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Journal of Hydrology 156 (1994) 47–59

Journal of Hydrology

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Estimating the spatial variability of groundwater recharge in the Sahel using chloride

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(Received 16 April 1993; revision accepted 3 November 1993)

Abstract

Thirteen interstitial water chloride profiles have been obtained from the unsaturated zone of the coastal Quaternary aquifer in Senegal over depth intervals ranging between 7.0 and 35.5 m; three of these profiles reached the water table. A regional study of 119 dug wells was also carried out over an area of some 1600 km^2 for the measurement of chloride, as well as other parameters, in samples taken from the water table.

These two sets of data have been used, together with rainfall input chemistry collected over a 3 year interval to derive regional estimates of recharge for this area typical of the Sahel margin (mean annual rainfall 1970–1990 around 280 mm). Recharge estimates range from 13 000 to 1100 m^3 km^{-2} $year^{-1}$. It is concluded that the conjunctive use of interstitial water profiles and regional shallow groundwater chemistry provide an inexpensive technique for recharge estimation which can be widely applied in sedimentary terrains.

1. Introduction

The problems of recharge estimation in semi-arid zones have received much recent attention by hydrogeologists (e.g. Simmers, 1988, Lerner et al., 1990). On the whole, physical or piezometric approaches have been more widely used than tracer techniques (isotopic and chemical). However, detailed studies of the unsaturated zone using chemical or isotopic techniques are considered to offer definite advantages in arid regions (Gaye and Edmunds, 1994). Profile techniques using tritium or chloride in unsaturated zones have now been successfully applied in Africa (Edmunds et al., 1988), the Middle East (Edmunds and Walton, 1980), Australia (Allison and Huges, 1978), India (Sukhija et al., 1988) and North America (Stone and McGurk,

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SSDI 0022-1694(93)02414-S

1985), and generally provide realistic mean recharge estimates over periods of years or decades. Of the three possible tracer methods (tritium, stable isotopes and chloride) the use of chloride proves especially attractive as a low-cost tracer for recharge estimation (Gaye and Edmunds, in press). Chloride has the advantage over tracers involving the water molecule (^3H, $\delta^{18}O$, δ^2H) in that atmospheric inputs are conserved during the recharge process, allowing a mass balance approach to be used. In comparison with other inorganic ions, chloride is neither added nor removed by water–rock interaction during percolation in the vast majority of environments. Most published results using tracers, however, represent point source information and there remains the question of spatial variability of recharge.

The question of the spatial variability of groundwater recharge has been discussed by Wellings and Cooper (1983), Allison (1988) and Johnston (1987) among others. Various factors have been put forward to explain variability including differences in geology and climate and especially soil type and depth. Cook et al. (1989), investigating a semi-arid region of southern Australia, successfully used chloride profiles coupled with electromagnetic techniques to determine spatial variability of recharge. This study was, however, a specialised case where increased recharge occurred following clearance of vegetation; this allowed electromagnetic measurements to follow the vertical movement of the saline recharge pulse on a field-sized area.

Work by Eriksson and Khunakasem (1969) and Eriksson (1976) showed that chloride in groundwaters could be used to provide regional estimates of recharge provided there was no geological or marine input, and if atmospheric deposition of chloride was known. In general it is difficult to establish recharge from a consideration of the chemistry of water in the saturated zone alone; chemical data on atmospheric deposition are also rarely available.

Conjunctive use of unsaturated zone profile data (which provide information on inputs) combined with regional data on the phreatic aquifer can overcome the limitations outlined above. Results from 13 unsaturated zone chloride profiles from northern Senegal and chemical analyses from shallow groundwater from over 100 shallow wells are used here to estimate groundwater recharge both at site and regional scales and to show that chemical data, obtained using easily applied techniques, may be used to provide regional recharge estimations.

2. Environmental background

The area chosen for this study is approximately 1600 km^2 lying in the northwest of Senegal (Fig. 1). It is an area underlain by Quaternary sands which form a phreatic aquifer, typical of the coastal plains of the country. These sands are thickest in the centre and south of the area. They thin as the ground elevation decreases towards the coast and towards the north. In the east they thin or disappear completely as they are succeeded by rocks of Tertiary age. The area is representative of much of the Sahelian region over which unconsolidated sandy deposits are exploited for water resources.

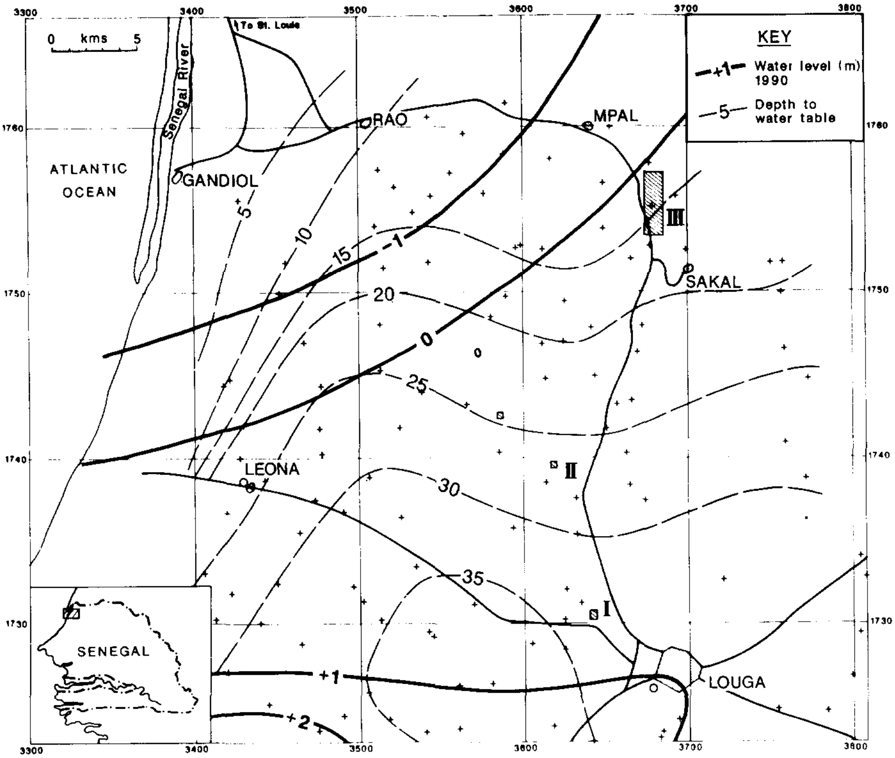

Fig. 1. Hydrogeological map of the Louga–Leona area, northern Senegal, showing piezometric surface and depth to the water table. The main Louga unsaturated zone site is marked [I], with subsidiary sites [II] and [III] to the north. The locations of shallow traditional wells sampled in this study are shown.

The soil cover is thin and consists of a semi-arid red-brown soil. Vegetation cover consists of occasional shrubs and acacia, the density of which has decreased over recent decades or even centuries owing to the increasing pressure for agriculture and for firewood. These cleared areas around each village can be seen clearly on satellite photographs and represent some 40% of the area of the aquifer. Removal of biomass over the years has probably progressively reduced evapotranspiration and increased the recharge which would be expressed in a decreasing chloride concentration with time (though probably imperceptible on the time scale of present data). Agricultural activity at the present day is rainfed, mainly groundnut and millet cultivation to which no fertilizer applications are made.

The climate is typical of the Sahel with summer monsoon rains and a distinct winter dry season. The present-day mean annual rainfall at Louga in the centre of the area is 250–300 mm. This represents a decline of 36% of the regional long-term records 1895–1970 (Edmunds et al., 1992). Groundwater levels have been falling at a rate of 0.2 m $year^{-1}$ over much of the phreatic aquifer due to over-abstraction and possibly exacerbated by drought (Gaye, 1990). The present-day piezometric surface over the area lies close to sea level (Fig. 1) and depths to the water table are mostly between 15 and 35 m.

3. Methods

Samples for chloride analysis were obtained from two sources — interstitial water extracted from unsaturated zone core material taken by hand auger at 25 or 50 cm intervals and secondly, water samples from traditional dug wells which intercept the upper 1–2 m of the water table (Fig. 1). The chloride was extracted from the sand profiles by elution with ultrapure water (Edmunds et al., 1988). Good correspondence was found between chloride measured on these eluted samples and samples from the same profiles obtained directly by centrifugation (Edmunds et al., 1992), although for the purpose of consistency in this study only those data obtained by elution from 13 profiles were used. Three profiles reached the water table but the remainder are partial profiles, which reached depths between 7 and 25 m (Table 1). Chloride was measured using automated colorimetry (Technicon AA-II) using mercuric thiocyanate and the method had a detection limit of 0.5 mg l^{-1} Cl.

Samples were taken from 119 dug wells in the area north and west of Louga. All of these wells were in daily use by villagers. Most were sited on the edge of the village on open ground and are considered to be unaffected by pollution.

Rainfall was also measured over a 3 year period at Louga about 5 km from the main research site. Samples were collected on an event basis and weighted means calculated to provide annual averages (Table 1). Highest chloride concentrations occurred in the lightest rains.

4. Theory

Chloride can reasonably be regarded as an inert element in the shallow hydrological cycle with its source derived from atmospheric deposition. Provided the

Table 1
Summary of rainfall and weighted mean chloride concentrations for Louga and Leona

Location	Year	Total rainfall (mm)[a]	Weighted mean chloride (mg l^{-1})
Louga	1988	443.2	1.14
	1989	436.1	5.95
	1990	255	1.43
Leona	1988	302	1.63
	1989	319	9.30

[a] Rainfall amounts are those recorded over the period of chemical sampling and do not necessarily correspond to official annual totals

inputs of rain (P) and chloride C_p are known, the average chloride concentration of interstitial water in an unsaturated zone profile (C_s) will, under steady-state conditions be proportional to the concentration factor $P/P-E$ where P is the mean annual precipitation and E is evapotranspiration. The direct recharge R_d at a given location is given by

$$R_d = \frac{P(C_p + C_d)}{C_{si}} \quad (1)$$

where P is the long-term mean annual precipitation, C_p is the weighted mean concentration of chloride in rainfall, C_d is the amount of chloride in the dry deposition and C_{si} is the average concentration of chloride over interval i in interstitial water in the unsaturated zone. The theoretical basis of using chloride to measure recharge has been described elsewhere (Allison and Hughes, 1978; Edmunds et al., 1988).

The chloride technique has the important feature of integrating recharge at a given site over many years. The main source of uncertainty in applying the technique, however, lies in knowing the chemistry of rain for the antecedent period. In the present study 3 years rainfall data have been averaged but ideally longer runs of data are considered necessary to calculate C_p. Total deposition (i.e. wet and dry deposition) has been measured on an event basis during the rainy season. It has been assumed that dry deposition at other seasons is not significant in the solute balance since it is in steady-state circulation in the atmosphere during the dry season.

The conjunctive use of unsaturated and saturated zone data for measuring recharge avoids the uncertainties derived from using the water table data alone. The chemistry of groundwater at the water table may be further enriched in chloride owing to uptake of evaporite salts or formation water in the saturated or unsaturated zone leading to underestimation of recharge: similarly lateral flow from a different recharge area in non-homogeneous porous media may give rise to salinities different from those derived locally from the unsaturated zone.

5. Results and discussion

Thirteen chloride profiles are shown in Fig. 2. Seven of these (L2, L3, L5, L6, L11, L12, L18) are from the main Louga research site I and are taken within an area of 0.5 km^2. The other six are from sites II and III shown in Fig. 1.

The chloride concentrations differ considerably with depth and from site to site. In most of the profiles there is a relatively high concentration of chloride within the upper metre. This zone (Cook et al., 1992) forms a separate reservoir within a surface mixing layer. Free draining water obtained from the zone by centrifugation is always lower in chloride than the sample obtained by elution (Edmunds et al., 1992), showing that the soil zone must contain occluded pore spaces which are not in contact with water and solutes draining more freely.

At the main research site (I), only one profile (L18) reaches the water table at 35 m. This profile and L2 were drilled within a few metres of each other on a dune ridge and

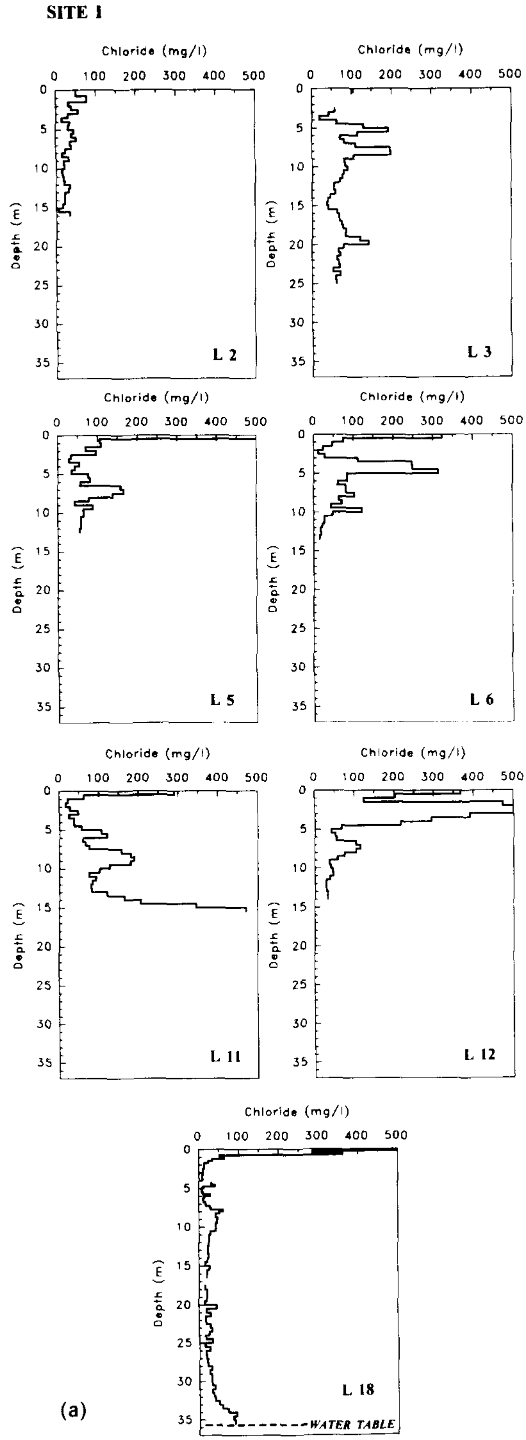

Fig. 2. Chloride profiles from the main research site at Louga (L2, L3, L5, L6, L18, L11, L12) and elsewhere in the north of the study area (L13, L14: site [II], and L7, L8, L9, L10: site [III]).

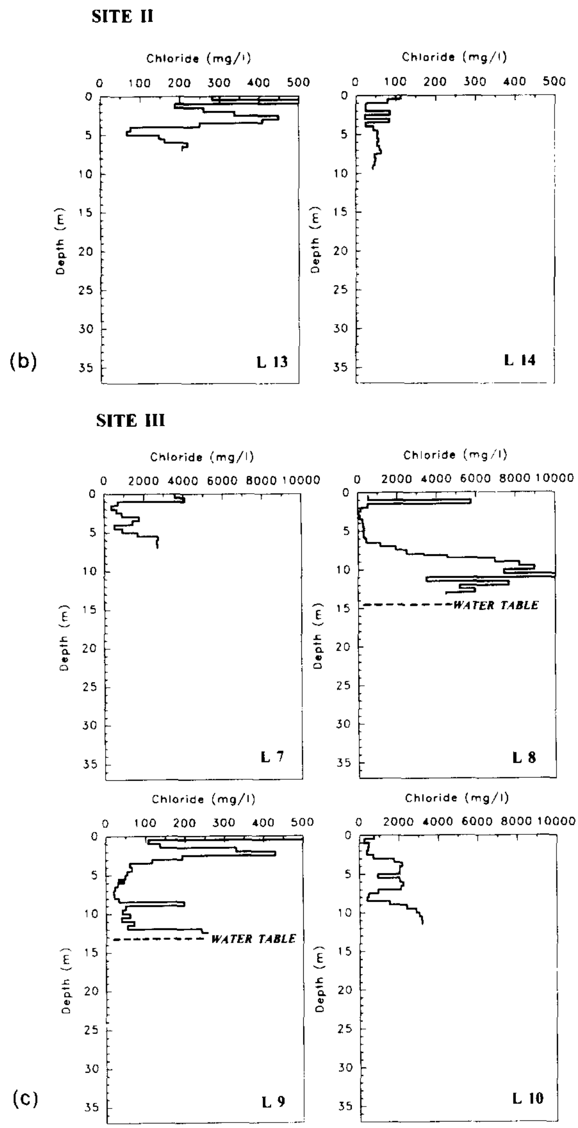

Fig. 2. (Continued)

have low chloride concentrations corresponding to relatively high recharge rates. Profiles L3 and L11 were drilled at a different location on the same ridge whilst L5, L6 and L12 were all drilled on slightly lower ground in the interdune areas but through older, more compacted, dune sands. Chloride concentrations are considerably higher at these sites (up to $500\,mg\,l^{-1}$) and must indicate lower rates of recharge.

Each profile shows a considerable variation in the concentration of chloride with depth. This can be related to the variable inputs of chloride corresponding to different amounts of recharge during different climatic periods (Edmunds et al., 1988). Thus, high chloride corresponds to periods of low mean annual rainfall and lower chloride to wetter episodes. For the purposes of the present discussion only the mean values of chloride representing the average long-term recharge are relevant.

Similar profiles for the research sites (II and III) can be seen in Fig. 2. Of these sites only L8 and L9 reached the water table. The much higher chloride concentrations are discussed below but may be interpreted in detail in relation to the past climatic conditions (Cook et al., 1992).

The rainfall chemistry was measured at two sites, Louga and Leona within the study area over three seasons (two in the case of Leona) and the results are summarized in Table 1. It was found that at each site the concentration in rainfall varied from year to year, but that the relative amounts of chloride at each site were comparable in any year. These results reflect the coastal influence, with lower deposition at Louga. The annual variability probably reflects the trajectory of the monsoonal rain, in particular the extent of passage over the continent or the sea. For this study the average of the Louga data (2.8 mg l^{-1} Cl) was used in all calculations.

The mean chloride concentrations (C_{si}) in the profiles and calculated values for mean annual recharge (R_d) for the intervals (i) are summarized in Table 2. The mean recharge rates for the seven holes at the main 0.5 km^2 research site west of Louga have a range 4.6–34.4 mm $year^{-1}$ and a mean value of 15.5 mm $year^{-1}$. The observed range

Table 2
Summary of recharge estimates derived for all interstitial water chloride profiles

Profile	Interval (i) m	Mean rainfall P	Mean Cl in rainfall C_p	Mean Cl in profile C_{si}	Mean annual recharge R_d	Time interval of profile t (year)
Main site [I]						
L2	1.5–16.0	290	2.8	27.9	29.1	45
L3	2.5–25.0	290	2.8	81	10.1	118
L5	1.5–12.5	290	2.8	73	11.1	40
L6	1.0–13.5	290	2.8	80	10.1	50
L11	1.0–14.0	290	2.8	175	4.6	68
L18	1.5–35.5	290	2.8	23.6	34.4	74
			Site average		15.5	
Area [II]						
L13	1.0–7.0	290	2.8	231	3.5	38
L14	1.0–9.5	290	2.8	50	16.2	20
Area [III]						
L7	1.0–7.0	290	2.8	1403	0.59	–
L8	1.5–7.0	290	2.8	752	1.08	229
L9	1.0–12.0	290	2.8	95	8.6	55
L10	1.5–12.0	290	2.8	1660	0.49	527

of values is large and quite clearly indicates a significant spatial variability over the area of the detailed investigation site. From the first impressions the site appears relatively homogeneous, apart from the slight topographic difference noted above. One explanation for the variability is thought to be the slight variations in soil texture, especially in the top 0.5 m; the other is vegetation. Natural vegetation cover at the research site is relatively sparse and some clearance for rainfed agriculture (especially groundnuts) has taken place. The root system of most of the plants in the area (observed in a local quarry) is laterally extensive although deep-rooted vegetation is not common at this cleared site. Chemical evidence, discussed in Edmunds et al. (1992), indicates that solute recycling is restricted to the top 2 m and therefore that the effect of any deep-rooted vegetation (mainly isolated acacia trees) on recharge fluxes is likely to be small.

The time interval recorded by each profile also varies, and the recharge estimate given by chloride is usually an integral over several decades (Edmunds et al., 1992). This is in marked contrast with physical estimates which are typically valid for single years. In fact the information contained in the profiles may also be used to determine the recharge history at the decade scale (Cook et al., 1992). At the main site, the time-span ranges from 45 to 118 years, which covers changing rainfall conditions and climatic episodes. Recharge rates may therefore vary within the time scale of the

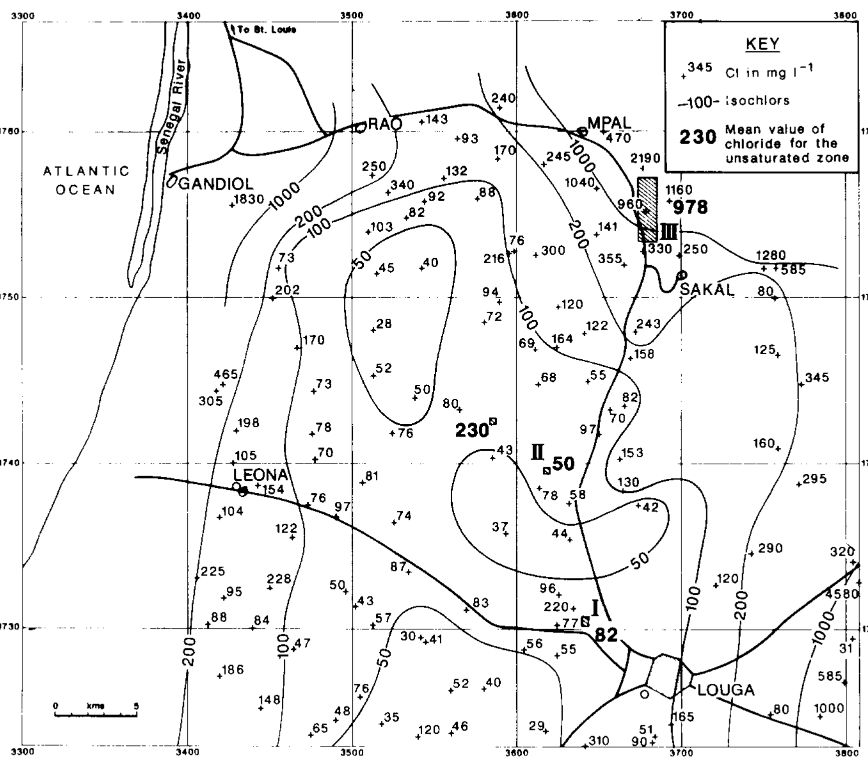

Fig. 3. Regional distribution of Cl in groundwater and isochlors drawn on the phreatic aquifer.

whole profile and represent long-term averages. For Louga 3, where the long-term average is 10.1 mm, the lowest recharge during periods of drought will have been of the order 4 mm, whilst for period with high rainfall (e.g. 1920s) recharge may have been as high as 20 mm. Some of the apparent spatial variability across this site may therefore be due to the range of climatic periods recorded in the different profiles.

In the north of the area, recharge rates determined from profiles are generally much lower than at the main Louga research site. At these sites the ground elevation is lower and the soils contain more fine-grained material, with the result that the mean annual recharge is typically in the order of 1 mm or less.

Isochlors constructed from analyses of the shallow groundwaters are compared in Fig. 3 with the mean chloride values obtained from the unsaturated zone profiles in each of the three areas (average of seven, two and four profiles, respectively). The ischlors define a relatively low area of salinity over the main Quaternary aquifer, with chloride increasing towards the lower lying areas. The impact of pollution from agricultural or other sources as a contributor to the chloride balance can be ruled out in this area where the wells are mainly located outside the villages. The residual effects of vegetation clearance may have had some impact on the results, but the smoothing of the contouring process has largely compensated for local effects.

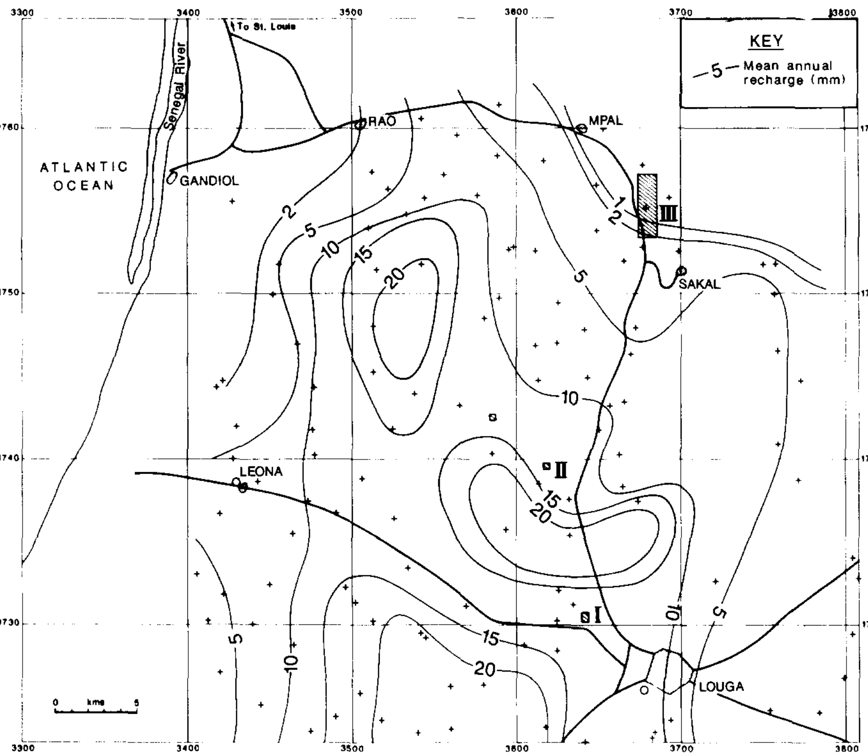

Fig. 4. Regional estimation of groundwater recharge derived from chloride. The contours have been drawn using Louga rainfall data. The apparent lower recharge near the coast may be the result of a higher rainfall chloride (see text).

The unsaturated and saturated zone data combined indicate that the chloride variation in northwest Senegal is essentially derived from atmospheric inputs and that the unsaturated zone data can be used to estimate the regional recharge. The chloride values have been replotted in Fig. 4 as recharge contours by substituting the contour chloride values for C_s in Eq. (1). This enables a calculation of replenishable resources to be made. It can be seen that recharge rates are highest in the area where Quaternary sands are thickest (around 20 mm year^{-1}), and decrease particularly to the north and east where clay-rich, more compact sediments occur with values close to 1 mm year^{-1}). The map has been plotted using the single value for rainfall for Louga. This is a simplification and does not take account of the possible regional variations in the chemistry that might take place towards the coast. If the rainfall gradient between Louga and Leona (Table 1) is taken into account (an increase in chloride of some 60% at Leona compared with Louga), then correspondingly higher recharge might be experienced in the west of the area. The apparent east–west gradient north and south of Louga probably reflects this phenomenon and is probably an artefact of the chloride gradient in the total deposition.

In the area of the main research site west of Louga, the areal recharge is estimated at 13 000 m^3 km^{-2} year^{-1}, although in the north only 1100 m^3 km^{-2} year^{-1} of more brackish water is replenished. Overall, the area is one favourable to recharge. Natural recharge greatly exceeds the domestic use by village wells (estimated at 300 m^3 km^{-2} year^{-1}) even during periods of drought when recharge rates may be halved.

6. Conclusions

The conjunctive use of unsaturated zone profiles of interstitial water chemistry and the chemistry of groundwater at the immediate water table, described above, presents a simple yet effective means of recharge estimation at the regional scale, taking account of spatial variability. It relies on an understanding of the geochemical cycling of chloride, tracing atmospheric-derived chloride through the soil and unsaturated zone to the water table. It is clearly unreliable to use data from the saturated zone alone without some validation that the chloride is derived solely from atmospheric sources.

The use of chloride for recharge estimation at local or regional scale relies on a knowledge of the antecedent rainfall chemistry. In the present study, data are available for 3 years, and the accuracy of the recharge estimates depends strongly on the reliability of the rainfall record. Errors are estimated to be within 30% using data for rainfall measured in the project area over the 3 year period. The increase in the precision of the method clearly improves with the increasing number of rainfall sites used and with the length of record. It has been assumed that the rainfall chemistry has been similar with time, since the unsaturated zone records used provide a recharge estimate measured in decades or centuries.

The chloride technique was developed to provide a simple, reliable method for recharge estimation which did not rely upon the need for expensive equipment or sophisticated measurements. Logistics and costs make the method applicable for use by local scientists and technicians without resort to specialists, although valuable additional information may be obtained on the recharge regime using other techniques, stable isotopes in particular. Therefore the method is applicable to many semi arid and arid terrains where unconsolidated deposits allow profiles to be obtained using auger techniques. Elsewhere, consolidated porous media may also be sampled using samples taken from dug wells during excavation. The measurement of direct recharge to aquifers at a regional scale using the technique described above may also be applied to areas where unsaturated, unconsolidated sediments overlie deeper hard rock aquifers. Thus, the technique has worldwide application in areas with sedimentary formations dominated by intergranular unsaturated flow, as well as selected hard rock terrains.

The methods developed allow regional recharge estimates to be made in northern Senegal with far greater confidence than hitherto. These results can also be extrapolated to the south to the whole of the Quaternary aquifer as well as to similar areas of the Sahel margin. It is apparent that the areas of fixed dune sands provide significant recharge but that the recharge rate falls off both to the west and east. This area of highest recharge coincides with the thickest dune sand deposits. Lower recharge rates on a regional scale probably relate to areas of thicker soil development on the flanks of the former dune field and/or to marginal facies of the sands since it is known that the sediments become finer grained towards the east. Vegetation does not apparently influence recharge at the regional scale since the local variation in cover is smoothed out over the whole area as shown by the chloride contours. Nevertheless, unpublished data on areas with higher rainfall in central Senegal with similar lithology suggest that as vegetation density increases across the Sahel zone corresponding recharge rates do not increase owing to the proportionally higher water use by the plants.

The highest recharge rates (13 000 m^3 km^{-2} $year^{-1}$) over the area and time scale studied are at first glance encouraging from a water resources standpoint. However it must be recognized that significant losses take place by flow towards the coast and vertically to the underlying Tertiary and Cretaceous formations. In fact the Quaternary aquifer acts as an important recharge window to replenish the deeper formations. Outside the Quaternary aquifer the recharge rates are likely to be much lower. The falling water tables recorded in the area reflect the overall water balance and further studies must include the local differences in transmissivity, the total abstractions from both the shallow and deep aquifers as well as the impact of climate change.

Acknowledgements

We wish to thank J.M. Trafford and staff at BGS, Wallingford for carrying out the analyses of chloride. This work was supported by the Overseas Development Administration. We wish to acknowledge helpful comments from a review by John

Barker. This paper is published by permission of the Director, British Geological Survey (Natural Environment Research Council).

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