, the lowest in August (during the rainy season).

## GEOLOGICAL SETTING

In northwestern Nigeria the sediments of the Sokoto Basin were deposited during three main phases of deposition: Continental Mesozoic and Tertiary phases, with an intervening marine Maastrichtian to Paleocene phase. Table 1 shows the succession of sediments in the Sokoto Basin. Overlying the Precambrian basement unconformably is the Illo and Gundumi Formations, made up of grits and clays, forming part of the “Continental Intercalaire” of West Africa (Kogbe, 1989). These are overlain unconformably by the Maastrichtian Rima group, consisting of mudstones and

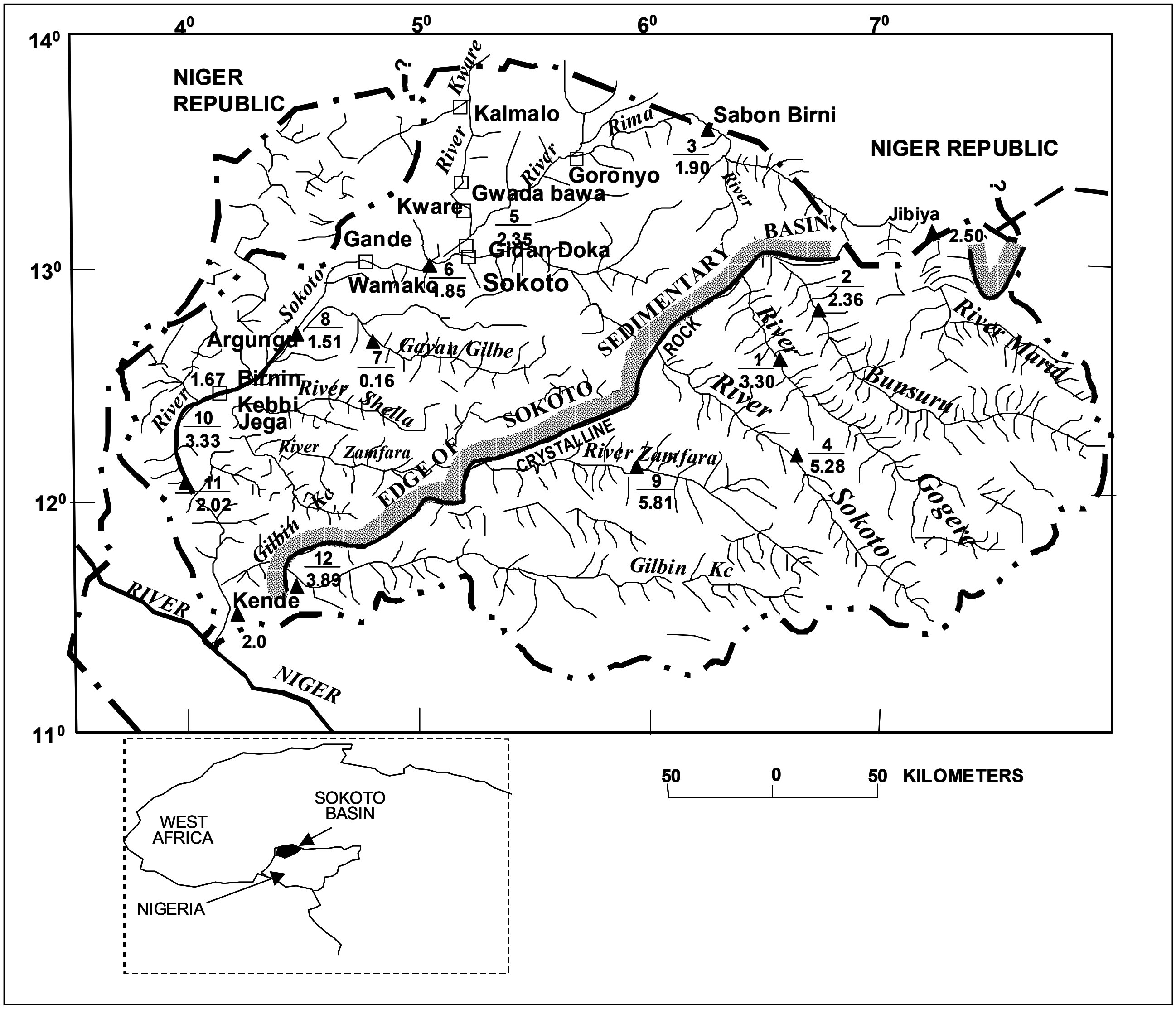

Figure 1. Location map of the Sokoto Basin with drainage pattern (Inset: Map of West Africa showing the location of Nigeria with reference to the position of Sokoto Basin)

friable sandstones (Taloka and Wurno Formations); separated by the fossiliferous shaly Dukamaje Formation. The Paleocene Dange Formation (mainly shales) is separated by the calcareous Kalambaina Formation. The overlying continental Gwandu Formation (Continental Terminal) is of Tertiary age (Jones, 1948; Kogbe, 1989). These sediments dip gently and thicken gradually towards the northwest, with a maximum thickness of over 1,200 m near the frontier of Niger Republic (Wright et al., 1985; Kogbe, 1989).

## HYDROGEOLOGICAL SETTING

The principal water-bearing beds in the Sokoto sediments are the surface laterites, sandstones and grits in the Gwandu Formation, limestone beds in the Kalambaina Formation, sandstones in the Wurno and Taloka Formations as well as grits and sandstones in the Gundumi Formation/Illo Formations (Jones, 1948). Groundwater occurs under water table conditions throughout the area. Moreover, the association of inclined impervious beds alternating with water-bearing horizons gives rise to pressure-water conditions in some parts of the Sokoto Basin. Perched bodies of groundwater also exist in the area. In the valley depressions along the watercourses, alluvial

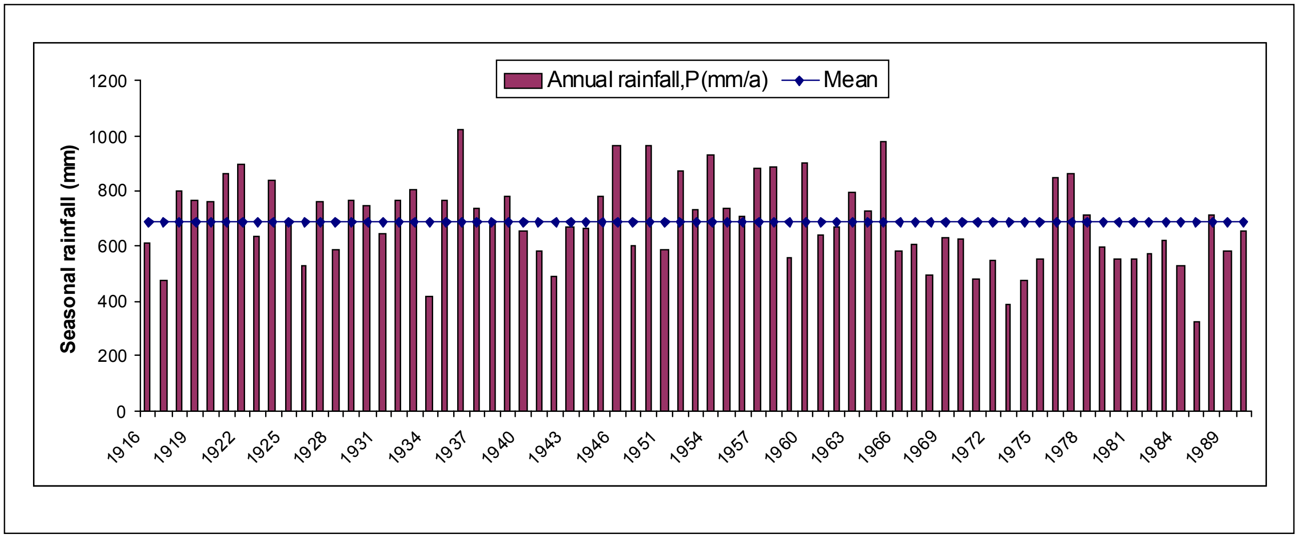

Figure 2(a). Annual rainfall at the Sokoto Airport with a calculated mean (1916-1996)

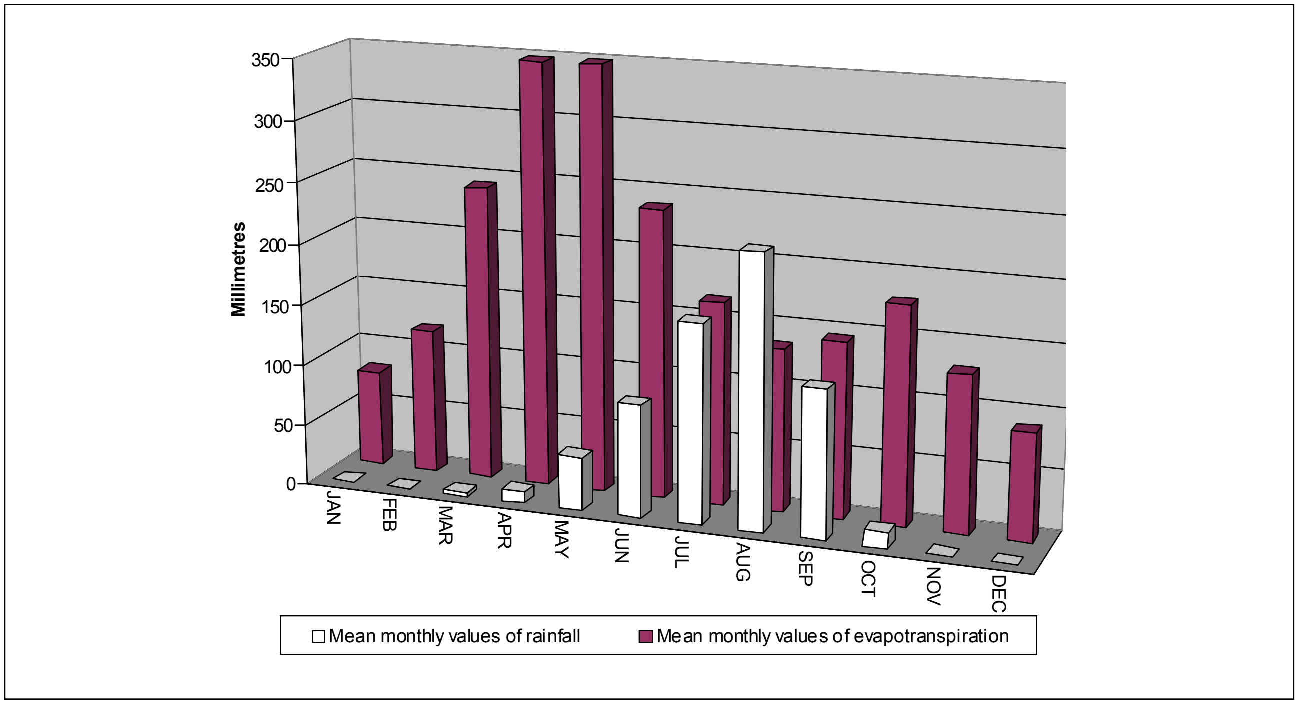

Figure 2(b). Mean monthly rainfall and evapotranspiration at Sokoto Airport (1916-1996)

aquifers up to 20 m thick can be found consisting of intercalations of gravels, sands, silt and clay causing locally confined conditions.

The depth to groundwater in the alluvium of Wurno area is about 1-3 m, but reaches several tens of meters under topographic highs. Some of the tubewells provided for irrigation purposes in the study area have been sampled for both physical and chemical parameters. Analyses of pumping tests carried out in the shallow aquifer yielded transmissivities in the range of 200 to 5000 $m^2/d$ and storage coefficients of $10^{-2}$ to $10^{-5}$ indicating semi-unconfined to confined conditions. Based on these results, the hydraulic conductivity varies between $10^{-4}$ to $10^{-3}$ m/sec. The yield of tubewells up to 20 m depth is generally 0.2 L/s. The fluctuation of the water table in the fadama areas is about 2-3 m throughout the year. The water table is lowest in June and highest in September, during the rainy season.

Table 1. Summary of geological sequence in Sokoto Basin, Northwestern Nigeria.

| AGE | GROUP | ENVIRONMENT | FORMATION | HYDROLOGICAL SIGNIFICANCE |
|---|---|---|---|---|
| QUATERNARY | | Continental | Sandy drifts, laterites | Aquiferous |
| EOCENE-MIOCENE | "Continental Terminal" | Continental | Gwandu Formation | Prolific Aquifer |
| UPPER PALEOCENE | Sokoto Group | Marine | Gamba Formation | Aquiclude |
| | | | Kalambaina Formation | Aquifer in outcrop area |
| | | | Dange Formation | Aquiclude |
| MAASTRICHTIAN | Rima Group | Brackish water with brief Dukamaje marine Intercalation | Wurno Formation | Moderate Aquifer |
| | | | Dukamaje Formation | Aquiclude |
| | | | Taloka Formation | Good Aquifer |
| TURONIAN | "Continental Intercalaire" | Continental | Gundumi Formation | Moderate Aquifer |
| | | | Illo Formation | Locally flowing |
| PRECAMBRIAN | | | Basement Complex | Isolated Aquifers But mostly aquiclude |

## METHODS OF RECHARGE ESTIMATION

Several methods of estimating groundwater recharge have been used in Nigeria in the last two decades (Uma and Egboka, 1988; Oteze, 1989; Okagbue and Agbo, 1989; Carter, 1994; Udoh, 1995; Carter and Alkali, 1996; Agbo et al., 1998; Edmunds et al., 1999; Goes, 1999; Shekwolo, 2000; Goni, 2001; Edmunds et al., 2002). Some of the methods are empirical, using simple mathematical relations. Others are hydrologic budgeting methods, the chloride mass balance method, and the groundwater level fluctuation method.

In previous studies within northern Nigeria, estimating recharge involved a high degree of relative uncertainties due to low rainfall and high evapotranspiration coupled with inadequacies of long-term data. However, by using multiple methods of recharge estimation in the present research it is hoped that some consistency in the result will be achieved. Therefore, in this study, attention was directed to the determination of groundwater recharge using a combination of empirical methods, chloride mass balance (hydrochemical method) and climatic-hydrological balance. The three empirical methods (developed to suit the climatic and hydrogeological conditions of the study area) were applied to estimate recharge rates. The hydrochemical data collected between July 1997 and January 2004 were used for the chloride mass balance method. Climatic-hydrological balance methods included recharge estimates from water balance, stream flow hydrograph and water table fluctuation.

For the chloride mass balance method, the chloride concentration of groundwater in the study area (outside the irrigation schemes) was measured from over 90 water samples collected from wells. About 32 water samples collected from the Wurno and Goronyo areas are mainly from tubewells. Three dugwells downstream of the Wurno Irrigation Scheme (whose chloride contents were thought to have been severely influenced by anthropogenic effects and outwash of chemical fertilizers from the farmland) were not included in the recharge estimation using the chloride method. Samples from tube wells and dug wells around the Irrigation Scheme (where intense irrigation farming is practiced all the year round) were treated separately.

Moreover, all samples having electro-neutrality (EN) above 10% were not used in the calculation of mean chlorideconcentration. Hence, the computed mean of chloride used in this calculation is a close approximation to that of groundwater in the study area, bearing in mind other minor sources of error.

The balance methods are only subject to analytical errors and the low accuracy of discharge measurements. All the hydrological analyses and interpretation done in this section are based on the number and quality of data available. In a dry climate such as the northern part of the Sokoto basin, the amount of water that infiltrates below the root zone is only a small percentage of the annual precipitation. Therefore, potential evapotranspiration was estimated for specific towns (in the study area) with the available meteorological information.

## RESULTS AND DISCUSSION

### Empirical Recharge Estimation

This method shows great potential as an easy means of estimating recharge, which is often difficult if not impossible to obtain reliably by other techniques. Generally, in the estimation of recharge many attempts have been made to find simple relationships between precipitation and recharge. This has led to a number of empirical formulae applied (by different authors in different places) to estimate recharge. In the present study, however, three empirical methods, using simple mathematical relations were developed and employed in the estimation of recharge following the work of Bredenkamp (1990), Sinha and Sharma (1988) and Turc (1954).

A brief description of how these methods have been applied and the results obtained are discussed next.

(a) Empirical method 1

In a quantitative study of groundwater recharge in non-dolomitic aquifers in the Pretoria-Rietondale area (South Africa) a linear rainfall-recharge relationship was obtained (Bredenkamp, 1990). This relationship yields a recharge equation as follows:

$$RE = A\,(RF - B) \qquad (1)$$

where RE is recharge, RF is rainfall, and A and B are simulated parameters.

Considering the general applicability of this method and the soil types, together with the range of annual rainfall in the Sokoto area, the following simulated parameters were applied, bearing in mind the factors that influence precipitation in northern Nigeria: $A = 0.2$ and $B = 395$. The relation becomes:

$$RE = 0.2\,(RF - 395) \qquad (2)$$

where RF is rainfall (in mm/yr). This mathematical relation was used in the estimation of recharge for selected areas within the Sokoto Basin.

From Equation (2), it is important to note that $A = 0.2$ is the optimized lumped parameter representing threshold rainfall that has to be exceeded to effect recharge while $B = 395$ is a constant representing integrated accumulated soil moisture deficit for a non-dolomitic area. In the simulation of these parameters an aquifer porosity of 0.028 was assumed.

The estimated recharge obtained using the rainfall data from Sokoto airport, Goronyo Dam meteorological station and Wurno Irrigation Scheme are summarized in Table 2.

Table 2. Summary of results of empirical methods of recharge estimation applied in the study area.

| Area/ Station | Method 1 (Recharge in mm) | | | Method 2 (Recharge in mm) | | | Method 3 (Recharge in mm) | | | Annual rainfall (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Max. | Min. | Mean | Max. | Min. | Mean | Max. | Min. | Mean | Mean |
| Sokoto | 126 | 3.2 | **60** | 275 | 5 | **105** | 185 | 29 | **134** | 670 |
| Goronyo | 39 | 0 | **13** | 52 | 2.5 | **21** | 118 | 0 | **63** | 454 |
| Wurno | 24 | 14 | **19** | 33.5 | 19 | **26** | 99 | 81 | **90** | 489 |

(b) Empirical method 2

Another empirical method was developed and applied for the purpose of comparison and to ascertain the reliability of method 1. This method was developed, after that of Sinha and Sharma (1988), assuming the only variable is rainfall and the local climate is semiarid, and applied to areas where precipitation is greater than 380 mm/yr. This formula, as applied to define recharge in the study area, is as follows:

$$r = 50.8\ (p/25.4-15)^{0.4} \quad (3)$$

where r and p represent recharge and precipitation respectively.

The constants are simulated parameters that were adjusted to suit the available data in the Sokoto and Goronyo areas. The results gave a mean recharge rate of 134, 90, and 63 mm/year in Sokoto, Wurno and Goronyo respectively (see Table 2). This was interpreted as an overestimation of recharge in these areas since the only parameter incorporated into the formula is rainfall and the degree of uncertainty in the confidence intervals of the coefficients seems high.

(c) Empirical method 3

Unlike the methods 1 and 2 described above, empirical method 3 incorporated mean annual temperature in the estimation of recharge.

It was developed after Turc's (1954) empirical formula for estimating recharge, which is defined by:

$$r = P(1-(0.9+P^2/L^2)^{-0.5}) \quad (4)$$

where

r is annual average recharge (in mm/yr)

P is annual precipitation (in mm/yr)

T is the mean annual temperature (°C)

$L = 300+25T+0.05T^2$

In order to develop an empirical method, based on Turc's formula, that is applicable to the study area incorporating annual rainfall and temperature at Sokoto from 1916-1996, a number of parameters were assumed. These assumptions are based on the degree and frequency of rainfall in the area as well as sunshine hours, which are important parameters influencing evapotranspiration. The resulting annual recharge as estimated using this method is shown in Table 2.

## Discussion of the empirical methods

The estimation of recharge in the study area by method 1 gave the smallest values of the three empirical approaches, and these values agree with Bredenkamp's (1990) estimates for a semiarid area. For the estimate at Sokoto, the long-term mean of rainfall from 1916-1996 was used in the calculation. It must be borne in mind that there is high variability of rainfall in this area and a decreasing trend is observed from the high rainfall of the past (i.e. maximum of 1025 mm in 1936 and minimum of 324 mm in 1987, see Figure 2). This was considered while interpreting the recharge estimates. High recharge coincided with periods of high rainfall and low recharge with low rainfall. For example, for the highest rainfall (1025 mm recorded for 1936) a recharge of 126 mm was estimated while for the lowest rainfall (324 mm, value for 1987) the value -14 mm was computed. This is the case with the other stations. Actually, the negative value is not possible in nature but it indicates that the threshold value (i.e. minimum value of precipitation below which no recharge is taking place) was not reached. Such values were not interpreted to mean that there is no recharge taking place from rainfall for that period. It has been demonstrated that even though the departure of rainfall from the mean rainfall is negative, the natural water level may continue to rise as long as there is surplus of recharge as opposed to discharge (Xu and Van Tonder, 2001). In addition, recharge may occur through other means like interflow of groundwater where less pervious layers underlie the aquifers or inter-aquifer flow (since a multi-aquifer system exists in the area). This is likely to be the case in the Rima Group aquifers where a "plastic" clay horizon exists in the basal part. These clays may be encountered up to 30 - 60 m or more without break in a single borehole (Oteze, 1989).

The results obtained for annual recharge using method 2 agree closely with those estimated with the use of method 1 but the overall mean differs significantly because of the high variations in the rainfall and temperature over Sokoto. The values estimated for recharge from this method were thought to be a little exaggerated because the estimates used to derive the formula were not checked, for example, by a groundwater model as described in Lerner (1986). The recharge estimates using method 3 are the highest. This was attributed to possible errors from the simulation of the parameters used in the empirical formula. It was, however, applied here not only for it's readily usability but also for a closer comparison with other empirical formulae employed in the study area. In all, the three empirical methods were found useful as quick estimates, especially in a semiarid area where hydrogeological information is sparse but cannot be rely upon for specific hydrological and management planning.

## Chloride Mass Balance Recharge Estimation

In attempting to determine the mean annual recharge using the chloride method it is assumed that the only possible source of chloride ion in groundwaters of the study area is at the soil surface (either in precipitation or as dry fallout) and that there is no contribution from weathering. Since there are no evaporites in the study area there is unlikely to be any significant contribution of chloride from the weathering of host rocks. Based on this assumption the ratio of chloride in rainfall to that in groundwater is proportional to recharge as shown in the following relationship developed by Eriksson and Khunakasem (1969):

Recharge (mm) = rainfall (mm) × Cl concentration in rainfall (mg/L)/Cl concentration in groundwater (mg/L)

Chloride ion is a highly soluble, non-absorbing, chemically conservative and easily measurable environmental tracer that has successfully been used to estimate recharge in arid and semiarid areas for more than two decades (Allison and Hughes, 1978; Allison et al., 1994; Edmunds et al., 2002). According to Houston (1990) in different rock types a significant relationship exists between rainfall and chloride content suggesting recharge is a function of rainfall. Also, most plant species do not take up significant quantities of chloride from soil water, thus concentrating chloride by evapotranspiration in the root zone (Allison et al., 1994).

The chloride method was applied to estimate recharge in the study area. The result gave an overall mean of annual recharge rate of 15 mm/yr for regions outside the Irrigation Schemes. The recharge estimated for the Wurno and Goronyo areas is as follows: 3.5 mm/yr for 1998 and 1999 rainy years (at Wurno) and similarly 3.6 mm/yr (at Goronyo). For these two areas the annual precipitation is slightly different yet the same recharge rate was estimated. The results show that recharge in these areas represents 0.7 % of annual rainfall. This may suggest another source of chloride in groundwaters of this area apart from precipitation. Since the study area is more than 700 km away from the coast, the effect of seawater on the chloride concentration of groundwater is not expected. Contributions from weathering of host rocks are negligible. Direct evaporation from the shallow water table (1-3 m) in the depression areas as well as intense use of chemical fertilizers, particularly in the irrigated areas, could have influence downstream in the wells in the Wurno and Goronyo areas.

Since chloride tends to remain in solution and is difficult to remove through most natural processes, which tend to separate out other major dissolved ions (Davis and De Wiest, 1976; Hem, 1985), the samples low in Cl from the eastern as well as the northwestern parts of the study area indicate no anthropogenic effect. These samples either originate from deep waters or from the less cultivated areas. For areas particularly around Sokoto town, an aquifer recharge rate of 19.6 mm/yr (i.e. 3.2 % of rainfall) was calculated. However, around Argungu/Birnin-Kebbi area (southwest of the study area, in the Gwandu Formation) the estimated recharge from the Cl method is 18.1 mm/yr. The average Cl concentration of groundwater (sampled mainly from dug wells and a few boreholes) in this area is 14.5 mg/L. This value, together with the mean annual rainfall of 821 mm (averaged over 39 years) in Birnin-Kebbi, was used in the estimation of the recharge. These recharge rates agree with the 2-7 % estimated for Sahel regions of West Africa (Van der sommen and Geirnaert, 1988). However, the 0.7 % obtained for Goronyo and Wurno in the present study seems not to agree with this value but rather with the 0.5-1 % of Houston (1990) derived from the application of the chloride method for recharge estimation in Zimbabwe (where rainfall distribution is similar to the present study area). This further shows that the chloride method is useful and widely applicable in estimating low recharge rates as lately reported (Scanlon et al., 2002) even though higher values of recharge have also been recorded elsewhere using this method.

It is important to mention that the percentage of annual precipitation recharging the study area needs further clarification. When the recharging rates obtained from the chloride method are compared with the recharge estimates from empirical methods, an overestimation is obvious on the parts of the empirical formulae. The average recharge rate of 19.6 mm/yr estimated for the Sokoto area in the present study from the chloride method is, however, far closer to the estimated value from baseflow recession discussed in the following section. This seems to be a closer overall estimate for the study area since all possible factors that could increase the error in the estimation have been avoided.

## Climatic-Hydrological Balance Recharge Estimation

### (a) Water balance

Usually, groundwater recharge can be determined with the help of the climatic-hydrological conditions using the following equation:

Precipitation (P) = evapotranspiration (ET) + groundwater runoff ($A_u$) + surface runoff ($A_o$)

In the study area, the calculated evapotranspiration is several times as high as precipitation. Also the measured evapotranspiration in the study area seems too high to be representative of the region. However, using the calculated evapotranspiration values in the study area, an estimate of recharge was computed for each of the stations in Table 3.

Table 3 shows the parameters of water balance for the year 1969 with the estimated groundwater recharge. Evapotranspiration and groundwater recharge are given as one value. If the groundwater recharge is low, a large part of the precipitation is lost to evapotranspiration (Udoh, 1995). However, the accuracy of this method in estimating recharge depends on the accuracy with which the components of the water budget equation are measured (Scanlon et al., 2002).

(b) Stream flow hydrographs

Stream flow hydrographs have been used to estimate recharge especially in watersheds with gaining streams since the early 1960's (Meyboom, 1961; Rutledge, 1997; Halford and Mayer, 2000). The method of stream flow analysis was adapted in the study area to differentiate among the various components of stream runoff; to determine to what extent the aquifers are affected by the natural seasonal recharge and also to obtain quantitative information concerning the basic hydrologic equation:

Groundwater recharge = groundwater discharge + change in storage

The base flow recession for a basin is a hydromorphic characteristic, which is a function of the overall topographic drainage pattern, soils, and geology of the watersheds (Udoh, 1995). The base flow recession equation is given by:

$$Q = Q_o.e^{-}a^{t} \qquad (5)$$

where Q is the flow at some time t after recession started, $Q_o$ is the flow at the start of recession, a is a recession constant for the basin and t is the time since recession started.

This equation shows that $Q_o$ varies logarithmically with time, t. A plot of a stream hydrograph with discharge on a logarithmic scale and time on an arithmetic scale will therefore yield a straight line for the base flow recession.

The baseflow recession starts with the first slope or the first low value of the recession graph

Table 3. Water balance of part of the study area.

| River | Catch-ment area | Runoff (Surface runoff) ($m^3$) | Runoff factor (%) | Precipitation ($m^3$) | Evapotrans-piration & groundwater recharge ($m^3$) | Estimated recharge (mm) |
|---|---|---|---|---|---|---|
| Rima (at Sabon-Birni) | 19758 | $8.84 \times 10^8$<br>(44.7mm) | 5.38 | $1.64 \times 10^{10}$<br>(830.4mm) | $1.55 \times 10^{10}$<br>(785.7mm) | 157.1 |
| Sokoto (at Gidan-Doka) | 12249 | $7.43 \times 10^8$<br>(60.7mm) | 7.17 | $1.04 \times 10^{10}$<br>(846.5mm) | $9.63 \times 10^9$<br>(785.8mm) | 157.2 |
| Rima (at Wamako) | 56753 | $1.65 \times 10^9$<br>(29.1mm) | 3.85 | $4.29 \times 10^{10}$<br>(975.7mm) | $4.12 \times 10^{10}$<br>(926.7mm) | 185.3 |

and ends with the first flood. The complete potential groundwater runoff ($Q_{tp}$) represents the runoff of a complete groundwater recession. It is calculated as follows:

$$Q_{tp} = (Q_o * t_1)/ 2.3 \tag{6}$$

where $Q_o$ is runoff at time $t = 0$ and $t_1$ is time of a logarithmic cycle of the recession,

The remaining potential groundwater runoff is calculated as follows:

$$Q_t = Q_{tp}/10(^{t/t}{}_1) \tag{7}$$

The difference between the remaining potential groundwater runoff ($Q_t$) at the end of one recession and the complete potential groundwater runoff ($Q_{tp}$) at the beginning of the next recession yields the groundwater recharge between the two recessions (Figure 3). Table 4 shows the calculated $Q_{tp}$ and $Q_t$ and the storage change in the study area. The recession factor was calculated using Equation 5 with Q and $Q_o$ (Udoh, 1995). The recession factor is 0.01.

On the basis of this analysis the mean variance of storage (actual groundwater recharge) is 24 mm for both of the years 1969 and 1970 (see Table 4 above), that is, about 3.8 % of the precipitation at Sokoto Airport. The amount of water taken out of the aquifers has to be added back in order to keep a balance. That amount has been determined as being 2 million $m^3$/yr during that period (Udoh, 1995). Thereafter, 4 % of the precipitation makes up the groundwater recharge (within the sedimentary terrain). This ratio seems sensible and can be compared to the ratios in the Sahel regions (2-7 %, Adanu, 1989). The FDWR-JICA (1990, unpublished report) recharge estimate of 17 % of annual rainfall recharging the groundwater in the Sokoto area is further shown to be too high by the present results.

The rivers in the study area cross several aquifers. It has to be determined which aquifers in the study area contribute to the baseflow in Wamako, because that defines the size of the catchment area. Because of the greater depth to the water table of the Gundumi and Rima aquifers, these cannot contribute to the baseflow. Accordingly, the baseflow originates from the local aquifers of Kalambaina and Fadama (flood sediments), and the catchment zone is approximately 3400 $km^2$. It is important to make these distinctions before interpreting the runoff data to determine the groundwater recharge. Because of the existence of multi-aquifer formations, it was also thought possible for water to be exchanged between the aquifers depending on the groundwater level and hydraulic potential, respectively (Udoh 1995). This is an internal process, which could also change storage.

### (c) Water-table recharge

Recharge estimation from water level hydrographs as applied in part of the Sokoto basin is discussed here. The water table fluctuation method seems to be among the most widely used techniques for recharge estimation based on its simplicity and the relative abundance of available groundwater level data. The applicability of this method is well documented in the literature (Meinzer and Stearns, 1929; Rasmussen and Andreasen, 1959; Gerhart, 1986; Fetters, 1988; Hall and Risser, 1993; Salama et al., 1993; Healy and Cook, 2002). The principle used by Fetters (1988) was adopted for recharge estimation for the present study area. When the front of infiltrating water reaches the capillary fringe, it displaces air in the pore spaces and causes the water table to rise. The capillary fringe is also higher, and the latest arriving recharge is actually found at the top of the capillary fringe. The time of movement of the infiltrating water is a function of the thickness of the unsaturated zone and the vertical unsaturated hydraulic conductivity.

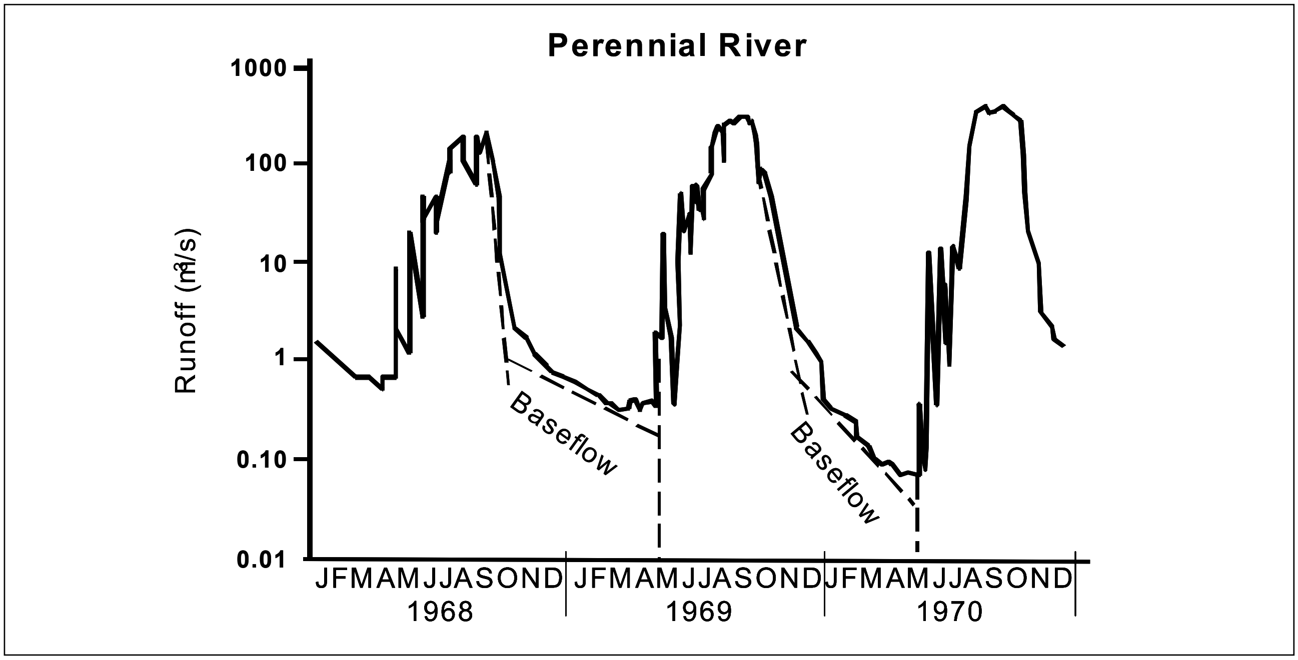

Figure 3. Monthly runoff of River Sokoto at Wamako (near Sokoto town)

In the present study, three tube wells at the Lugu seed farm (near Wurno) monitored daily from March to December 1987 were used to plot the water level hydrograph shown in Figure 4.

The observed range of static water level of the three tube wells suggests a strong influence of the rainy season. A significant drop of water level is seen starting at the end of the rainy season, September/October, and continuing for the entire dry period lasting for 9 months (October through June). With the onset of rain towards the end of June, however, there is an almost immediate and continuous rise in water table till the end of the rainy season. The recharge, by rain and river water, in the period shown, induces a rise of about 2 m in only 3 months. The depth-to-groundwater is about 3 m at the onset, and 1 m or less at the end of the rainy season.

These findings from the 1987/1988 hydrological year are corroborated by direct field observations in September 1998, when both the Sokoto and the Rima Rivers had completely flooded the 2-4 km wide fadama area. With a frequency of 9-10 years, both the Sokoto and the Rima Rivers are reported to flood the whole width of the river plains with 1-2 m of water for a period of several weeks. It is during these periods that the aquifer is recharged possibly on a regional scale by precipitation directly and on a local scale by floodwater (from rain and the rivers).

The presence of layers of low-permeability material, such as silts and clays, can retard the rate of recharge, even if the layers are thin. The rate at which water table recharge occurs is variable,

Table 4. Baseflow analysis of River Sokoto at Wamako, near Sokoto town (1968-1971

| $Q_{tp}$ ($m^3$) | $Q_t$ ($m^3$) | Recharge ($m^3$) | Storage change ($m^3$) | Time (period) | Precipitation (mm) |
|---|---|---|---|---|---|
| $5.4 \times 10^7$ | - | - | - | 1968-1969 | - |
| $1.38 \times 10^8$ | $1.05 \times 10^2$ | $1.3 \times 10^8$<br>(38 mm) | $7.6 \times 10^7$<br>(22 mm) | 28/9/69 to<br>30/5/70 | 630 |
| $2.2 \times 10^8$ | $1.26 \times 10^{-4}$ | $2.19 \times 10^8$<br>(64 mm) | $9.0 \times 10^7$<br>(26 mm) | 27/9/70 to<br>2/6/71 | 629 |

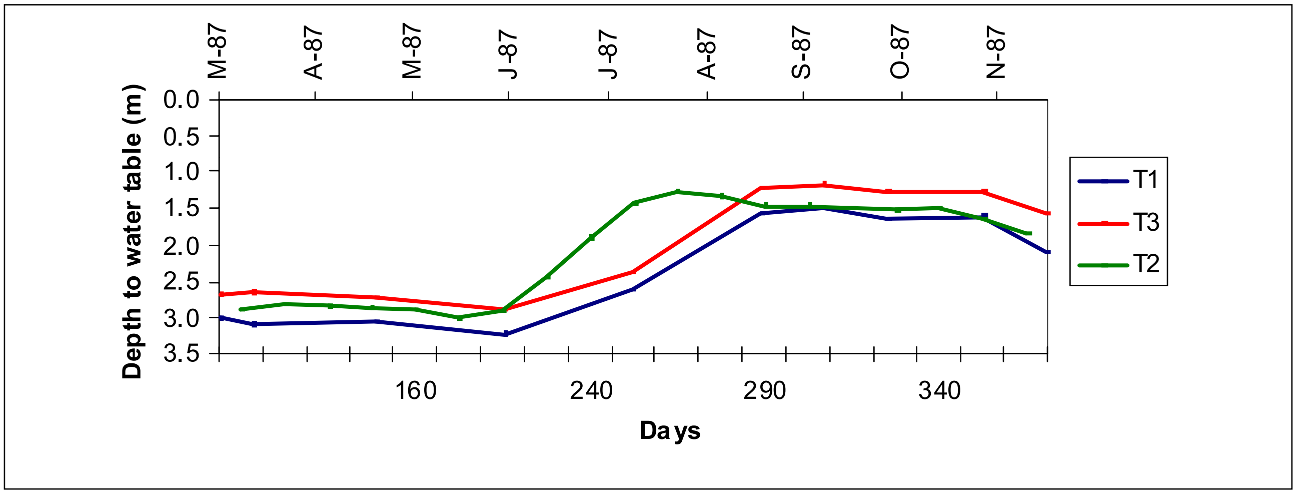

Figure 4. Hydrograph of groundwater table fluctuation at Lugu Seed farm (near Wurno)

depending on the thickness of the unsaturated zone. Where the unsaturated zone is thinner, recharge can reach the water table first, resulting in a localized groundwater mound (Fetters 1988). The unsaturated zone is known to be thinner in topographically low places, e.g. near a lake or in a lowland. Soil moisture percolating through the unsaturated zone beneath the upland areas takes longer so that if the water table is initially level, localized high spots can develop on the water table. Localized flow systems can develop that move water laterally from the temporary groundwater mounds towards the water table beneath the upland, where the infiltration has yet to reach the water table. Therefore, the resulting rise in water level beneath the upland areas is not only due to the vertical percolation of infiltrating water but also from the lateral movements of groundwater.

## CONCLUSION

This paper presents the methods used to estimate recharge in the semiarid northwestern Nigeria, where rainfall is low and variable. The high variability of climate both in time and space strongly affects recharge in this area. High recharge coincided with periods of high rainfall and low recharge with low rainfall. Relatively higher chloride contents in soil water (low recharge) correspond with low rainfall areas, and low chloride concentrations (high recharge) with higher rainfall areas. It was also observed that there is variation in the rates of recharge from one locality to another within the basin. Results show recharge around the Wurno and Goronyo areas at <1 % of annual rainfall while for areas outside this region 3.2 % of annual rainfall recharges the groundwater. This sharp variation was attributed to local conditions of climate and lithology.

It was further observed that changes in groundwater chloride concentrations might be used to estimate the mean recharge rates over given time intervals but due to inadequacies of long-term data this was not carried out. However, a combination of the chloride mass balance method and environmental isotopes was used to understand recharge conditions within the groundwater system as documented in Adelana et al. (2002).

Considering climatic-hydrological methods, analysis of baseflow recession in the estimation of recharge yields more reliable results than those of water balance and water level hydrographs. However, the chloride mass balance method appears to be most suited for the estimation of recharge in the study area. Empirical methods developed and applied in areas of similar climate and soil types have proved useful in giving quick estimates of recharge in the present study area as well as defining a threshold value below which no recharge of rainwater takes place. Notwithstanding, the recharge estimates obtained for parts of the study area from these methods seem to be high. The chloride mass balance method, which appears to be the most suited for estimation of recharge in the study area, is still limited by lack of chloride measurements in rainwater.

Finally, from the consideration of all methods, it was concluded that recharge still occurs through other means like interflow of groundwater where less pervious layers underlie the aquifers or inter-aquifer flow. A rise in water levels beneath the upland areas and below depression zones is not only due to the vertical percolation of infiltrating water but also from the lateral movement of groundwater and infiltration of river water during flooding. This is not generally the case for the entire Sokoto basin and as such, requires further investigation and verification in some other parts of the basin.

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