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Comparison of isotopic (^{18}O and ^{2}H) and chemical (Cl^-) methods to calculate the dry season evaporation rate of near surface groundwater in a Sahelian region, Niamey (Niger)

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Abstract The estimation of the measurement of soils evaporation in semiarid conditions is especially difficult, due to the fact that the limits of classical methods such as neutron probe and tensiometry measurements are reached. This paper presents the results of chemical and isotopic methods used to estimate the evaporation rate of near surface groundwater across the unsaturated zone in a Sahelian region. Measurements were carried out in the valley of the Niger, in different kinds of soils, with variable groundwater levels beneath the surface (60-500 cm). The method used, based on the analysis of stable isotopes (^{18}O and deuterium) and chloride content of water in the unsaturated zone, allows the measurement of evaporation rates in agreement with values commonly found in these regions (10 mm year^{-1} beneath 5.00 m of sandy clay to 290 mm year^{-1} beneath 0.60 m of silt). The two methods yield similar results in most cases with the isotopic method being generally more precise. In particular, for low water contents, the estimation error is much larger with the chloride profile method, leading to preclusion of the use of this method in such conditions.

INTRODUCTION

The region studied (Fig. 1) belongs to the Sahelian zone (semiarid climate), and is situated in western Niger in the region of Niamey (annual rainfalls of 505 mm over the period 1968-1989). The region is influenced by the inter tropical front (ITF), whose fluctuations in latitude are directly bound to the reinforcement of the anticyclonic zones alternately of the Azores and of Saint Helena. Thus, the ITF goes to the north between May and September (winter), and to the south from October to April (dry season). The average yearly temperature is about 30°C. The relative humidity is correlated with the alternation of air mass movements above Niger, which causes an important variation during the year (from 20 to 90%).

The sites studied (13.6°-14.5°N and 1°-2°E) are located on the three more recent quaternary terraces of the Niger river (Fig. 2). They are composed of fine to coarse textured deposits, where a near surface groundwater lies.

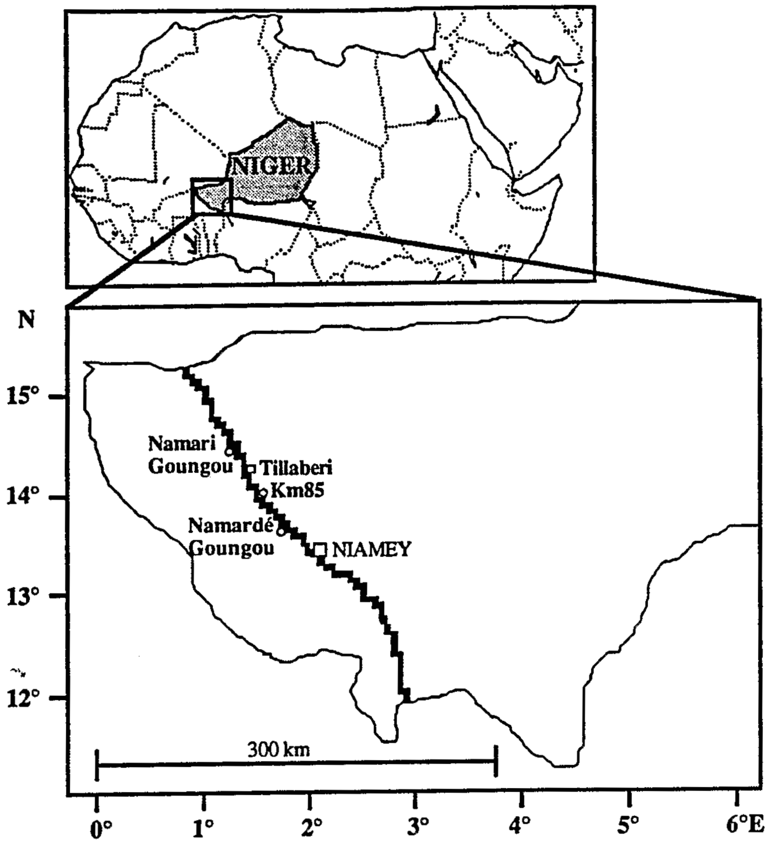


Fig. 1 Research area.

METHODOLOGY

A sample of the soil profile was taken, up to the groundwater if possible, using an open-checked hand auger. The sampling step was 5-10 cm long in surface and 20 cm long in depth. Then the samples were put into airtight aluminum boxes in order to be analysed. In the laboratory, our method is as follows:

- Solid phase: measurement of water contents, of volumetric density, of the porosity and the granulometry of deposits.
- Liquid phase: measurement of stable isotopes (^{18}O and ^{2}H) and chloride content. So as to measure the isotopic contents, soil water (100 g) is extracted by distilling using vacuum at 50°C during 8 h; then water is condensed by liquid nitrogen trapping (Gouvea da Silva Rosa, 1980).

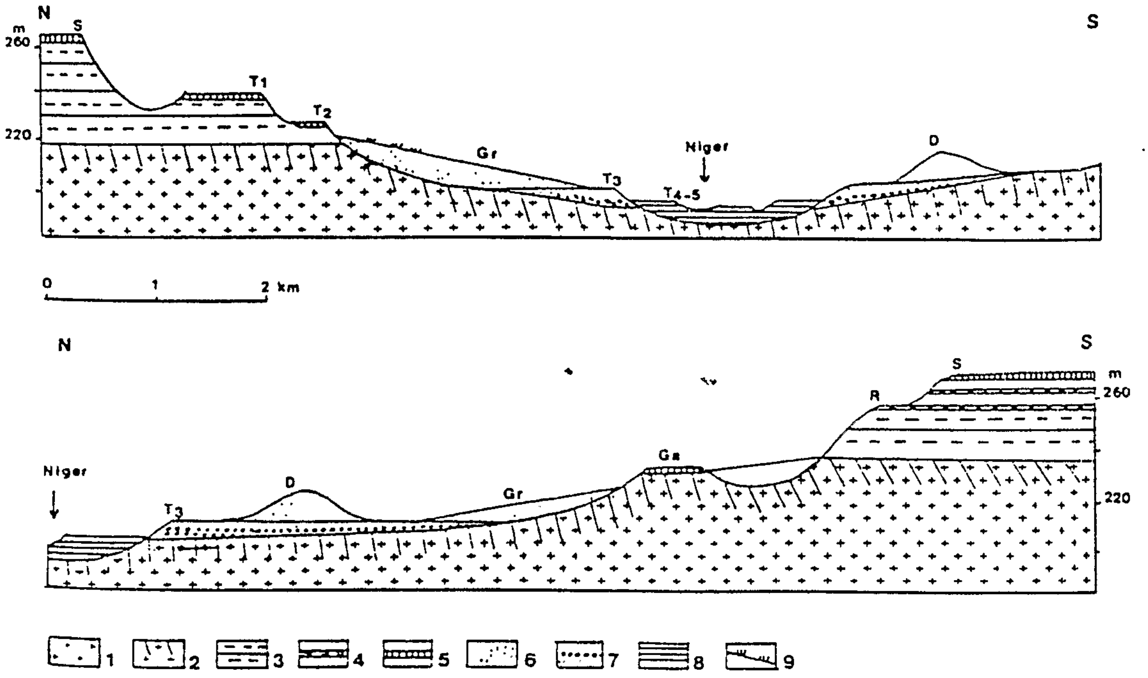
The measurement of the two isotopes is realized using mass spectrometry (VG micromass 602D and 602C); the measurement error is ±0.15‰ for oxygen-18 and ±1‰ for deuterium. To measure chloride, if the soil profile is wet enough the analysis is done directly on a soil water sample which has been centrifuged (18 000 rounds min^{-1}), or if the profile is too dry the analysis, indirect, is done on a leached soil sample.

PRINCIPLE OF THE MODEL

Isotopic model

A soil containing a superficial groundwater, submitted to an evaporative regime and under a flow equilibrium, elaborates from the groundwater (Zimmermann *et al.*, 1967) a characteristic isotopic profile with:

- a zone of enrichment looking like an exponential with a concavity to the bottom, between the groundwater and a proof z_{ef} (evaporation front) located at a few tens of centimetres under the surface; that portion of the profile is due to water transit in a composite form, vapour and liquid; and
- if conditions allow, a more or less linear zone, or with a small concavity to the bottom between z_{ef} and the surface where the isotopic content is depleted to the top; the transit of water in that dry part of the profile is in the vapour form. The depletion of isotopic contents in that case is due to a mixing by diffusion with a high isotopic content depleted of the atmospheric water vapour.



1 : basement
2 : lithomarge
3 : Continental terminal
4 : oolitic ferruginous bed
5 : ferruginous cuirasse
6 : sand
7 : gravel
8 : clay
9 : tubed incrustation
S : Ct surface
R : structural flat
D : ancient dune
Ga: ancient glacis
Gr : recent glacis
T1,T2 : ancient terraces
T3 : middle-age terraces
T4,T5 : recent terraces

Fig. 2 Geomorphological description of terraces along the Niger river near Niamey (in: Ousseini & Morel, 1989).

Thanks to the isotopic modelling of that system (Barnes & Allison, 1983; 1984; Allison *et al.*, 1983), the rate of evaporation E of the groundwater across the two zones of the soil in a permanent regime can be evaluated:

- **In the zone of composite transit**, the equation of the isotopic profile is:

$$(\delta_i - \delta_i^{res}) = (\delta_i^{ef} - \delta_i^{res})\exp[f(z)/ -Z_i] \tag{1}$$

where:

$$f(z) = \bar{\theta} * \int_{z_{ef}}^{z} dz/[\theta + N_{sat} * D_{atm} * (n-\theta)/(\rho_W * D^i_{liq})]$$

where δ_i, δ_i^{res}, δ_i^{ef} are respectively the isotopic contents of soil water at the level z, of the groundwater, and of the evaporation front, θ is volumetric water content, n porosity, ρ_W density of liquid water and N_{sat} saturated water vapour concentration of the soil. It is also necessary to know the diffusivity of the isotope i in the air, D_{atm}, the diffusivity of the isotope i in water D^i_{liq}, and Z_i which is the mean penetration depth of the isotopic species i into soil.

If the model is valid (from equation (1)), a linear relation should be obtained:

$$\ln(\delta_i - \delta_i^{res})/(\delta_i^{ef} - \delta_i^{res}) = -1/Z_i * f(z) + b$$

from which Z_i can be extracted, and reported in the equation of the rate of evaporation:

$$E = D^i_{liq} * \tau * \theta/Z_i \tag{2}$$

where τ = tortuosity.

- **In the zone of transfer of water in a vapour form**, the rate of evaporation is calculated using the equation:

$$E = (1 - h_{atm}) * N_{sat} * D_{atm} * \tau * (n-\theta)/\rho_W * z_{ef} \tag{3}$$

where h_{atm} = relative humidity of the air.

Chloride model

Chlorides in soil and groundwater only come from rainfall if there is neither evaporitic sedimentary deposit, nor a domestic pollution zone. Due to the great solubility of chlorides, a leaching to the groundwater takes place when the soil profile is saturated by rainfall.

If the chloride concentration of groundwater is considered as constant during time, the quantity of chloride ions stored in the soil by evaporation from groundwater is (Black *et al.*, 1969):

$$\chi(t) = C_{res} * \int_{t_0}^{t} E(t) * dt \tag{4}$$

where $\chi(t)$ is the quantity of salts in the profile per surface unit at time t, C_{res} the chloride concentration of the groundwater, $E(t)$ the instantaneous evaporation and t_0 the date of the last leaching.

The cumulative water evaporation between t_0 and t is then:

$$E_{cum} = E_{t-t_0} = \chi(t)/C_{res}$$

In addition, the rate of evaporation of a soil, saturated at the beginning, decreases with time in an exponential way (Black *et al.*, 1969), so:

$$E(t) = E(t_0) * \exp[-K * (t-t_0)] \tag{5}$$

where K is the calibration constant. $E(t_0)$ and the time of last leaching must be known in order to solve this equation.

In the region studied, as local superficial groundwaters of terraces are refilled annually during the rainy season, chloride accumulated during the dry season might be leached during the wet season. So the interval $t - t_0$ can be grossly defined, if the rainfall distribution in time is known. In addition, if you consider that just after the leaching, $E(t_0)$ can be linked to the ETP value, then this equation can be solved. When integrating on the period $t - t_0$, the result is:

$$E_{cum}/E(t_0) = [1 - \exp(-K * T)]/K$$

where T is the time elapsed since the last leaching. The above expression enables us to know K, which can be reintroduced into equation (5).

The total quantity of chloride stored in the soil is also given by the relation:

$$\chi = \int_{Z=surf}^{Z=res} (\mathrm{Cl}^-) * \theta * 10_3 * \mathrm{d}z \tag{6}$$

where θ is the volumetric water content at level z, and (Cl^-) the chloride concentration of soil water.

In the case where all chlorides accumulated in the soil are not totally leached at the annual scale, another method to measure the evaporation using chloride consists of considering that the profile has come to a chemical equilibrium, so that laws of transfer of isotopes into soil solutions can be used on chemical species. Then, a modelling of evaporation can be obtained from an Allison-type model for a chloride profile (Allison & Barnes, 1985). When using the model of Allison applied to chlorides in a mainly liquid transfer, one obtains:

$$[\mathrm{Cl}^-] = ([\mathrm{Cl}^-]^{ef} - [\mathrm{Cl}^-]^{res}) * \exp[-f(z)/Z_{\mathrm{Cl}}] + [\mathrm{Cl}^-]^{res} \tag{7}$$

where:

$$f(z) = \bar{\theta} * \int_{z_{ef}}^{z} \mathrm{d}z/\theta \qquad \text{and} \qquad Z_{\mathrm{Cl}} = D^{\mathrm{Cl}} * \tau * \theta/E$$

RESULTS

This study was carried out over five sites (Taupin, 1990; Taupin *et al.*, 1991), but in order to compare the isotopic and chemical methods of calculating the evaporation rate, only three sites were chosen.

The two methods were compared using soils of different textures and levels of groundwater at the following sites:

- Namarde Goungou, on the right bank of the river (13°37′N, 1°52′E), sampled in April;
- Namari Goungou, on the left bank of the river (14°34′N, 1°12′E), sampled in April; and
- Km 85, on the left bank of the river (13°58′N, 1°33′E), sampled in November.

Soil characteristics

The boreholes of Namarde Goungou and Km-85 are located on a mid-terrace, and that of Namari Goungou on a lower terrace, in a paddy zone. The groundwater has been reached at 3.50 m in Namarde Goungou, 0.60 m in Km-85 and 0.60 m in Namari Goungou.

Granulometry reveals an homogeneous loamy texture, whose average density is 1.45 g cm^{-3} and porosity 30% on the whole profile of Namarde Goungou (median texture 150 μm and fraction superior to 50 μm equal to 70-80%) (Fig. 3).

The granulometric profile of Km-85 is entirely composed of homogeneous coarse sand, of average density 1.60 g cm^{-3} and of porosity 35% (median texture 300 μm and fraction superior to 80 μm equal to 99%) (Fig. 4).

The profile of Namari Goungou reveals an homogeneous loamy texture (85% coarse and medium-grained sand, 15% clay). The measurement of the volumetric mass gives an average value of 1.35 g cm^{-3} and a porosity of 35% (Fig. 5).

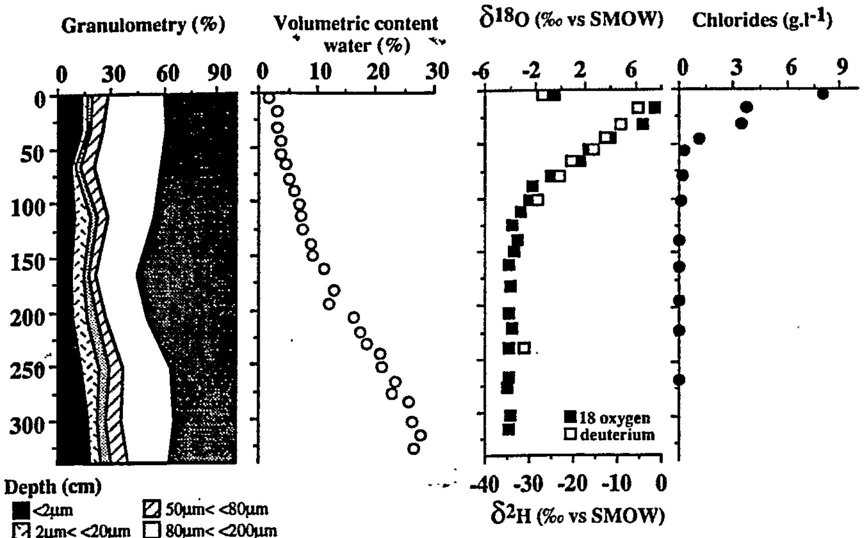


Fig. 3 Characteristics of soils profile in Namarde Goungou site function of depth: granulometry, volumetric water content, isotopic content, chloride.

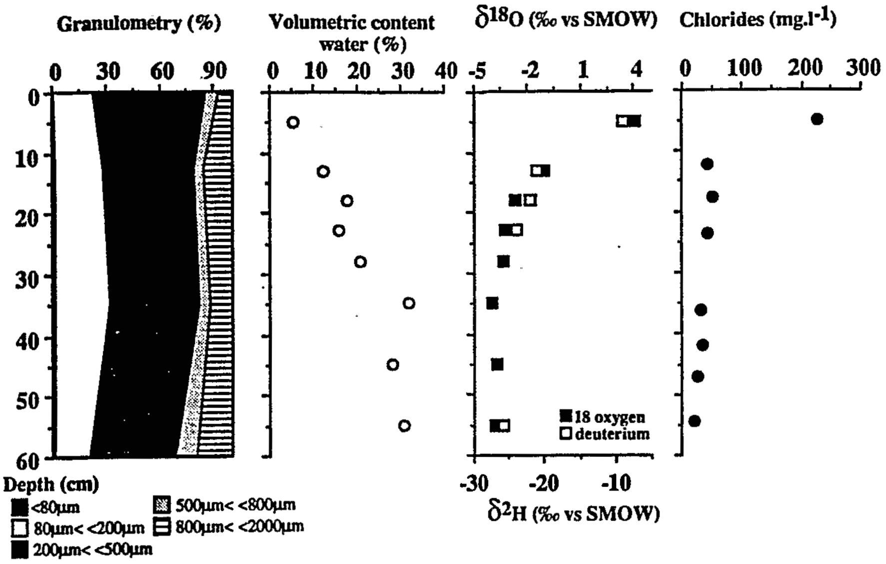


Fig. 4 Characteristics of soils profile in Km-85 site function of depth: granulometry, volumetric water content, isotopic content, chloride.

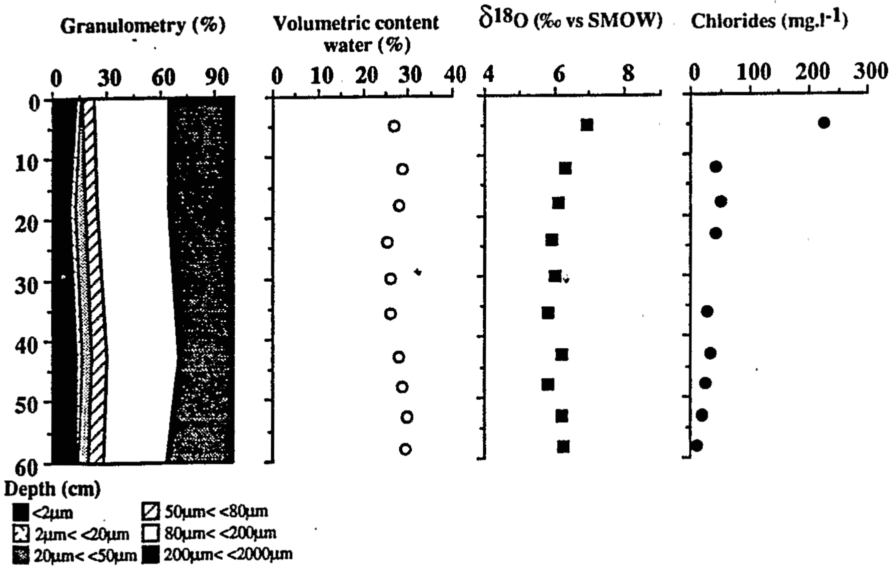


Fig. 5 Characteristics of soils profile in Namari Goungou site function of depth: granulometry, volumetric water content, isotopic content, chloride.

Drought conditions during at least two months preceded the samplings, and the soil moisture reserves, coming from previous rainy seasons, had been strongly reduced (or even eliminated) so the setting up of the moisture profile in the unsaturated zone is largely controlled by the hydrodynamic properties of the soil towards the groundwater. The profiles of water contents reveal an evaporated facies, diminishing strongly from bottom to top in Namarde Goungou and Km-85. In the case of Namari Goungou, soil texture eases capillary raising, which explains the important water contents that can be found up to the top of the profile.

Isotopic content profiles in Namarde Goungou and Km-85 show characteristic profiles of evaporation with, in the case of Namarde Goungou, the presence of two zones of transfer, liquid-vapour and vapour. Chloride profiles are also characteristic; it can be noticed on the Namarde Goungou profile that the chemical evaporation front, situated near the surface, does not coincide with the isotopic evaporation front.

RESULTS OF MODELS

Namarde Goungou site

Isotopic model: The modelling was done in the composite flow transfer zone and in the vapour transfer zone.

Composite transfer zone: As the variation of temperature in soil is weak, the temperature was considered as constant in all the depth, equal to the annual average temperature ($T = 30°C$). The values of the different variables, depending on temperature, are: $N_{sat} = 30.4 \times 10^{-3}$ kg m^{-3}, $D^{i}_{atm} = 0.264 \times 10^{-4}$ m^2 s^{-1} (De Vries & Kruger, 1967), $D^{i}_{liq} = 2.6 \times 10^{-9}$ m^2 s^{-1} (Harris et Woolf, 1980). The function (1) for $\delta_{18}O$:

$$\ln[(\delta_{18_O} - \delta^{res}_{18_O})/(\delta^{ef}_{18_O} - \delta^{res}_{18_O})] = -2.827 * f(z) - 0.292 \tag{8}$$

with $r^2 = 0.98$ and $n = 16$, reveals a linearity good enough to apply the model (Fig. 6). The least well known parameter in equation (2) is tortuosity (0.3 for clay and 0.67 for coarse sand in Barnes & Allison, 1983). As the soil texture is principally composed of medium and fine-grained sand, and little clay, the tortuosity value was estimated between 0.6 and 0.67. The evaporation values obtained, depending on $\tau = 0.6$ or 0.67, range from 18 to 21 mm year^{-1} for a groundwater depth of 3.50 m.

Vapour flow transfer zone: When the relative humidity of the air varies between 20 and 30%, which are the monthly average values observed during the dry season, the evaporation values, calculated from equation (3), range from 11 to 15 mm year^{-1}. As the interval of evaporation values measured in the zones of vapour and combined transfer

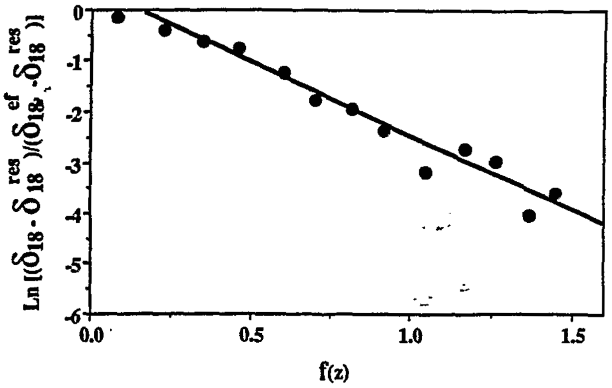


Fig. 6 Isotopic model (profile of Namarde Goungou): relationship between $f(z)$ and $\ln[(\delta_i - \delta_i^{res})/(\delta_i^{ef} - \delta_i^{res})]$.

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Chloride model: Using equation (6), in the profile of Namarde Goungou, χ = 51.9 g m^{-2} and the chloride content of the groundwater is known by sampling in a drilling (C_{res} = 5 g m^{-3}). So the evaporated section, $E_{t\text{-}t0} = \chi(t)/C_{res}$, can be evaluated to about 10 m during 210 days, considering that the last leaching of the profile coincides with the last rainy month (September). Of course, these results show up the weakness of the hypothesis of total leaching of the profile during the rainy season. It is obvious that a large part of the seepage does evaporate before reaching the groundwater. Thus, there would be an addition of chloride into the profile. As there is no total leaching of the profile, the hypothesis of chemical equilibrium in the profile can be tested, so modelling of evaporation with an Allison-typed model for a chloride profile can be used. The diffusivity of chloride, D^{Cl}, into soil from a solution of NaCl at a temperature of 30°C is 1.77 10^{-9} m^2.s^{-1} (in Allison & Barnes, 1985).

As the equation:

$$\ln\{([Cl^-]-[Cl^-]^{res})/([Cl^-]^{ef}-[Cl^-]^{res})]\} = -2.037 * f(z) + 0.066 \qquad (9)$$

where n = 13 and r^2 = 0.97, is linear (Fig. 7), the model can be used.

The evaporative flow, calculated with a tortuosity of 0.67, is 10.2 mm year^{-1}. The evaluation of chloride leads to an evaporation value smaller than that indicated by the evaporation evaluation calculated with the isotopic modelling. That could be due to the errors when measuring chloride content using the leaching method, or to the fact that the chloride profile is not in equilibrium. Indeed, it has been said that the scale of time to create that chloride profile was not one year but the result of the partial accumulation of chloride during many years. Nevertheless, the establishment of an isotopic profile of equilibrium takes place a few months after the rainy season, so the criterion of time scale can be taken into account and it is not certain that the chloride profile has reached a state of equilibrium; then the lower size of the chloride spike compared to the oxygen 18 spike could be linked to a still transitory state of the chloride profile (the diffusion velocity of the two species affects the difference of depths of the spikes). Still, the evaporation value obtained belongs to the range of feasible values.

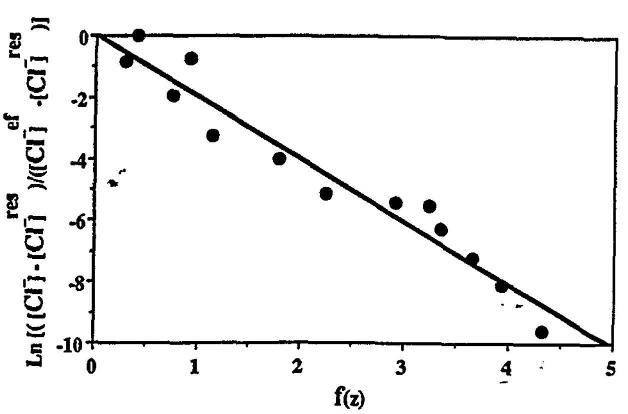

Fig. 7 Chloride model (profile of Namarde Goungou): relationship between $f(z)$ and $\ln\{([Cl^-] - [Cl^-]^{res})/([Cl^-]^{ef} - [Cl^-]^{res})\}$.

The Km 85 site

Isotopic model: Modelling was been done in the composite vapour-liquid flow transfer zone as follows. The function:

$$\ln[(\delta_{18_O}-\delta^{res}_{18_O})/(\delta^{ef}_{18_O}-\delta^{res}_{18_O})] = -9.555 * f(z) - 0.068 \qquad (10)$$

with $r^2 = 0.86$ and $n = 8$ (Fig. 8), is linear enough to apply the model. As the texture is coarse, tortuosity can be estimated close to 0.67. Then the calculation, using such a value, of the evaporative flow across the composite transfer zone gives, at a depth of the groundwater of 0.60 m, a value of 115 mm year^{-1}.

Chloride model: In the case of the Km-85 site, from surface to the groundwater situated at a depth of 0.60 m, the chloride quantity, χ, is 0.78 g m^{-2}. The chloride content of the groundwater is 5.1 g m^{-3}, so the total part evaporated since the last leaching is χ/C_{res} = 152.9 mm. The time interval between the last leaching and the moment of the sampling has been estimated ranging from 70 to 80 days, using pluviometric data of the zone. The ETP (Turc's method) calculated over the three months preceding the sampling, is 5.7 mm day^{-1}. So E_{cum} = 152.9 mm, $E(t_0)$ = 5.7 mm day^{-1}, and the time period between the sampling and the profile's last leaching is available. Thus, K can be obtained from the equation:

$$E_{cum}/E(t_0) = [1 - \exp(-K * T)]/K \qquad (11)$$

and it is reintroduced into equation (5). The values of the constant K (calculated by an iteration method for a calculated evaporation varying at a maximum of 0.5 mm year^{-1}) and of the instantaneous evaporation are:

$t - t_0$ = 70 days K = 0.03376 E = 195.8 mm year^{-1}
$t - t_0$ = 80 days K = 0.03501 E = 126.5 mm year^{-1}

Compared to the values obtained by the isotopic evaluation (115 mm year^{-1}), the results are in the same size order for an 80 day period. So it seems to be important to know local pluviometric data exactly, in order to obtain an evaporation value as exact as possible.

Namari Goungou site

Isotopic model: In the case of Namari Goungou, whose groundwater is at 0.60 m from the surface, the lack of characteristic isotopic profile, due to the shallow depth of the groundwater and especially to the kind of soil, which eases capillary raising, does not allow the modelling of evaporation in good conditions.

Chloride model: The quantity of chloride stored in the profile is evaluated as χ = 7.97g m^{-2} and chloride content of the groundwater is 12.7 g m^{-3}, so the total portion evaporated since the last leaching is χ/C_{res} = 627.6 mm. That profile was sampled at the end of April 1988, so the time interval between the profile leaching and the sampling

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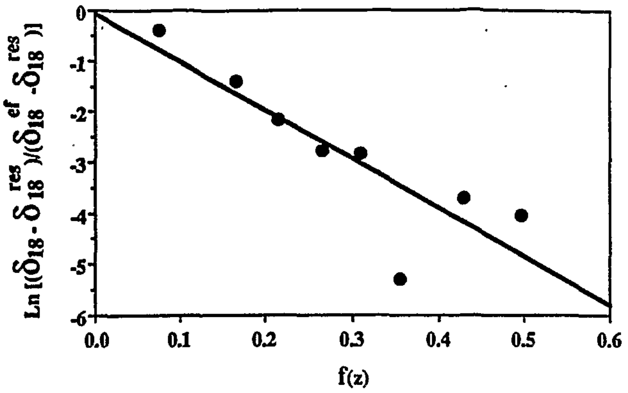

Fig. 8 Isotopic model (profile of Km-85): relationship between *f*(z) and $\ln[(\delta_i - \delta_i^{res})/(\delta_i^{ef} - \delta_i^{res})]$.

moment can be evaluated ranging from 210 to 220 days. The ETP (Turc's method) calculated over the 7 months preceding the sampling is 7 mm day^{-1}.

The values of the constant K and of the instantaneous evaporation are:

$t - t_0 = 210$ days $K = 0.00970$ $E = 333.3$ mm year^{-1}
$t - t_0 = 220$ days $K = 0.00989$ $E = 290.1$ mm year^{-1}

For this profile, important evaporation values are obtained, which seem to be coherent in the case of identical-textured wet soils. The mis-appreciation of pluviometric conditions does not allow the exact determination of the rate of evaporation, but that rate tends to become steady after a long period of dewatering; thus the error gets diminished.

CONCLUSION

The two methods proposed appear to be interesting tools in the case of a Sahelian climate. The isotopic modelling is performs better when the soil is strongly drained, with a flow equilibrium between the atmosphere and the groundwater. Indeed the modelling can be done for the two zones of composite and vapour transfer, which allows one to check the validity of the model. Moreover, only accessible parameters, such as soil characteristics or average meteorological values are used in that model, which reduces the error possibilities. Finally, the method of analysis of the isotopic composition leads to very reliable results. The chloride evaluation method to estimate the evaporation rate of a groundwater is interesting in the case of soil profiles which do not follow an exponential isotopic profile, easing modelling. But it seems to be difficult to obtain a good estimation of evaporation without having any local pluviometric data. All the more, in Sahelian regions where pluviometry is weak, soil chloride leaching at each rainy season can be considered only in the case of soils whose groundwater depth is shallow. In the case of deeper groundwaters, Allison's model applied to chloride can be used; it gives less reliable results, due to the indirect analysis method used (leaching), and to the difficulty of defining a state of chemical equilibrium in the soil.

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