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Estimation of rainfall inputs and direct recharge to the deep unsaturated zone of southern Niger using the chloride profile method

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Abstract

An estimate of direct groundwater recharge below a region of natural woodland (tiger bush) has been made in south-west Niger using the solute profile technique. Data has been collected from a 77 m deep well dug within the study area covered by HAPEX-Sahel (Hydrological and Atmospheric Pilot Experiment), an international large-scale energy, water and carbon balance experiment carried out during the summer of 1992. During well construction samples were taken from the unsaturated zone at the following intervals: every 25 cm from 0–10 m, every 50 cm from 10–62.5 m, then every metre to the bottom of the well. Pore water was extracted from each sample either by centrifugation or elutriation and analysed for chloride; moisture contents of samples were obtained gravimetrically. These data have been used to produce depth profiles of pore water chloride concentration and moisture content throughout the unsaturated zone. From these profiles it has been possible to derive an estimate of historic direct recharge at the site. The chloride concentration of rainfall, which is required to make the estimate, was determined from the analysis of 123 rainfall samples collected from five EPSAT (vers une Estimation des Précipitation par Satellite au sahel) rain gauges in 1992. A mean recharge rate of 13 mm year^{-1} (range 10–19 mm) is estimated for the upper 70 m of the profile, with a total residence time of 790 years (range 520–990 years). This is considered to be a representative estimate of the magnitude of direct recharge taking place below tiger bush areas.

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1. Introduction

An international large-scale energy, water and carbon balance experiment, HAPEX-Sahel, was conducted within a 100 km × 100 km area of south-west Niger in the summer of 1992. Bounded by longitudes 2° to 3°E and latitudes 13° to 14°N, the area is part of the Sahel, a climatic region characterised by variable rainfall, high temperatures and high evaporation rates.

In this environment surface water resources are scarce for much of the year which means that groundwater plays a vital role as a source of water supply. The long-term sustainable yield of this resource depends ultimately on the rate of recharge, which is determined by the amount of water draining through the deep unsaturated zone to the water table.

Groundwater recharge in this region takes place either as indirect (localised) recharge through the beds of ephemeral streams and temporary pools, or as widespread direct (or diffuse) infiltration through the soil. Both processes are important and both contribute to total recharge. Localised recharge, via stream beds and temporary pools, is dealt with elsewhere (Leduc et al., 1997). This paper describes the results of a study to determine the rate of direct recharge below a region of natural vegetation, known locally as tiger bush. Tiger bush consists of alternating strips of mixed vegetation and bare ground, aligned parallel to the contours of virtually flat to gently sloping terrain, which when viewed from the air gives rise to a pattern similar to that of a tiger skin (White, 1970; Ambouta, 1984; Culf et al., 1993). Approximately 25–30% of the HAPEX-Sahel region is covered by tiger bush; most of the remainder is given over to millet fields or fallow bush (d'Herbes et al., 1992; Wallace et al., 1994).

There are many physical and chemical techniques available to measure direct recharge, a comprehensive summary of these being given in Simmers (1988). One of the most powerful of the chemical techniques is solute profiling, whereby chemical or isotope depth profiles of pore water extracted from unsaturated zone samples are used as natural tracers to provide an estimate of recharge. The most common natural tracers used in recharge studies are chloride, and the isotopes tritium (^{3}H), oxygen 18 (^{18}O) and deuterium (^{2}H). There are, however, disadvantages in using ^{3}H, ^{18}O and ^{2}H for recharge estimation, not the least of which is that during the recharge process the water molecule of which they form a part, is not conserved. This means that mass balance studies are not possible (Edmunds and Walton, 1980; Gaye and Edmunds, 1996). Chloride on the other hand is conserved and, therefore, preferred as a simple and effective alternative.

This paper describes the results of a chloride profile obtained from unsaturated zone samples taken from a 77 m deep well dug at the edge of a tiger bush area in south west Niger. So far as the authors are aware this is the deepest profile to have been obtained in the Sahel region and as such provides a uniquely long record of recharge in the historic past.

2. The chloride profile technique

Detailed descriptions of this technique have been made in a number of papers (Allison and Hughes, 1978; Allison, 1988; Edmunds et al., 1988), so that only a brief outline need be presented here.

Chloride is introduced into the soil both in rainfall and as dry deposition. Since chloride does not evaporate from the soil surface, and vegetation does not take up significant quantities, it becomes concentrated by evapotranspiration. Water in the soil can be broadly categorised into either upward or downward moving water, with the zero flux plane (ZFP) separating the two (Wellings and Bell, 1982). The upward water flux is driven by evaporation of water from the soil surface and transpiration through plants taking up water via their roots. The position of the ZFP in the profile changes through the year, depending on the depth of rooting, atmospheric evaporative demand, and the water status of the soil. In some regions of the world, all the water which enters the soil is eventually returned to the atmosphere via evaporation, and there is no net downward movement or deep drainage. However, where there is sufficient infiltration for water to move below the root zone and the maximum depth of the ZFP, the water will continue to move down as deep drainage until it eventually reaches the water table.

Thus, once below the ZFP water will continue moving down to the water table, while above the ZFP it continues to evaporate and increase the chloride concentration. Under conditions of recharge the ZFP represents the point below which a net, steady state, moisture and solute transfer takes place toward the water table. The amount of chloride crossing the ZFP varies in relation to antecedent rainfall over one or more seasons, thus causing oscillations in the chloride profile. Under steady state conditions the average chloride concentration of pore water in this profile, $\bar{C}_s$, will be proportional to the concentration factor, $\bar{P}/(\bar{P}-\bar{E})$, (where: $\bar{P}$ = long-term average precipitation and $\bar{E}$ = long-term average evapotranspiration). This assumes no loss or gain of chloride to or from minerals, and that the water and chloride are transported at the same rate. Where the surface run-off component is negligible, the water balance equation is given by:

$$\bar{R}_d=\bar{P}-\bar{E} \tag{1}$$

where $\bar{R}_d$ is the space and time averaged direct recharge flux.

The Cl balance is given by:

$$\bar{F}_p+\bar{F}_d=\bar{F}_s+\bar{F}_m \tag{2}$$

where $\bar{F}_p$ and $\bar{F}_d$ are the average rainfall and net dry deposition fluxes (= input), and $\bar{F}_s$ and $\bar{F}_m$ are the net steady state output fluxes in the drainage water and the net flux of chloride precipitated or adsorbed by minerals. $\bar{F}_s$ is given by the recharge multiplied by the mean chloride concentration i.e.:

$$\bar{F}_s=\bar{R}_d\cdot\bar{C}_s \tag{3}$$

Assuming there are no reactions with minerals (i.e. $\bar{F}_m = 0$) then Eqs. (2) and (3) can be combined and re-arranged to give:

$$\bar{R}_d=\frac{(\bar{F}_p+\bar{F}_d)}{\bar{C}_s}=\frac{(\overline{PC}_p+\bar{F}_d)}{\bar{C}_s} \tag{4}$$

It follows that direct recharge can be calculated if the following values are known – the volume averaged concentration of chloride in the rainfall ($\bar{C}_p$); the averaged interstitial water concentration ($\bar{C}_s$); the long-term average rainfall ($\bar{P}$) and, the net dry deposition chloride flux ($\bar{F}_d$). If $\bar{F}_d = 0$, then the fraction of rainfall contributing to direct recharge is given by the ratio $\bar{C}_p/\bar{C}_s$.

Finally, it should be emphasised that the validity of this technique depends on six important assumptions:

1. That the concentration of Cl in rainfall has been constant over time and that this concentration is accurately represented by the mean concentration measured ($\bar{C}_p$) from available rainfall samples. A minimum of 3 years is considered necessary for reliable estimates (Edmunds and Gaye, 1994).
2. There have been no external additions of chloride to the soil (e.g. fertilisers, animal and/or human urine and faeces).
3. There is no net change of chloride storage below the ZFP due to the action of plants or soil fauna, or by water–rock interactions.
4. That most water movement is through the matrix (not as bypass flow through large interconnected pores or fissures), and that within the upper 4–5 m bypass flow is mixed with matrix flow.
5. That vertical flow takes place homogeneously over the area concerned either at the surface or at least below the depth to which bypass flow might reach (4–5 m).
6. There is no significant net surface run-on, or run-off at the site.

3. Site description and geology

The well is at latitude 13°15′44″N and longitude 2°3′31″E, at an elevation of 262 m. It lies close to the village of N'douroua on the western side of the Say plateau (Fig. 1). Locally, the ground slopes gently toward the south-west at a gradient of 1 in 120, a slope which is sufficiently steep to generate sheet flow at high storm intensity, but not to erode channels. The well is situated just inside the western boundary of a large area of tiger bush. The tiger bush here is typical of the region; strips of vegetation, up to 20 m wide, aligned parallel to the ground contours, are separated by areas of bare, crusted soil up to 50 m in width (Ambouta, 1984). Vegetation is dominated by five woody species, *Guiera senegalensis*, *Combretum micranthum*, *Combretum nigricans*, *Acacia ataxacantha* and *Acacia macrostachya*. Downslope the tiger bush gives way to millet fields which are periodically given over to fallow bush.

During intense rainstorms sheet flow is generated over the crusted soil of the bare ground and moves downslope, where it becomes ponded beneath adjoining strips of vegetation. This water harvesting mechanism ensures that infiltration is concentrated below the vegetation, where it is most needed. Such redistribution of surface water, however, tends to be a very localised process since run-off is quickly intercepted by the nearest vegetation strip situated downslope. Thus although run-off takes place in the immediate vicinity of the solute profile well it forms part of a local redistribution system rather than a large-scale regional outflow. Because of the localised nature of run-off and because the vegetation strips themselves are

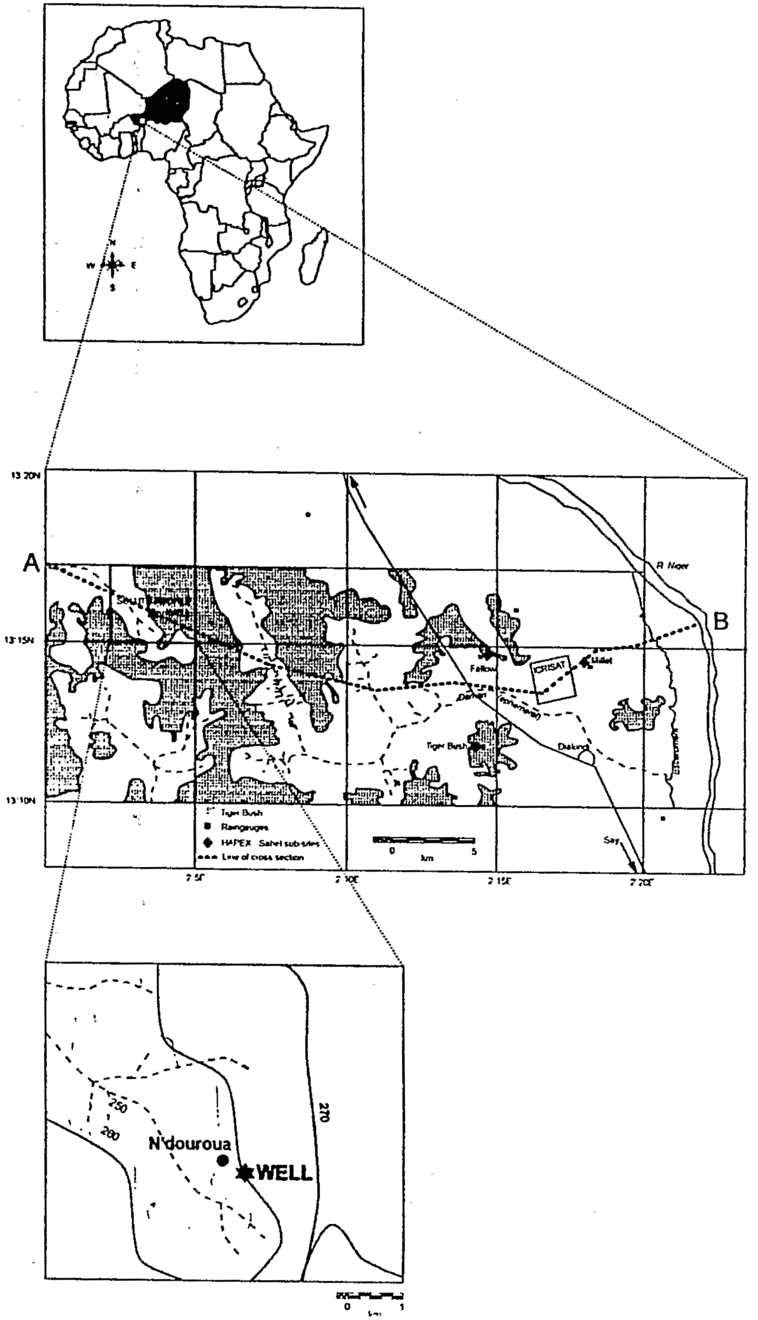

Fig. 1. Location of well and extent of tiger bush cover in the study area.

mobile and migrate slowly upslope with time, the impact of run-off on the chloride profile will tend to become smoothed out at increasing depth.

The site is underlain by the Continental Terminal formation, a 49.4 m thick sequence of terrestrial sediments, which are Miocene to Pliocene in age. These sediments rest on a pre-Cambrian basement of mainly granitic gneiss (Fig. 2). Only the upper unit of the Continental Terminal, the "Grès argileux du moyen-Niger" is present in this area. This is because the Say plateau occupies a position at the extreme western edge of the main sedimentary basin in which there is overlap of successively younger formations to the west (Greigert, 1966; Burri, 1987).

At the surface there is a thin 25 cm cover of silty sand which overlies a 4.25 m layer of laterite. The laterite is typically reddish brown, indurated and perforated by numerous, sinuous, tubular cavities either empty or filled with softer red brown to yellow, clayey material. It is recognised that the structure of the laterite means that bypass flow is likely to be an important mechanism in this layer, a feature which has been taken into account in the recharge calculation. White (1971) considered the laterite to be an exhumed feature of late Tertiary (Pliocene) age and thus to be part of the Continental Terminal sequence. The presence of laterite at shallow depth is characteristic of tiger bush areas throughout the region. The laterite forms the caps of plateaux, which are often gently sloping and in places dissected by ephemeral streams. Along the valleys and occasional depressions within the laterite surface, wind blown and water borne sand and silt form pockets of deeper soil, which are used for millet cultivation.

Below the laterite there is a variable sequence of sandstones, silty sandstones and mudstones (Fig. 2). The contact with the basement is at a depth of 49.4 m. Most of the sedimentary sequence is composed of alternating yellowish-brown silty sandstones and variegated mudstones. There are only two significantly thick horizons of sandstone or sand; these are between 7.5 m to 10.9 m and 38.3 m to 42.8 m. The sediments are generally friable, the most indurated section being the laterite layer at the surface. Kaolinite is present throughout as an alteration product, either disseminated or in the form of stringers or more extensive patches. In places throughout the upper 20 m, the remnants of what appear to be old termite burrows, discontinuous tubes up to several centimetres long, are common. With increasing depth these become less common, but examples were also recorded much lower in the sequence (e.g. at 47 m).The dominant constituents of the main sedimentary lithologies are quartz, kaolinite and minor amounts of hematite. Within the laterite layer at the top, small amounts of goethite, illite and smectite are also present. Significantly, so far as the validity of the chloride profile technique is concerned, none of them contain chloride.

The upper 8 m of granitic basement has been extensively altered to kaolinite. In this zone the texture of the parent rock is totally destroyed; all that remains are isolated flakes of muscovite or fragments of quartz set in a white matrix of kaolinite. Below 57.4 m the degree of alteration progressively diminishes until at 77 m, it displays only a slight degree of weathering.

The hydrogeological setting of the site is illustrated by the E–W cross-section through the Say plateau shown in Fig. 3. At the site of the well the water table lies within the basement complex at a depth of 74.1 m. This is 24.7 m below the base of the Continental Terminal. Toward the east, however, the water table elevation rises steeply and within 8

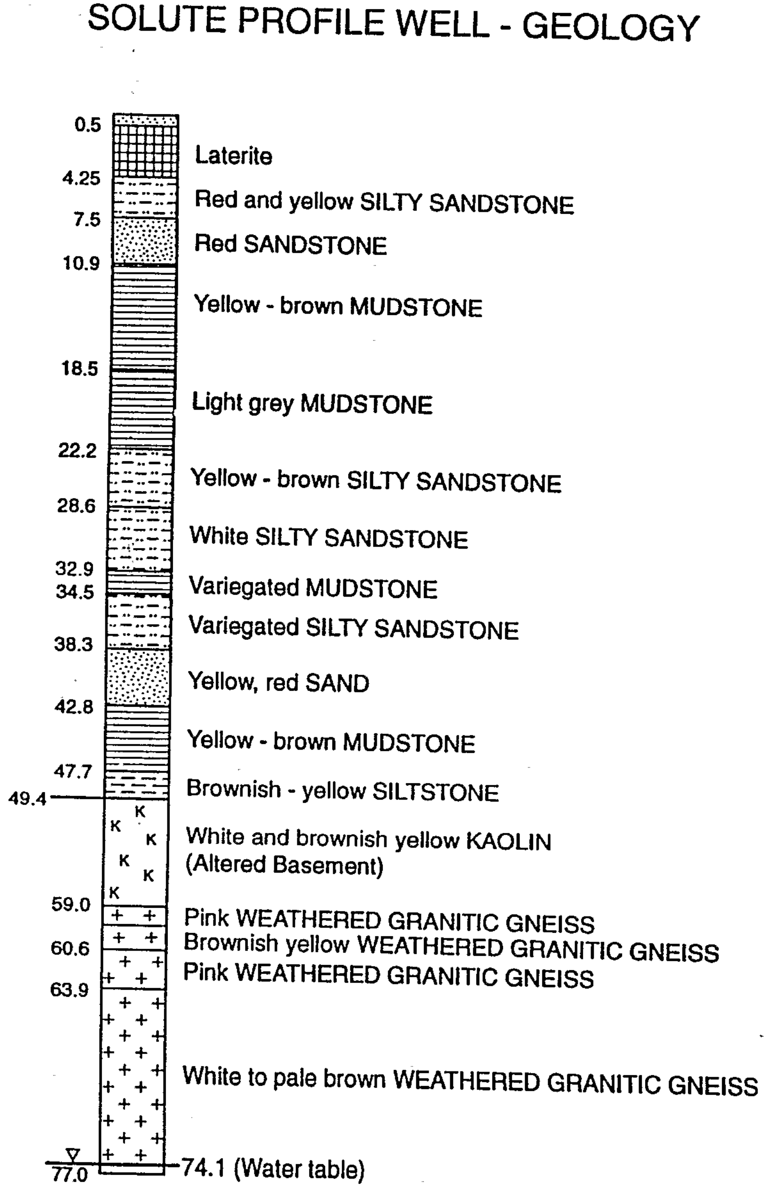

Fig. 2. Lithology and water level.

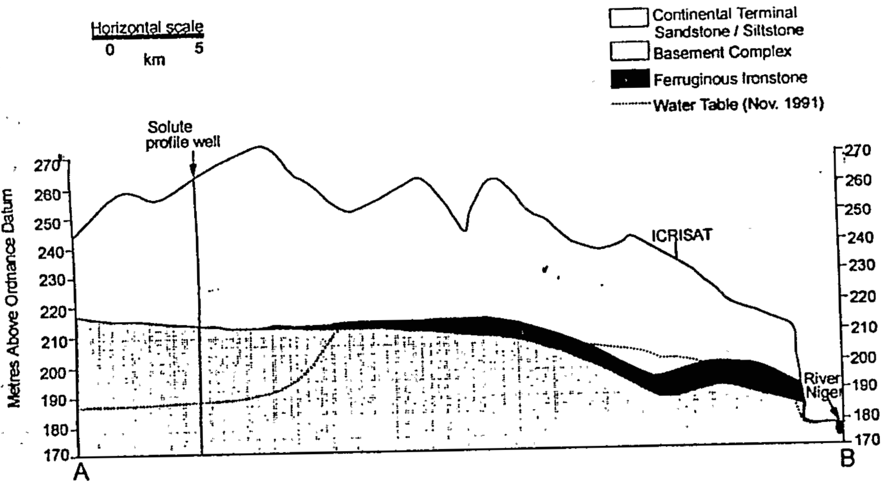

Fig. 3. Hydrogeological cross section through the Say Plateau (line of section shown on Fig. 1).

km passes up into the Continental Terminal, where the main aquifer is an oolitic ironstone, developed at the base of the sequence. This ironstone thins out to the west and is not present at the site of the well. Groundwater elevations are generally much lower over the western part of the plateau, where tiger bush vegetation dominates, than over eastern areas where the main vegetation type is millet and fallow land. The implication from observed water levels is that recharge below tiger bush areas is much lower than other land use types in the region. Results from the current study support this.

4. Climate

At Niamey, approximately 45 km to the north of the well site, the mean annual rainfall for the period 1905–1989 is 564 mm, although in more recent years, from 1968–89, there has been a period of drought over which time the average reduces to 495 mm (Lebel et al., 1992). These trends are illustrated by the plot of the cumulative departure from the mean shown in Fig. 4. Inter-year variability is high, with a standard deviation of 137 mm and a coefficient of variance of 24% (Sivakumar, 1986). Spatial variability is also very marked. Taupin et al. (1993) notes that in 1992 within the HAPEX-Sahel 100-km square, rainfall totals for the period 15th April–15th October exhibited a 50% variation (from 389 mm to 782 mm) over distances of less than 60 km. About 75% of the rain falls in July, August and September, generally as localised storms during which rainfall intensities of 100 mm h^{-1} are not uncommon (Hoogmoed and Stroosnijder, 1984). At the well site, although some local re-distribution of surface flow takes place, conditions suggest that net run off from the area is not likely to be significant. Annual potential evaporation is almost 2500 mm and exceeds rainfall during every month except August (Sivakumar, 1986).

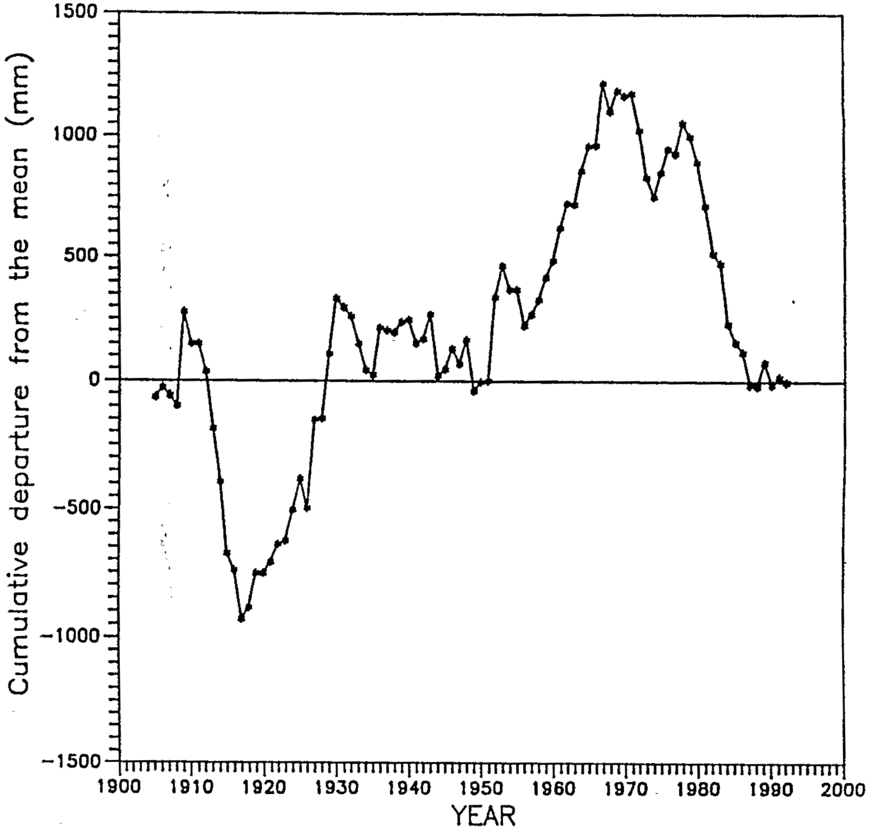

Fig. 4. Cumulative departure from the mean rainfall at Niamey from 1905–1991.

5. Methodology

5.1. Collection and analysis of well samples

The well was hand dug over a 2 year period using traditional methods. In the course of construction samples were taken at the following intervals; every 25 cm from 0–10 m, every 50 cm from 10–62.5 m, then at every metre from 62.5 m to the bottom of the well at 77 m. In the upper 44 m duplicate samples were collected every metre from opposite sides of the 1.5 m diameter well. As the digging of each interval was completed, samples were carefully scraped from the sides into a plastic bag, the handlers wearing rubber gloves to prevent contamination from hand contact. At the surface, samples were immediately transferred to a 500 ml glass Kilner jar. To permit the measurement of matric potential a filter paper was inserted between the sample during filling and a second placed at the top, before the jar was sealed (Hamblin, 1981).

In the laboratory, water was removed from the sample for chemical analysis using one of two techniques, centrifugation or elutriation, the technique used depending on the water content. The centrifugation method (Kinniburgh and Miles, 1983) relies on the displacement of water by an immiscible liquid and was used for most of the samples; elutriation was used only when moisture contents fell below about 3%. For the elutriation method a known volume of distilled de-ionised water is added to the sample, and the supernatant solution used for analysis after 1 h stirring and settling (Edmunds, 1990). This technique was used for the drier intervals from 0–7.75 m and from 45.05–69.76 m, while the remainder of the samples were centrifuged. Moisture contents for all samples were determined gravimetrically.

A total of 170 pore water samples (3 to 8 ml) were extracted, or elutriate obtained, and chloride determined by automated colorimetry using a Technicon AA II® with mercuric thiocyanate as reagent. The detection limit of the method was 0.05 mg l^{-1} and even at low concentration precision was within 2% of actual concentration. The samples were also analysed for NO_3^-, pH and a range of major and minor elements to examine the hydrogeochemical processes, the results of which will be presented elsewhere as part of a more regional West African study.

5.2. *Collection and analysis of rainfall samples*

Throughout the 1992 wet season rainfall samples were collected for chloride analysis on an event basis from five rain gauges within the EPSAT network described in Taupin et al. (1993). In addition, another 11 gauges were sampled on a more irregular basis. The five gauges selected for event based sampling were arranged in a 60 km east–west line extending from Niamey eastward to Sameday. Identification numbers of the gauges were 9, 28, 70, 94 and 102, the locations of which are given in Taupin et al. (1993). In total 123 rainfall samples were collected and analysed for Cl.

Edmunds and Gaye (1994) considered it necessary to have at least 3 years data to obtain reliable recharge estimates for profiles taken in Senegal. For the current study, however, only 1 year of data (1992) is available, but this has been collected from 16 stations scattered over a wide area (60 km). Thus, although there is no measure of inter-year variability, the influence of spatial variability is well represented and the data set is considered to reflect the range of values to be expected from a smaller number of stations taken over a 3-year period.

6. Results and discussion

The chloride data for the five EPSAT sites, which were analysed on an event basis and for which the greatest number of samples were available, are summarised in Table 1. It should be noted that absolute chloride values vary through the season, being higher at the beginning of the rainy season; absolute values also differ according to rainfall intensity and rainfall amount, and the weighted mean value is used to minimise these effects.

The moisture content by weight lies between 6–14% (Fig. 5). These values are high and mainly reflect the dominance of mudstone throughout the sequence. Where sandy horizons are present they are marginally drier than the mudstones. The driest section, however, is the laterite layer in the top 4 m where moisture contents are below 4%.

Table 1
Weighted mean chloride for EPSAT rainfall stations

Station (with EPSAT site number)	Rainfall (mm)	No. samples	Weighted mean chloride[a] (mg l^{-1})	Range (mg l^{-1})
Niamey (ORSTOM) (70)	368.2	30	0.37	0.12–3.88
Fandou Beri (9)	417.6	23	0.51	0.15–3.24
Berkiawel (28)	365.5	24	0.29	0.12–1.11
Samadey (102)	417.1	24	1.43[b]	0.42–10.2
Niamey (94)	424.8	22	0.5	0.11–6.04
Mean	398.6		0.62	
Standard deviation	26.1		0.4	

[a] Weighted mean chloride for each station: Σ[rainfall amount (individual event/season total) × Cl (individual event)].

[b] Values throughout the season are consistently high for this station, with no obvious explanation.

The chloride data are also shown in Fig. 5. The upper 7.75 m have relatively high concentrations of chloride, most probably related to the texture of the laterite and the method used to extract the water. It has been noted that chloride concentrations obtained by elutriation are sometimes higher than those from centrifugation above the zero flux plane (Edmunds et al., 1988). This is attributed to occlusion of some chloride in soil mineral structures, resulting from evaporation gradients and formation of secondary minerals. This chloride can be accessed by the elutriation technique, where the soil is disaggregated, but not by the centrifuge technique where the sample remains mainly intact. Passage of water through the laterite is likely to be via preferential flowpaths and chloride will be stored at some distance from these flowpaths. While this chloride store is not affected by, and does not reflect, the chloride content of the recharge water, it does show up in the chloride analysis of bulk laterite samples by elutriation. The average chloride value for the profile as a whole is 36.4 mg l^{-1}. However, this includes data from the upper 7.75 m where much of the chloride remains immobile and is effectively isolated from the drainage process. It is, therefore, considered more relevant to use an average chloride value which excludes the upper 7.75 m. This value is calculated to be 27 mg l^{-1}. Using Eq. (4) and the values shown in Table 2, a long-term estimate of 13 mm $year^{-1}$ for direct recharge is obtained for the upper 70 m of the profile.

If any one of the input variables is changed, such as $\bar{C}_p$, the value of the recharge estimate will change proportionally. For example, if the station with high Cl is omitted, then the mean of the weighted mean chloride values reduces from 0.62 mg l^{-1} to 0.42 mg l^{-1} and this in turn lowers the recharge estimate from 12.8 mm $year^{-1}$ to 8.7 mm $year^{-1}$. It should, therefore, be stressed that the recharge value given here is an estimate based on several assumptions and only a single year of data. Nevertheless, as an estimate of the magnitude of recharge it remains a valid result, especially since spatial variability of rainfall of rainfall chloride is taken into account.

Another potential source of error is the estimate of the long-term average value for annual rainfall. The long-term average used (564 mm) is from the station at Niamey.

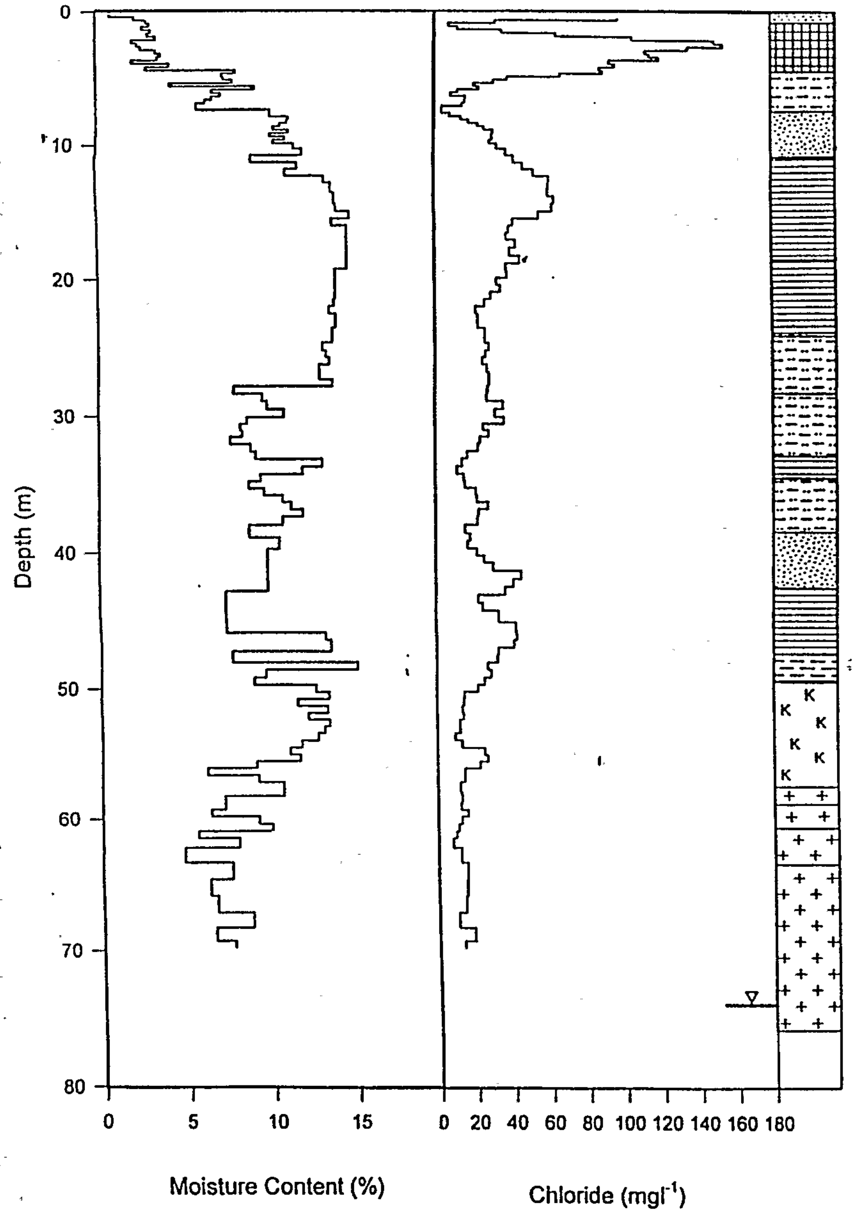

Fig. 5. Profiles of soil moisture content g per 100 g (%) and chloride concentration (mg l^{-1}) plotted against the lithology. For details of the lithological log see Fig. 2.

Table 2

Mean annual recharge for upper 70 m

Depth in (m)	Mean rainfall P (mm)	Mean Cl in rain C_p (mg l^{-1})	Mean Cl concentration in profile C_{si} (mg l^{-1})	Mean annual recharge R_d (mm year^{-1})
70	564	0.62	27	13

approximately 45 km from the well site, where there is a continuous record from 1905 1989. However, rainfall in this area is extremely variable, both temporally and spatiall and it is difficult to select an appropriate value to use in the recharge estimate. Lebel et al (1992) for example show how in this area in 1990, differences of 183 mm (about 60% were observed over distances of less than 10 km, though of course in the long term suc variability will even out to some extent.

As a check on the validity of the average figure selected, all the stations in the EPSA study area lying within a 40 km radius of the well site were averaged for the 1992 rain season. This gave a mean value of 532 mm, with a standard deviation of 69.7 mm; th difference between this value and the long-term mean for the Niamey station was approxi mately 5% and on this basis it was decided reasonable to use the value of 564 mm for th recharge calculations.

Using the long-term average recharge estimate of 13 mm year^{-1} it is possible to calibrat the profile chronologically and to calculate the rate of movement and residence time fo water in the profile (Cook et al., 1992). To do this it is necessary to know the moistur content (Fig. 5) and the bulk density of the rock or sediment, which is assumed to be 1.5 cm^{-3} (Edmunds et al., 1992). Using the data in Table 2 a residence time of 765 years fo the entire profile is obtained. However, it is of more interest to calculate recharge rates an residence times for different sections of the profile, in order to demonstrate how recharg conditions might have changed in the past. Hence, the chloride profile (Fig. 5) has bee sub-divided into five zones of contrasting chloride concentration, and the recharge rate an residence time calculated for each zone (Table 3).

Using the data in Table 3 the residence time of water in the entire profile totalle 790 years. This is slightly more than the 765-year record obtained from the bulk dat given in Table 2, but the difference is not significant. The calculation of residence tim assumes that piston flow is the dominant process of water movement in the unsaturate zone at this site, and that flow through fissures is, in comparison, relatively insignifican any by pass flow in the upper few metres would rapidly be dispersed in contact wit the unsaturated wall rock of the fissures. Given the silty and clayey nature of the mud stones and silty sandstones, and the lack of observable open fissures during well constru tion the piston flow model is considered to be a reasonable assumption. This method o estimating recharge and residence times has been shown to be reliable where independen checks such as data from ^{3}H or ^{36}Cl have been available to confirm results (Cook et al. 1992).

The concentration of Cl of the water table (12.3 mg l^{-1}) is less than the mea concentration in the profile (27.4 mg l^{-1}). The implication is that regional flow in th aquifer beneath the site is derived from an area with a slightly higher recharge. A value o

Table 3
Recharge rates and residence times in upper 70 m

Depth (m)	Interval (mm)	C_d (mg l^{-1})	P (mm)	C_p (mg l^{-1})	R_d (mm year^{-1})	t (years)
0.0–7.75	7750	27[a]	564	0.62	13	44
7.75–21.70	13950	39	564	0.62	9	295
21.7–32.89	11190	27	564	0.62	13	145
32.89–49.95	17060	27	564	0.62	13	185
49.95–69.76	19810	15	564	0.62	24	119
						Σ790

[a] This value is the average for 7.75–70 m.

12.3 mg l^{-1} Cl interpreted as a regional recharge flux (Edmunds and Gaye, 1994) and using the rainfall from this study would give a recharge of 28.4 mm year^{-1}. This is consistent with the local terrain features, since the tiger bush is likely to contribute a lower water flux than other land use types in the area, such as millet or fallow ground.

These results have far-reaching implications regarding palaeoclimatic reconstruction and information about past recharge, but a detailed discussion of this will be presented elsewhere in the literature in combination with results from other sites in the Sahel. In the context of the HAPEX-Sahel study, the most important aspect is that direct recharge below tiger bush, which covers 20–30% of the area, is shown to be limited. This needs to be taken into account when the renewable water resources of the region are assessed.

7. Conclusions

Using solute concentrations in a 77-m well profile it has been shown that under areas of tiger bush in the HAPEX-Sahel degree square, the average rate of direct (diffuse) recharge throughout the 790 (200) year record preserved in the unsaturated zone is 13 mm year^{-1}. The accuracy of the result obtained depends upon the validity of a number of assumptions, but as a cautious estimate of magnitude is valid. These assumptions are:

1. The mean annual precipitation of 564 mm year^{-1} obtained from the long-term record at Niamey is representative of the entire well record.
2. The mean chloride content of rainfall has remained constant through time, and the value of 0.62 mg l^{-1}, obtained for 1992, is valid for the well record.
3. The volume of net run-off from the area is not significant.
4. The dominant mechanism of moisture transfer in the unsaturated zone is by piston flow.
5. There has been no net change of chloride below the root zone by plants, animals or rock–water interactions.
6. There have been no external additions of chloride to the soil (e.g. fertiliser).

The result represents the average rate of direct recharge integrated over a long period of time, and as such is not unduly influenced by short-term changes of annual rainfall. This unique feature of the solute profile technique provides it with a significant advantage over other methods where results are often linked to recent rainfall regimes which may or may not be representative of the long-term situation.

In the regional context of the HAPEX-Sahel square the direct recharge taking place below areas of tiger bush is quantitively one of the least significant sources of groundwater recharge. It has been shown by Leduc et al. (1997), that regional recharge rates, including direct and indirect sources from all land use types average 50–60 mm year^{-1}, while Gaze et al. (1997), indicate potential recharge rates in excess of 100 mm year^{-1} below millet fields. However, because tiger bush covers up to 30% of the HAPEX area it exerts a major influence on the regional recharge rate, tending to reduce the overall figure.

Another factor to take into account is the impact that degradation of tiger bush (e.g. by wood gathering) will have on future levels of recharge. The data obtained from the solute profile well reflects the mean recharge rate below non-degraded bush over a long period. However, as bushes and trees are removed, the hydrology will inevitably be changed. Evaporation rates may be reduced in response to thinning vegetation thus potentially increasing the rate of recharge; on the other hand increased areas of crusted soil will tend to increase surface run-off thus reducing the opportunities for infiltration. The net effect of degradation on recharge is still uncertain and is an aspect of the hydrology of the region that needs to be further investigated.

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Hydrology of the HAPEX-Sahel Central Super-Site: surface water drainage and aquifer recharge through the pool systems

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Abstract

The hydrology of the Sahel is characterised by the degradation of the drainage network, resulting in the lack of large watersheds over which the spatial integration of the hydrological processes could be studied. The main hydrological units are small endoreic areas, measuring a few hectares to a few square kilometres and the surface runoff is collected into pools. A detailed investigation of the role of these pools in the hydrology of the HAPEX-Sahel Central Super-Site was carried out from 1991 to 1993. The first results of this investigation are presented. A typology in three classes of the endoreic systems (valley bottoms; sinks; plateaux) is proposed. The behaviour of one representative pool in each class is analysed, showing that the partition between evaporation and deep infiltration depends on the level of filling of the pools. The bottom of the pool is clogged by clay deposits, which prevent infiltration. Above a threshold varying between 1 and 2 m most of the water stored in the pool after runoff infiltrates, contributing to the recharge of the aquifers. On a seasonal basis, deep infiltration accounts for less than 50% of the water collected by the plateau pool, and more than 80% for the valley bottom pools. Almost all the water running off to the sink pools infiltrates rapidly and deeply into the ground. The valley pools (both valley bottoms and sinks) appear to be the major contributors to the recharge of the upper aquifer. The proportion of the HAPEX-Sahel Central Super-Site water balance that is taken by the deep infiltration from the pools varies greatly depending on the temporal distribution of rainfall. Whereas similar seasonal rainfalls were recorded in 1991 and 1992, it is estimated that 5% of the water precipitated over the valley pool watershed infiltrated towards the aquifer in 1991 and 20% in 1992. This difference is explained by a very irregular time distribution of precipitation in 1992, most of the major rainfall events being observed over a short period during the intensive observation period. In conclusion some preliminary figures are given regarding the importance of recharge from the pools as compared with in situ recharge.

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