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ESTIMATING GROUNDWATER RECHARGE FOR SUSTAINABLE MANAGEMENT IN THE NIGERIAN SECTOR OF THE CHAD BASIN

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Abstract

Groundwater is the perennial source of water supply for domestic and other applications in the Nigerian sector of the Chad basin. Therefore, quantifying the current rate of recharge is fundamental to sustainable management of the resource. The chloride (Cl) mass balance technique was used to estimate the rate of recharge. Average Cl concentrations in rainfall from three stations over eight years were used as input data. Eight unsaturated zone Cl profiles were obtained and Cl concentrations in the groundwater were measured for over 400 samples from wells and boreholes. An average recharge rate of 41 mm per annum was estimated from the unsaturated zone profiles. The regional rate obtained using Cl concentrations in groundwater is slightly higher, estimated at 48 mm per ammum, which is attributable to other mechanisms of recharge such as river channels, pools, depressions and regional flow that bypass the unsaturated zone.

The estimated recharge to the shallow groundwater in this region is considerable and can sustain present day abstractions. The observed decline in water table in recent years is largely due to reduced rainfall during the Sahel drought and consequent reduction in recharge, although human impacts are also identified as is common with most semi-arid areas of the world. Although the flood plains aquifers (*fadamas*) are probably fully recharged annually through river channels, caution must be exercised in introducing irrigation schemes. Any agricultural development should be preceded by detailed studies, so as to utilise the quantity of water that is recharged annually and must also adopt water saving techniques.

1. Introduction

The Nigerian sector of the Chad basin falls within the semi-arid region of NE Nigeria (Figure 1), which is characterised by low rainfall (<500 mm/annum), high evaporation (>2000 mm/annum) and almost non-existent surface water, apart from the Lake Chad and seasonal rivers. The area is mostly underlain by the Chad Formation, the youngest stratigraphic sequence in the Chad Basin. This formation is a Plio-Pleistocene mainly argillaceous sequence with three well defined arenaceous horizons (Figure 2), which serve as aquifers and are termed upper, middle and lower aquifers (Barber and Jones, 1960). The upper aquifer is unconfined and semi-confined in places whereas the middle and lower aquifers are confined. These confined aquifers are under sufficient pressure in some places and provide artesian wells with piezometric heads of up to 20 m above ground level (Goni *et al*., 2000). The confined aquifers are generally exploited via boreholes, whereas the shallow unconfined aquifer is mostly abstracted by large diameter wells.

Oteze and Fayose (1980) and Goni *et al*. (2000) have shown that the water table and piezometric head in deep artesian aquifers are rapidly declining, and thus raising questions on the overall sustainability of the groundwater resource. The main control on the sustainable resource is the balance between the rates of recharge and that of discharge. These

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fundamentals are not clearly understood in this region, and indeed in most semi-arid and arid regions. Little work has been carried out to assess the total water balance in this region.

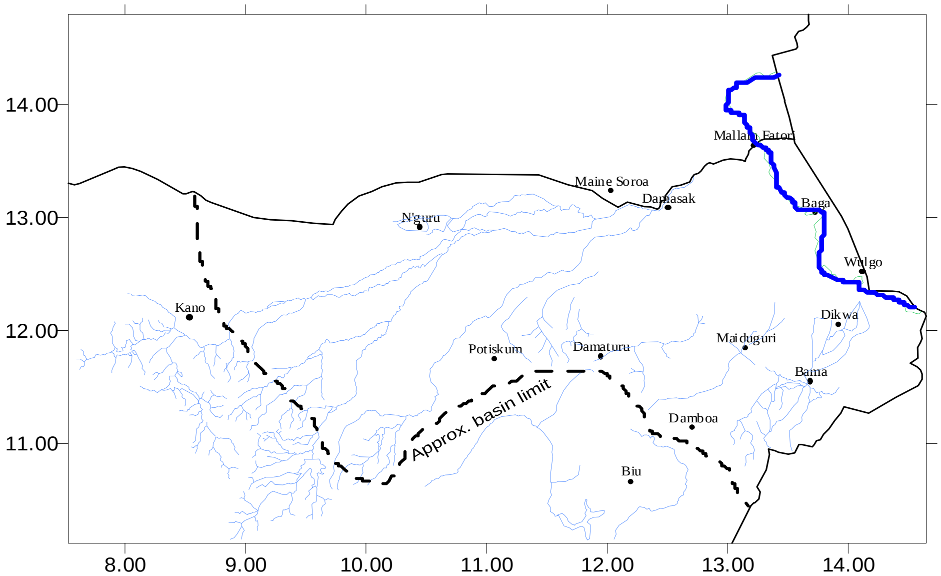

Figure 1 Map of study area showing the drainage network and major towns

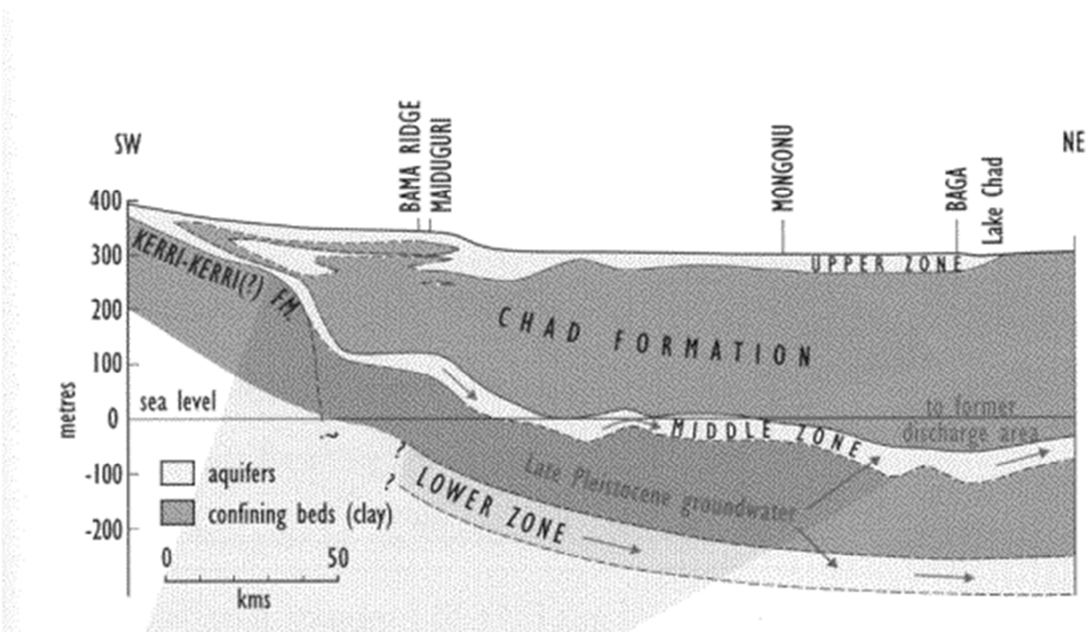

Figure 2 Geological cross section of the Chad Formation with the three aquifer zones

There is a need for efficient groundwater management in order to sustain the existing water resource. This is important because human existence and development schemes (agricultural, industrial or health related) in the region are strongly dependent on the reliability of water supplies. Since sustainable management, especially from the context of supply planning, requires knowledge of the renewal rate, estimation of groundwater recharge becomes fundamental. This paper attempts to estimate the amount of recharge to the phreatic aquifer of the region using the chloride (Cl) mass balance method.

1.1 Chloride mass balance method

Chloride is ubiquitous in groundwater and soil water, and often constitutes the most dominant ionic species. One of the most useful properties of Cl ion is that it is highly soluble, forming individual minerals at only very high concentrations. Chloride may be present in some high temperature minerals such as biotite (Fuge and Power, 1969; Edmunds *et al*., 1985). Thus, it is highly mobile and is not involved in the common geochemical reactions that occur in aquifers. Chloride therefore is a conservative element with a mobility in water very similar to that of water molecules (Hill, 1984) and has a self-diffusion coefficient of 2×10^{-5} cm^2 sec^{-1} (Li and Gregory, 1974). The geochemical cycle of Cl is very similar to that of water, with one important exception – when water evaporates, or is transpired through plants, chloride remains in the residual solution and is therefore concentrated in proportion to the amount of water removed. Once water containing the ‘enriched’ chloride signature leaves the zone of evapotranspiration it carries the signature to the groundwater and can be used to estimate the net water loss compared with rainfall and hence the amount of recharge. The amount of recharge from the Cl mass balance equation (Edmunds *et al*., 1988) is given below:

$$R_d = C_p P / C_s \qquad (1)$$

where R_d = recharge,

P = precipitation

C_p and C_s = Cl concentrations in precipitation and in soil water respectively

In order to use Equation 1, rainfall amounts and rainfall chemistry (total Cl deposition) must be known and the data for at least three years. Errors associated with rainfall measurements as well its spatial variability are likely to constitute the largest uncertainties in recharge estimation using chloride mass balance method. Also, assumption must be made that the average atmospheric chloride flux remains constant (Edmunds, 2001), the surface runoff is negligible and that homogeneous movement of solutes through the unsaturated zone is by piston flow is taking place. The chloride estimates usually provide long-term mean recharge values. Short-term effects such as change in land use may change the recharge rates and these may be followed by monitoring the changes in the unsaturated zone, using subsequent chloride profiles (Andrew and Edmunds, 2000).

2. Materials and methods

2.1 Sample collection

The chloride mass balance method was used in this study to estimate the amount of recharge to phreatic aquifer of the Nigerian sector of the Chad Basin. Rainfall samples on event basis were collected from three meteorological stations in north east Nigeria, namely Kaska, Garin

Alkali and Maiduguri (Figure 3). The rainfall samples were collected for the rainy seasons of 1992 to 2000, although with some gaps over the period due to logistic problems.

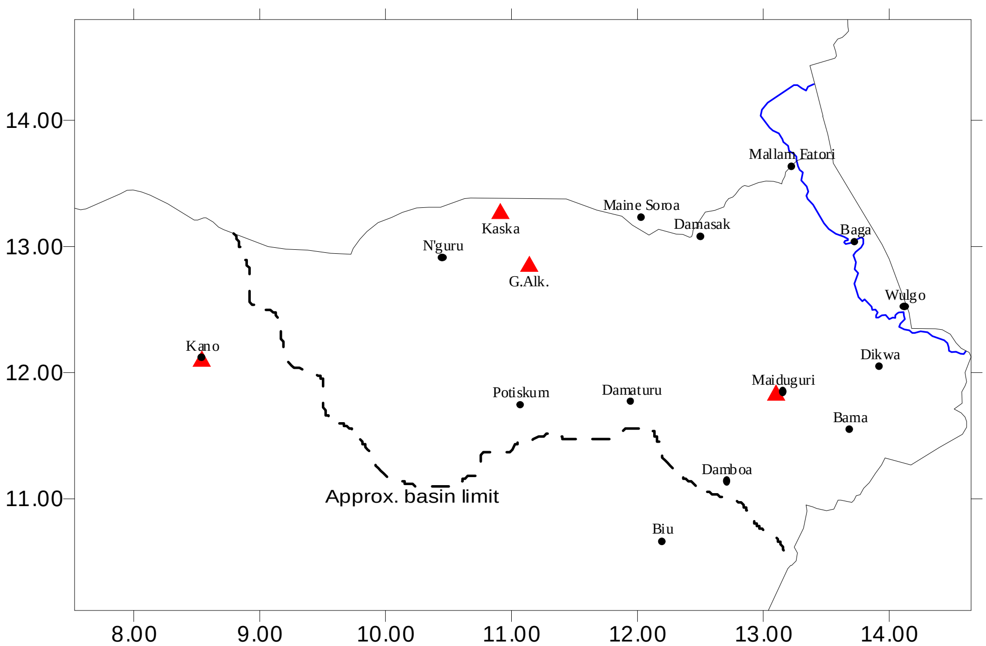

Figure 3: Map of study area showing location of the three meteorological stations

Hand augering was used to drill eight unsaturated zone profiles (Figure 4) in the region. Samples of moist sand were obtained at regular intervals of 0.25 m over the first 10 m and then at 0.5 m interval thereafter to the total depth of profile. Moisture contents were measured gravimetrically and chloride was determined on samples obtained either by centrifugation (Kinniburgh and Miles, 1983) or by elutriation with distilled water. Groundwater samples from 400 wells and shallow boreholes were collected with the assistance of North East Arid Zone Development Programme (NEAZDP) staff from villages across NE Nigeria. The wells were located on the outskirts of the settled areas and away from areas of possible contamination. All the wells were in daily use and produced fresh water. Two samples were collected in polythene bottles and filtered through Whatman 0.45 µm membrane filters. One of the samples was acidified to 1% HNO_3. Automated colorimetry was used in the laboratory to determine the concentration of Cl in all the samples.

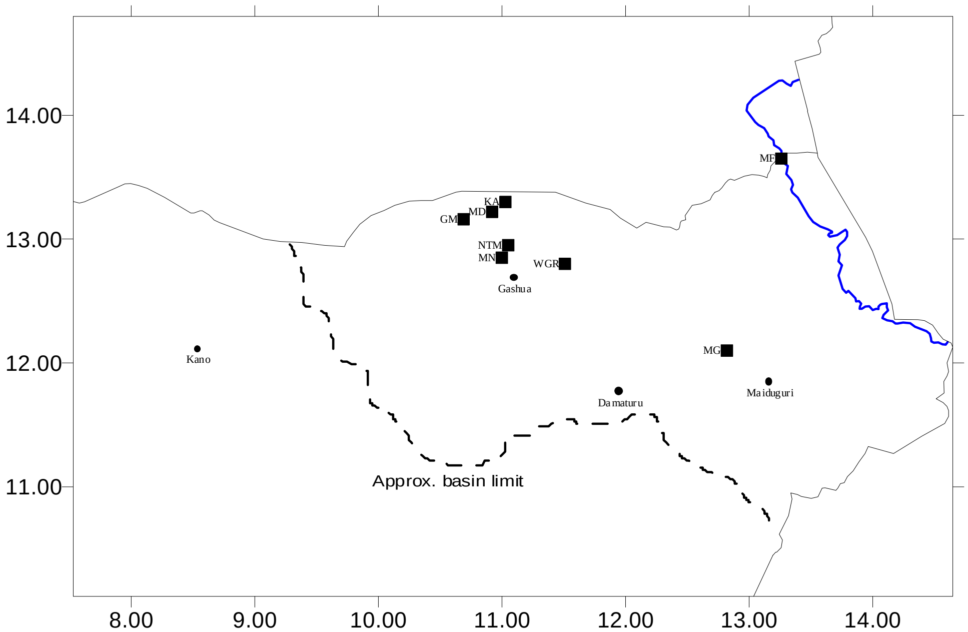

Figure 4: Map of study area with location of unsaturated zone profiles in solid squares

2.2 Recharge estimation using the Cl mass balance formula

The Cl mass balance (Equation 1) was used to calculate the rate of direct recharge (R_d) through the profiles. Seven site-year rainfall data was used in the estimation. The average chloride concentration in rainfall (C_p) for the study area was obtained using data from the three stations of Kaska, Garin Alkali and Maiduguri. The amount of rainfall and Cl concentration in the rain were the input data, and these together with the average Cl concentration in the profiles (C_s) were used to estimate the amount of recharge (R_d).

3. Results and discussion

Table 1 shows the weighted mean chloride values for all the meteorological stations. The table also shows the mean rainfall and mean weighted chloride of 4.34 mm and 1.77 mgl^{-1} respectively for the study area. These form input data for the estimation of groundwater recharge using the chloride mass balance technique.

Table 1: Weighted mean chloride values for rainfall stations in Northern Nigeria

Station and year	*Annual rainfall*	*Weighted mean Cl (mg l^{-1})*
Kaska 1992	320	2.8
Kaska 1993	327	1.3
Garin Alkali	549	1.6
Garin Alkali	819	3.4
Garin Alkali	297	0.6
Garin Alkali	226	0.7
Maiduguri 2000	502	2.0
Average	**434**	**1.77**

Source: Goni et al. (2001)

The concentration of Cl with depth for the eight profiles is presented in Figure 5. With the exception of the MF profile, the other seven profiles give recharge rates ranging from 19 to 66 mm a^{-1} with an average of 48 mm a^{-1}. There is no visible difference between rates obtained in the dune sands from those of the alluvial sands; the major control for moisture movement in the unsaturated zone has been the texture of the sediments. The upper layer of the MF profile gave an estimated rate of recharge of 16 mm a^{-1} slightly lower but similar to the general range of the other seven profiles. The lower clayey layer is clearly distinct with almost no recharge, which is attributable to the impermeable nature of clays.

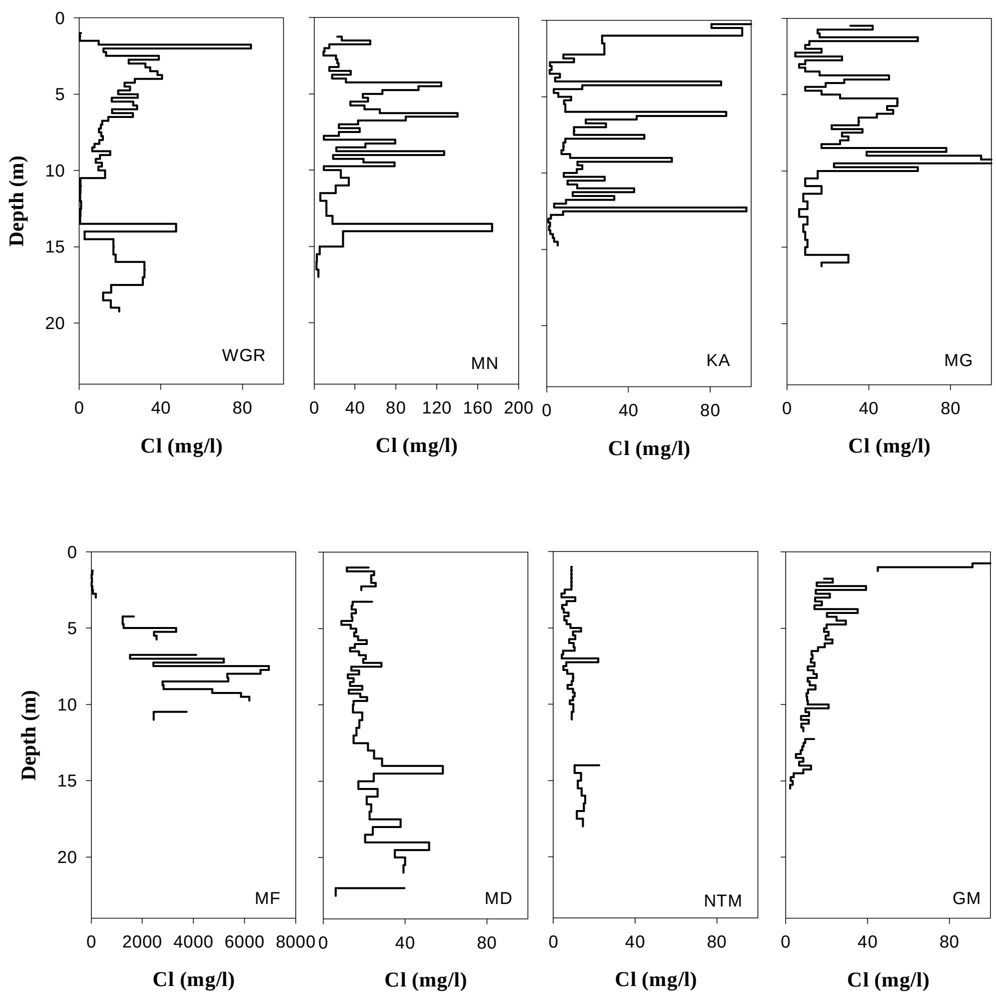

Figure 5: Depth distribution of Cl in the unsaturated zone profiles

Chloride concentration in groundwater is of special value since it can usually be treated as a conservative reference element (Allison and Hughes, 1978; Edmunds and Walton, 1980) of value in recharge studies and be used to monitor additions from the aquifer matrix. Distribution of chloride in groundwater for the study area is shown in Figure 6. The concentrations vary from 0.5 to 96 mg/l, with an average of 16.0 mg/l.

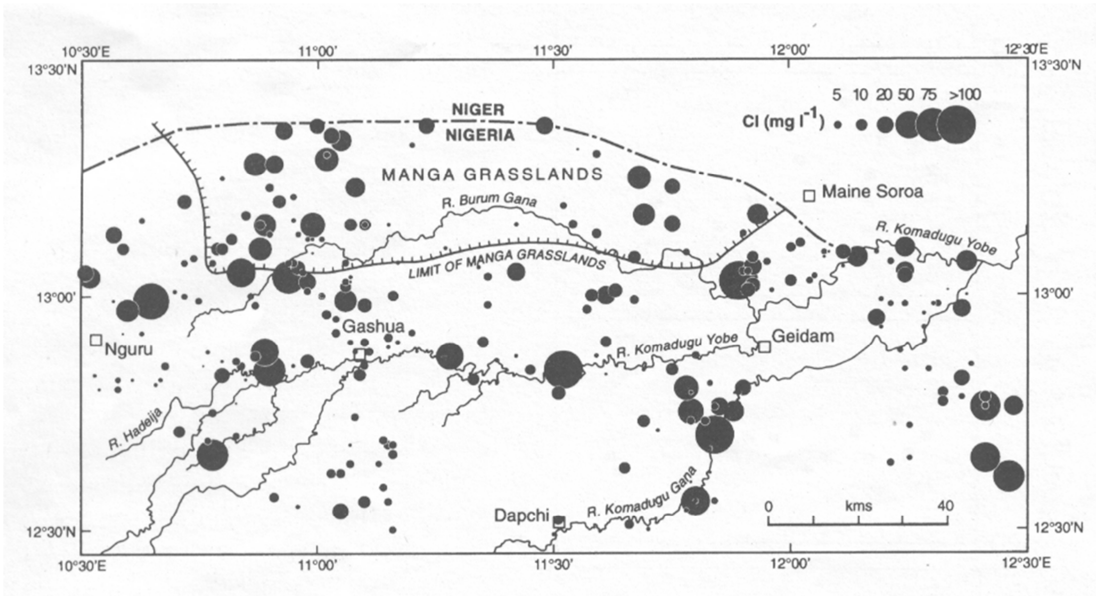

Figure 6: Chloride concentrations in groundwater of the study area

Results from the unsaturated zone profile (Table 2) suggest that the water table Cl concentrations represent atmospheric inputs and, therefore may be used to determine recharge rates for the study area. The estimated recharge rate for the area studied is 48 mma^{-1} obtained over a period of seven site-years.

Table 2. Unsaturated zone profiles weighted mean Cl concentrations and recharge estimates from the study area using average rainfall of 434 mm

Profile	Geology	Depth (m)	No. Samples (n)	Mean Cl C_s (mg/l)	Mean annual recharge R_d (mm/annum)
(1) Garin Mamadu 1	Manga dune sands	*15.5	51	14	55
(2) Madugubari 1	Manga dune sands	22.5	65	21	37
(3) Mainari 1	Manga dune sands	*16.5	53	41.5	19
(4) North Tamsugu	Alluvial sands	*18.75	58	11.7	66
(5)West Waggari	Alluvial sands	*19.25	60	17.7	43
(6) Magumeri	Fixed dune sands	16.25	53	29.5	26
(7) Kajimarum 1	Manga dune sands	*15.5	50	18.3	42
(8a) Malam Fatori (upp)	Fixed dune silt	03.00	10	47	16
(8b)Malam Fatori (Lower)	Lacustrine silt/Clay	3-16.00	42	2892	0.2

* profile reached the water table.

Rainfall chemistry is likely to introduce error in the recharge estimation if short term data is used. However, the error can be reduced with long term data

The range of recharge values of 19 to 66 mma^{-1} (excluding the Malam Fatori profiles) quite clearly indicates a significant spatial variability for the profile sites of the study area. Spatial variability of recharge rates using the Cl mass balance equation has been explained by Edmunds and Gaye (1994). In the present study, texture of the unsaturated zone sediments was observed to be the major factor for this variability as differences exist in the texture of the profiles. Due to its relative uniformity in the sites, vegetation may not be a significant cause of variability.

Chloride concentrations in groundwater in NE Nigeria range from 0.5 to 96 mgl^{-1}. This range reflects the heterogeneity in recharge rates resulting from variations in soil type and depth, vegetation type and coverage, as well as the slope of the area. Lower values reflect preferred infiltration routes. However, no geographical bias to Cl was observed in this study. Some of the high values probably relate to salinity acquired near playas or modern lakes. No high Cl concentrations were observed, suggesting that saline lakes (or their vestiges) are rare and very local in extent (Edmunds *et al*., 2002).

From the average Cl concentrations in groundwater, a regional recharge rate of 48 mm a-1 was obtained. This is slightly higher than the 41 mm a-1 for the unsaturated zone estimates if the Malam Fatori profile is excluded. This would suggest that additional recharge might be occurring preferentially from the depressions and channels in the sandy terrain. This is similar to the observations made by Edmunds *et al*., (2002). From the above, the wells in Lambawa and Abadam are hydrologically connected with the nearby Yobe river. This indicates that other sources of recharge through the unsaturated zone exist.

Piezometric studies by Carter (1994) indicate flow gradients towards the Lake Chad, implying recharge through the dunes. Recharge rates of the order of 60 mm a^{-1} are required to satisfy the water balance of the lakes. This is consistent with the higher values obtained from Cl mass balance from the Manga Grasslands. These results reinforce the concept of active modern day recharge, dispelling the earlier assumptions that effective recharge by precipitation is zero. It is considered that from modelling studies (Carter and Alkali, 1996) in the flood plain, significant regional recharge must also be taking place, although this remains to be quantified. The regional recharge estimates from the present study imply that rainfall recharge is of the same order of magnitude in the extensive sandy flood plain areas near the Komadugu Yobe river as in the Manga Grasslands. Also, Adeniji (1991) estimated substantial quantity of water (14.83 MCM) that flows from Lake Chad to recharge the [pper aquifer of the Nigerian sector of the basin. This has implications for small-scale development in the region, since the regional estimates are much larger than those found in the immediate vicinity of the river estimated at 1mm a-1 by Carter and Alkali (1996).

Management implications

The Cl mass balance method indicates that significant recharge both vertically and laterally along river channels is taking place in the study area. The rate of recharge estimated remains considerably in excess of the local demands in the villages (Adeniji, 1991). However, increase in irrigation activities and changes in urban water supplies by exploiting aquifers are major threats to sustainability. Geochemical data indicate that water in the deep aquifers is old (20 Ka BP) and recharged during cooler climates although there is no evidence of present day recharge from available data. Further work is required to focus on the edges of the basin in the south and southwest, where the confined aquifers crop out. Adeniji (1991) observed that there is possibility of the middle and lower aquifers receiving their recharges from wetter distant sources. Until this is proven the present day abstraction shall be regarded as effectively mining the system.Piezometric heads of the confined artesian wells are declining (Goni *et al*., 2000), due to demands by increase in population.

It is clear from the foregoing that the upper aquifer receives considerable recharge that can sustain the present day abstraction, but perhaps cannot sustain mechanised pumping. The observed decline in water table in recent years is largely climate-controlled (reduced rainfall during the Sahel drought), although human impacts are also identified as the case in most semi-arid areas of the world. The flood plains are probably fully recharged annually through river channels. However, for sustainable management of the flood plain aquifers (fadamas), caution must be exercised in introducing large irrigation schemes. Any agricultural use should be preceded by detailed studies, so as to utilise the quantity of water that is recharged annually.

The key to managing groundwater in this region (and all semi-arid and arid regions) is to understand the cost involved. Also, reliable databases and comprehensive monitoring programmes are needed to assess changes in quality and quantity of water resources. Educative programmes related to water and the environment can make costing and planning easier.

4. Conclusion

The Cl mass balance technique was used to estimate the amount of groundwater recharge in NE Nigeria. Using Cl concentrations in rainfall of 1.77 mg/l as input, the eight unsaturated zone Cl profiles chosen gave an average recharge rate of 41 mma-1. In the study profiles of the region, average recharge rate from Cl concentrations in the groundwater was 48 mm a^{-1}.

The recharge rate of the shallow groundwater in this region is significant and sustainable with the current rate of abstraction. Sustainability of the shallow groundwater depends on sound management. Although the flood plain aquifers are fully recharged annually, caution must be exercised before introducing large irrigation schemes. In this water-scarce region management strategy aimed at reducing wastage must be adopted.

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