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Naturally High Nitrate Concentrations in Groundwaters from the Sahel

W. M. Edmunds* and C. B. Gaye

ABSTRACT

Nitrate concentrations in excess of 50 to 100 mg L^{-1} NO_3–N are found widely in interstitial waters from unsaturated Quaternary sands in northern Senegal. These high concentrations and correspondingly enhanced NO_3/Cl ratios are being produced in the soil zone beneath both uncultivated and rain-fed cultivated areas. High nitrate (avg. 11 mg L^{-1} NO_3–N) is also found extensively in shallow groundwaters. The NO_3–N signature is preserved as a result of the aerobic conditions. The unsaturated zone contains a history of N inputs over a period of approximately 50 to 400 yr. Variations in the NO_3/Cl ratio are mainly related to the growth of natural or introduced leguminous vegetation. There is also evidence that high ratios relate to wetter and low values to more arid climatic periods. These results, taken together with evidence from other parts of the world, demonstrate that high nitrate concentrations are likely to be a widespread and established phenomenon of groundwaters in semiarid regions.

BASELINE CONCENTRATIONS of NO_3 in groundwaters beneath grassland in temperate regions are typically below 2 mg L^{-1} NO_3–N (Foster et al., 1982) and concentrations significantly above this are generally regarded as indicating anthropogenic pollution. Many sources of groundwater in Europe and other developed parts of the world may approach or exceed the maximum admissible concentrations for drinking water set by the European Community (CEC, 1980) and the World Health Organization (WHO, 1993)—set at 10 mg L^{-1} NO_3–N. In developing countries, the impact of rising NO_3 concentrations clearly resulting from human activities can also be recognized (Lagerstedt et al., 1994; Chilton et al., 1995).

In semiarid and arid regions, however, some occurrences of high NO_3 groundwaters have been recorded, which are difficult to explain by pollution. In the Kalahari, for example, groundwaters with between 4.8 and 37 mg L^{-1} NO_3–N are widely distributed (Heaton, 1984) and are explained by a natural origin from the soil. Palaeowaters in Libya (Edmunds and Wright, 1979) as well as in the Kalahari (Heaton et al., 1983) contain high NO_3 concentrations beneath areas of present day desert; these high concentrations of NO_3 have persisted for 10^4 yr or more in both unconfined and confined aquifers under aerobic conditions. In the Sirte Basin, Libya, NO_3–N often in excess of 30 mg L^{-1} was originally considered (Wright and Edmunds, 1969; Edmunds, 1994) to have resulted from the contact with NO_3-rich shales (Hume, 1915). However, their widespread distribution prompted the view that palaeoenvironmental factors, related to former vegetation cover, in a region where there is no current recharge, were responsible. Near Khartoum in Sudan, concentrations of NO_3–N up to 2800 mg L^{-1} were recorded in interstitial waters of unsaturated sediments. These were attributed to very low recharge rates and the accumulation from vegetation over many centuries (Edmunds et al., 1992a). Other natural occurrences of high NO_3 have also been described from tropical regions. In Cote d'Ivoire, up to 45 mg L^{-1} NO_3–N has been observed in shallow wells associated with weathered basement, thought to be related to localized deforestation (Faillat and Rambaud, 1991). High concentrations of NO_3 were found in desert soils in the Mojave Desert, California, and attributed to possible geological sources (Marrett et al., 1990). In Arizona, Hunter et al. (1982) attributed concentrations of several grams per litre NO_3 in the unsaturated zones of desert regions to litter decomposition. High NO_3 groundwaters are also common in arid regions of Australia (Barnes et al., 1992), where NO_3 fixation by cyanobacteria in soil crusts and bacteria in termite mounds provide the most likely explanation. Naturally high nitrate therefore seems to be a common feature of groundwaters in certain arid and semiarid (as well as some humid) tropical areas low in organic C, where aerobic conditions have persisted.

The results from Libya in particular prompted this investigation of NO_3 distribution elsewhere in northern Africa over a number of years, especially in the Sahel. This paper describes new investigations carried out in Senegal where present day climatic and environmental conditions may be considered as typical of the Sahel. Special attention was paid to the records of NO_3 contained in interstitial waters in the unsaturated zone and their relationship to the underlying groundwater. These data were then used together with the other published records to examine the hypothesis that naturally high NO_3 concentrations are a widely distributed baseline feature of groundwaters in semiarid regions and that human pollution is only a local phenomenon.

AREAS OF STUDY

Samples have been taken from an area (about 1600 km^2) of northern Senegal near the town of Louga (Fig. 1). In this region the groundwater resources are developed largely in an unconfined Quaternary sand aquifer, which provides most of the traditional water supplies in the coastal region of northern Senegal. This shallow aquifer system, comprising sequences of fine-grained and medium-grained sands, overlies a mixed succession of Tertiary sediments, which in some places may be in hydraulic continuity with the overlying sandy aquifer. Both formations overlie Maastrichtian (Cretaceous) sands, and together these form the aquifer system of the Senegal basin. Settlements (small villages of around 200 people) are found at approximately 4 km distance from each other. Progressive development of the semi-confined deeper groundwater to provide supplies for

W.M. Edmunds, Hydrogeology Group, British Geological Survey, Wallingford, Oxon, OX10 8BB UK; and C.B. Gaye, Dep. of Geology, Univ. C A Diop, Dakar, Senegal. Received 23 Aug. 1996. *Corresponding author (wme@bgs.ac.uk).

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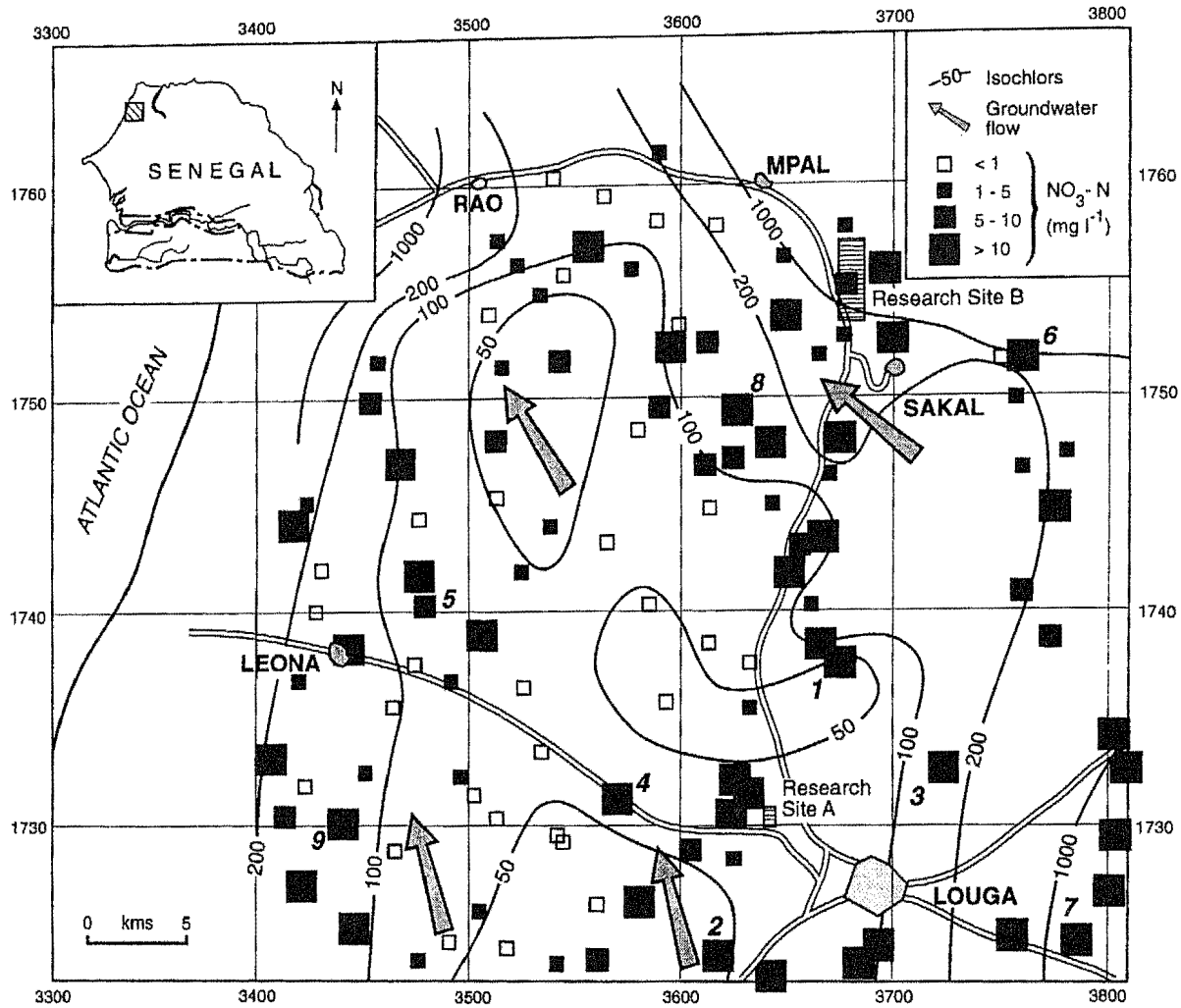

Fig. 1. Location of Louga area in N Senegal and distribution of NO_3 in shallow groundwaters. The concentration of Cl^- in the phreatic aquifer is shown as isochlors. Arrows denote the directions of groundwater flow. The location of two research sites from which unsaturated zone profiles were taken are also shown (Site A—Profiles LG 6, LG 11, LG 12, LG 18; Site B—Profiles LG 9, LG 10).

the towns is thought to have led to a decline of some 0.1 to 0.2 m yr^{-1} in the shallow aquifer (Gaye, 1990).

The decline in the water levels in the shallow aquifer could also be explained partially by a reduction in groundwater recharge during the prolonged Sahel drought (Edmunds et al., 1992b). The long-term (1893–1969) yearly average rainfall at St. Louis (close to the study area) was 356 mm, but during the period 1968 to 1986 the mean annual rainfall had fallen by around 37% to 223 mm. The original vegetation, which consists amongst others of N-fixing species *Acacia radiana* and *Acacia albida*, has been greatly reduced especially in recent decades by clearing in favor of rainfed agriculture (mainly millet, *Pennisetum* sp., and groundnut, *Arachis hypogaea* L.).

Estimates of groundwater recharge in the area have been carried out using geochemical techniques. Using the chloride mass balance approach, it has been possible to determine the spatial variability of recharge across the area (Edmunds and Gaye, 1994). A regional value for long-term recharge of around 15 mm yr^{-1} has been calculated with local extremes between 1 and 74 mm yr^{-1}.

METHODS

Samples of shallow groundwater were collected between 1990 and 1992 over the whole area north and west of Louga from traditional wells on the edge of villages, which reached the water table at depths of up to 40 m. All samples were filtered on site and well-head measurements were also made for pH and HCO_3. Nitrate was determined by automated colorimetry (AA II TECHNICON Autoanalyzer), first by reducing NO_3 to NO_2 and then measurement of a red-purple azo-dye complex at 520 nm (Cook and Miles, 1980). Chloride was similarly determined using mercuric thiocyanate. Major cations, SO_4, and total Fe were analyzed by ICP-OES. The analytical precision for all determinands was ±1%.

Samples of moist sand were recovered from unsaturated zone profiles obtained by hand augering to depths of up to 35 m in the research areas near Louga. The basis of the technique has been described by Edmunds et al. (1988). Samples were bulked over 25- or 30-cm intervals and subsampled for determination of moisture content and for Cl and NO_3 analysis by elution. Then 50 g moist sand samples were eluted with 30 mL ultrapure water and, after stirring and allowing to settle for 1 h, the supernatant was filtered through 0.45-μm filters. Analysis for NO_3 and for Cl^- was carried out as above. Interstitial water was extracted for intercomparison with NO_3 on certain samples where moisture contents were high enough

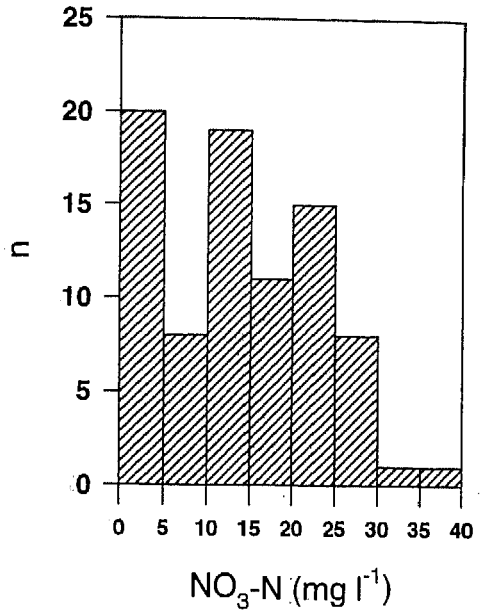

Fig. 2. Histogram of NO_3–N distribution in shallow groundwaters from the Louga area.

to allow extraction by centrifugation using immiscible liquid displacement (Kinniburgh and Miles, 1983) and gave comparable results.

RESULTS

Regional Scale

The geographical distribution of NO_3 in the Quaternary phreatic aquifer is shown in Fig. 1. There is a high frequency of sources (34% of the total) with NO_3 above 10 mg L^{-1} NO_3–N (Fig. 2) and the average concentration of all samples is 11 mg L^{-1}. The high NO_3 groundwaters are widely distributed although interspersed in the center of the area with a number of waters (around 10% of the total) having values below the 0.1mg L^{-1} NO_3–N detection limit) and it is likely that some of these may have undergone denitrification under reducing conditions. In the absence of measurements of dissolved O_2 or redox potential, dissolved Fe concentrations may be used as a rough guide to the redox conditions (Edmunds, 1994). A plot of Fe against NO_3–N (Fig. 3) shows that a few of the low NO_3 groundwaters also contain Fe concentrations above 0.1 mg L^{-1} Fe and many of these may originally have contained higher NO_3 concentrations, which have subsequently been reduced. The bulk of the high NO_3 groundwaters have total Fe concentrations of <0.1 mg L^{-1} Fe, which signifies aerobic conditions in the phreatic aquifer. Several waters with values between 0.1 and 1.0 mg L^{-1} Fe are also aerobic but may have low pH.

Representative groundwater analyses are shown in Table 1. The concentrations of NO_3 range from 13 to 57.5 mg L^{-1} NO_3–N (57.5–254 mg L^{-1} NO_3). The range of Cl^- concentrations reflects the spatial variability of recharge across the area (Edmunds and Gaye, 1994). The low concentration of K (and low K/Na ratios) together with the absence of detectable PO_4^{2-} in all but two wells are the only independent evidence for the

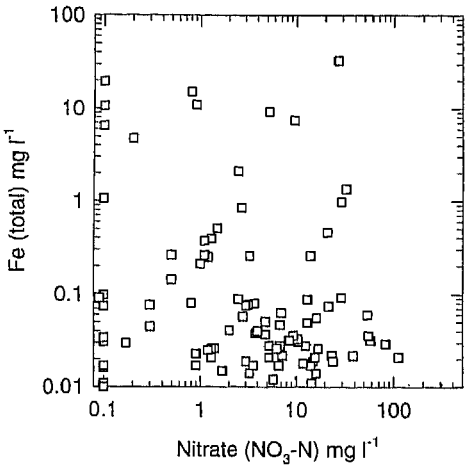

Fig. 3. Concentrations of nitrate (NO_3–N) vs. total Fe. Aerobic conditions are generally represented by those waters with less than 0.1 mg L^{-1} Fe and many waters with NO_3 below 1 mg L^{-1} NO_3 may have undergone denitrification. Some high NO_3 waters with high Fe are likely to be either acidic (pH < 5.5) or to be mixed waters.

absence of pollution. However, the well depth (20–40 m), the fine-grained porous media, the location of wells at the edge of the villages, and the adequate well construction rule out pollution at the vast majority of well sites.

Data for N species in rainfall are taken from Travi et al. (1987). Weighted mean concentrations (1981) for seven coastal and continental stations are used and these have values of 2.6 mg L^{-1} Cl and 0.064 total nitrogen as N, representing the totals of NO_3 and NH_4 in total deposition. This gives a corresponding NO_3/Cl of 0.061; the ratio NO_3/Cl is expressed here and elsewhere in the paper as a molar ratio. An assumption has been made in this and other studies in the region that rainfall samples represent total deposition of wet and dry fallout and that net deposition of particulate Cl or NO_3 outside the rainy season is insignificant. No long-term data for Cl^- or NO_3 is available for the Sahel region. The weighted mean annual concentrations of Cl in rainfall measured over a 5-yr period in the present studies ranges from 1.14 to 5.95 with an overall mean of 2.8 mg L^{-1}, which compares well with the above data from Travi (1987). This large range reflects the intensity and trajectory of the monsoon in this coastal area. The input values for rainfall solutes inevitably will have a large error associated with them, but the enrichment in NO_3 described in this paper is considerably greater than any uncertainty in the rainfall inputs.

Almost all groundwaters and interstitial waters have NO_3/Cl ratios exceeding that of rainfall (Fig. 4). Most of those with ratios lower than in rainfall are those that have undergone reduction of NO_3. Nitrate concentrations in waters with NO_3/Cl ratios roughly equal to rainfall can be accounted for by the concentrating effect of evapotranspiration. The majority of waters with NO_3/Cl ratios higher than rainfall became enriched in NO_3 in the soil by some process other than evapotranspiration and once below the zero flux plane (Wellings and Bell, 1980) are transmitted through the unsaturated zone by homogeneous displacement.

Table 1. Representative analyses of groundwaters and interstitial waters from the unsaturated zone from northern Senegal. The sites are shown in Fig. 1. Phosphorous was also analyzed and was below 0.5 mg L^{-1} total P in all samples. Rainfall data are from Travi et al. (1987) and are the weighted mean values of all sites (except St. Louis) for 1981. The NH_4 and NO_3 results have been combined and are expressed in terms of NO_3 or NO_3–N.

Locality	Depth	pH	Na	K	Ca	Mg	HCO_3	SO_4	Cl	NO_3	NO_3–N	NO_3/Cl	Fe (total)
Shallow groundwaters													
1. Baïnak	36.8	7.13	28.5	3.1	33.8	5.5	69.6	1.9	42	70.4	15.9	0.96	0.015
2. Ndame Ngot	38	6.26	19.9	3	15.0	3.2	25.4	1	29.4	57.5	13	0.76	0.089
3. Ndeukt Gueye	34.3	6.95	31.5	3.3	144.0	17.5	125.6	2	120	244.8	55.3	1.17	0.036
4. Bangadji Samb	38	6.35	53.1	6.2	28.3	14.1	34.1	1	83	144.3	32.6	0.66	0.014
5. Ndiayène	29.1	6.7	63.8	5.1	23.0	8.2	54.9	13	78	91.6	20.7	0.67	0.007
6. Bakhdad Mbeng	20.3	6.86	246	3.1	177.0	42.9	170.7	47	585	170.4	38.5	0.17	0.022
7. Keur Ibra Maram	32.7	6.77	399	4.9	299.0	99.6	213.4	196	1000	254.5	57.5	0.15	0.032
8. Santiou Merina	12	5.2	72.4	3.7	13.4	9.0	6.0	16.2	120	52.2	11.8	0.25	0.27
9. Diama Beye	29.1	5.53	57.6	4.9	11.0	11.2	8.5	3	84	102.6	23.2	0.7	0.38
10. Tanim	28.7	7.64	656	1.1	44.0	21.9	601.0	245	585	105.8	23.9	0.11	0.019
Interstitial waters													
LG 18	10	4	18.5	4.9	18	11.6	0	1	38.4	105.9	23.9	0.62	0.036
LG 18	20	5.1	30.1	2.4	10	5.5	0	9	16.8	103.2	23.3	1.39	0.001
Rain													
Senegal 1981		nd	2.15	0.47	1.9	0.31	7.06	2.19	2.6	0.28	0.064	0.061	nd

Unsaturated Zone Profiles

Moisture content and Cl^- are shown together with NO_3–N in Fig. 5 for one unsaturated zone profile that reached the water table (LG 18). This site is in open terrain that is cultivated (millet and groundnut) during the rainy season and it lies about 30 km from the coast. The volumetric moisture content ranges between 1 and 8% and rises to 10% as the capilliary fringe is approached. The variation in moisture content is closely related to grain size; higher moisture contents denote a finer-grained sediment. It can be shown using tritium and Cl^- (Gaye and Edmunds, 1996) that negligible bypass flow of water takes place through this and the other profiles and therefore that water is transmitted in a uniform pulse through the profile. The chemistry of the interstitial water at two depths (10 and 20 m) is also shown in Table 1 where the relative enrichment in NO_3–N is shown by the high NO_3/Cl ratios, providing supporting explanation for the high NO_3 results obtained from samples at the water table.

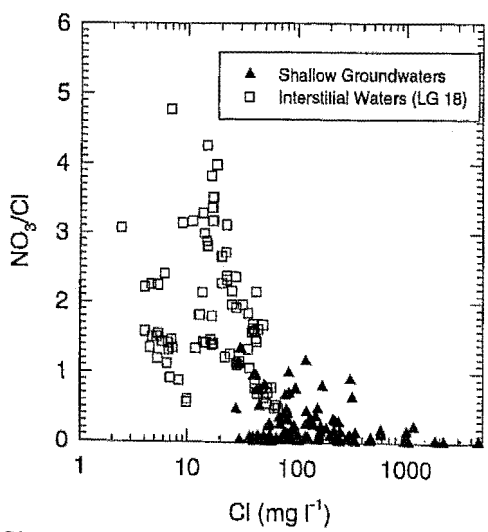

Fig. 4. Plot of NO_3/Cl for results from shallow wells and for interstitial waters from profile LG 18. The NO_3/Cl in rainfall has a value of 0.064.

The Cl^- concentrations in this profile vary between 8 and 60 mg L^{-1} with an average concentration of 24 mg L^{-1} corresponding to a mean recharge rate of 34 mm yr^{-1}. Oscillations in the Cl concentrations record variations in the recharge in response to climatic controls (Cook et al., 1992; Edmunds et al., 1992b). Using Cl^-, the moisture contents, the bulk density of the sediments, and the weighted mean Cl concentrations of the rainfall (data collected over a 4-yr period), it is possible to calculate the residence times of water in the profiles (Edmunds et al., 1992b). The L18 profile has been calibrated using the variations in these parameters and contains an input record of about 74 yr (Table 2, Fig. 4). The broad peak at around 10 m represents the prolonged drought of the 1970s and 1980s; the lower concentrations around 20 to 25 m indicate the wetter climate of the 1950s and 1960s. These recharge estimates established using Cl have been validated using tritium, which produces a distinct peak, corresponding to the 1963 maxima of atmospheric nuclear weapons testing (Gaye and Edmunds, 1996).

The enrichment in NO_3, expressed as the NO_3/Cl ratio, is shown in Fig. 4 in terms of cumulative Cl^- in the interstitial water, which allows the unsaturated zone record to be linearly related to time. A depositional flux of 100 mg m^{-2} is realistic for this area and would represent, for example, a rainfall of 400 mm yr^{-1} and a rainfall Cl^- of 2.5 mg L^{-1}, close to measured values. The accumulated Cl^- of 7.2 mg cm^{-2} in the LG 18 profile, therefore, would correspond to a record of 72 yr.

The interstitial water results for the LG 18 profile have been added to the plot of Cl vs. NO_3/Cl (Fig. 4). This shows clearly that the extent of enrichment of NO_3 generally exceeds that found at the shallow water table. The highest Cl^- concentrations in the interstitial waters just overlap with the shallow groundwaters. This profile has a lower Cl^- (and therefore a higher recharge rate) relative to the other profiles described below as well as having the highest enrichment in NO_3 of the profiles considered.

Nitrate concentrations in a further five profiles of interstitial water from the unsaturated zone from re-

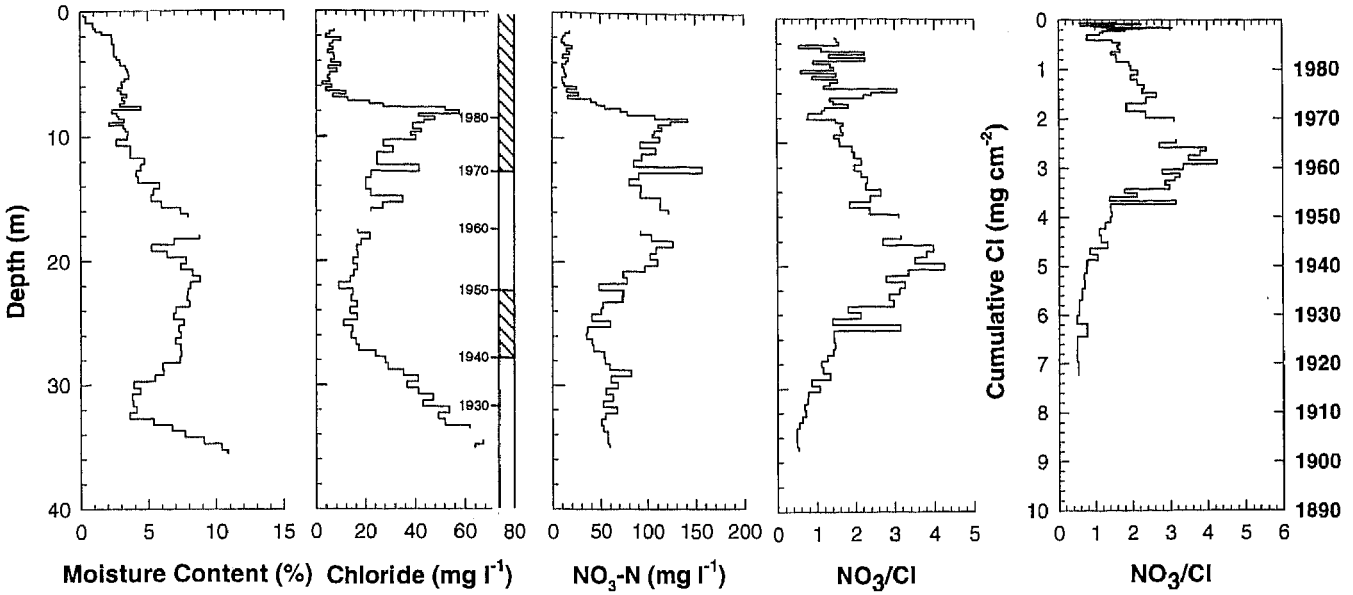

Fig. 5. Nitrate (NO_3–N), Cl^-, moisture content, and NO_3/Cl in interstitial waters from the unsaturated zone for profile LG 18 (map research Site A). Results have been expressed also in terms of cumulative Cl^-. This allows the variations in NO_3 enrichment to be linearly related to time. A depositional flux of 100 mg m^{-2} Cl has been used to create the timescale for the profile.

search Sites A and B (Fig. 1) are summarized in Fig. 6 to 10. One of these profiles—LG 9 (in addition to LG 18)—reached the water table. At research Site A, profile LG 11 is from within several meters of LG 18 within the area of fixed dunes; profiles LG 6 and LG 12 are from an interdune area at the same 1 km^2 site. Profiles LG 9 and LG 10 are from area (B) farther north. The mean NO_3 interstitial water concentrations and the average recharge rates calculated using the Cl^- method and residence times represented by the sampled depths for each of these profiles are indicated in Table 2. Results for each profile have been normalized with respect to time by plotting against cumulative Cl^-, giving a timescale for each profile of 100 yr.

The LG 11 profile (Fig. 6) contains NO_3–N concentrations in places in excess of 50 mg L^{-1}, and the NO_3/Cl ratio exceeds 1 in the upper profile. These higher concentrations are restricted to inputs during the past 30 yr, coinciding approximately with the record of the adjacent LG 18 site. The profile LG 6 (Fig. 7) has a pulse of NO_3 (>100 mg L^{-1} NO_3–N) dating from the 1960s, but at the nearby LG 12 site (Fig. 8), enrichment of NO_3 is found around 1950. At LG 9 NO_3 enrichment also dates from the 1950s (Fig. 9). The unsaturated moisture record at LG 10 has a Cl^- age of >400 yr (Table 2), but in Fig. 10 only the last 100 yr are represented; NO_3 enrichment occurs mainly after 1960 in this profile.

DISCUSSION

Once NO_3 has entered the largely inorganic and aerobic unsaturated zone, it will behave as a conservative anion and its geochemical behavior will be similar to Cl^-. Total NO_3–N concentrations derived from atmospheric inputs in the Sahel are low (Travi et al., 1987). Subsequent variations in the concentrations of NO_3 will be modified by physical processes (evapotranspiration) or biochemical transformations in the soil and rooting zone. The evolution through the unsaturated zone may be followed conveniently using the NO_3/Cl ratio.

Using the flux of Cl^- through the profile as an indicator of residence time, the timescale represented by each profile has been calculated as described above for LG 18. Timescales have been added to each of the profiles in Fig. 6 to 10. The uneven timescales between profiles are due to variations in the recharge rates and in the moisture content (mainly a function of the sediment grain size); the higher the moisture content, the longer the solute travel time. Infiltration records from 50 to several hundred years are retained in the unsaturated zone of this region of northern Senegal (Edmunds et al., 1992b; Cook et al., 1992). This provides the basis for examining the corresponding changes in N inputs.

The molecular diffusion coefficients of NO_3 and Cl in dilute aqueous solutions are very similar (Robinson and Stokes, 1968) and their dispersion in porous media can be expected to be similar (Hill, 1984). At low flux rates and with molecular diffusion the only control on dispersion, the dispersion of NO_3 would be only slightly lower than Cl. Rates of solute movement through profile LG 18 are on average 0.7 m yr^{-1}, which greatly exceed the rates expected for molecular diffusion alone. In the

Table 2. Summary of information for average Cl^-, nitrate (NO_3–N mg L^{-1}), recharge (mm yr^{-1}), and residence time represented by the unsaturated zone contained in profiles LG 6, LG11, LG 12, LG 18, LG 9, and LG 10.

	Cl	NO_3–N	Recharge	Residence
	mg L^{-1}		mm	yr
LG 6	80	26.1	10.1	50
LG 11	89	21.7	9.1	92
LG 12	54	22.4	15	68
LG 18	23.6	14	34.4	74
LG 9	95	25.5	8.6	55
LG 10	1660	71.4	0.49	400

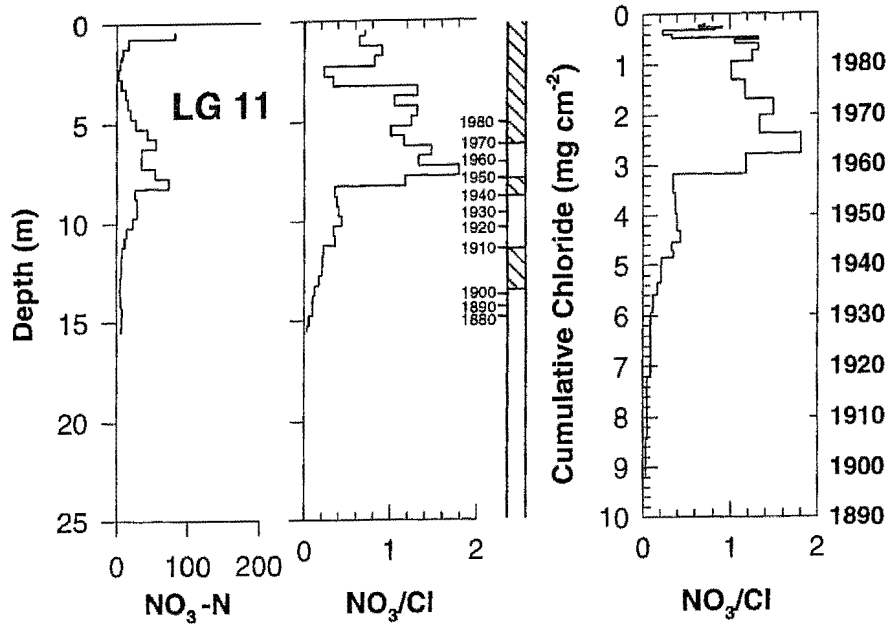

Fig. 6. Nitrate-N concentrations and NO_3/Cl ratios for profile LG 11 (research Site A). The timescale has been constructed as described for Fig. 5 and in the text.

present context, therefore, the concentrations of NO_3 and the NO_3/Cl ratios in the unsaturated zone are unlikely to be significantly changed by diffusion or by chemical reaction. Therefore, they can be used to determine the contemporaneous flux of N from the soil, through the unsaturated zone to groundwater over the timespan of decades or even centuries in an analogous way to the use of Cl^- to measure residence times.

Nitrogen, in addition to atmospheric deposition, accumulates in arid/semiarid soils by microbially assisted mineralization of soil litter and nitrification of NH_4 (Sprent, 1987). Nitrogen fixation by nodulation on the root systems of leguminous plants is also an important process in many semiarid areas. Denitrification is likely to be insignificant under the oxidizing conditions of most semiarid environments, especially where water contents are low and organic C contents are also low (Tindall et al., 1995); NO_3, therefore, is likely to be conserved during passage through the unsaturated zone in semiarid/arid regions. In the rainy season, rapid mineralization of soil N occurs, with most being oxidized to NO_3. This then accumulates and moves into the profile with the onset of the subsequent wet season. In contrast, N production, especially by leguminous plants, is likely to be lower during arid periods when nodulation is inhibited.

The concentrations of NO_3 in the profiles are very

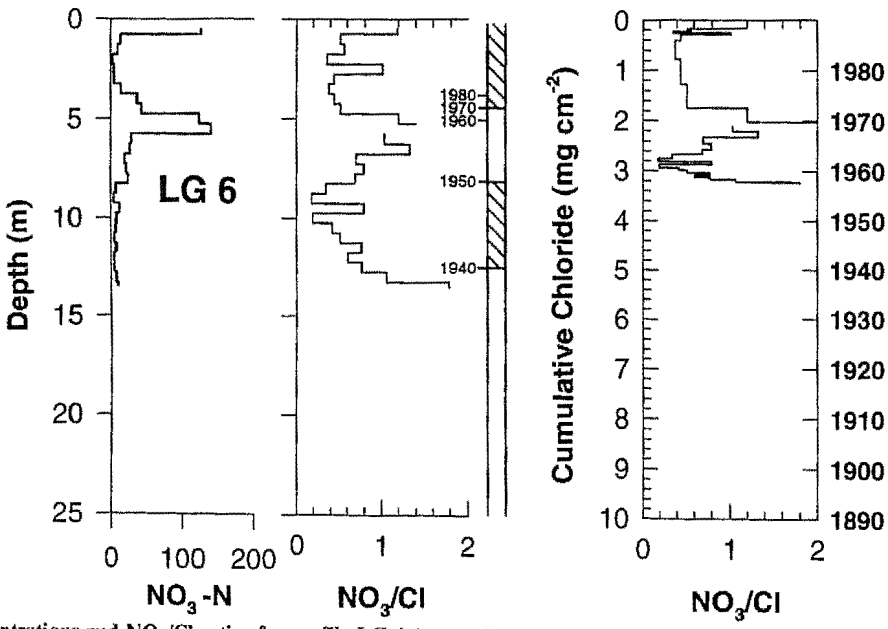

Fig. 7. Nitrate-N concentrations and NO_3/Cl ratios for profile LG 6 (research Site A). The timescale has been constructed as described for Fig. 5 and in the text.

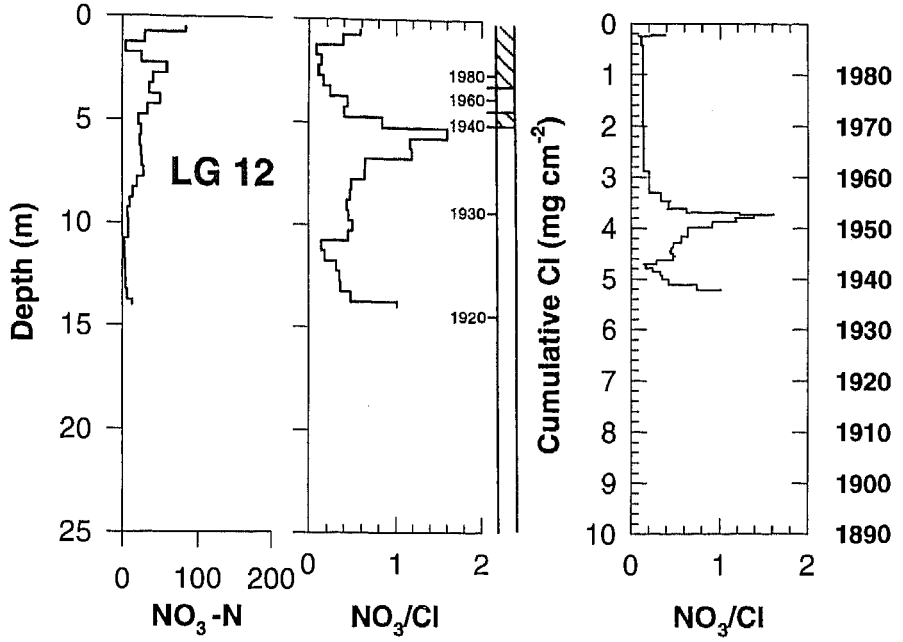

Fig. 8. Nitrate-N concentrations and NO_3/Cl ratios for profile LG 12 (research site A). The timescale has been constructed as described for Fig. 5 and in the text.

high and approach or exceed 100 mg L^{-1} NO_3–N in a number of cases. The enrichment of NO_3 as shown by the NO_3/Cl ratios shows a wide variation between and within the individual profiles and exceeds 1 in parts of profiles LG 18 and LG 6. Since all results are plotted as NO_3–N, the concentrations of ionic NO_3 will be higher by a factor of 4.43; NO_3 therefore is quite frequently the predominant anion. Using the Cl^--derived timescale, it is seen that whilst there are some similarities, NO_3 enrichment is not synchronous and that more than one process is likely to be controlling NO_3 enrichment. Profiles in which the NO_3/Cl increases are restricted to the past few decades may indicate recent land use changes and/or the introduction of leguminous crops. Profiles that show intermittent increases in NO_3/Cl are more likely to indicate that NO_3-fixing vegetation was growing for a given time span and that the history of vegetation at that site was changeable.

There is a good indication from profiles LG 6, LG 11, LG 9, and LG 18 that variations in the record at least since the 1940s correspond with climatic variations. The wetter period from 1950 to 1970 is matched by higher NO_3/Cl values whilst the lower rainfall during the 1940s and in the post-1969 period, corresponding to the prolonged Sahel drought, has produced lower NO_3/Cl ratios.

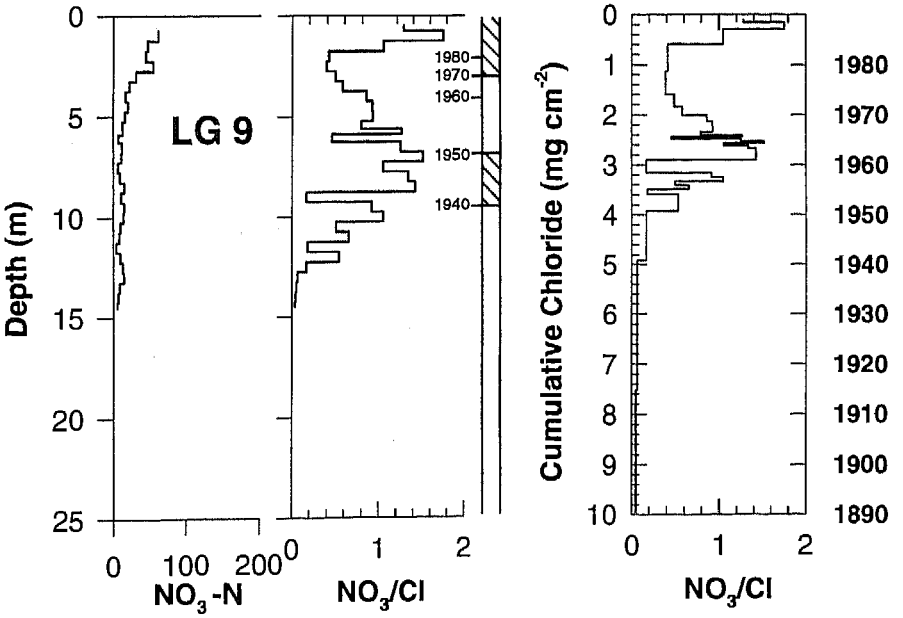

Fig. 9. Nitrate-N concentrations and NO_3/Cl ratios for profile LG 9 (research site B). The timescale has been constructed as described for Fig. 5 and in the text.

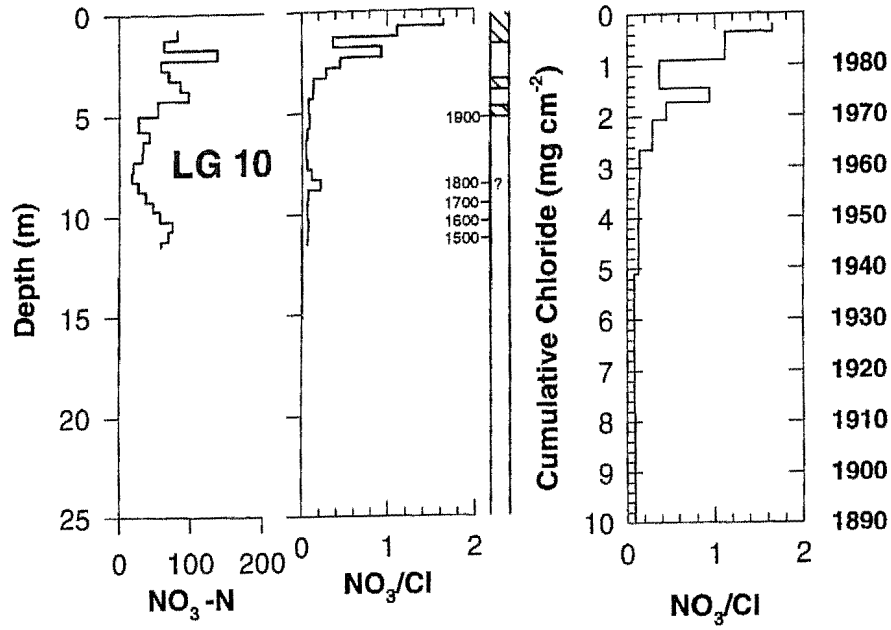

Fig. 10. Nitrate-N concentrations and NO_3/Cl ratios for profile LG 10 (research site B). The timescale has been constructed as described for Fig. 5 and in the text. This profile spans a period of ca 400 yr but only that portion covering the past 100 yr is shown.

Extrapolation beyond about 1940 becomes difficult although in one profile (LG 10) there is evidence that high NO_3 is restricted to the mid/late 20th century. The source of NO_3 could either be from the indigenous leguminous plants (e.g., *Acacia* spp., *Prosopis* spp.) or due to the variety of rainfed agriculture, especially groundnuts, which are also N-fixing plants, which were introduced to the region mainly in the postwar period. The high NO_3 concentrations observed in the upper profiles may therefore be a mixture of both natural vegetation and crops. The apparent absence of such high NO_3 concentrations in the deeper profiles may be due to a timescale that predates the introduction of groundnuts. The concentrations of total N released to the water table, as shown by NO_3–N in the profiles, are, however, consistent with those found at the regional scale (Fig. 1).

CONCLUSIONS

Results from northern Senegal provide evidence that a significant build-up in NO_3 is taking place in the unsaturated zone as a result of natural processes under present day climatic and environmental conditions and is giving rise to high concentrations of NO_3 in shallow groundwaters. The source of NO_3 is the soil zone, as indicated by the increase of the NO_3/Cl ratios between rain (total atmospheric deposition) and the unsaturated zone. The mechanism of enrichment is likely to be fixation of N by indigenous or introduced leguminous plants, the fixation being greater during more humid episodes. The variations of NO_3 in the unsaturated zone may be used as a record of changing inputs over a timescale from decades to centuries. In some profiles there is evidence that higher NO_3 production corresponds to the wetter climatic period from 1950 to 1970 and contrasts with the lower NO_3 concentrations related to the recent drought. The unevenness of the NO_3/Cl enrichment between some profiles is considered to be in line with differences in natural vegetation, clearance of vegetation, or the introduction of rainfed leguminous crops. Clearly the N status of soils in these areas is favorable for cultivation and there may be little need for additions of artificial N fertilizers, which would otherwise only serve to increase the stress on the shallow groundwater resources.

Since it is possible to follow the movement of NO_3 through the pathway atmosphere–soil–unsaturated zone, the environmental rather than any geological control over high NO_3 occurrence in shallow groundwaters can be demonstrated. The evidence from the shallow wells also shows that this is a regional phenomenon in N Senegal. The enrichment in NO_3 concentrations are of the same order as those found in unconfined groundwaters elsewhere in northern Africa and reinforces the conclusion that high NO_3 in groundwater is likely to be a widespread feature of arid and semiarid zones.

From the point of view of water quality the question of what constitutes an acceptable baseline concentration of NO_3 in groundwater, especially in semiarid tropical regions, may need reexamination. The stringent water quality standards for NO_3 adopted for northern countries and which form the basis for global standards (WHO, 1993) may therefore be inappropriate for semiarid tropical areas. Further assessment of NO_3 concentrations in drinking water in rural areas of the Sahel and other semiarid regions is required to confirm that the distributions highlighted here are valid worldwide. Further epidemiological evidence is also needed from these semiarid regions to assess the health impacts of these high NO_3 concentrations in groundwater.

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