Spatial and temporal distribution of groundwater recharge in northern Nigeria

W.M. Edmunds · E. Fellman · I.B. Goni
C. Prudhomme

Abstract Moisture samples obtained from unsaturated-zone profiles in sands from northern Nigeria were used to obtain recharge estimates using the chloride (Cl) mass-balance method and to produce records of past recharge and climatic events. Recharge rates range from 14–49 mm/year, on the basis of unsaturated-zone Cl values and rainfall chemistry measured over eight years at three local stations. The unsaturated-zone results also provide a record of the changing recharge and climatic events of the past 80 years; this record compares quite well with modelling results using precipitation data from Maiduguri, especially for the late 20th-century period of drought. The best fit for the model is made, however, by using a lower mean rainfall Cl (0.65 mg/l) than that obtained from the mean of the field results (1.77 mg/l Cl). This result implies that the measured rainfall Cl probably overestimates the depositional flux of Cl, although the lower value is comparable to the minimum of the measured rainfall Cl values (0.6 mg/l Cl). Recharge estimates made using these lower Cl values range from 16–30 mm/year. The spatial variability was then determined using results from 360 regional shallow wells over 18,000 km^2.

Using the revised rainfall estimate, the Cl balance indicates a value of 43 mm for the regional recharge, suggesting that either additional preferential flow is taking place over and above that from the vadose one, or that the regional recharge represents inputs from earlier wetter periods. These recharge estimates compare favourably with those from hydraulic modelling in the same area and suggest that the recharge rates are much higher than values previously published for this area. High nitrate (NO_3) concentrations (NO_3-N>Cl) preserved under aerobic conditions in the vadose zone reflect secondary enrichment from N-fixing vegetation, as occurs elsewhere in the Sahel.

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W.M. Edmunds (✉)
British Geological Survey, Crowmarsh Gifford, Wallingford, Oxon, OX10 8BB, UK
e-mail: wme@bgs.ac.uk
Fax: +44-1491-692345

E. Fellman
Natural Environment Research Council, Swindon, SN2 1EU, UK

I.B. Goni
Department of Geology, University of Maiduguri, Nigeria

C. Prudhomme
Centre for Ecology and Hydrology, Crowmarsh Gifford, Wallingford, Oxon, OX10 8BB

Résumé Des échantillons d’humidité extraits de profils de zone non saturée dans des sables du nord du Nigéria ont fourni des estimations de la recharge en utilisant le bilan de masse de Cl et de construire des chroniques de la recharge et des évènements climatiques passés. Les taux de recharge varient entre 14 et 49 mm an^{-1}, sur la base des teneurs en Cl de la zone non saturée et de la chimie des pluies mesurée pendant 8 ans en 3 stations locales. Les résultats tirés de la zone non saturée donnent aussi une chronique de la recharge variable et des évènements climatiques au cours des 80 dernières années; cette chronique s’ajuste assez bien aux résultats de la modélisation utilisant les précipitations de Maiduguri, en particulier pour la dernière période de sécheresse du 20ème siècle. Cependant, le meilleur ajustement du modèle est fait avec une teneur moyenne en Cl dans les pluies (0,65 mg l^{-1}) inférieure à celle données par la moyenne des résultats de terrain (1,77 mg l^{-1}). Ce résultat implique que la teneur en Cl mesurée dans la pluie surestime probablement le flux de dépôt de Cl, bien que la teneur plus basse soit comparable au minimum des teneurs en Cl mesurées (0,6 mg l^{-1}). Les estimations de recharge faites avec ces teneurs en Cl plus basses sont comprises entre 16 et 30 mm an^{-1}. La variabilité a ensuite été déterminée à partir de 360 puits peu profonds de la région, sur une surface de 18,000 km^2.

À partir de l’estimation de pluie revue, le bilan de Cl donne une valeur de 43 mm pour la recharge régionale, ce qui laisse penser que soit il se produit une recharge préférentielle en plus de celle de la zone vadose, soit la recharge régionale représente des entrées correspondant à des périodes plus humides plus anciennes. Ces estimations de recharge s’ajustent bien avec celles fournies par la modélisation hydraulique dans la même région, ce qui laisse penser que les taux de recharge sont beaucoup plus élevés que les valeurs publiées précédemment

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pour cette région. Les fortes concentrations en nitrates (NO_3-N>Cl), préservées du fait des conditions aérobies régnant dans la zone vadose, rendent compte d'un enrichissement secondaire par de la végétation fixant l'azote, ce qui se produit ailleurs au Sahel.

Resumen Se ha utilizado las muestras de humedad obtenidas en perfiles de la zona no saturada en arenas del norte de Nigeria para estimar la recarga por medio de un balance de masas de cloruro, y para generar registros de recarga y eventos climáticos pretéritos. La recarga estimada vale entre 14 y 49 mm a^{-1}, de acuerdo con los valores de cloruro en la zona no saturada y con la química de la lluvia determinada durante ocho años en tres estaciones locales. Los resultados de la zona no saturada también proporcionan un registro de la evolución de la recarga y de los eventos climáticos durante los últimos 80 años. Este registro está bien correlacionado con los resultados de una modelación realizada con datos de precipitación de Maiduguri, sobre todo con el último período de sequía del siglo XX. El mejor ajuste del modelo se obtiene cuando se utiliza un valor promedio de cloruro en el agua de lluvia (0,65 mg l^{-1}) menor que el obtenido a partir de las muestras de campo (1,77 mg l^{-1}). Este resultado implica que los valores medidos de cloruro en la lluvia probablemente sobreestiman la aportación de cloruro, aunque el valor más bajo es comparable con el mínimo de los valores medidos en la lluvia (0,6 mg l^{-1}). La estimación de la recarga empleando estos valores menores de cloruro varía entre 16 y 30 mm/a. La variabilidad espacial fue determinada por medio de los resultados de 360 pozos someros en un área de 18,000 km^2.

Aplicando la estimación modificada de la precipitación, el balance de cloruro lleva a un valor de 43 mm para la recarga regional, cosa que sugiere que o bien existe un flujo preferente adicional en la zona no saturada o bien la recarga regional representa las entradas de períodos pasados más húmedos. Estas estimaciones se correlacionan bien con un modelo hidráulica de dicha región, hecho que sugiere que las tasas de recarga son mucho mayores que los valores publicados anteriormente. La existencia de elevadas concentraciones de nitratos (mayores que los cloruros) en la zona no saturada, conservadas en condiciones aerobias, refleja que hay un enriquecimiento secundario por la fijación de nitrógeno por parte de la vegetación, como sucede en cualquier lugar de Sahel.

Keywords Unsaturated-zone · Groundwater recharge · Semi-arid regions · Hydrochemistry · Nigeria

Introduction

The unsaturated zone in semi-arid regions holds vital information as to whether or not rain water is transmitted as recharge to groundwaters. The investigation of the soil zone alone is inadequate to determine the properties of drainage irreversibly moving to the water table, because in the upper few metres both water and solutes are commonly recycled. In this paper, two inert tracers, chloride and nitrate, are used to determine the climatic and environmental record from recent decades and to compare these with records of precipitation.

This study focuses on the unsaturated zone of mainly Quaternary aquifers in the northeastern part of Nigeria, adjacent to Lake Chad, representing a typical area of the Sahel zone of Africa. The Quaternary deposits mainly constitute sands and clays of the Chad Formation, which underlies the whole region. These deposits originated largely as colluvial sediments from the Komadugu Yobe River and its tributaries, which drain the igneous terrain to the west and south. North of the Komadugu Yobe River, the Manga Grasslands form a separate ecosystem, with dune-sand deposits of Holocene to Recent age. These deposits contain a series of playa lakes, a few of which also contain fresh water; some lakes are alkaline and deposit trona, which is mined locally. Previous studies show that discharge to these lakes is supported by modern recharge (Carter 1994; Edmunds et al. 1999). Uncertainties exist, however, about the magnitude of this recharge as well as hydraulic continuity over the region. Earlier studies (IWACO 1985; NEAZDP 1990) propose that recharge is from the south and that current rates of local direct recharge are minimal. Using water-balance studies, Carter (1994) and Carter et al. (1994) show that modern recharge must be occurring to sustain the lake systems and also that some lateral recharge from the Komadugu Yobe River is occurring. The importance of the flooding of the Komadugu Yobe River system as a component of groundwater recharge in the Hadeija wetlands west of the area is also indicated by Goes (1999).

The objectives of this paper are: 1) to evaluate the local direct recharge rates in the Manga dune fields of northern Nigeria, 2) to determine the regional recharge in the extensive sandy alluvial or colluvial deposits of the Quaternary aquifer system, and 3) to compare the point-source with the spatially derived recharge estimates. This Upper Zone aquifer was the traditional source of shallow groundwater supplies until the discovery of high-quality artesian groundwater in the Middle and Lower aquifers of the Chad Basin. The artesian sources, however, are palaeowaters, and the declining piezometric surface means that in the near future the population may be forced once again to rely on the finite amounts of rainfall recharge.

The present study uses the chloride (Cl) mass balance to evaluate the direct rainfall recharge, using unsaturated-zone profiles. This approach is now widely recognised as a primary tool for recharge assessment in semi-arid regions (Allison et al. 1994; Edmunds and Gaye 1994; de Vries et al. 2000). However, there remain problems of extrapolating point-source data to determine spatial variability of recharge, and this is one objective of the present study. Vadose-zone records that describe climatic change and vegetation impacts in this region are

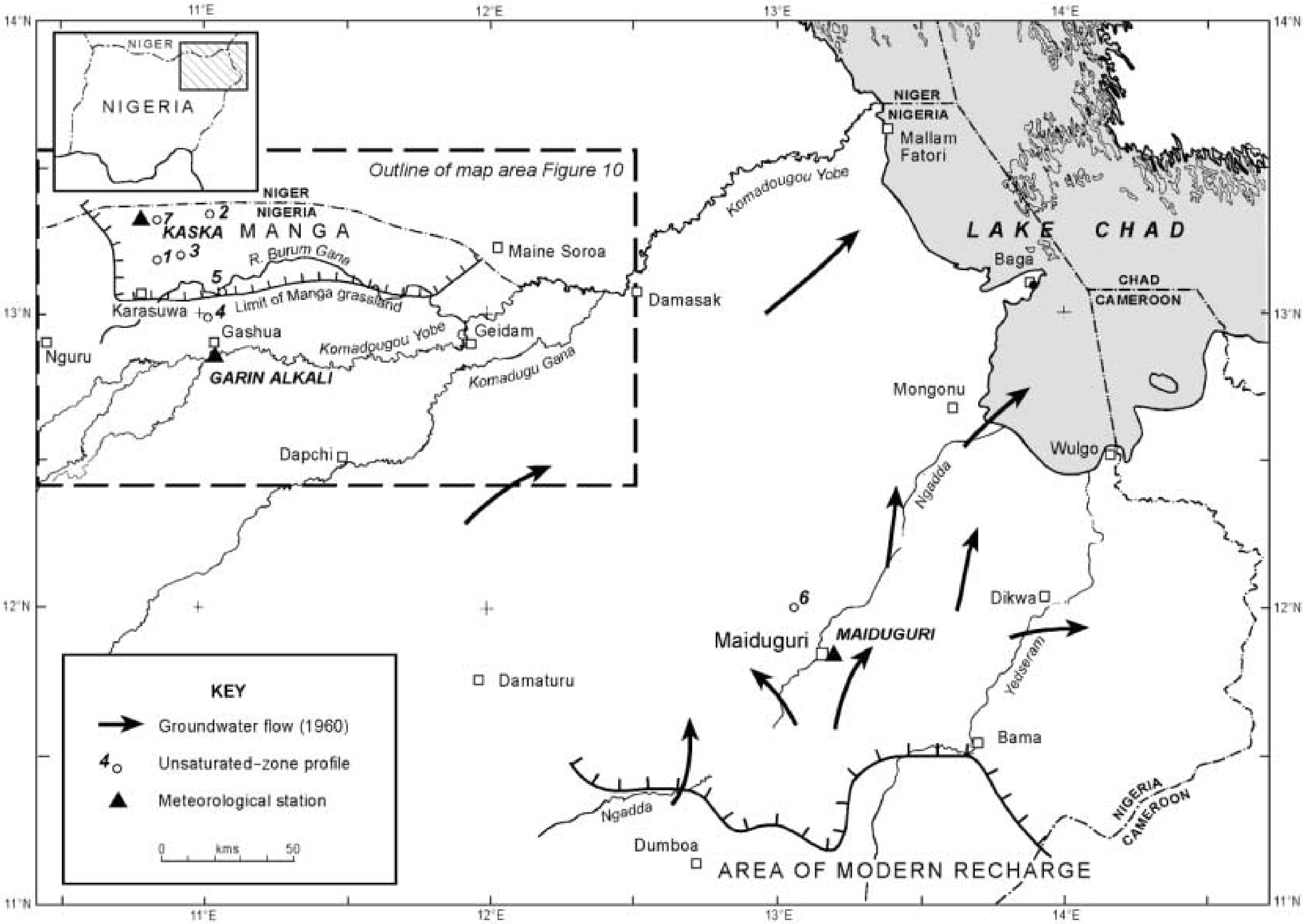

Fig. 1 Location of project area in relation to Lake Chad. Meteorological stations and unsaturated-zone profiles (*1–7*) are indicated, details of which are given in Table 1. The regional groundwater flow is from Barber (1965). The area of Fig. 10 is shown as the *inset* area

examined using records of Cl and nitrate (NO_3). Nitrate, like Cl, remains inert in aerobic groundwaters, including the unsaturated zone of most semi-arid regions. Nitrate was measured in parallel with Cl in the present study, and values are compared with results obtained from elsewhere in the Sahel (Edmunds and Gaye 1997).

Hydrogeological Setting

The area of study in northeastern Nigeria lies in the Sahel region of Africa, west of Lake Chad and close to the Komadugu Yobe River (Fig. 1). The Plio-Pleistocene Chad Formation and the younger overlying Quaternary sediments are the main sources of groundwater. The Chad Formation is essentially an argillaceous sequence in which minor arenaceous horizons occur (Barber 1965), and the formation has considerable lateral and vertical variability in lithology. Barber and Jones (1960) named three clearly defined arenaceous horizons of the Chad Formation as the Upper, Middle, and Lower Zone aquifers. The Lower and Middle Zones are confined, whereas the Upper Zone, of interest in the present paper, varies from confined to semi-confined and unconfined in places. The Upper Zone sands are lake-margin deposits, alluvial fans, or deltaic sediments, related to sedimentation in and around Lake Chad, which has varied considerably in size throughout the Quaternary Period (Durand 1995). The clays are mainly lake deposits laid down under non-turbulent conditions and are most extensive near the present-day lake shore. The lithological logs from the area are highly variable, and the stratigraphy of the near-surface formations is not clearly defined. One of the outstanding problems is whether modern direct recharge reaches the main groundwater system at depth.

Longitudinal dunes trending ENE-WSW of late Pleistocene age occur in the southern part of the study area and predate the main set of barchanoid dunes of the Manga grasslands, which overlie the alluvium (Stokes and Horrocks 1998; Holmes et al. 1999). The Manga dune system overlies alluvial sediments of the former Burum Gana River (Hazell and Barker 1995). Concern also exists over modern dune reactivation (Mortimore 1989). The Manga dunes produce a unique ecosystem. The elevation is 330–350 m above sea level and inter-dune depressions exist that are 20–30 m below the dune ridge. These depressions host several small lakes, some saline, which are in hydraulic contact with the phreatic

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aquifer of the dunes and possibly with the deeper aquifer system of the Chad basin.

The region receives summer rainfall from the south-western monsoon derived from the Gulf of Guinea. Rainfall during 1940–1970 averaged 456 mm compared to 1971–1991, when the average was 314 mm, a reduction of 31% (Carter 1994).

Methods

In this study, estimates of recharge are based on the Cl mass-balance method, which is described elsewhere (Allison et al. 1994; Edmunds et al. 1988). This technique is being widely applied in other parts of the world such as in the Sahel region (see, for example Gaye and Edmunds 1996). Samples of rainfall, unsaturated-zone moisture and shallow groundwaters were obtained. Chloride is used as the principal variable because it remains inert during the recharge process and, unlike water, is conserved in the unsaturated zone. Assuming that all Cl is atmospherically derived, its concentration in moisture in the unsaturated-zone should be proportional to recharge. Samples were taken on an event basis from rain gauges set approximately 1 m above the ground surface; collector bottles were set below ground to avoid evaporation. Rainfall-collection procedures are described in Goni et al. (2001).

Samples of the unsaturated-zone were obtained using a hand auger fitted with a 50-cm hollow-stem attachment. Samples were obtained at 25-cm intervals and immediately homogenised and stored in polythene bags, care being taken to avoid moisture loss. Samples were quickly transferred to glass 500-ml Kilner® jars for shipment to the laboratory (BGS). Moisture contents were determined gravimetrically, and pore waters were extracted where moisture contents were sufficient (approx. >5%) by centrifuge drainage. Extraction was carried out using heavy liquid (arklone) displacement methods (Kinniburgh and Miles 1983) and also by elutriation using aliquots of distilled demineralised water (typically 30 ml water to 50 g sand). The elutriate samples were used for analysis of Cl and NO_3, which were extracted quantitatively and analysed colourimetrically on the diluted samples. Following dilution, centrifuged samples (typically 3–5 ml) were used for microanalysis of a wide variety of species using ICP-AES and ICP-MS, as well as colourimetry for Cl, representing direct analysis of the pore solutions. The latter results (Edmunds et al., unpublished data, 2001), served as a check on the Cl analysis in the present study; good agreement was also obtained for Cl from samples extracted by both methods. All Cl values are reported as pore-water concentrations.

Samples from approximately 360 shallow wells with a mean depth of about 25 m were collected from villages in an area of about 18,000 km^2 in northern Nigeria (Fig. 1). Most of these wells are on the outskirts of the settled areas and away from areas of possible contamination. All are in daily use and all produce fresh water. For the purposes of the present comparison, all data are used; thus, a few wells may be included that are biologically contaminated, although the overall interpretation of the Cl and NO_3 is not affected. Two samples from each well were collected in polythene (LDPE) bottles. Both samples were filtered through 0.45-µm membrane filters and one sample was acidified to 1% with HNO_3. These samples were analysed by the above methods for Cl and major ions. Accuracy checks were made using standard samples (including international reference material), and analyses that did not balance within ±5% were rejected.

Table 1 Weighted mean chloride values for rainfall stations in northern Nigeria (Goni et al. 2001)

Station and year	Annual rainfall (mm)	Weighted mean Cl (mg/l)[a]
Kaska 1992	320.5	2.8
Kaska 1993	327.3	1.3
Garin Alkali 1992	549.4	1.6
Garin Alkali 1995	819.7	3.4
Garin Alkali 1996	297.5	0.6
Garin Alkali 1997	226.7	0.7
Maiduguri 2000	502	2.0
Regional average	–	1.77

[a] Weighted mean chloride for each station = Σ[(individual event total/season total) × Cl (individual event)]

Results

Rainfall Inputs

Rainfall amount and chemical data provide the primary information for the measurement of recharge. In particular, chloride is effective as an inert tracer, because atmospheric deposition is the only source of Cl. No additional input to the unsaturated zones from geological sources is expected in these samples, although buried playa deposits may be present in the Manga area. Chloride and nitrate data have been measured intermittently for 10 years at three climatic stations – Kaska, Garin Alkali and Maiduguri (Fig. 1). Details of the rainfall studies are described in Goni et al. (2001) and a summary of the chloride data is given in Table 1. The regional mean Cl value is 1.77 mg/l. Rainfall studies show that a linear relationship generally exists between Cl and increasing rainfall at any station, and thus partial data for any year can be used to derive Cl deposition.

Rainfall solutes in the Sahel region are derived from two principal sources, marine aerosols and terrestrial sources as dust that becomes entrained as air masses pass over increasingly arid areas. During passage over humid tropical areas, the monsoon is also modified by uptake of soil dust or debris from fires resulting from human activity (Goni et al. 2001). An assumption was made (Edmunds and Gaye 1994) that only solutes deposited during the rainy season (both wet and dry deposition) form the effective solute load for geochemical mass-balance calculations in groundwater recharge studies; thus

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Table 2 Unsaturated-zone profiles, weighted mean Cl and NO_3 concentrations, and recharge estimates from SW Chad Basin, using rainfall data from Table 1. The * symbol indicates that the profile reached the water table. A mean rainfall value (C_P) of 1.77 mg/l was used, together with the mean rainfall (P) for the past 30 years

Profile	Geology	Depth (m)	No. Samples	Rainfall, P (mm)	Mean Cl, C_s (mg/l)	Mean NO_3-N (mg/l)	Mean annual recharge, R_d (mm/year)
(1) GM 1	Manga dune sands	15.5*	51	320	14.1	18.2	40
(2) MD 1	Manga dune sands	22.5	65	320	21.3	5.0	27
(3) MN 1	Manga dune sands	16.5*	53	320	41.6	134.4	14
(4) N-TM	Alluvial sands	18.75*	58	320	11.5	13.8	49
(5) W-WGR	Alluvial sands	19.25*	60	320	17.6	67.8	32
(6) MG	Fixed dune sands	16.25	53	400	29.5	36.4	25
(7) KA 1	Manga dune sands	15.5*	50	320	27.9	14.3	20

any dust passing over these sandy Sahel regions in the dry season is likely to be in a quasi-steady state, in which the amount of dust deposited is equal to that taken up. The amount of aerosols fixed by vegetation is assumed to be negligible in this area. Therefore, in this region, rainfall is assumed to be the only source of solutes entering the groundwater.

The chemical composition of rainfall for northern Nigeria is discussed elsewhere (Goni et al. 2001). The rains are characterised by high Br/Cl ratios, which signify an addition from the biomass during burning and forest fires. Nitrate in the rainfall also has its origin in terrestrial aerosol. The rainfall is enriched relative to the marine aerosol, as are most other major, minor, and trace elements. Nitrate concentrations of the lighter stratiform rains (<15 mm) average 0.62 mg/l NO_3-N, compared with an average of 0.53 mg/l in the heavier convective rains (>15 mm). This condition is consistent with the fact that lighter stratiform rains contain more near-surface particulate material (Lacaux et al. 1987).

Recharge Estimation From Unsaturated-Zone Profiles

A total of seven profiles were obtained from the sites shown in Fig. 1; details of the depths and summary information are given in Table 2. These sites are representative of the Manga Grasslands (profiles 1, 2, 3, and 7) and the fine-grained colluvial deposits (profiles 4, 5, and 6) of the Komadugu Yobe flood plain. The sands in the Manga grassland are generally fine to medium grained and mainly fine-grained sands form the alluvial plains.

A first estimation of recharge was carried out using the measured regional average values for rainfall and precipitation chemistry. The profiles are constructed from samples obtained at 0.25-m intervals over a depth range of 14–23 m. The direct recharge, R_D, can be derived from:

$$R_D = \frac{P \cdot C_P}{C_S} \quad (1)$$

where P is the regional rainfall (last 30 years in each location) in mm/year; C_P is the spatially-averaged Cl concentration in rainfall; and C_S is the mean unsaturated-zone Cl concentration.

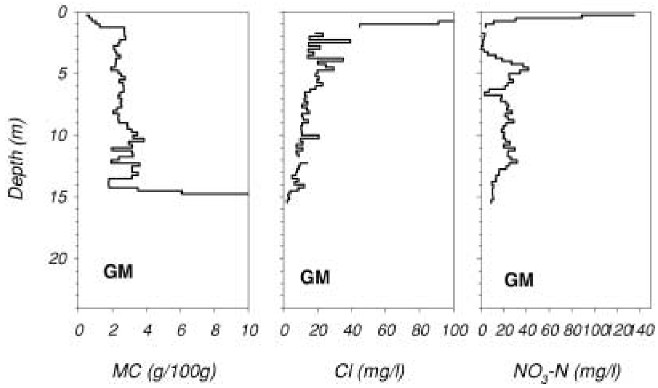

Fig. 2 Profile of unsaturated-zone moisture content (*MC*) for site 1 (*GM* Garin Momadou) showing the relation between depth and pore-water Cl and nitrate concentrations

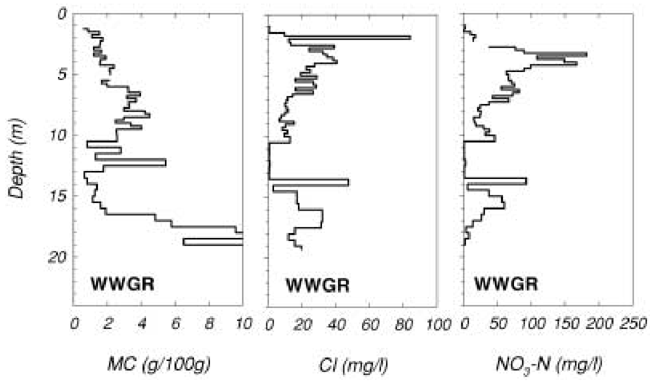

Fig. 3 Profile of unsaturated-zone moisture content (*MC*) for site 2 (*WWGR* West Waggari) showing the relation between depth and pore-water Cl and nitrate concentrations

Table 2 shows results, assuming a fixed C_P value of 1.77 mg/l Cl (see Table 1) and a regional rainfall of 320 mm, which are representative of the drier periods of the last half of the 20th century, except for Maiduguri, farther south, for which a value of 400 mm/year was used.

Figures 2, 3, 4, 5, 6, and 7 show moisture contents and Cl and NO_3-N concentrations in the unsaturated zone as a function of depth for six of the sites. The mois-

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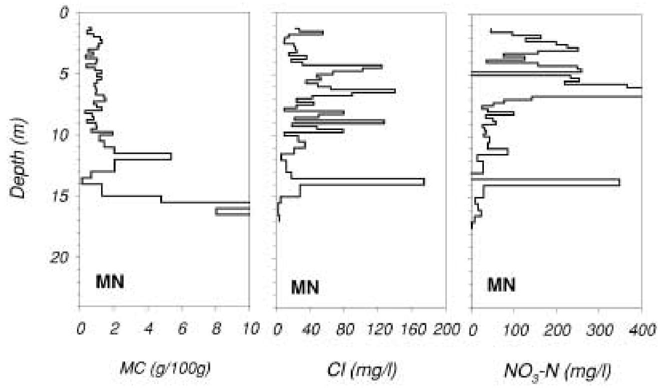

Fig. 4 Profile of unsaturated-zone moisture content (*MC*) for site 3 (*MN* Mainari), showing the relation between depth and pore-water Cl and nitrate concentrations

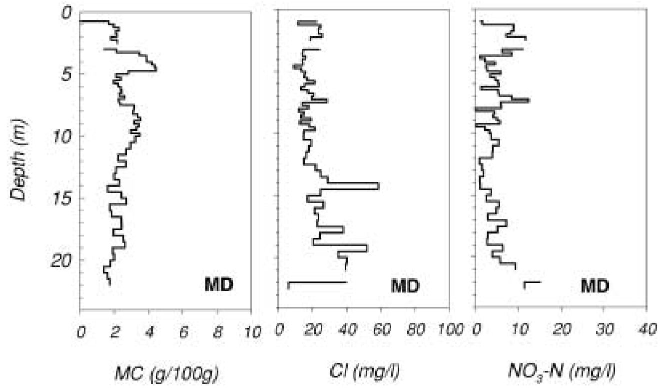

Fig. 6 Profile of unsaturated-zone moisture content (*MC*) for site 5 (*MD* Modugubari), showing the relation between depth and pore-water Cl and nitrate concentrations

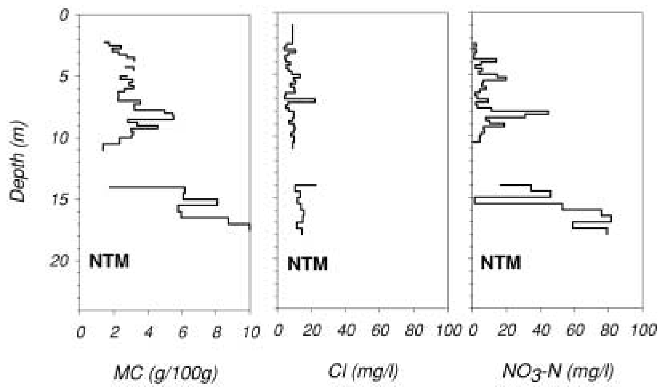

Fig. 5 Profile of unsaturated-zone moisture content (*MC*) for site 4 (*NTM* North Tamugu), showing the relation between depth and pore-water Cl and nitrate concentrations

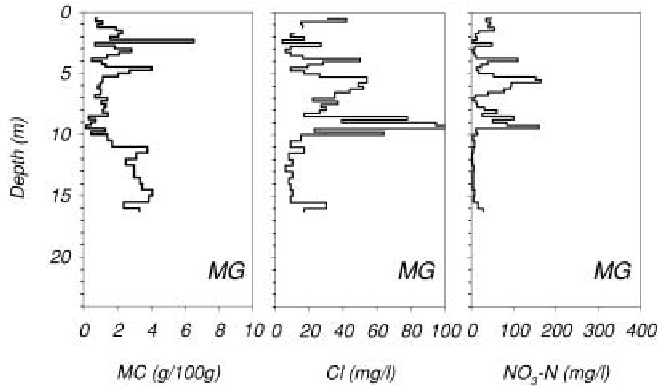

Fig. 7 Profile of unsaturated-zone moisture content (*MC*) for site 6 (*MG* Magumeri), showing the relation between depth and pore-water Cl and nitrate concentrations

ture contents are generally 2–4 wt%, typical of fine- to medium-grained sands. The small moisture-content variations observed reflect changes in the grain size of the sediments, except at the capillary fringe near the water table. The samples were all collected in the dry season; on the basis of the drier top sections of the profiles, the zone of moisture and solute recycling does not exceed 2 m below the surface.

Profile GM is the only site that has a high chloride concentration in the upper 1 m of the profile. The reason for this high concentration is unknown, although this phenomenon is commonly observed in other parts of the Sahel (Gaye and Edmunds 1996). This condition may be the result of mineralisation, in which salinity is trapped in pore spaces (elution recovers the total porosity); it may also indicate a degree of seasonal evapotranspiration, in which mixing and recycling of solutes and moisture take place forming an open- rather than a closed-system separate reservoir (Cook et al. 1992). However, below this zone in the relatively homogeneous sands, solutes and moisture are likely to drain by piston flow to recharge the groundwater. In all other profiles, no Cl accumulation is detected, implying that no near-surface mineralisation has taken place.

The Cl concentrations in the profiles range from 12–42 mg/l, and no difference exists between samples from the dune sands and from the alluvial sand deposits. These low concentrations indicate significant recharge must be taking place. From the Cl mass-balance equation, direct recharge rates of 14–49 mm/year are derived; surface runoff in these environments is negligible. Significant variations are observed in the Cl concentrations with depth, which relate primarily to climatic oscillations, and this is examined further below.

The concentrations of NO_3-N in the unsaturated zone are highly variable and range from 5–134 mg/l as NO_3-N, with NO_3>Cl on a weight basis; below the soil zone, nitrate concentrations vary with Cl (see MG and W-WGR). Nitrate concentrations in the rain from the region average 0.57 mg/l N (Goni et al. 2001), and, after allowing for evapotranspiration of 90% implied by the recharge estimates, concentrations as great as 6 mg/l are expected in the unsaturated zone. Therefore, in all except two sites in the dunes (MD), a distinct enrichment occurs in nitrate, which agrees with observations at other Sahel sites and further afield (Edmunds and Gaye 1997). This enrichment is compatible with the fixation of N by vegetation, bacteria, or both, giving rise to concentrations

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well in excess of atmospheric inputs. The nitrate also serves as a qualitative, independent control on the conservative behaviour of Cl.

Temporal Variability of Recharge

Under conditions of piston flow, both water and inert solutes are displaced at regular intervals from the soil horizon into the unsaturated zone; higher solute concentrations correspond to lower recharge. The theory of the movement of solutes through the unsaturated zone and the transmission of solute peaks corresponding to recharge episodes is described and critically reviewed by Cook et al. (1992) and is discussed elsewhere in this volume (Edmunds and Tyler 2002). Variations in chemistry are preserved only if the time scale for hydrological change is large relative to the diffusive time scale. Using the model developed by Cook et al. (1992), a "persistence time" is defined that represents the time that it takes for the relative difference in the solute (chloride) concentration to be reduced to 20% of its original value.

Due to recycling in the soil zone and dispersion, annual oscillations are not likely to persist in the record. However, if the oscillations have a time scale (half wavelength) of 5 years, then these should persist for more than 50 years if the recharge rate is more than 20 mm/year, and for more than 100 years if the rate is greater than 40 mm/year. A 20-year event, such as the recent Sahel drought, should persist at a recharge rate of 10 mm/year and at a moisture content of 5% (typical of fine-grained sands) for about 800 years.

A simple spread-sheet model was developed to calibrate the profiles in terms of the time scale that is represented by the chloride and moisture stored in the unsaturated zone, assuming that cumulative chloride is proportional to time (Cook et al. 1992). The approximate time corresponding to a given depth can be calculated from chloride data by assuming a constant rate of chloride deposition:

$$t = \frac{\int C_S \theta dz}{C_P P} \qquad (2)$$

where C_S = chloride concentration, in mg/l; t = time, in years; C_P = chloride concentration in rainfall, in mg/l; P = average precipitation, in mm/year; z = depth, in m.

Modelling of the recharge history was carried out using local precipitation records. The first step was to evaluate the robustness of long-term records of rainfall. Several stations are available for northern Nigeria and two of these, Kano (west of the area shown in Fig. 1) and Nguru, were selected to compare with the climatic records at Maiduguri, which serves as the main station for the area and has a 90-year rainfall record from 1909. The 5-year averaged records for these stations are shown in Fig. 8, where a good correlation of the major events is observed, although some local differences occur. For example, the onset of the Sahel drought, which occurred over the Sahel as a whole in the late 1960s, is more pronounced in Maiduguri than in the other two stations and ended in the mid-1990s. In the two stations to the west, a distinct wet interlude occurred around 1980; this wetter period is less apparent in Maiduguri. Nevertheless, sufficient correlation exists to be able to extrapolate to the region as a whole.

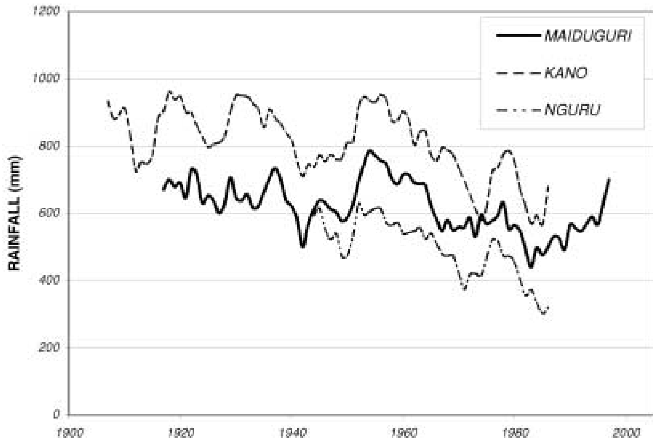

Fig. 8 Rainfall records for Maiduguri (1916–1998), Kano (1906–1986), and Nguru (1942–1986), northern Nigeria

Rainfall chemistry is likely to be the greatest source of error in the recharge estimation and modelling, although Cl increases linearly with rainfall amount (Goni et al. 2001). For the long term, however, some smoothing in the signal occurs so that the average Cl value is probably the most appropriate value to use. In the model calculations below, however, the C_P and P values are allowed to vary to provide the best fit.

A second value of recharge is derived using the relationship shown in equation (2). The chloride concentration profile is calculated from this equation, C_PP being adjusted so that good agreement occurs with the rainfall series. Profiles (unsmoothed) are shown for all sites in Fig. 9. Higher values of the ratio 1/Cl indicate wetter years and are compared here with the 5-year averaged rainfall records for the past century from Maiduguri. The model data are summarised in Table 3, and the main features are summarised as follows:

Magumeri (MG)

This site at Magumeri is on the top of a low line of fixed dune sands, almost 40 km north of Maiduguri. Because C_P is not known with certainty, C_PP is adjusted using Eq. (2). An excellent match is obtained between the Maiduguri rainfall and the Cl profile by assuming P=400 mm and C_P=0.75 mg/l (Table 3). This C_P value is considerably lower than that measured as the regional recharge from the rain gauge. However, this is close to the lower values for Cl obtained at the Garin Alkali site (Table 1). Using this value, a good model fit is obtained, which corresponds to the rainfall patterns within the Sahel drought period. The matching is good even at the scale of 1–3 years, which is taken as an indication of piston flow with only limited dispersion. The profile corresponds to 26 years of recharge; the mean recharge rate derived from the model for this location is 18 mm/year.

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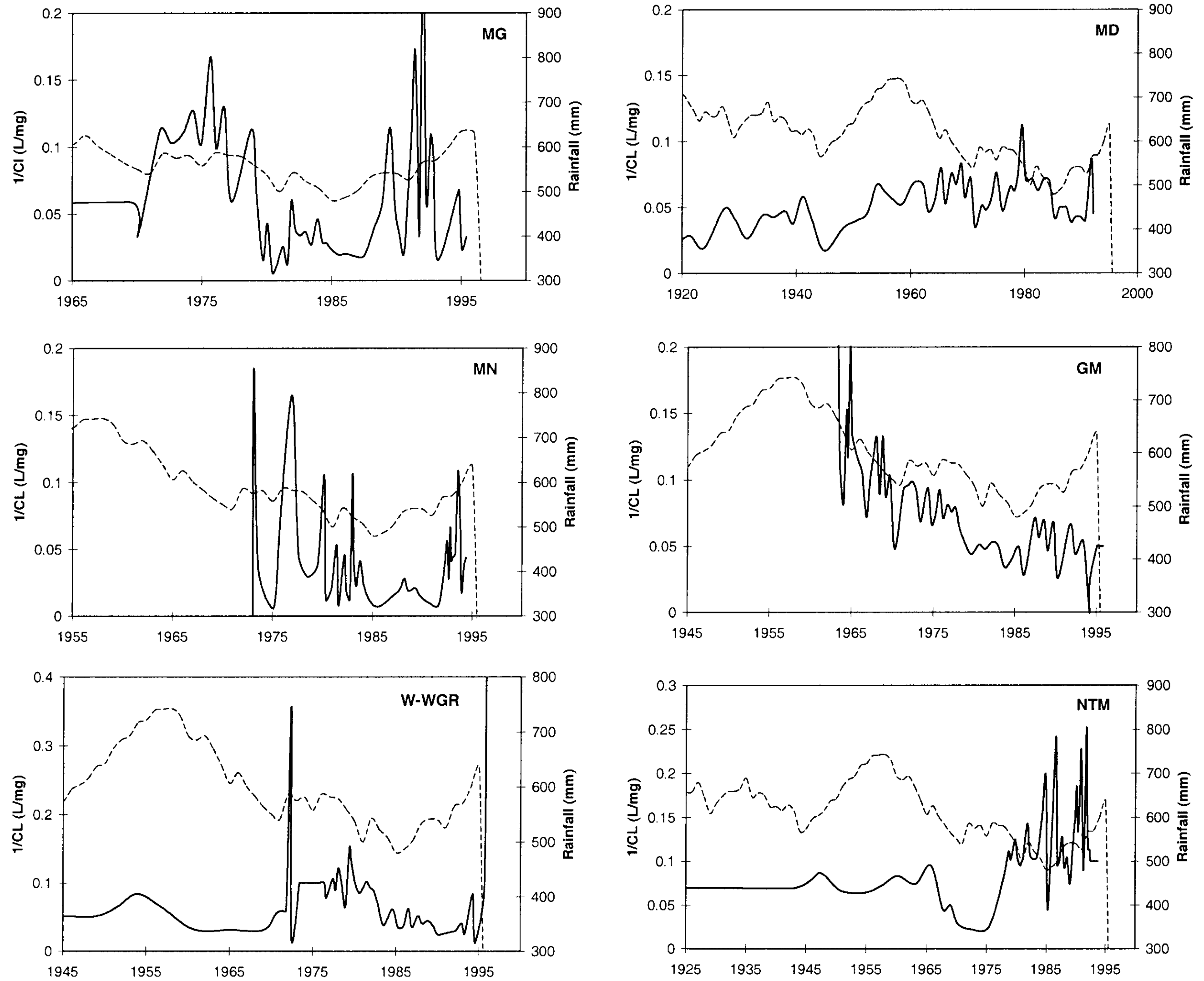

Fig. 9 Model results for the six profiles (*GM, MD, MN, NTM, WWGR, MG*) using the moving 5-year average for rainfall from Maiduguri (shown as *dotted line*). Higher 1/Cl values indicate wetter periods

Modugubari (MD)

The height of the Sahel drought is well indicated, and this profile with the longest record (82 years) also defines well the previous drought of the 1940s. The intervening wetter period is less well indicated. A recharge rate of 25 mm/year is obtained.

Mainari (MN)

This profile also records the height of the drought (mid-1980s) but only extends back to 1975. The resolution of peaks is less than 5 years and the recharge rate for this period is 30 mm/year.

Gavin Momadou (GM)

The lowest values of 1/Cl also coincide with the Sahel drought maximum. This site contains increased salinity in the top 1 m (see above) and for the modelling the average Cl value for the profile beneath was substituted. The profile corresponds to a 35-year record with a recharge rate of 22 mm/year.

West Waggari (WWGR)

The 1975–1980 wetter interval is indicated as well as the driest period, 1985–1990. The recharge rate is 19 mm/year.

North Tamugu (NTM)

This record provides a good correlation with the start of the Sahel drought in the early 1960s. Less obvious is the reason for the set of higher 1/Cl values in the late 1980s. The recharge rate is 16 mm/year.

These profiles all show a good match between the rainfall record using the lower recharge Cl values. This match suggests that the measured rainfall Cl values are probably anomalously high for some years, with measurements biased due to the incorporation of dry deposition. This in turn implies that the groundwater recharge rates are slightly lower, if the model-derived rainfall Cl concentrations are accepted.

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Table 3 Model summary results for six profiles. The data used for the model fit for each profile are shown. For P and C_P, two values provide similar interpretations

Profile	Density	Rainfall, P (mm)	Rainfall, Cl C_P (mg/l)	Mean annual recharge, R_d (mm/year)	Residence time (years)
GM 1	1.5	400 600	0.6 0.4	22	35
MD 1	1.5	400 600	0.5 0.35	25	86
MN 1	1.5	400 600	0.9 0.6	30	22
NTM	1.5	400 600	0.5 0.4	16	63
WWGR	1.5	400 600	0.8 0.5	19	45
MG	1.5	400 600	0.75 0.5	18	27

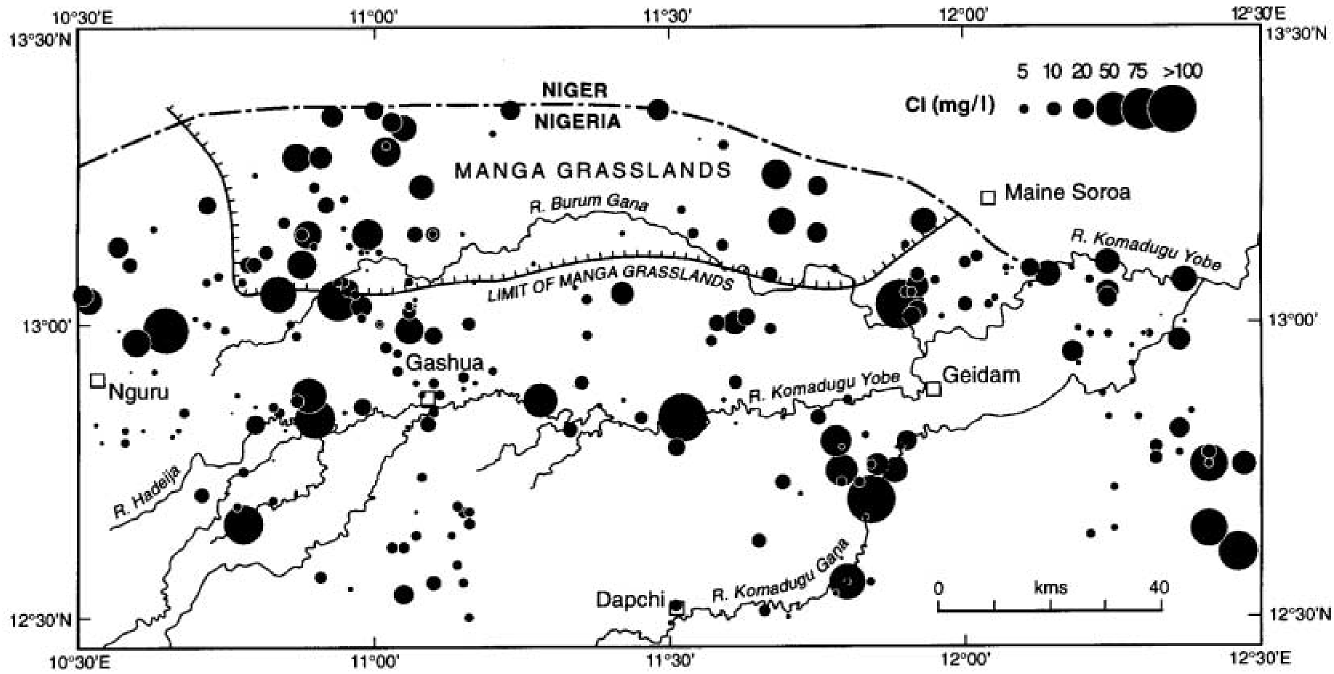

Fig. 10 Chloride concentrations in shallow wells in the Gashua-Geidam area, northern Nigeria. Location of area is shown in Fig. 1

Spatial Variability of Recharge

In unconfined aquifers, the chemistry of groundwaters at the water table is representative of the composition of recharge arriving from the unsaturated-zone. Assuming that solutes are derived solely from rainfall, then the data from wells are appropriate to estimate the spatial variability of the recharge (Eriksson and Khunakasem 1969; Edmunds and Gaye 1994). A robust way of determining the spatial variability in areas where diffuse recharge predominates and where surface runoff is negligible is to combine unsaturated-zone, point-source data, which represent decades, with water-table values, which represent integrated recharge estimates for the most recently arrived water. In this paper, both sets of information are used for the Manga grasslands and nearby areas.

The hydrogeochemical distribution of Cl from about 360 dug wells sampled in the northern part of the study area is shown in Fig. 10. The distribution of values is not uniform, and the range is 0.8–96 mg/l Cl. This range reflects the heterogeneity in recharge rates resulting from differences in soil type and depth, vegetation type and coverage, as well as slope variations. Some lower values reflect preferred infiltration routes; no geographical bias to Cl is observed. Some of the high values probably relate to salinity acquired near playas or modern lakes, although, remarkably, no very high Cl samples occur, suggesting that saline lakes (or their vestiges) are rare and very local in extent.

The shallow groundwater data have a strong negative skew, with a median value of 6.35 mg/l Cl. This value was used to derive a regional recharge value. Using a measured rainfall value of 1.77 mg/l Cl (Table 1) and a value of 500 mm as a mean long-term estimate (i.e. not just the last 30 years) for rainfall for the area gives a recharge rate of

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139 mm/year. The profile modelling results, however, show that a best fit for the profiles corresponds to rainfall Cl of 0.55 mg/l Cl. This result further indicates that the rainfall chemical data are probably overestimating the true flux of Cl to the land surface and into the soils. Using this lower Cl value, a regional average charge value of 43 mm/year is obtained, closer to the estimates from water-balance calculations (Carter and Alkali 1996).

Discussion

The results from northern Nigeria provide a unique opportunity to compare (1) estimates of point-source recharge, including both spatial and temporal data in semi-arid terrain, based on a single method (solute chemistry), with (2) results for an area where recharge estimates have been obtained from water-balance studies.

Recharge from point-source data ranges from 14–49 mm/year. This range is not unexpected and is comparable with results in similar terrain with lower rainfall from Senegal (Edmunds and Gaye 1994). The range is due to several factors that are inherent in small-scale terrain heterogeneity (e.g. soil type and depth, vegetation characteristics, ponding, and compaction). Because of the large range, spatial averaging from several sites (as many as 20 in Senegal and seven in the present study) is needed to provide reasonable estimates for regional use.

An estimate of regional recharge of 135 mm/year was obtained using the integrated values from 360 shallow wells over an area of 18,000 km^2, using the median Cl concentration of 6.35 mg/l. The spatial variability of the recharge (proportional to the Cl in shallow groundwater) is evident at the regional scale. This variability is due to the factors noted above but also reflects larger-scale features of the terrain. Some areas are distinctive because of high Cl (lower recharge), such as in the northwestern part of the area, but no clear zonation of the recharge pattern emerges. Spatial data indicate that the Manga Grasslands dune-covered area does not have higher recharge than the rest of the mainly sand-covered region, as supported by the profile data in these two terrains. However, uncertainty remains as to the exact recharge amounts represented by the Cl.

The modelling results for six profiles, with records ranging from 22–86 years, all produce a best fit with the 5-year averaged rainfall record from Maiduguri (85 years) in every case where a *lower* rainfall Cl value than that measured in the field is substituted. However, these values are close to the lowest measured yearly mean rainfall (for 1996 and 1997) from the Garin Alkali site, suggesting that the rainfall-solute amounts are over-estimated.

These results have implications for the recharge measurements here and in studies elsewhere in dusty arid regions. One implication is that the analysed rainfall chloride includes a component of dry deposition as an artefact, producing bias in the recharge estimates. This possibility needs further investigation, but the rain gauge probably acts as a preferential collector of dry deposition. Alternatively, the unsaturated-zone estimates, based on rainfall from dry years of the late 20th century, may not be representative of the recharge period(s) from which the shallow groundwater originates.

The effect of using the lower values for Cl in the rain is to reduce the recharge estimates from the vadose-zone profiles to 16–30 mm/year, compared to the estimates obtained using field-measured rainfall Cl of 14–49 mm/year. Similarly, for the regional data, if a value of 0.55 mg/l Cl for the rainfall (average of the model results) is used, a spatially-averaged recharge estimate of 43.3 mm/year is obtained. This value is slightly higher than the revised vadose-zone estimates and suggests that additional regional recharge might occur preferentially from the depressions and channels in the sandy terrain, which would be in addition to that from direct recharge.

The measurement of rainfall chemistry in arid regions is particularly difficult, and no dedicated investigation of the relationship between dry and total deposition is known from the literature. In the interim, further unsaturated-zone comparisons using model studies may help resolve the actual transfer from rain solutes to the aquifer as an outcome of similar recharge assessments. Nevertheless, controlled studies of the measurement of rainfall chemistry in semi-arid regions are needed, especially because this is likely to be the single largest source of error in the chloride mass balance.

Recharge estimates from the present study were compared with those from water-balance studies of the Manga Grasslands by Carter (1994) and Carter et al. (1994), who derived likely recharge estimates as part of their modelling studies. Piezometric studies in boreholes normal to the inter-dune lakes and playas indicate flow gradients toward the lake, implying present-day recharge through the dunes. The model studies require recharge rates of about 60 mm/year to satisfy the water balance of the lakes. This value is consistent with the higher values obtained from Cl mass balance from the Grasslands area. Both studies reinforce the concept of active modern recharge, dispelling the earlier assumptions that effective recharge by precipitation is nearly zero (IWACO 1985; NEAZDP 1990). Based on modelling studies in the flood plain (Carter and Alkali 1996), significant regional recharge is also occurring, although this phenomenon has not been quantified. The regional recharge estimates from the present study imply that rainfall recharge is similar in the sandy flood plain areas near the Komadugu Yobe River and in the Grasslands. This conclusion has positive implications for small-scale development in the region, because the regional estimates are much larger than those (1 mm/year) for lateral recharge from the river (Carter and Alkali 1996).

High nitrate concentrations also occur in the vadose zone of northern Nigeria of similar magnitude to those elsewhere in arid regions, indicating additions from natural processes (Edmunds and Gaye 1997; Hartsough et al. 2001). The average concentration of 41 mg/l NO_3-N from the seven sites in the unsaturated zone compares with a median value of 7.8 mg/l for the whole region in the water-table samples. The latter value includes only those water samples above detection limit; about half of the ground-

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water samples were anaerobic, and nitrate was reduced below detectable limits. This condition implies that some organic sediments from intermittent lake or alluvial deposits (Edmunds et al. 1999) are preserved in the shallow aquifer.

Conclusions

Estimates of groundwater recharge obtained from the Cl mass-balance method using seven profiles from the unsaturated-zone range from 14–49 mm/year. Regional recharge estimates were also obtained using the same approach, giving a mean recharge rate of 139 mm/year. These estimates were derived using Cl in rainfall measured over 10 years at three stations. Cumulative Cl in the unsaturated-zone profiles compares well with rainfall records from Maiduguri and contains a reasonable record of the late 20th-century Sahel drought. The modelled results, however, produce the best fit if *lower* rainfall Cl concentrations are used than those determined on samples collected from rain gauges (a mean value of 0.65 mg/l for the former compared with 1.77 mg/l Cl for the latter). Thus, for this region at least, the effective Cl depositional flux to the land surface is lower than that measured in rain gauges. Using the lower value for Cl in rain, the vadose-zone recharge rates range from 16–30 mm/year, and the regional recharge rate, based on data from shallow wells, is 43 mm/year. These values are similar to those calculated from water-balance modelling.

In this semi-arid environment, nitrate also behaves conservatively and generally mirrors the concentration distribution of Cl below the soil horizons. The high nitrate concentrations (NO_3-N>Cl) indicate nitrogen fixation by vegetation in the soils, adding to the evidence for the widespread occurrence of this phenomenon in arid and semi-arid regions.

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