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WATER BUDGET OF A DAM IN THE SEMI-ARID NORTHEAST OF BRAZIL BASED ON OXYGEN-18 AND CHLORINE CONTENTS

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Abstract

WATER BUDGET OF A DAM IN THE SEMI-ARID NORTHEAST OF BRAZIL BASED ON OXYGEN-18 AND CHLORINE CONTENTS.

The water balance of an artificial reservoir in the northeast of Brazil is derived by using the variations of oxygen isotopes and chlorine contents. With these two methods, the water losses through subsurface outflow are estimated at 20–40%. A more accurate evaluation would require an investigation of the variability of the relative humidity of the atmosphere.

Subsurface loss of water from dams and lakes can seldom be determined by tools of physical hydrology and indirect methods have to be employed. Chemical and isotope mass balance analyses are here of special importance [1–7].

In this study we present water budgets for a dam in northeastern Brazil (Quebra Unhas, latitude 8°28' south, longitude 38°13' west) based on ¹⁸O and chlorine analyses. The study is part of a larger investigation focusing on the

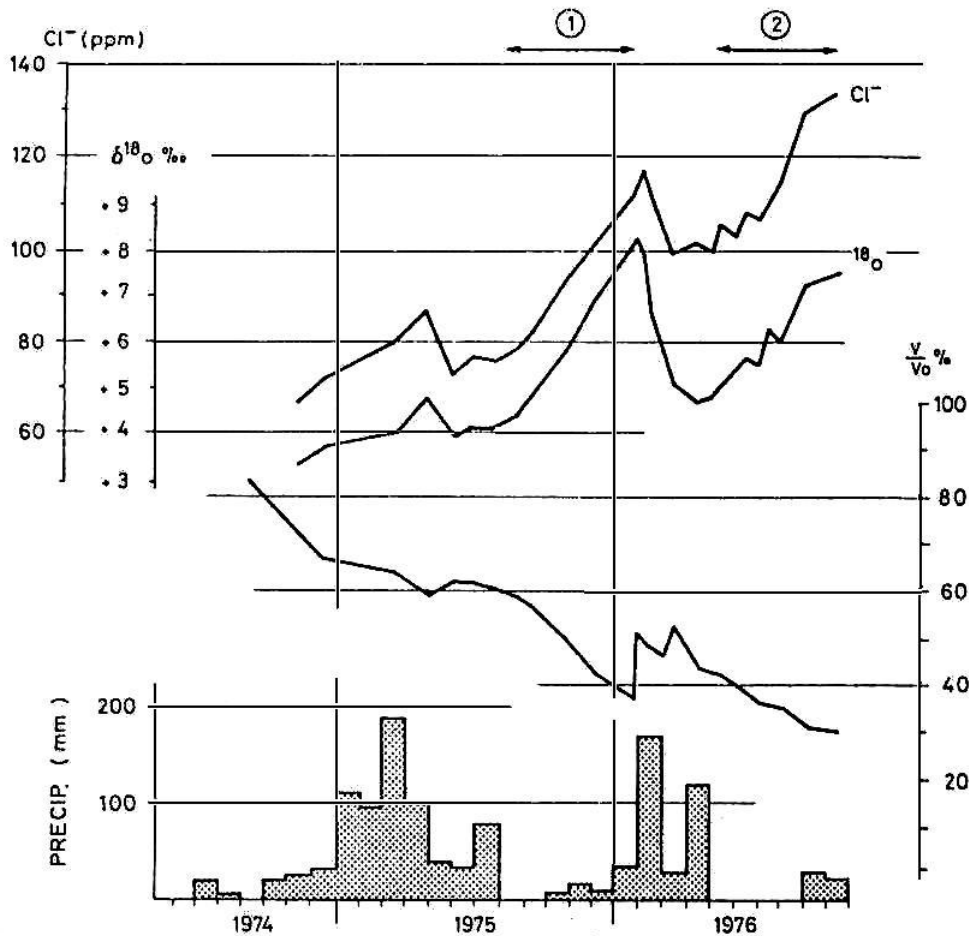


FIG.1. Variations in chlorine (Cl^{-1}) and oxygen-18 contents in relation to variations of water volume in the Quebra Unhas dam and amount of precipitation in the region.

causes of the widespread salinization of groundwaters in shallow aquifers on the crystalline rocks of the Brazilian Shield where the total dissolved solids range from 350 to over 25 000 ppm.

The dam was built in 1934 as part of water supply schemes designed to store freshwater during the rainy season for use during the long dry spells which in the semi-arid environments may exceed 12 months. It is fed by a small intermittently flowing creek and possibly some shallow groundwater systems. Surface discharge occurs only in the form of overflow during maximum water levels in the reservoir. The maximum storage capacity of the reservoir is $3.19 \times 10^6 \text{ m}^3$ with a maximum depth of 12.8 m. It is stratified and, as far as known, well mixed at most times. Volume variations can be determined from calibrated water level measuring devices.

The sampling programme for isotope analyses was initiated during May 1974 and terminated during October 1976. The dry periods of 1975 (28 July 1975 to 26 January 1976) and 1976 (30 April to 12 October 1976) were selected for the water budget analyses. Isotope data, chlorine analyses and volume variations for the sampling periods are shown in Fig. 1.

For the calculations it is assumed that the reservoir is well mixed and that volume variations are caused only by evaporation and subsurface outflow. Water and isotope mass balance equations can then be written, where

$$dV = dV_c - dV_v - dV_{out} \quad (1)$$

and

$$d(R_L \times V) = R_c \times dV_c - R_v \times dV_v - R_L \times dV_{out} \quad (2)$$

dV are the changes in total water volume during time dt ; dV_v and dV_c are respectively the amounts of vapour lost and condensed on the water surface whereby the net evaporative loss $dV_e = dV_v - dV_c$. Subsurface outflow during dt is described by $dV_{out} \times R_L$, R_v and R_c are the $^{18}\text{O}/^{16}\text{O}$ ratios of the reservoir, the vapour lost and condensed.

Furthermore,

$$dV_c = h dV_v \quad (\text{Ref.}[8]) \quad (3)$$

where h is the relative humidity of the atmosphere normalized to the surface temperature of the liquid (reservoir).

'Evaporation' and 'condensation' are isotope fractionating processes where

$$R_v/R_L = \alpha \quad (4)$$

and

$$R_c/R_a = \beta \quad (5)$$

R_a is the isotope ratio of the atmospheric vapour. The fractionation factors α and β depend on climatic parameters and vary as a function of temperature. In this case, however, it is assumed that α and β remain constant during the observation period, i.e. average values would have to be used if numerical values were required for the calculations.

Combining Equations (1)–(5) one obtains

$$V \cdot dR_L = \left(\frac{h}{\beta(1-h)} \times R_a - \frac{1-\alpha(1-h)}{\alpha(1-h)} \times R_L \right) \times dV_e \quad (6)$$

and if

$$\frac{h}{\beta(1-h)} = B \text{ and } \frac{1-\alpha(1-h)}{\alpha(1-h)} = A$$

then

$$V \cdot dR_L = (B \cdot R_a - A \cdot R_L) \times dV_e \quad (7)$$

In closed basins with no surface or subsurface outflow $dV_{\text{out}} = 0$ and thus $dV_e = -dV$ and Eq.(7) becomes

$$\frac{dV}{V} = \frac{dR_L}{A \cdot R_L - B \cdot R_a}$$

If A, B and R_a are assumed to be constant, then this equation can be integrated and leads to

$$\frac{V}{V_0} = \left(\frac{R_L \cdot A - B \cdot R_a}{R_L^0 \cdot A - B \cdot R_a} \right)^{1/A}$$

As the final volume of the evaporating water body approaches zero one has

$$R_L \rightarrow \frac{B \cdot R_a}{A} \quad (8)$$

and then

$$\frac{B \cdot R_a}{A} = R_L^f$$

R_L^f is the final isotopic composition of the liquid. With this one obtains

$$\frac{V}{V_0} = \left(\frac{R_L - R_L^f}{R_L^0 - R_L^f} \right)^{1/A} \quad (9)$$

or, expressed in terms of δ ‰,

$$\frac{V}{V_0} = \left(\frac{\delta_L - \delta_L^f}{\delta_L^0 - \delta_L^f} \right)^{1/A} \quad (10)$$

This equation is equivalent to one derived by Fontes and Gonfiantini [2] through computer analyses of two evaporating basins in the Sahara.

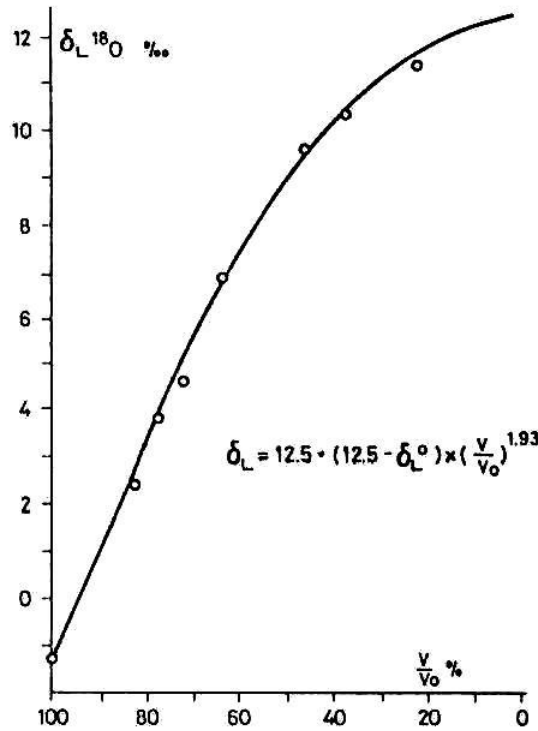


FIG.2. Class A evaporation pan experimental data from the evaporation experiment carried out during July 1974.

The ratio V/V_0 defines the amount of residual liquid (f). The exponent $1/A$ is equivalent to $1/m$ used by Welhan and Fritz [7] and is a 'climatic parameter' which is almost totally dependent on the (normalized) relative humidity h .¹ Applied to evaporation pan data obtained in northeast Brazil one finds $A = 1.93$ and $\delta_L^f = -12.5\%$ (Fig.2). The remoteness of the area did not yet permit a detailed investigation of the variability of these two values. From a practical point of view this is a rather serious shortcoming but the data obtained will nevertheless serve to illustrate the approaches proposed in this study.

In the case of a leaky system with, for example, subsurface outflow this relationship between residual liquid and $1/A$ will change. However, if the water body goes to dryness then δ_L^f will be identical for a leaky and non-leaky system. Thus, the rate of change becomes different and A in Eq.(9) can be replaced by A' :

$$\frac{V}{V_0} = \left(\frac{R_L - R_L^f}{R_L^0 - R_L^f} \right)^{1/A'} \tag{11}$$

¹ ALLISON, G.B., BROWN, R.M., FRITZ, P., "Evaluation of water balance parameters from isotopic measurements in evaporation pans", these Proceedings.

A' is like A dependent on the relative humidity but also incorporates the influence of water loss through outflow. A' can further be defined depending on the relationship between the rate of subsurface outflow and other parameters important for the water budget. For example, with the reduction of water volume in a lake both surface area and water depth are reduced and therefore both the rate of evaporation (dV_e) and the rate of subsurface outflow (dV_{out}) will be increasingly smaller. Therefore one could assume that the ratio between the two is constant:

$$\frac{dV_{out}}{dV_e} = k \quad (12)$$

and thus

$$dV = -dV_e - kdV_e$$

or

$$dV_e = -\frac{dV}{kH} \quad (13)$$

Combining Eqs (7) and (8) one obtains

$$dV_e = \frac{V}{A} \left(\frac{dR_L}{R_L^f - R_L} \right) \quad (14)$$

which combined with Eq.(13) yields after integration

$$\frac{V}{V_0} = \left(\frac{R_L - R_L^f}{R_L^0 - R_L^f} \right)^{(k+1)/A} \quad (15)$$

$$\text{Thus } A' = \frac{A}{k+1}$$

The ratio A'/A describes the percentage of water loss through evaporation compared with the total water loss. Thus, if A can be defined through pan or other experiments then it is possible to determine from the rate of change of the isotope content in a reservoir its water loss through outflow.

Figure 3 illustrates graphically the difference in isotopic behaviour of a leaky and non-leaky system, in this case the dam during period 1 (Fig.1) and the evaporation pan. $A' = 1.3$ can be determined from a linear regression of $\ln(V/V_0)$ versus $\ln(12.5 - \delta_L)$, and a correlation coefficient of 99.2% is observed for this period.

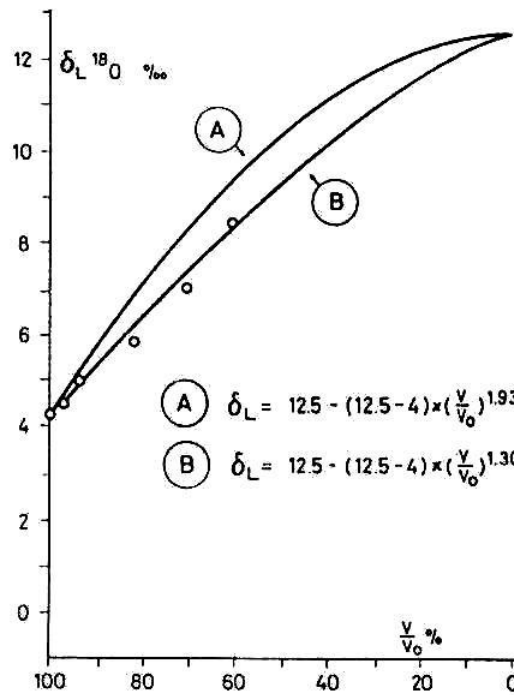


FIG.3. The differential behaviour of a system with subsurface outflow (the dam) with a non-leaky system (the evaporation pan).

The ratio $A'/A = 1.30/1.93$ indicates that 67% of the total water loss from the dam was due to evaporation, whereas 33% was lost by subsurface outflow. Since water volumes are known this signifies that the average outflow during period 1 was close to 16 litres/s and the mean evaporation rate close to 4.5 mm/day.

These results are summarized in Table I which also gives the relevant data and results for the second study period. Also shown are the results from the water budget based on chlorine analyses.

The only assumption made in the 'chlorine balance' was that rock dissolution and fall-out did not add chlorine during the observation period. Again, water and chemical mass balance equations are solved and one finds

(a) for a totally closed system (e.g. evaporation pan)

$$\frac{V}{V_0} = \frac{C_0}{C}$$

and

(b) for a system with constant outflow

$$\frac{V}{V_0} = \left(\frac{C_0}{C}\right)^a$$

TABLE I. COMPARISON OF WATER BUDGET FROM OXYGEN-18 AND CHLORINE ANALYSES

		Evaporation	Subsurface discharge
<i>Period 1</i>	Oxygen-18, $A' = 1.30 \pm 0.08$, $r = 99.2\%$	$67 \pm 4\%$ or 4.8 mm/day	$33 \pm 4\%$ or 16 ± 2 litres/s
Aug. 1975 – Jan. 1976	Chlorine, $\frac{1}{a} = 0.75 \pm 0.4$, $r = 99.4\%$	$75 \pm 4\%$ or 5.4 mm/day	$25 \pm 4\%$ or 12.2 ± 2 litres/s
<i>Period 2</i>	Oxygen-18, $A' = 1.18 \pm 0.1$, $r = 96.8\%$	$61 \pm 5\%$ or 3.2 mm/day	$39 \pm 5\%$ or 11.4 ± 1.5 litres/s
May 1976 – Oct. 1976	Chlorine, $\frac{1}{a} = 0.77 \pm 0.08$, $r = 95.2\%$	$77 \pm 8\%$ or 4.0 mm/day	$23 \pm 8\%$ or 6.7 ± 2.3 litres/s

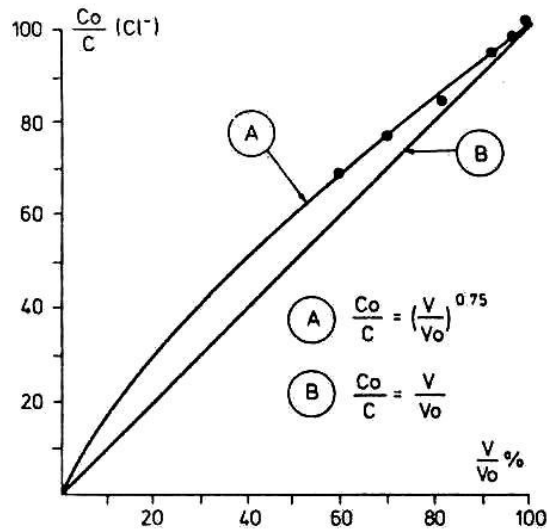


FIG.4. The changing Cl^- contents in the dam are plotted against residual water levels in the dam. The straight line (B) describes a non-leaky system.

The exponent a describes again the changing rate of approach towards final conditions, i.e. dryness and maximum salinity, and can be obtained from a linear regression analysis of $\ln V$ versus $\ln (1/C)$. For $a > 1$ the increase in chlorine concentration in the leaky system is slower than in a pure evaporative one, and for $a < 1$ the Cl^- -mass in the reservoir increases as the volume decreases, i.e. chlorine is added from the outside to the system. This is shown on Fig.4 which utilizes the changing Cl^- contents during the first sampling period. Similar to what has been done in the isotope water budget one can show that $1/a$ is the fraction of water lost by evaporation whereas $1 - 1/a$ determines the relative subsurface outflow.

Using the data shown in Fig.1 for the two observation periods, the water budget of the dam was determined. The results are summarized in Table I and agree fairly well with those obtained from ^{18}O -analyses.

CONCLUSION

Both methods of estimating the water budget of the reservoir show that somewhere between 20 and 40% of the total water loss occurs through subsurface outflow. This is very important for the salt budget since it is the principal mechanism by which salt is removed from the reservoir. No artificial outlet exists, overflow occurs only rarely and if all water loss were due to evaporation the water quality of the reservoir would deteriorate very rapidly. For a more

accurate assessment of this leakage the variability of A (i.e. the relative humidity) would have to be investigated in more detail during dry periods. Rating curves which describe water mass in terms of water levels show that because of the reservoir shape a given amount of outflow has much less influence on the water levels if the reservoir is full than if 50% is already removed. Nevertheless, it is probable that some dependence exists, and the lower discharge calculated for period 2 compared with period 1 (Table I) might well reflect this fact.

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