ELSEVIER

Journal of Hydrology 188–189 (1997) 155–178

Journal of Hydrology

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

J.C. Desconnets[a,*], J.D. Taupin[b], T. Lebel[c], C. Leduc[a]

[a]ORSTOM, Laboratoire d'hydrologie, BP 5045, 34032 Montpellier Cedex 1, France
[b]ORSTOM, Groupe PRAO, BP 11416, Niamey, Niger
[c]ORSTOM/LTHE, Groupe PRAO, BP 53, 38041 Grenoble Cedex 9, France

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.

* Corresponding author.

PII S0022-1694(96)03158-7

1. Introduction

The HAPEX-Sahel study area, and more generally the Sahel as a whole, is characterised by an almost permanent water deficit (the precipitation exceeds the potential evapotranspiration only during the month of August) and by a flat landscape, resulting from 100 000 years of erosion. During the dry season, which lasts on average from mid-October to mid-April, the predominant winds (Harmatan) blow from the Sahara desert, transporting large quantities of dust. Locally these winds also move the sand, forming dunes and favouring the blocking of the valley bottoms. The combination of these climatic factors and surface conditions leads to a marked degradation of the drainage network. The surface runoff is extremely intermittent, both in space and time. The lack of large functional watersheds, which would allow for hydrological studies based on spatial integration, is striking. This is especially true for the part of the study area located on the left bank of the Niger River. Over this 7000-km^2 area, the proportion of the yearly precipitation reaching the Niger is of the order of 1–2%. This does not mean that important local runoff is never observed. Peugeot (1995) has observed runoff coefficients of up to 75% at the outlet of runoff plots covering 130 m^2 on the lateritic plateaux. In fact the surface runoff is collected into gullies before spreading into flat sandy areas or reaching small pools formed by the blocking of the pathways into the valley bottoms by sandy deposits. Typically, the topographical watershed of these pools is of the order of 1 km^2. Exceptionally, it may reach 10 km^2. On the lateritic plateaux, pools are also found, but their watershed is smaller (of the order of a few hectares).

The surface hydrology of the Sahel is thus the juxtaposition of hundreds of small endoreic hydrologic systems rarely, if ever, connected to each other, at least in the present climatic conditions. This poses an especially tough problem for the hydrologic component of HAPEX-Sahel. One of the few things hydrologists and atmosphere physicists would easily agree upon is the requirement for any water balance model to calculate a reasonably accurate estimate of the surface runoff component over GCM mesh-size areas. Stating that this component is close to zero at the scale of a 1° square in the Sahel does not help very much the validation usually based on the runoff of one or two large rivers (such as was possible in HAPEX-MOBILHY; Girard, 1984).

Most of the upscaling methods used in hydrology have thus to be reconsidered in the light of this particular environment. The only reliable integrators of hydrological processes are the pools, but their functioning has been little studied before the setting up of HAPEX-Sahel. Previous research in this climatic zone concentrated mainly on large water bodies such as Lake Chad (Vuillaume, 1981), Lac de Bam (Ibiza, 1972; Pouyaud, 1986) or Mare d'Oursi (Chevallier et al., 1985). Beyond research on local runoff, which is presented in this issue by Peugeot et al. (1997), the major challenge of the surface hydrology in HAPEX-Sahel was thus to understand how the pools intervene in the Sahelian water cycle, and how their monitoring could help in computing and modelling the water balance of these regions. A survey of the pools was thus designed using an experimental setup which is presented in Section 2 below. In the following sections, the various mechanisms intervening in the hydrology of the pools are studied: surface runoff reaching the pools (Section 3), infiltration and evaporation (Section 4). It is then shown that the pools play an important role in the recharge of the phreatic aquifers (Section 5). Finally, the prospects of using the pool monitoring for computing the water budget over large areas in the Sahel are presented (Section 6).

2. Experimental setup

2.1. The Central Site hydrologic survey

A study area (hereafter referred to as the PSA: pool study area) of 600 km^2 has been selected (Fig. 1). It includes the East Central Super-Site (ECSS) and a large portion of the West Central Super-Site (WCSS) (see Goutorbe et al., 1994, and Goutorbe et al., 1997, for a description of these sites). This zone is sufficiently large to include the major components of the hydrologic landscape in proportions similar to those holding for the HAPEX-Sahel degree square on the left bank of the Niger river. A preliminary survey carried out after the 1990 rainy season produced an inventory of 40 pools over the PSA. A complementary aerial survey, performed during the 1991 rainy season, led to the detection of another 20 pools or so, which had escaped the first inventory because of their quick drying out (Desconnets et al., 1995). It was then decided to monitor a dozen pools, as part of the HAPEX-Sahel long-term monitoring period (1991–1993). These are a representative sample of the PSA endoreic watersheds. Observations made during the 1991 rainy season identified three basic hydrologic units: (i) plateau pools; (ii) valley bottom pools, installed in the sandy bed of old valleys; (iii) 'sink' pools, so called due to their very rapid drying out (the small watersheds connected directly to the Niger river represent less than 5% of the PSA and were thus not considered).

Among the 15 pools initially chosen (their precise coordinates and periods of measurements can be found in Desconnets et al., 1995), 12 were monitored extensively in 1992 and 1993. One of them (Massi Koubou), equipped with a level recorder, does not belong to the PSA. It is located in the northern part of the 1° square (13°50.31′N, 2°24.56′E) and was selected to compare the influence of the rainfall variability on the hydrologic regime of the pools. The locations of the remaining 11 pools belonging to the PSA are given in Fig. 2. In

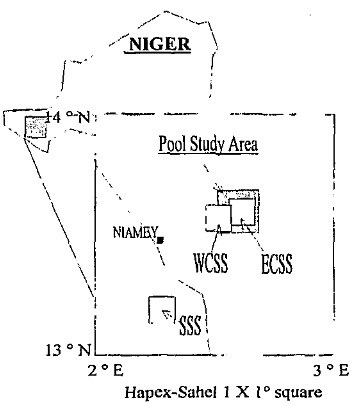

Fig. 1. The HAPEX-Sahel pool study area (PSA).

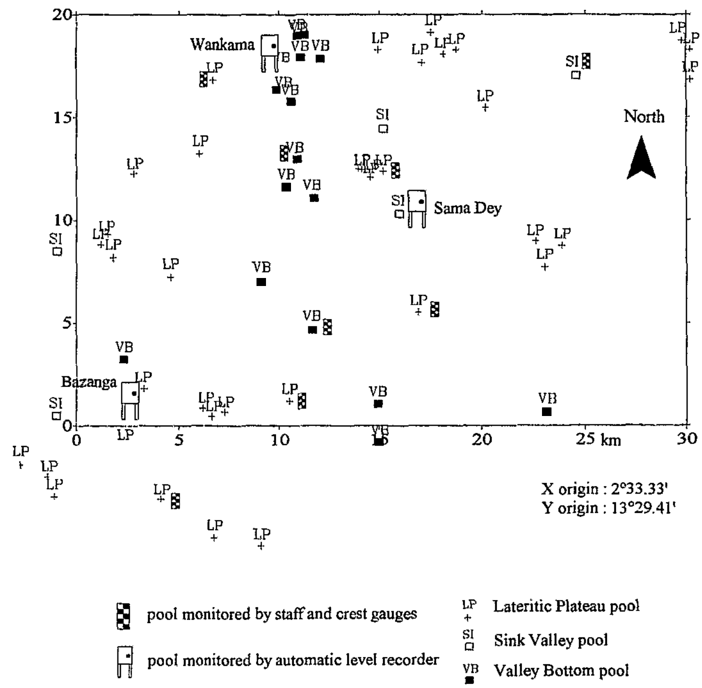

Fig. 2. The main pools of the PSA.

addition to Massi Koubou, four pools were equipped with static memory level recorders, allowing the water level variations to be monitored with an accuracy of 1 cm. The other pools were equipped with staff and crest gauges, readings being taken once a week during the period extending from their first flooding until their drying out. This means a period of between 4 and 9 months, depending on the starting of the rainy season and on the regime of the pool under consideration.

Other measurements taken as part of the hydrologic study of the Central Super-Site (CSS) include rainfall (Lebel et al., 1995), water sampling for chemical and isotopic analysis, pan evaporation measurements, aerial photographic survey (for a detailed overview see Desconnets et al., 1995). In addition extensive monitoring of the phreatic aquifer was carried out over the 1° × 1° square (Leduc et al., 1997) and, finally, one site (Wankama) was equipped with neutron probe access tubes.

Another important component of the field work carried out between 1991 and 1994 is related to the characterisation of the topographic, pedologic and vegetation environment of the instrumented pool sites, all of which are described in Desconnets (1994).

2.2. The reference pools

In this paper we will concentrate on three reference pools equipped with level recorders, each representing one of the three main hydrologic units of the area. The coordinates and

Table 1
Measurement periods of the reference pools

Name	Latitude	Longitude	Location	Gauge	Measurement period
Bazanga[a]	13°30′35″	2°35′11″	Plateau	Level recorder	1991–1993
Wankama[a]	13°39′00″	2°38′91″	Dry valley	Level recorder	1991–1993
Sama Dey[a]	13°35′12″	2°42′07″	Sink	Level recorder	1992–1993
Banizoumbou[a]	13°32′00″	2°39′73″	Dry valley	Staff gauge	1992–1993
Maourey	13°38′12″	2°39′15″	Dry valley	Staff gauge	1992–1993

[a] For these pools the monitoring was continued in 1994.

periods of operation of these sites are given in Table 1, along with those of two others, the data of which are used in Section 5.

Plateau pools, such as Bazanga, are situated on a very flat terrain. Their watershed never exceeds 1 km^2 (0.35 for Bazanga), but the exact area is difficult to determine and may change from one flood to another. The vegetation of the plateaux is a sparse coverage of trees arranged in strips and forming the so-called tiger bush. The maximum extension of the pool itself is of the order of a few tens of thousands of square metres corresponding to a storage volume smaller than 10 000 m^3 in the case of Bazanga. The bed of the pool is rather flat (Fig. 3). The central part of the pool, which is permanently inundated during the rainy season, is clogged with clay, whereas the peripheral zone is mostly sandy, with a decreasing amount of clay when moving away from the centre.

Valley bottom pools, such as Wankama, are situated in the bottom of valleys which, under the present climatic conditions, are reduced to a string of elongated and disconnected depressions. Their topographic watershed is of the order of a few square kilometres (2 for Wankama), but not all the surface runoff generated over this area reaches the pool, due to intermediate flat sandy zones in which the surface runoff often dissipates. The soil is predominantly sand and the vegetation is a mixture of crops (millet) and more or less degraded fallow. At Wankama the maximum extension of the pool, observed between 1991 and 1993, was 36 700 m^2 corresponding to a storage volume of 42 000 m^3. These pools are the most deeply embanked of all (Fig. 3). Here also the central zone is permanently inundated during the rainy season and clogged with clay.

Sink pools, such as Sama Dey, are installed in depressions remaining from very ancient valleys (probably older than the dry valleys of the previous category). Their emptying is much faster than for the two other types of pools, due to preferential pathways that facilitate the deep infiltration of water. Apart from these characteristics, the area, soil and vegetation cover of these pools are very similar to those of the valley bottom pools.

3. Hydrologic regime of the pools

There are two main components of the hydrologic regime of the pools. One is the filling up by surface runoff. The other is the emptying, through drainage and evaporation. The filling stage quickly follows rainfall, which generally begins with the strongest intensities

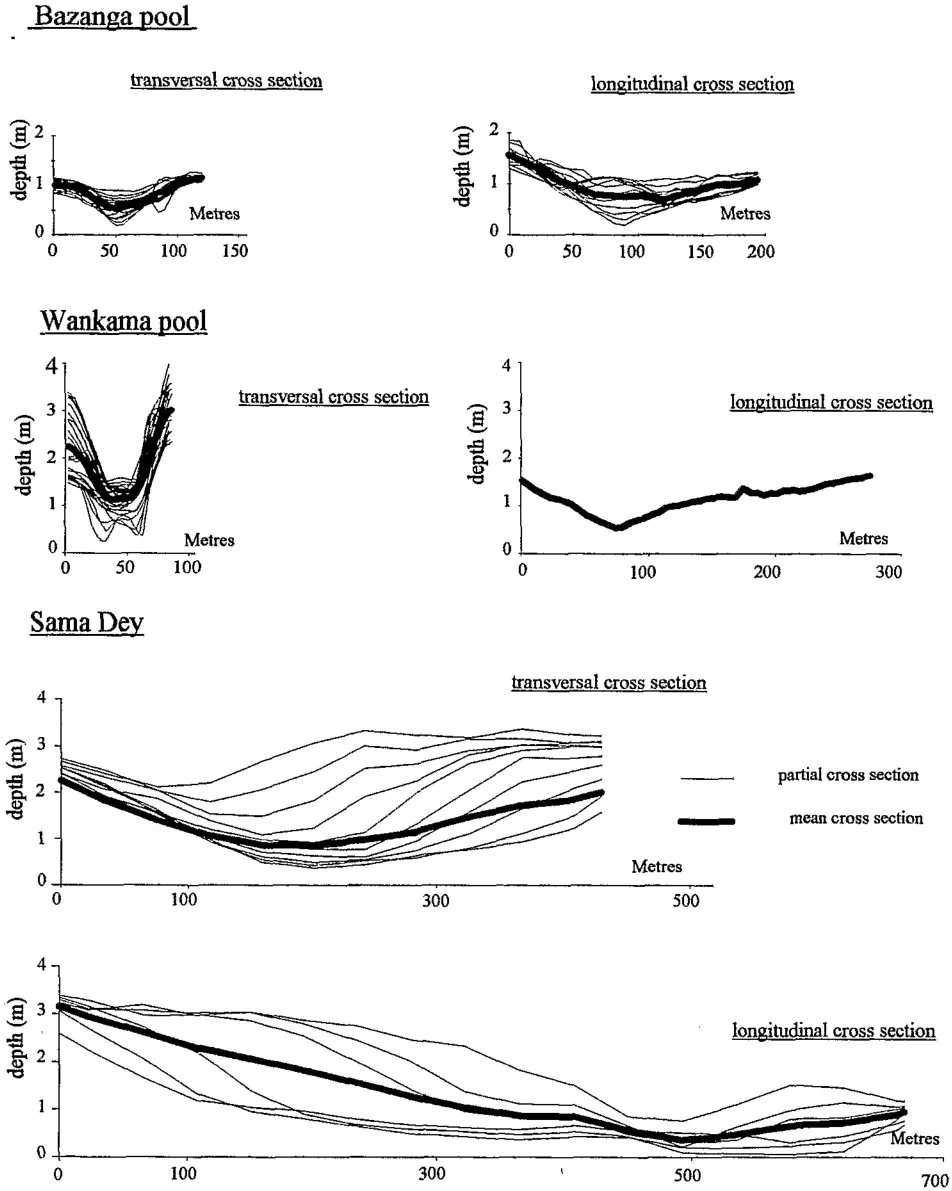

Fig. 3. Topography of the three reference pools. Cross-sections are separated from each other by an average distance of 15 m at Bazanga, 5 m at Wankama, 100 m at Sama Dey.

and last only for a few hours. The emptying stage starts immediately after the end of rainfall and lasts until the next rainfall event producing runoff, which means a few hours in very rare cases, and more generally a few days (Fig. 4).

Runoff studies in the ECSS are presented by Peugeot et al. (1997). They include

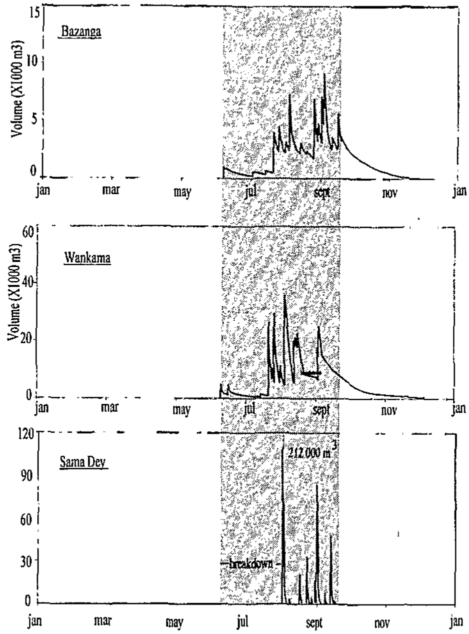

Fig. 4. Level fluctuations of the three reference pools in 1992. An exceptional flood was observed at Sama Dey on 31/7/92. Note the total emptying of the Sama Dey pool between floods. The shaded area represents the period between the first flooding of the pools and the end of the rainy season.

measurements carried out on the reference pools. Rainfall (intensity and distribution) is shown to be the major factor controlling runoff. Runoff is heavier and less sensitive to changes in the time distribution of rainfall on the plateau pools (Bazanga: 23%, 19% and 21% in 1991, 1992 and 1993) than on the valley bottom or sink pools (Wankama: 3%, 15% and 10% in 1991, 1992 and 1993). These figures confirm that a significant amount of the precipitated water ends up in the pools. We will concentrate below on studying how this water is subsequently recycled towards the atmosphere and the aquifer.

The emptying regimes of most of the pools studied have a common pattern. After the end of rainfall the water depth begins to diminish at a strong, but decreasing, speed until the level has reached a value that is somewhat the same for every event (Figs. 5 and 6). At that point the emptying rate reduces dramatically. There is thus a threshold separating a zone of rapid emptying and a zone of slow emptying. The value of this threshold is about 0.9 m for Bazanga and 1.5 m for Wankama. The only possible cause for such a break in the emptying rate is a change in the permeability of the pool substratum. Field observations confirm this assumption, by showing that the depth threshold corresponds to the edge of the clay-clogged area at the centre of the pool. The first stage of the emptying is thus very likely associated with an important infiltration through the flooded sandy zone, while below the threshold, the infiltration plays a lesser role. The contribution of the infiltration to the emptying of the pools will be quantitatively assessed in the next section. Note that the Sama Dey pool does not present a final stage of low emptying rate and dries out totally in a few days. In that case (as for all the sink pools) the infiltration accounts for almost the

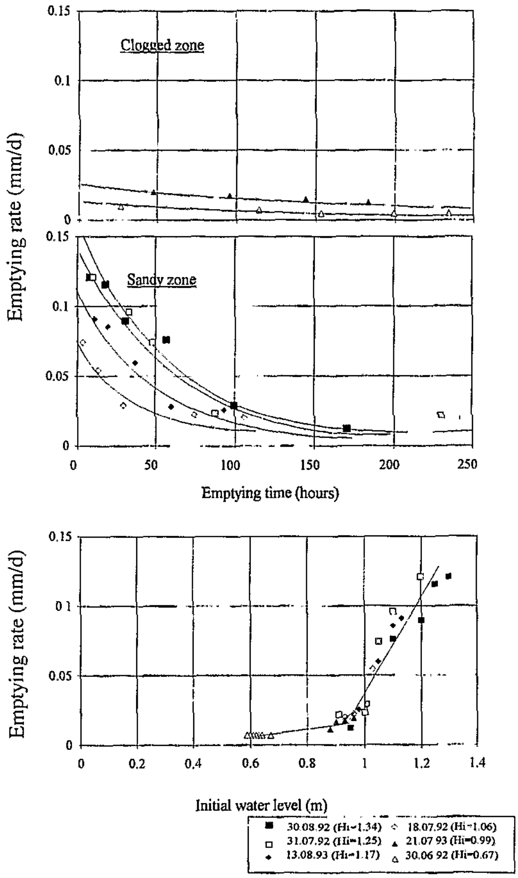

Fig. 5. A sample of six characteristic emptying curves at Bazanga. For two events (30/6/92 and 21/7/93) the maximum level remained below the limit of the clogged zone.

totality of the water losses. By contrast, water is present until a few weeks after the last rainfall at Bazanga and for at least 3 months after the last rainfall at Wankama, which gives time for evaporation to contribute to the emptying. In Figs. 5 and 6 it should also be noted that at the beginning of the rainy season, the first floodings may not reach the permeability threshold (events of 30/6/92 and 21/7/93 at Bazanga and events of 10/8/1991 and 8/7/1993 at Wankama).

4. Water budget of the pools between rainy events

4.1. Statement of the problem

The water budget of the pools between rainy events consists of two terms: evaporation and infiltration. In most former studies dealing with Sahelian surface water reservoirs,

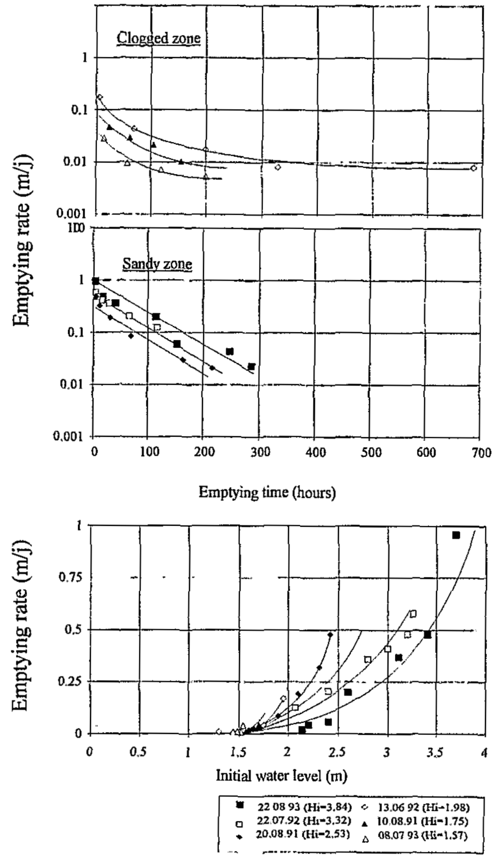

Fig. 6. A sample of six characteristic emptying curves at Wankama. For two events (10/8/91 and 8/7/93) the maximum level remained below the limit of the clogged zone.

infiltration was more or less explicitly considered as negligible (see e.g. Riou, 1975, and Brunel and Bouron, 1994). Given the fast emptying observed shortly after flooding, as described in Section 3, this hypothesis can hardly be accepted a priori for the small reservoirs of the Niamey area. A major difficulty arising when trying to assess the respective contributions of evaporation and infiltration in the emptying of the pools is that neither process is directly measurable. During the rainy season, the frequent cycles of flooding/drying up make it especially difficult to estimate the evaporation, for several reasons: (i) the meteorological parameters conditioning the release of water to the atmosphere change rapidly; (ii) the flooding of the pools brings new water, the composition of which is likely to be different from that of the water remaining in the pool from the previous floodings; (iii) the partitioning between infiltration and evaporation changes rapidly with the fast decrease of the pool water level. Point (i) is an impediment to the utilisation of energy budget methods; Point (ii) is an impediment to the utilisation of chemical/isotopic analysis methods; Point (iii) prevents reliance on linear correlations between the evaporation and the variations of the level of the pool, since the ratio between evaporation and infiltration is not constant. Consequently it is during the dry period following the end of the rainy season that evaporation can be best studied, for only the central and clogged zone of the pool is flooded. The infiltration is thus reduced and its rate varies little. Several methods were tested for estimating the evaporation during this period: pan measurements, chemical survey and isotopic survey. Methods based on the energy budget could not be considered because the area of free water is too small and the fetch of the atmospheric parameters would include land areas.

4.2. Assessment of the evaporation during the dry season based on isotopic analysis

It was shown by Desconnets et al. (1993) and Desconnets (1994) that the chemical survey did not provide adequate data, due to anthropic interference (mainly cattle) modifying the composition of the water and the possible fixing of chemical elements by clay particles. On the other hand the evolution of the isotopic composition in oxygen 18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$) is directly linked to the evaporation and is not influenced by cattle watering or clay adsorption. It is the only reliable method based on data coming from the pool itself. The evaporation rate computed from the isotopic survey can then be compared with pan measurements, in order to provide reasonable ratios to convert pan evaporation into pool evaporation when no isotopic data are available.

In a water body subjected to an evaporation process the ^{18}O and ^{2}H contents will increase with time. This enrichment originates in the isotopic fractioning between the evaporated vapour phase and the remaining liquid phase. It depends on two parameters: an equilibrium enrichment factor depending only on the air temperature and a kinetic enrichment factor function of the atmospheric conditions (turbulence, temperature, relative humidity). The isotopic composition of the water entering the pools is known through an extensive campaign of rainwater analysis, which yielded the following equation relating the ^{2}H content to the ^{18}O content (Desconnets and Taupin, 1993):

$$\delta^{2}H = 8.11\delta^{18}O + 5.82 \qquad (1)$$

Note that the slope of this regional meteoric line (RML) is close to that of the world meteoric line (WML), equal to 8.

The isotopic survey of the Bazanga and Wankama pools, carried out in 1991 and 1992 from the end of the rainy season to the complete drying out of the pools (this survey was impossible on Sama Dey, since this pool dries out in a few days), leads to the following equation:

$$\delta^{2}H = 4.53\delta^{18}O - 11.53 \qquad (2)$$

The slope here is significantly smaller than that of the RML (Fig. 7), and is characteristic of the evaporation from a water body (Fontes, 1976). While the relationship between the ^{2}H content and the ^{18}O content is the same for the two pools, the isotopic enrichment, as well as the conductivity, of the valley bottom pool (Wankama) is much smaller than that of the plateau pool (Bazanga) for the same fraction of remaining water, as may be seen from Fig. 8. This implies a smaller evaporation rate from Wankama and, consequently, a greater

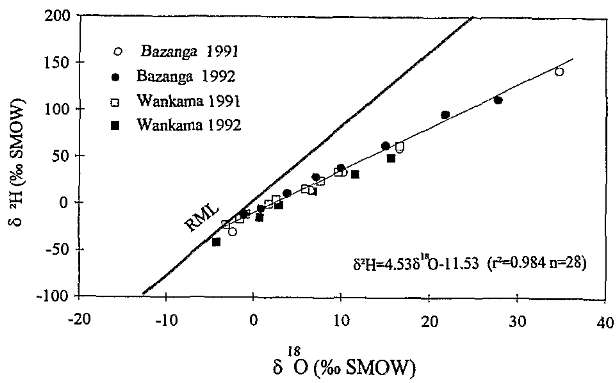

Fig. 7. Relationship between oxygen 18 and deuterium isotopic contents for the Bazanga and Wankama water. The slope is much smaller than that of the regional meteoric line, due to evaporation. SNOW, standard mean ocean water.

infiltration rate. This first qualitative result is in agreement with the hypothesis that could be made from the description of the hydrologic regimes in Section 3.

The Raleigh distillation law, which accounts only for the equilibrium enrichment process has been tested by Desconnets and Taupin (1993). They have shown that this model could not fit properly the evolution of the isotopic contents for fractions of remaining water below 0.2. Thus, the model proposed by Craig and Gordon (1965), which takes into account both the equilibrium and the kinetic processes, is used here. Its general expression is:

$$\frac{\partial \delta}{\partial \ln f} = \frac{h_a(\delta - \delta_a) - (\delta + 1)(\Delta\varepsilon + \varepsilon/\alpha)}{1 - h_a + \Delta\varepsilon} \tag{3}$$

where δ is the isotopic composition at time t, f is the remaining fraction of liquid water, h_a is the mean relative air humidity, δ_a is the isotopic composition of the air, α is the isotopic fractioning factor between the liquid and the vapour phases, $\varepsilon(\varepsilon = 1 - \alpha)$ is the isotopic enrichment at the equilibrium (function of the air temperature), and $\Delta\varepsilon$ is the kinetic

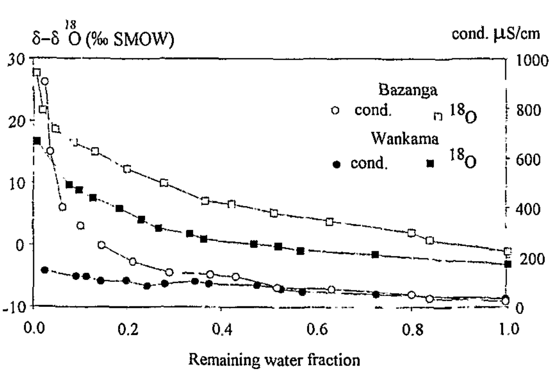

Fig. 8. Evolution of the conductivity and isotopic enrichment of the water remaining in the pool during the final period of drying out.

isotopic enrichment. By assuming that h_a, δ_a, α, ε and $\Delta\varepsilon$ are constant over the drying period, integrating Eq. (3) yields:

$$\delta = \left(\delta_0 - \frac{A}{B}\right) f^B + \frac{A}{B} \tag{4}$$

where δ_0 is the initial isotopic composition ($t = 0, f = 1$) and with:

$$A = \frac{h_a\delta_a + \Delta\varepsilon + \varepsilon/\alpha}{1 - h_a + \Delta\varepsilon} \text{ and } B = \frac{h_a - \Delta\varepsilon - \varepsilon/\alpha}{1 - h_a + \Delta\varepsilon} \tag{5}$$

When infiltration is present along with evaporation, Eq. (4) becomes:

$$\delta = \left(\delta_0 - \frac{A}{B}\right) f^{Bz} + \frac{A}{B} \tag{6}$$

where $z = Q_{evap}/(Q_{evap} + Q_{inf})$ (Gonfiantini, 1986), Q_{evap} and Q_{inf} being, respectively, the cumulative losses by evaporation and infiltration between times $t = 0$ and t.

The parameters of the model depending on the atmospheric conditions were computed using the average air temperature from the Banizoumbou station (29°C) this temperature varying little during the period of interest (Goutorbe et al., 1994). By contrast the monthly mean relative humidity decreases from 73% in September to 34% in November and this was accounted for by running the model on a monthly time step. The isotopic parameters α and ε are set equal to 1.00907 and 0.00907, after Majoube (1971), and $\Delta\varepsilon = 14.2(1 - h_a)$, after Gonfiantini (1986). The isotopic composition of the atmosphere, δ_a, was taken as equal to 17‰ (Colin-Kaczala, 1986). Once the values of the isotopic parameters have been set, the parameter z is determined by minimising the following error function between observed ($\delta_0^{18}O$) and computed ($\delta_m^{18}O$) values of the ^{18}O composition:

$$E(z) = \sqrt{\sum_{i=1}^{n} (\delta_m^{18}O(z) - \delta_0^{18}O)^2} \tag{7}$$

where n is the number of observations (water analysis) during the drying period.

As may be seen from Fig. 9, the minimum of the function $E(z)$ is easily identified, with z^*, the value at the optimum, equal to 0.7 for Bazanga (70% of the water present in the pool at the beginning of the dry season evaporates) and 0.3 (only 30% of the water present in the pool at the beginning of the dry season evaporates) for Wankama. The fit between

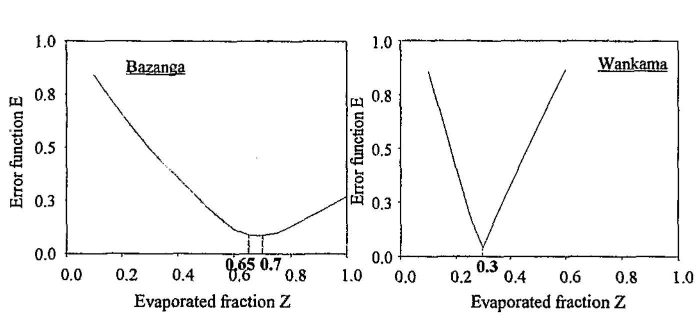

Fig. 9. Determination of the evaporated fraction z, by minimisation of the error function of the Craig and Gordon (1965) model.

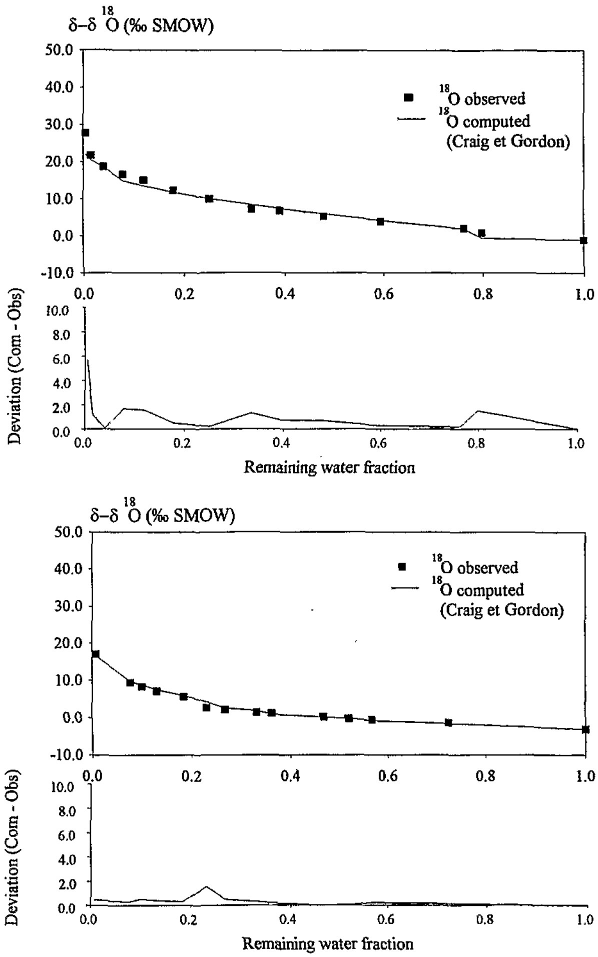

Fig. 10. Observed and computed isotopic contents using the Craig and Gordon (1965) model for Bazanga (top, $z = 0.7$) and Wankama (bottom, $z = 0.3$).

observed and computed values is excellent (Fig. 10), except for the very end of the drying out period. At this stage the error in the computation of the remaining fraction of water and the influence of cattle watering becomes significant, which may explain this deviation. It has a negligible impact on the estimation of the total evaporated and infiltrated fractions.

From Table 2 it can be seen that the clogged zone represents 13% only of the area of maximum extension at Wankama, against 57% at Bazanga, which explains the much larger ratio of infiltrated water computed for Wankama.

4.3. Correction of pan measurements for the estimation of the pool evaporation

The results of the isotopic analysis can be compared with the pan measurements in order to provide a transposition coefficient with which to estimate pool evaporation from pan

Table 2

The reference pools, equipped with level recorders

Name	Watershed area (km^2)	Difference in altitude (m)	Maximum extension (1991–1993)		Clogged zone	
			Surface (m^2)	Volume (m^3)	Surface (m^2)	Volume (m^3)
Bazanga	0.35	3	20600	9100 (30/8/92)	11700 (57%)	3000 (33%)
Wankama	2.2	50	36700	42000 (22/8/93)	4600 (13%)	1500 (3.6%)
Sama Dey	6.3	30	135300	212000 (31/7/92)	0	0

Table 3

Comparison between pan measurements and the isotope based estimation of the pool evaporation during the 1992 drying out

	Bazanga			Wankama		
	Total losses 23/9–23/11: 2360 m^3			Total losses 24/9–30/11: 5650 m^3		
	Total (mm)	Daily rate ($mm\ d^{-1}$)	% of total losses	Total (mm)	Daily rate ($mm\ d^{-1}$)	% of total losses
In situ pan	468	7.6	81	426	6.3	42
Class A pan	608	9.8	105	660	9.7	65
Isotopes	406 (1670 m^3)	6.6	70	306 (1695 m^3)	4.5	30

evaporation when only such data are available. For each pool, two series of pan measurements are considered: one comes from an in situ sunken pan filled up with the water of the pool; the other is a Class A pan located at the Niamey Airport Meteorological station which provides a regional reference and the only measurement routinely available. Table 3 shows that both pans overestimate the evaporation, which was expected, given the strong oasis effect in such a dry and hot climate. The overestimation is especially large for the Class A pan, which is more sensitive to the oasis effect and is filled with clean water, the albedo of which is smaller than that of the muddy pool water used for the in situ pan. The pan measurements nevertheless allow the detection of the large difference between the evaporated fraction of Bazanga (81% for the in situ pan) and that of Wankama (42% for the in situ pan).

In order to compute a transposition factor between the regional evaporation index provided by the Class A pan (E_A) and the actual pool evaporation obtained by the isotopic method (E_p), the evaporation was estimated with the two methods over each interval between two successive water samplings. Imposing that the relationship between the two estimates goes through the origin, yields the following:

$$\text{Bazanga}: \quad E_p^* = 0.67 E_A, \quad (\sigma = 0.08; n = 18) \tag{8}$$

Fig. 11

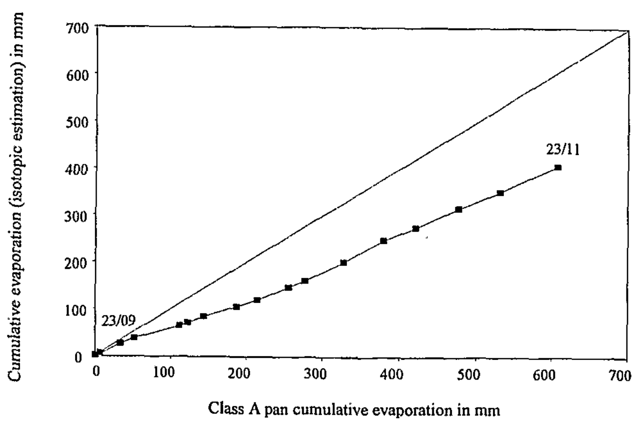

Fig. 11. Pool evaporation (as computed by the isotopic method) versus Class A pan evaporation (Bazanga).

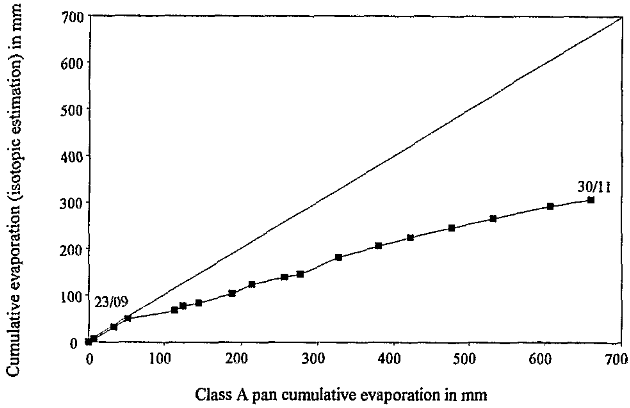

Fig. 12. Same as Fig. 11 except for Wankama.

$$\text{Wankama}: \quad E_p^* = 0.46E_A, \quad (\sigma = 0.18; n = 18) \tag{9}$$

Fig. 12

A smaller coefficient is found for the valley bottom pool, which is larger and shielded by the topography and the vegetation as compared with the plateau pool. These transposition factors are much smaller than those usually found in the literature for similar climates which are close to 1.0 for small reservoirs (a few hectares) and between 0.6 and 0.8 for large water bodies (e.g. Ibiza, 1972; Vuillaume, 1981; Chevallier et al., 1985; Cogels et al., 1991). It thus appears critical to take into account the infiltration when computing the water budget of the Sahelian pools.

4.4. Seasonal water budget

For the valley bottom pool 70% of the water present in the pool at the onset of the dry season is lost through infiltration. This volume of water represents only 4% of the total amount of water collected by the pool during its seasonal cycle. The other 96% is infiltrated and evaporated during the rainy season, a period when the estimation of the evaporation is difficult. We may nevertheless consider in a first step that the transposition factors computed for the dry season may be applied to the rainy season, in order to get a rough estimate of the total amount of water lost by the pool during the rainy season, based on the Class A pan measurements. Applied to the 1992 season, this approach yields an

Table 4
Water budget (in m^3) of the Wankama pool for 1992

	Rainy season (11/4–23/9)	Dry season (24/9–30/11)	Global (11/4–30/11)
Total losses	138780	5650	144430
Evaporation	5405 (4%)	1695 (30%)	7100 (5%)
Infiltration	133375 (96%)	3955 (70%)	137330 (95%)

Table 5
Water budget (in m^3) of the Wankama pool for 1993

	Rainy season (14/6–19/9)	Dry season (19/9–9/1/94)	Global (14/6/93–9/1/95)
Total losses	62770	32760	95545
Evaporation	3800 (4%)	4730 (15%)	8545 (9%)
Infiltration	58970 (96%)	28030 (85%)	87000 (91%)

estimate of 5000 m^3, value computed between the 11.04 and the 23.09. Over the same period the total amount of water collected and then lost by the pool is about 140 000 m^3, which means that the fraction of evaporated water is of the order of 5% of the losses during the rainy season. With such a small figure, it appears that a very precise estimate of the evaporation (such as the one obtained for the dry season) is not an absolute requirement when it comes to computing the water budget. An error of 50% on the evaporation estimate would translate into an error of less than 5% on the volume of infiltrated water during the rainy season or over the whole period of life of the pool. The water budget of the Wankama pool for each period, both in absolute values and in percentage, is given in Table 4 (1992) and Table 5 (1993). The major component of this budget is the infiltration (94% of the water collected by the pool during the rainy season). It has to be noted that the total drying out of the pool occurs only 10 weeks after the 30/11, but the water that remains in the pool at that date represents less than 1% of the total volume collected and subsequently lost by the pool during the whole period.

The same approach leads to the computation of a much smaller fraction of infiltrated water for Bazanga (85% in 1992, Table 6 and 84% in 1993, Table 7). This is due both to a smaller infiltration rate from the clogged zone (smaller infiltration fraction in the dry season) and to the previous sandy zone of temporary flooding being smaller (smaller infiltration fraction in the rainy season). It should be noted that, during the rainy season, the evaporation accounts for less than one fifth of the emptying of the pool. The infiltrated water is stored in the sandy soil between the surface and the impervious lateritic layer, allowing the growth of a denser vegetation around the pool.

5. Recharge of the aquifer and regional water balance

5.1. The phreatic aquifer of the pool study area

A large proportion of the water collected by the pools infiltrates, either below the pools

Table 6
Water budget (in m^3) of the Bazanga pool for 1992

	Rainy season (11/4–22/9)	Dry season (23/9–23/11)	Global (11/4–23/11)
Total losses	32140	2360	34500
Evaporation	4740 (15%)	1650 (70%)	6390 (19%)
Infiltration	27400 (85%)	710 (30%)	28110 (81%)

Table 7
Water budget (in m^3) of the Bazanga pool for 1993

	Rainy season (7/7–18/9)	Dry season (19/9–4/12)	Global (7/7–4/12)
Total losses	26418	2682	29100
Evaporation	4172 (16%)	1633 (61%)	5805 (20%)
Infiltration	22246 (84%)	1049 (39%)	23295 (80%)

(permanently inundated zone) or on the sides (temporary flooded zone). The question is then raised of what happens subsequently to this water. Obviously part of it is used by the vegetation which is denser around the pools than elsewhere. However, the area of dense vegetation has a relatively small extension and its evapotranspiration cannot account for all the water losses from the pools. It thus quickly becomes evident that these losses contribute to the recharge of the aquifer.

The 3-year survey of more than 300 wells has revealed the major role of the pools in the aquifer recharge: the largest variations of the phreatic level are observed in the vicinity of the pools and they diminish with distance from the pool (Leduc and Desconnets, 1994a). Moreover the time lag between pool floodings and aquifer level risings is at a minimum near the pools, and increases away from the pools.

The PSA is one of the most homogeneous parts of the phreatic aquifer: the hydraulic gradient is very weak (often less than 4×10^{-4}), the piezometric fluctuation is small (median is 30% lower than that of the whole degree square), the hydrochemical composition is rather constant. This region belongs to a large closed piezometric depression which seems to correspond with the fossil river bed of the Dantiandou kori.

Three sites along the kori of Dantiandou have been equipped with automatic level recorders for a detailed survey of interactions between pools and aquifer: Wankama (three piezometers and two wells), Maourey Kouara Zeno (one well, pool not monitored), Banizoumbou (two piezometers and two wells). Elsewhere, the piezometric survey consists of measurements in village wells.

In spite of an apparent homogeneity of the kori of Dantiandou regarding geomorphology or geology, the response of the aquifer to the rain infiltration is very variable. For instance, the maximum fluctuation of the phreatic level in 1993 is about 5.4 m in Wankama, 0.7 m in Banizoumbou and 0.3 m in Maourey (Fig. 13). In the same way, the aquifer rises early in Banizoumbou (mid-June) and much later in Wankama and Maourey (end of July). At a distance of 500 m from the pool, the infiltration impact is not measurable in Banizoumbou whereas it exceeds 2 m in Wankama. Since the vertical distance between the pool bottom and the water level is comparable in the three cases (between 15 and 20 m), these differences are explained by variations in infiltrated volumes and hydrodynamic characteristics of both the saturated and unsaturated zones. From pumping tests, the *T/S* ratio (transmissivity/storativity) is about 0.03 $m^2\ s^{-1}$ in Banizoumbou. From an analytical calibration of the response to infiltration in the different Wankama piezometers, this *T/S* ratio is estimated between 0.05 and 1 $m^2\ s^{-1}$. Also, the estimate of infiltrated volumes, based on the water budget of the pools, is 87 000 m^3 in Wankama and 38 000 m^3 in Banizoumbou.

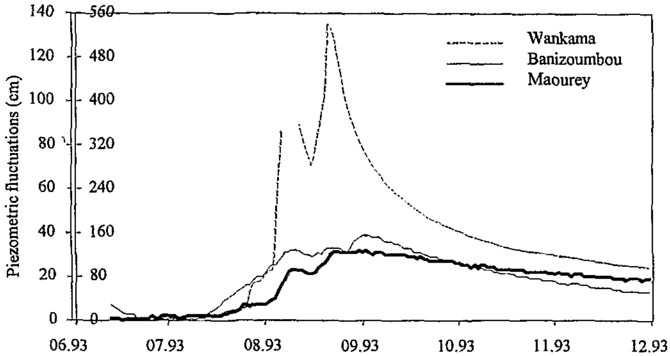

Fig. 13. Piezometric fluctuations for three valley bottom pools in 1993. The left scale of the vertical axis is for Maourey and Banizoumbou, while the right scale is for Wankama.

5.2. Recharge from a valley bottom pool: the Wankama case study

The Wankama area appears as a small mound on the piezometric map, which points to the importance of this site in the recharge processes. There is no higher annual fluctuation in the CSS. The three piezometers (P1, P2 and P3) are aligned perpendicular to the pool axis at distances of 30, 80 and 180 m from the pool level recorder, respectively. For all 3 years of observation (1992, 1993 and 1994) it was observed that the first floods of the rainy season have no impact on the groundwater level which continues to decrease very slightly until July (see the example of 1993 in Fig. 14), even though the rain depths and chronology

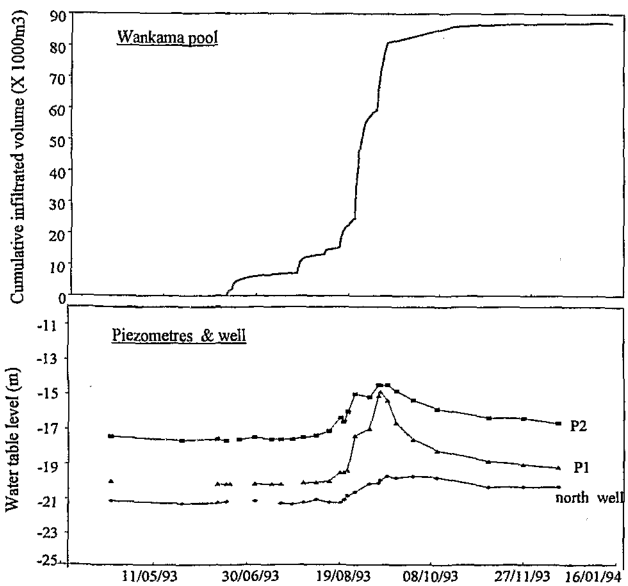

Fig. 14. Cumulated infiltrated volume of water from the Wankama pool (top) and corresponding piezometric fluctuations for two piezometres and the northern well (1993).

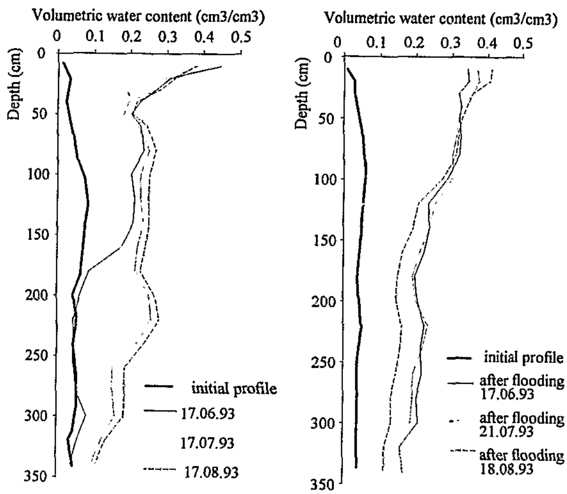

Fig. 15. Soil moisture profiles below the Wankama pool, as determined by neutron probe measurements. The left profile is below the clogged zone while the right one is below the sandy zone which is temporarily inundated after a rainfall event.

recorded were different each year. The aquifer begins to respond to the flooding of the pool at the end of July, at first weakly and slowly. Then the response becomes larger and faster. The time lag between the beginning of level rise in the pool and in the different piezometers is 2 to 6 h in P1 for the first floods (4 to 7 h in P2) and half that for the last events. In 1993, the total rise of the aquifer was 5.4 m in P1, 4.4 m in P2 and 2.8 m in P3; in 1994, it was 5, 4 and 2.6, respectively.

In fact, it appears that the rise of the aquifer is correlated to the cumulative infiltrated water rather than to the absolute water level in the pool (Fig. 14). In 1993 monitoring of the unsaturated zone below the pool with two neutron probe access tubes was started. That year it took until the end of June to saturate the first 8 m below the pool. Afterwards this zone remained saturated until the end of the rainy season (Fig. 15). It is thus a reasonable assumption to consider that it takes an additional few weeks (say between 2 and 4 depending on the rainfall) to saturate the remaining 8 m down to the aquifer. It is only when the whole column of soil between the pool and the aquifer is saturated that the aquifer starts to respond almost immediately to flood events.

A first attempt at a numerical modelling of the Wankama area led to an estimate of effective porosity lower than 10% and a transmissivity higher than 10^{-3} m^2 s^{-1}. With such figures, it was possible to estimate a volume of water reaching the aquifer which is similar to the computed volume infiltrated from the pool. There are still a number of uncertainties in the results of this modelling, however, which prevent the reaching of a definite conclusion regarding the exact recharge from the pool.

5.3. The role of the pools in the regional water balance

The pools concentrate precipitated water running off the fields and facilitate its infiltration deep into the soil below and around the permanently inundated central zone, allowing

Table 8
Water budget (in mm) of the Bazanga watershed 1991–1993. Figures between brackets refer to a partial total (lacunes in the level recording)

	1991	1992	1993
Precipitation	(150.5)	504.2	(387.5)
Runoff into the pool	34.8 (23%)	98.7 (19.6%)	83.1 (21.5%)
Evaporation from the pool	11.6 (6%)	18.3 (3.6%)	16.6 (4.3%)
Infiltration from the pool	25.6 (17%)	80.4 (16.0%)	66.6 (17.2%)

some of it to reach the aquifer. Leduc and Desconnets (1994b) estimate that, in 1992, which was close to normal as far as the seasonal cumulative rainfall is concerned, about 10% of the precipitation contributed to the recharge of the aquifer, which means an average of 50 mm over the left bank aquifer study area (7000 km^2). Now, the in situ percolation below the neutron access tubes on the HAPEX-Sahel WABs of the ECSS rarely exceeds 30 to 40 mm. Given that the depth of these tubes was limited to 4 m, it is very likely that some of this water was used by the vegetation during the dry spells and after the end of the rainy season. Thus, the in situ recharge is probably limited to less than 10 mm, if it occurs at all. The major role of the pools in the Sahelian water cycle is thus clearly to increase the recharge of the aquifers, making up for the difference between the in situ field recharge and the average recharge over large areas.

This role is enhanced or inhibited by the rainfall distribution. Tables 8–10 show the water budget of the Bazanga and Wankama pools for 1991, 1992 and 1993, for 1992 and 1993 only at Sama Dey. On the plateau, the water that infiltrates from the pool is roughly equal to 16–17% of the areal precipitation on the watershed and does not vary substantially from one year to another. By contrast this figure varies from 3 to 15% at Wankama, as a result of the difference in the runoff coefficient. The comparison between 1992 and 1993 is especially interesting since the total seasonal rainfall was identical and the infiltration ratio was twice as large in 1992. The difference is still larger on Sama Dey, confirming higher runoff in 1992 (note that the 1992 computation bears on 75% of the season only, which means that the precipitated water depth infiltrated from the pool must be at least equal to 80 mm). As shown by Lebel et al. (1997), the rainfall time distribution in 1992 was especially far from normal, with most of the rainfall concentrated during the last 15 days of July and the last 15 days of August. This brought heavy runoff and floodings of the valley and sink pools and favoured an above-normal infiltration from the pools.

Not all the water infiltrated from the pools goes to the aquifer however. In fact there is likely very little recharge from the plateau pool, given the presence of a double layer of

Table 9
Same as Table 8, except for Wankama

	1991	1992	1993
Precipitation	(351.5)	463.8	463.0
Runoff into the pool	10.4 (3.0%)	67.0 (14.4%)	44.7 (9.7%)
Evaporation from the pool	*1.1 (0.3%)*	*3.4 (0.7%)*	*4.0 (0.5%)*
Infiltration from the pool	9.1 (2.6%)	63.6 (13.7%)	40.5 (8.1%)

Table 10
Same as Table 9, except for Sama Dey

	1991	1992	1993
Precipitation	–	(314.7)	404.5
Runoff into the pool	–	71.5 (22.7%)	28.8 (7.1%)
Evaporation from the pool	–	0.8 (0.3%)	0.4 (0.1%)
Infiltration from the pool	–	70.7 (22.4%)	28.4 (7.0%)

clay and hardened soil between the bottom of the pool and the aquifer (Desconnets et al., 1994). On the other hand the quick emptying of the sink pools makes it probable that a great deal of the water infiltrated from the pools contributes to the recharge of the aquifer. The valley bottom pools constitute an intermediate case. The piezometric data presented in Section 5.2 clearly show a recharge higher in 1992 than in 1993, but only a careful modelling of the aquifer will allow the more precise assessment of how much of the 64 mm of areal precipitation infiltrated from the Wankama pool went to the aquifer.

6. Conclusion

The only reliable hydrologic integrators of the HAPEX-Sahel degree square are small pools, draining watersheds whose area ranges from a few hectares to a few square kilometres. The study of three reference pools, representing the three main hydrologic units of this zone, namely plateaux, valley bottoms and sinks, has led to a first set of results that are summarised below.

Field studies have first shown that both plateau and valley bottom pools share a similar emptying regime. After a flood event that replenishes the pool, a stage of a fast decrease in the water level in the pool is observed. During this stage the dominant process is infiltration. It is followed by a period of slow decrease, the infiltration being weakened by the clogged substratum in the central area of the pool. Evaporation then plays a larger role.

An isotopic survey, carried out in 1991 and 1992, allowed the confirmation of this scheme and the quantification of the evaporation during the final emptying stage of the dry season. While the evaporation is dominant in the plateau pools (70% of the dry season losses) it accounts for only 30% of the dry season losses in the valley bottom pools and almost zero in the sink pools which are emptied in a few days after the last rainfall. It is thus impossible to neglect the infiltration when studying the evaporation from small reservoirs in the Sahel and the correction factors used for estimating the pool evaporation from a reference Class A pan evaporation are much smaller than those computed in previous studies. While correction factors between 0.8 and 1.0 were usually given, the value found here is 0.67 for a plateau pool and 0.46 for a valley bottom pool.

The role of the pools in increasing the recharge of the aquifers has also been shown, both from piezometric data in the vicinity of the reference valley bottom pool and from the water budget computed for the watershed in 1991, 1992 and 1993. One can estimate that, on average, 10 to 20 mm of the total areal precipitation over the plateau watershed will infiltrate from the corresponding pool. In the valley and sink pools the precipitated water depth liable to infiltrate from the pool ranges from 10 to 80 mm, the actual value being mostly conditioned by the rainfall distribution in time. A large proportion, even if not precisely determined at that stage of the study, of this water contributes to the recharge of the aquifer.

Acknowledgements

The extension of the area covered by this study and the diversity of the methods used required the collaboration of people belonging to several institutes from different countries. It is impossible to name all those who supported or participated in this programme. However, we wish to mention here the late J.C. Fontes who invited us to use the facilities of his laboratory for the isotope analysis, S. Galle, from ORSTOM, who installed the neutron access tubes at Wankama and organised the measurements and P. Schroeter from DRE (Niger) who, on the same pool, spoiled some time and equipment.

This research was funded by the French Ministry for Cooperation and ORSTOM.

References

Brunel, J.P. and Bouron, B., 1994. Evaporation des Nappes D'eau Libre en Afrique Sahélienne et Tropicale. Rapport CIEH/ORSTOM, 342 pp.

Chevallier, P., Claude J., Pouyaud, B. and Bernard, A., 1985. Pluies et Crues au Sahel; Hydrologie de la Mare D'Oursi (Burkina Faso) 1976–1981. ORSTOM, Collec. Travaux et documents, No. 190, Paris, 251 pp.

Cogels, F.X., Dacruz Evora, N. and Gac, J.Y., 1991. L'évaporation du lac de Guiers (Sénégal) de 1976 à 1989. Bilan et essais d'interprétation. Rapport multigraphié, 40 pp.

Colin-Kaczala, C., 1986. Profils istopiques (oxygène 18 et deuterium) de fluides (eau liquide, vapeur et CO_2) de la zone non saturée en climat désertique: application à l'évaluation de l'évaporation des nappes libres au Sahara Nord Occidental. Thèse de Doctorat en Sciences, Université de Paris-Sud, 171 pp.

Craig, H. and Gordon, L.I., 1965. Deuterium and oxygen-18 variations in the ocean and the marine atmosphere. In: E. Tonyioryi (Editor), Stable Isotopes in Oceanographics Studies and Paleotemperatures. CNR, Laboratorio di Geologia Nucleare, Pisa, pp. 9–130.

Desconnets, J.C., 1994. Typologie et caractérisation hydrologique de systèmes endoréiques en milieu sahélien (degré carré de Niamey-Niger). Thèse de doctorat 3ème cycle ès sciences, Univ. de Montpellier II, 250 pp.

Desconnets, J.C. and Taupin, J.D., 1993. Comparison of various methods for estimating pools evaporation in the Sahel during the dry season. In: A. Becker, B. Sevruk and M. Lapin (Editors), Evaporation, Water Balance and Deposition, Proceedings of the Bratislava Symposium on Precipitation and Evaporation, September 1993. Vol. 3, Slovak Hydrometeorological Institute, pp. 62–67.

Desconnets, J.C., Taupin, J.D. and Lebel, T., 1993. Le rôle des mares dans le bilan hydrologique d'une région sahélienne. In: H.-J. Bolle, R.A. Feddes and J. Kalma (Editors), Exchange Processes at the Land Surface for a Range of Space and Time Scales, Proceedings of the Yokohama Symposium, July 1993. IAHS Publ. No. 212, pp. 299–311.

Desconnets, J.C., Lamotte, M. and Lebel, T., 1994. Fonctionnement hydrologique et organisation pédologique d'un système endoreique de plateau sur le degré carré de Niamey. Poster Presentation, 10ème journées hydrologiques de l'ORSTOM, Montpellier, September 1994.

Desconnets, J.C., Lebel, T. and Taupin, J.D., 1995. Bilan hydrologique de surface durant la période de suivi à long terme de HAPEX-Sahel à partir du suivi des mares temporaires sur une zone test de 600 km^2. In: T. Lebel (Editor), Hydrologie et Météorologie de Méso-Echelle dans HAPEX-Sahel: Dispositif de Mesures au Sol et Premiers Résultats. ORSTOM, pp. 69–112.

Fontes, J.C., 1976. Isotopes du milieu et cycles des eaux naturelles: quelques aspects. Thèse de doctorat d'état des sciences naturelles, Université de Paris 6, 208 pp.

Girard, G., 1984. Projet HAPEX-MOBILHY. Modélisation hydrologique de la maille M100 du Sud-Ouest. Note LHM/RD/84/104, Ecole National Supérieure des Mines de Paris/Centre d'Informatique Géologique, Fontainebleau, 44 pp.

Gonfiantini, R., 1986. Environmental isotopes in lake studies. In: P. Fritz and J. Ch. Fontes (Editors), Handbook of Environmental Isotope Geochemistry. Vol. 2. Elsevier, Amsterdam, pp. 113–165.

Goutorbe, J.P., Lebel, T., Tinga, A., Bessemoulin, P., Brouwer, J., Dolman, H., Engman, E.T., Gash, J.H.C., Hoepffner, M., Kabat, P., Kerr, Y.H., Monteny, B., Prince, S., Saïd, F., Sellers, P. and Wallace, J., 1994. HAPEX-Sahel. A large-scale study of land–atmosphere interactions in the semi-arid tropics. Ann. Geophysicae, 12: 53–64.

Goutorbe, J.P., Lebel, T., Dolman, A.J., Gash, J.H.C., Kabat, P., Kim, Y.H., Monteny, B., Prince, S.D., Sticker, A., Tinga, A. and Wallace, J.S., 1997. An overview of HAPEX-Sahel: a study in climate and desertification. J. Hydrol., this issue.

Ibiza, D., 1972. Mesure de l'évaporation d'un lac en milieu sahélien – Lac de Bam. Cah. Hydrol., 9(3): 47–64.

Lebel, T., Taupin, J.D. and Gréard, M., 1995. Rainfall monitoring: the EPSAT-Niger set-up and its use for Hapex-Sahel. In: T. Lebel (Editor), Hydrologie et Météorologie de Méso-Echelle dans HAPEX-Sahel: Dispositif de Mesures au Sol et Premiers Résultats. pp. 31-68 ORSTOM, in press.

Lebel, T., Taupin, J.D. and LeBarbé, L., 1997. Space–time fluctuations of rainfall during HAPEX-Sahel. J. Hydrol., this issue.

Leduc, C. and Desconnets, J.C., 1994a. Pools and recharge of the Continental Terminal phreatic aquifer near Niamey, Niger. In: C.P. Gupta and I. Summers (Editors), Groundwater monitoring and recharge in semi-arid areas, Proceedings of the UNESCO/IAH International Workshop, NGR, Hyderabad, pp. SV13–SV22.

Leduc, C. and Desconnets, J.C., 1994b. Variability of groundwater recharge in sahelian climate: piezometric survey of the Continental Terminal aquifer near Niamey (Niger). In: J. Soveri and T. Suokko (Editors), Future Groundwater Resources at Risk, Proceedings Helsinki Conference. IAHS Publ. No. 222, pp. 505–511.

Leduc, C., Bromley, J. and Schroeter, P., 1997. Water table fluctuation and recharge in semi-arid climate: some results of the HAPEX-Sahel hydrodynamic survey (Niger). J. Hydrol., this issue.

Majoube, M., 1971. Fractionnement isotopique en oxygène 18 et en deuterium entre l'eau et sa vapeur. J. Chem. Phys., 68: 1425–1435.

Peugeot, C., 1995. Influence de l'encroutement superficiel du sol sur le fonctionnement hydrologique d'un versant sahélien. Expérimentation in Situ et modélisation. Thèse de Doctorat de l'Université de Grenoble I, 200 pp.

Peugeot, C., Estèves, M., Vandervaere, J.P., Galle, S. and Rajot, J.L., 1997. Runoff generation processes. Results and analysis of field data collected on the HAPEX-Sahel East Central Super Site. J. Hydrol., this issue.

Pouyaud, B., 1986. Contribution à l'évaluation de l'évaporation des nappes d'eau libre en climat tropical sec. Exemples du lac de Bam et de la Mare d'Oursi (Burkina Faso), du lac Tchad et d'açudes du Nordeste brésilien. Thèse de doctorat d'état ès Sciences Naturelles, Université Paris-Sud, Collection Etudes et Thèses, ORSTOM, Paris, 254 pp.

Riou, C., 1975. La détermination pratique de l'évaporation. Application à l'Afrique Centrale. Orstom, Collection Mémoires, 231 pp.

Vuillaume, G., 1981. Bilan hydrologique mensuel et modélisation sommaire du régime hydrologique du lac Tchad. Cah. l'ORSTOM, Sér. Hydrol., XVIII(1): 23–71.

Reprinted from

JOURNAL OF HYDROLOGY

Journal of Hydrology 188–189 (1997) 155–178

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

J.C. Desconnets[a,*], J.D. Taupin[b], T. Lebel[c], C. Leduc[a]

[a]ORSTOM, Laboratoire d'hydrologie, BP 5045, 34032 Montpellier Cedex 1, France
[b]ORSTOM, Groupe PRAO, BP 11416, Niamey, Niger
[c]ORSTOM/LTHE, Groupe PRAO, BP 53, 38041 Grenoble Cedex 9, France

ELSEVIER