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COMPARISON OF VARIOUS METHODS FOR ESTIMATING POOLS EVAPORATION IN THE SAHEL DURING THE DRY SEASON.

DESCONNETS J.C., TAUPIN J.D.

Mission ORSTOM au Niger, BP 11416, Niamey, - Niger

Abstract

The Sahelian region in which the Hapex II Sahel project was conducted, is characterised by intense degradation of the hydrographic network. Thus, during the rainy season, surface runoff accumulates and is stored in numerous pools of various sizes (1 to 100 hectares). A study looking to discover the redistribution of the water from these pools, notably, the regime of release during the dry season, was undertaken. Two representative pools were studied. In order to estimate the percentages of water evaporated and infiltrated, several methods were used. An automatic recorder of the pool water level and an evaporation pan were installed and chemical and isotopic (oxygen 18 and deuterium) analysises were conducted. The study identifies the different infiltration behaviour of the two hydrological systems and quantifies the volumes of water evaporated and infiltrated during the study period. The isotopic method was found to be a well adapted tool for this type of study.

key words: Sahel, pools, isotopes.

Introduction

The study zone, situated in western Niger, is subject to a Sahel-Sudanian climate (Aubreville, 1949) characterised notably by a short rainy season and a long dry season. The annual wind (air mass) regime is dominated from October to March by a very dry, highly intense, continental wind, the Harmattan, which causes intense evaporation during the entire period. For the study period (April 1991 - November 1992) the mean daily evaporation from a class A pan situated at Niamey airport was 10.4mm per day (standard error: 3.1mm per day), the minimum being in the middle of the wet season (August), the maximum at the end of the dry season (March-April).

Due to the harsh nature of the climate and the weakened natural environment, the degradation of the hydrological network throughout a large part of the region has resulted in the storage of surface runoff in many small temporary natural reservoirs. They are normally to be found in valley floors or former water courses and on hardened furriginous plateaux (Continental Terminal) (Desconnets et al., 1992). Within the framework of the HAPEX II SAHEL project, aimed at establishing energy and matter budgets at the soil-atmosphere interface, a study of surface water storage systems has been undertaken. Its goal is to examine and quantify the division of the stored water between atmosphere, soil and subsoil. The preliminary studies, concerning the emptying process of the pools has shown a seasonal budget with losses to infiltration up to 90% of the volume of inflow (valley bottom pool) while the water budget of the pools on the hardened plateau is principally governed by evaporation (Desconnets et al., 1992). In the search for a regional hydrological budget of these pools, it is of primary importance to determine precisely the losses to evaporation of each type of pool identified, knowing their specific functioning (the processes involved). Thus, the variation of the evaporation term for each pool can be found. A posteriori, it should aid the choice of estimation method evaporation in order to extrapolate the hydrological budget to all the pools in the study zone.

Methodology

Choice of sites

Two pools characteristic of the most common endoreic systems were chosen as study sites:

- The first, a valley bottom pool, is a long, narrow pool enclosed in a sandy valley (a former water course), sheltered from the wind by the valley sides and the surrounding bush vegetation.
- The other pool is situated on the hardened furruginous plateau, being round, much smaller in size, with a flat basin. The exposed nature of the plateaux and the lack of substantial vegetation submits the pool to frequent strong winds throughout whole of the dry season.

Choice of period

The violent rains occured on the three or four months of the wet season, as well as the large variability of the hours of sunshine due to the rain events and the passage of cloud systems, introduce errors which are not easily estimated by evaporation pan. Frequent readings are required, these being poorly related from one site to site The hydrological regime of the pools during the wet season fluctuates greatly due to the frequency of inflows. They induce large variations of volume. Storage and release over short periods of time prevents the long term tracing of ionic and isotopic percentages, necessary for evaporation estimation by these methods.

Only the period from the end of the wet season (end of September) to the total drying out of the pools (end of November) combines the climatic and hydrological conditions best adapted to this type of comparative study.

Choice of methods

The estimation of evaporation from a free water surface has always arroused great interest. Numerous studies present the many direct and indirect methods. There are many empirical relationships as a result of the comparison of evaporation depth from lakes and from class A and Colorado type pans (Pouyaud 1986 - Riou 1975) or coefficients relating evaporation depth as a function of their size and season. (Molle et al., 1989 - Riou 1975). Initially, these experiments are of great interest because they demand little instrumentation and little supervision. However, The resulting relationships are only valid for the particular environmental conditions under which they were determined. Conversely, the other methods based on the measurement of the physical parameters directly influencing the evaporation process (Bowen's method, for example) are more satisfactory but require much instrumentation.

In a different way, the chemical tracing of a well chosen element allows the evaluation of the ratio of evaporation as a function of the chemical evolution of the water remaining in the pool (Laraque 1991). Nevertheless, this requires sustained analysis over a period with no inflow into the pool: absence of surface runoff and animal pollution.

The isotopical method of evaporation estimation is based on the tracing of the stable isotopes: oxygen 18 and deuterium. During a period of simple evaporation the percentages of both isotopes found in the pool increase with time. This concentration is solely due to the isotopic division between the evaporated vapour and the remaining water. It depends on two factors, the enrichment at equilibrium depending on the air temperature and the kinetic enrichment depending on various atmospheric conditions (turbulence, temperature, relative humidity, etc...). It allows the study of evaporation without interference as may be the case for the chemical model (Fontes 1976-Gonfiantini 1986). These last two methods give a direct mesure of the losses to evaporation from a volume of water.

The methods presented in our study, which is a compilation of measurements from seasons 1991 and 1992, are of two types: isotopic tracings and pan readings. The chemical tracing method undertaken during the 1991 season, did not produce good results due to the amount of animal pollution (Desconnets et al., 1993). It was not conducted for the 1992 season. Two sunken Colorado type pans, filled with water from the pool, were installed close to each study site. If we accept the hypothesis that the evaporation from each pan is a good estimation of the loss from its respective pool (identical wind conditions, hours of sunshine and albedo), we are able to test the empirical relationships established under the same climate with the evaporation measurements taken at the regional meteorological stations. The validation of these relationships will be achieved by readings from the pans in situ and the direct calculation of the volumes lost to evaporation by geochemical methods.

Instrumentation and measurements

At the end of the rainy season Colorado type pans (1m by 1m and 60cm deep) were installed close to each pool. They were refilled with water from the pool at each visit and the volume required was measured. A sample of water was taken for isotopic and electical conductivity testing. Variations in pool level were recorded automatically by pressure gauge at centimetre scale. For comparison we take into account the evaporation readings from the class A pan situated at Niamey airport.

The in situ measurements extend from the end of September to the end of November, when the pools were almost dry.

Hydrological budget by the classical method for evaporation pans

water budget equation:

Generally the water budget for a pool can be written in the following manner (1):

time interval ΔT

$$\Delta V = (\Delta V_{evap} + \Delta V_{inf} + \Delta V_{ani}) - \Delta V_{app}\ (m^3) \quad (1)$$

with

ΔV_{evap} = variation of volume by direct evaporation,
ΔV_{inf} = variation of volume by infiltration,
ΔV_{ani} = variation of volume by animal consumption,
ΔV_{app} = variation of volume by surface runoff.

during the dry season the water budget is simplified and becomes (2):

$$V_{inf\,(t-t+1)} = V_{tot\,t} - V_{tot\,(t+1)} - V_{evap\,(t-t+1)}\ (m^3) \quad (2)$$

V_{tot} = volume of water in the pool,
V_{inf} = volume lost to infiltation,
V_{evap} = volume lost to evaporation.

The estimation of losses due to consumption by cattle evidently cannot be calculated on a daily basis. However, we do take this into consideration in the seasonal water budget for the pool. Given the number of herds in the region and the reduction in the number of watering holes immediately following the end of the rainy season, these losses are not negligible during the dry season. They are highly variable throughout the season and become a function of the potability of the water and the geographic situation of the pool. Only an approximation of the maximum consumption is possible giving the order of magnitude of these losses. A surveillance of fifteen pools within the study zone, during October, provided data on the number, destination and frequency of visit of the cattle to the pool.

According to the sources of the geographical institute and of Gadelle (1989) on the daily water consumption of a tropical cattle unit, we obtain a maximum daily consumption of 10 m^3 for the plateau pool Bazanga Bangou. However, at the valley bottom pool, the surveillance showed that cattle don't come to water because of the hazardous nature of the pool bed.

Calculation of the water budget from the class A pan readings (Niamey airport):

The class A pan readings are taken daily. The low daily variability (standard error 1.3mm per day during October), allows us to establish a mean daily depth of evaporation.

Calculation of the water budget by corrected values (Pouyaud 1986) from the class A pan:

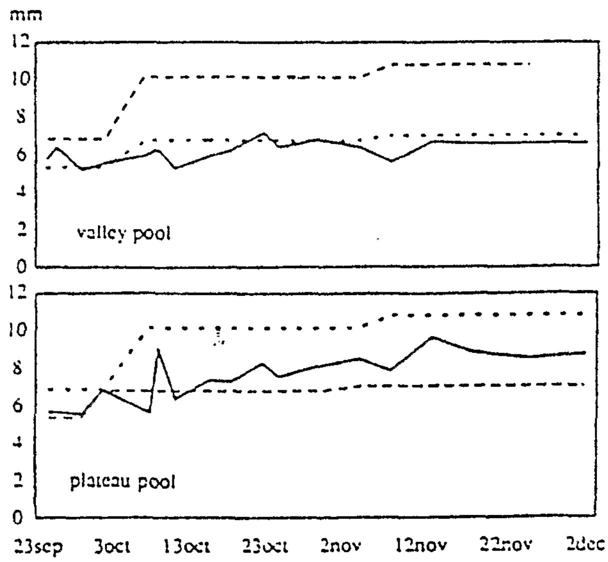
Following a study of lake Bam (Burkina Faso), Pouyaud(1986) proposed an empirical relationship linking evaporation from a lake and evaporation from a class A pan. This relationship uses a mean daily depth for the pan and is written as (3):

$$ELAC = 1.664 \cdot EBAC^{0.602} \text{ (mm per day)} \quad (3)$$

ELAC = evaporation of the lake,
EBAC = evaporation of the pan.

Calculation of the water budget by pan values from an in situ sunken Colorado pan:

The frequency of visit to the pans varied but was usually in average to two days. The raw data obtained are the volumes of water added, transformed into milimetres or milimetres per day.



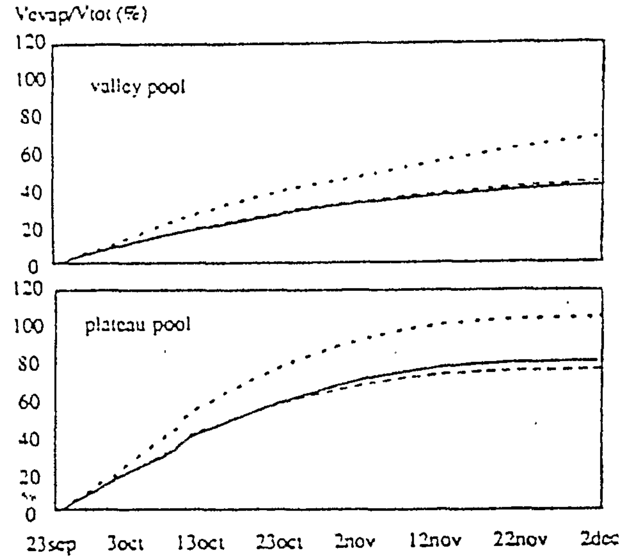
——— evaporation depth sunken pan
· · · evaporation depth class A pan (corrected values)
— — — evaporation depth class A pan

Figure 1: Comparison mean daily evaporation depth between class A pan, class A pan (corrected values) and sunken pan.

In figure 1 we can compare the mean daily depths found for each type of pan for the two study sites. The mean daily evaporation from the sunken pan at the plateau pool (Bazanga) is 1.5mm per day greater than that of the valley bottom pool (Wankama). The mean daily depth from the class A pan is clearly greater than the values from the other two pans: 9.8mm per day. The correction of the class A pan readings by the empirical relationship produces mean daily values practically identical to those of the sunken pan at Wankama: 6.5mm per day corrected class A pan and 6.1mm per day for the sunken pan, with small standard errors of 0.5mm per day and 0.6mm per day. However, the corrected values from the class A pan are slightly less (1mm per day) than those of the sunken pan at Bazanga. This difference of evaporation is explained by the position of the plateau pool which is subject to a wind regime of much greater frequency.

Comparison of the evaporation losses by different estimation methods.

In terms of water budget for each pool, it is evident that the values resulting from the class A pan give an over estimation of evaporation with respect to the calculations from the other pans. The class A pan presents the maximum evaporation figure due to the influence of the sun on the sides of the pan causing large thermic variations in the water and the water having a higher albedo.



——— accumulation V_{evap}/V_{tot} (sunken pan)
· · · accumulation V_{evap}/V_{tot} class A pan
— — — accumulation V_{evap}/V_{tot} class A pan (corrected values)

Figure 2: Cumulative evaporation throught the season by three methods.

Figure 2 shows the total water evaporated over the study period for the three methods at both pools. It appears that the estimation of evaporation calculated with the corrected class A pan values and the sunken pan values tend towards losses approximately equal. If we consider once more the sunken pan as giving the best estimate of the loss to evaporation from the pool, the losses calculated after correction from the class A pan slightly under estimate the evaporation from the plateau pool (with strong and frequent winds) and slightly over estimate the evaporation from the valley bottom pool.

As a percentage of the total volume, the losses to evaporation vary from 76.2% (sunken pan) to 104.8% (class A pan) for the plateau pool and from 41.6% (sunken pan) to 77.8% (class A pan) for the the valley bottom pool. These results demonstrate the difference in evaporation regime between the two pools in terms of seasonal water budget and show the similarities between the evaporation estimated by sunken pan and the corrected class A pan values.

Study of the water budget by isotopic content

In order to verify the results given by the evaporation pan, showing the importance of infiltration at certain pools during the dry season, and to quantify infiltration by other methodologies, the study of directed towards the characterisation of the isotopic evolution of the pool water throughout the dry seasons of 1991 and 1992.

The first results obtained in 1991, although incomplete, allow the different infiltration behaviour of the the valley bottom pools and the plateau pools to be identified (Desconnets et al., 1993). However the imprecision of the results for low volumes at Wankama, the low number of isotopic samples taken, the interference of a important rain event after a month of dryness and the absence of evaporation mesurements taken near the sites prevent us from accurately modelling the process. The 1992 study uncovers some of the uncertainties and so a quantification of the evaporation and infiltration is possible.

Qualitative comparison of the results

The oxygene18 content plotted against deuterium content for the samples from both pools (figure 3), at the time of drying out, gives a straight line correlation of slope 4.53 (4):

$$n = 28$$
$$\delta\, ^2H = 4.53\ \delta\, ^{18}O - 11.53 \qquad r^2 = 0.984 \qquad (4)$$

The slope is characteristic of the evaporation from a free water surface (Fontes 1976). For the four daily results available the gradients lie between 4.24 and 4.47. The point of intersection with the meteoric regional line (MRL), the line calculated from isotopic contents of unevaporated rain water collected during the 1991 and 1992 seasons at two stations close to the pools (5),

$$n = 70$$
$$\delta\, ^2H = 8.11\ \delta\, ^{18}O + 5.82 \qquad r^2 = 0.931 \qquad (5)$$

gives the isotopic composition of the stored water before evaporation. This corresponds to average composition of the final rains of the season. We can state that, for 1991 the point of intersection with the MRL is equal to - 6.92 ‰ oxygen 18 and - 50.3 ‰ deuterium, while for 1992 we obtain - 3.76 ‰ oxygen 18 and - 24 ‰ deuterium. This may be compared with the isotopic composition of the final rains of each season which contributed to the filling of the pools. Over the last two weeks of the two seasons, the isotopic content in 1991 was far more negative than in 1992: -7.8 ‰ oxygen 18 for 95mm of rainfall in 1991 and -5.0 ‰ oxygen 18 for 140mm of rainfall in1992.

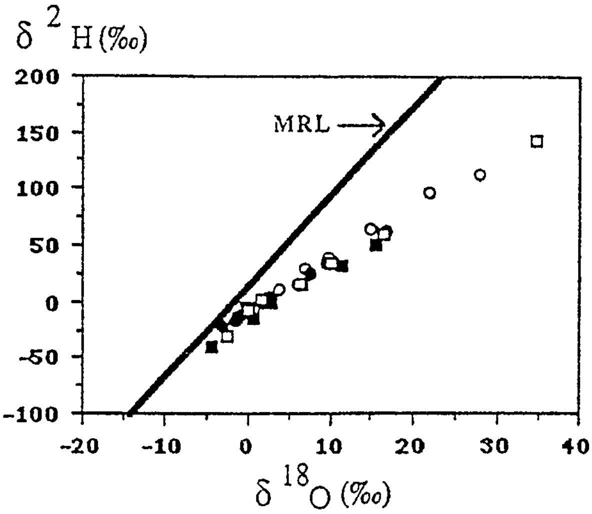


Figure 3: Oxygène 18 vs Deuterium
data 1991: ● , Wankama, ○ Bazanga ;
data 1992: ■ , Wankama, □ Bazanga.

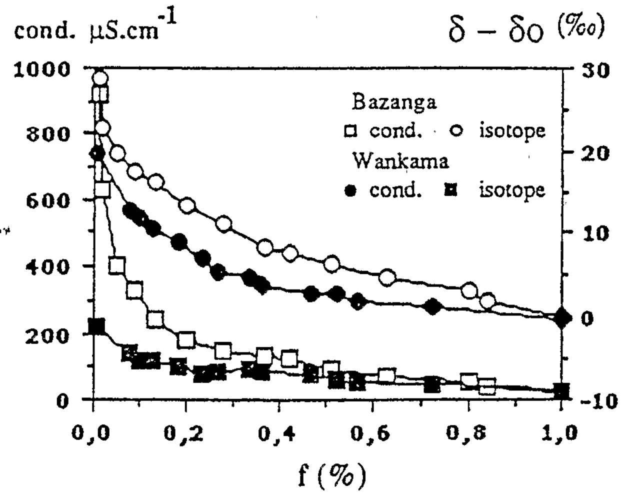


Figure 4: Comparison of oxygene 18 and conductivity increase function of remaining water f for the two pools.

The different infiltration behaviour of the two pools can be demonstrated by comparing the proportion of water remaining with, firstly, the evolution of the electrical conductivity and secondly, the evolution of the isotopic content (figure 4). Thus we find that the valley bottom pool has a lesser isotopic concentration and a lesser conductivity for the remaining proportion compared to the plateau pool.

This implies greater infiltration for the valley bottom pool.

Modelisation

If we consider that there is no exchange with the atmosphere, although this is unlikely to be the case, the modelisation of the evolution of the isotopic composition at the time of evaporation from a basin can be described simply by a Raleigh distillation equation. The model is dependant solely on temperature (6):

$$\delta - \delta_0 = -\mathcal{E} \ln f \qquad (6)$$

δ, δ_0 = isotopic composition of the pool: at time t, at time t = 0,

$\mathcal{E}$ = isotopic enrichment at the equilibrium function of the temperature,

f = fraction of water remaining.

The very simple model was used for the 1991 season where it appears appropriate given the evolution of the oxygen 18 content of the Bazanga pool. The more precise nature of the 1992 study, shows that where only small fractions remain the model diverges from reality (figure 5). We can attribute this to cattle watering (between 5 and 10m^3 per day) which becomes gradually more important with the drying out of the pool.

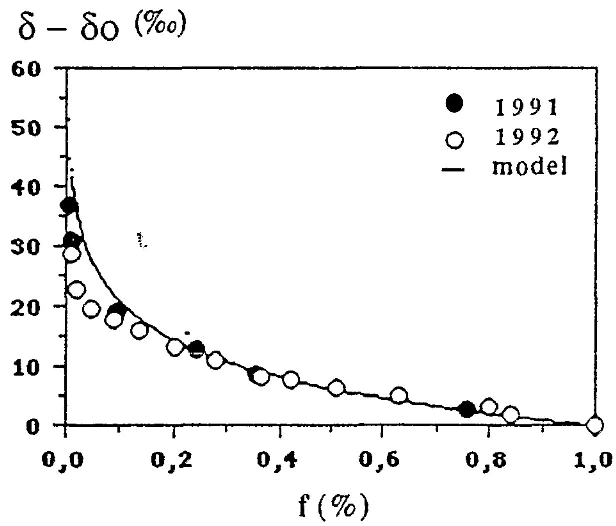


Figure 5: Comparison of Raleigh model against Bazanga isotopical data for seasons 1991 and 1992.

A more complex model of evaporation, taking into account environmental parametres, is given by the following expression (Craig and Gordon 1965) (7):

$$d\delta / d\ln f = \qquad (7)$$

$$(h(\delta - \delta_a) - (\delta + 1) + (\Delta\mathcal{E} + \mathcal{E}/\alpha) / (1 - h + \Delta\mathcal{E})$$

By considering that the parametres h, δ_a, $\mathcal{E}$, $\Delta\mathcal{E}$, α are constant, we obtain the following equation by integration (8):

$$\delta = (\delta_0 - A/B) f^{B} + (A/B) \qquad (8)$$

with

$$A = (h\delta_a + \Delta\mathcal{E} + \mathcal{E}/\alpha) / (1 - h + \Delta\mathcal{E})$$

$$B = (h - \Delta\mathcal{E} - \mathcal{E}/a) / (1 - h + \Delta\mathcal{E})$$

h = mean relative humidity of the atmosphere,

f = fraction of water remaining,

δ, δ_0, δ_a = isotopic composition of the pool : at time t, at time t=0 ; isotopic composition of the atmosphere,

α = isotope fractionation factor,

$\mathcal{E} = 1 - \alpha$,

$\Delta\mathcal{E}$ = kinetic enrichment.

Where the volume of the pool decreases by evaporation and infiltration, the equation can be written (Gonfiantini 1986) (9):

$$\delta = (\delta_0 - A/B) f^{Bz} + (A/B) \qquad (9)$$

$z = V_{evap}/(V_{evap} + V_{inf})$

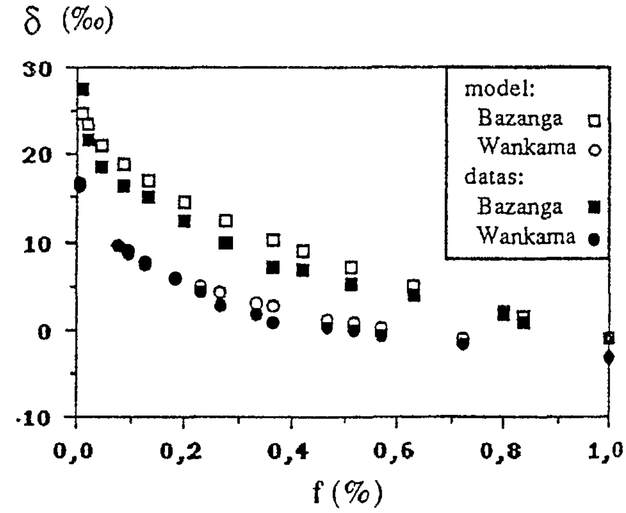


Figure 6: Comparison Craig and Gordon model against Bazanga and Wankama pool for 1992.

For the modelisation of oxygen 18, a mean temperature of 35°c and a humidity of 39.5% are taken as meteorological parametres. The oxygen 18 content of the atmosphere δ_a, is taken to be -17 ‰ a value consistent with this climatic zone, α =0,00856 (Majoube, 1971), $\Delta\mathcal{E}$ = 14,2 (1- h) (Gonfiantini, 1986).

The best adjustment of z, the fraction evaporated, to the data available is equal to 0.75 for Bazanga and

0.35 for Wankama (figure 6). These figures lie in the lower range of values found by the classic evaporatory methods.

Conclusion

Table 1 summarises the estimated values of losses to evaporation for all the methods tested. All three methods give results following the same form.

- a contrasting evaporation regime during the dry season between the plateau pool (evaporation between 75% and 80.7%) and the valley bottom pool (between 35% and 43.6%).
- A estimation of evaporation. where the maximum estimation being 8.6% for the season at Wankama (valley bottom pool) while this difference is reduced to 5.7% at Bazanga (plateau pool).

In terms of hydrological budget these results are satisfactory and allow a minimum precision in the budget of 10% of the depth evaporated. In fact the low importance of daily evaporation during the wet season, and a rapid constant emptying of the pool (Desconnets et al., 1993) minimise the evaporation term in the water budget for this period. Therefore the imprecision of the estimation of total annual volume is also minimised.

The extension of the hydrological budget of these two pools to the whole study zone, is conceivable using the methods employed in this study.

valley bottom pool	sunken pan	class A pan (values corrected)	isotopical method
evapored water volume (m^3)	2347.5	2471.0	1974.4
% of total water volume (m^3)	41.6	43.6	35.0
plateau pool			
evapored water volume (m^3)	1918.5	1818.2	1782.8
% of total water volume (m^3)	80.7	76.2	75.0

table 1: Estimation of evaporation losses during the dry season by three different methods.

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Slovak Hydrometeorological Institute, Bratislava, Slovakia
Swiss Federal Institute of Technology, Department of Geography, Zurich, Switzerland
IGBP/BAHC, Core Project Office, Free University of Berlin, Germany

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