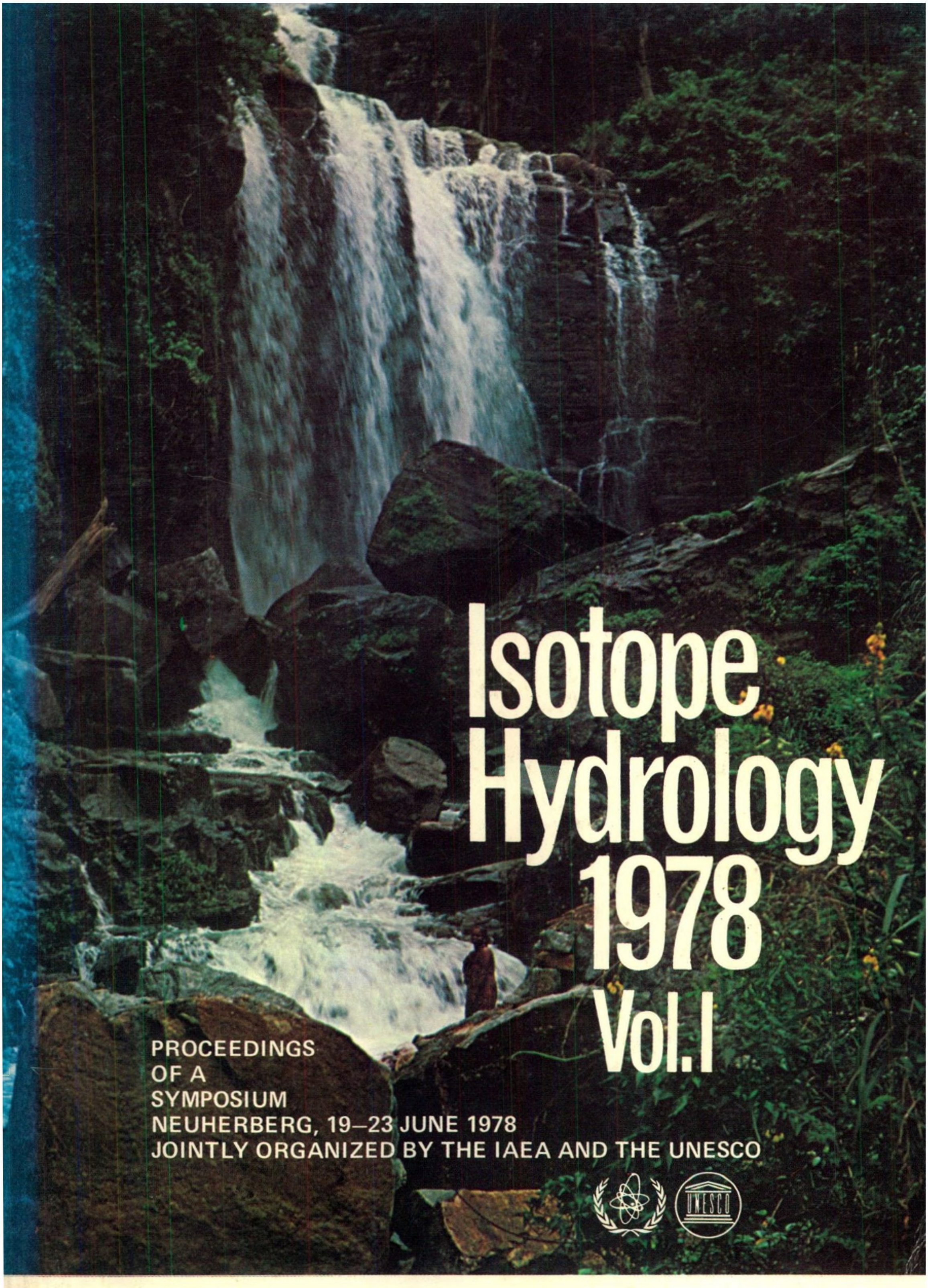

Isotope Hydrology 1978

Vol. I

PROCEEDINGS
OF A
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NEUHERBERG, 19–23 JUNE 1978
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STUDY, USING STABLE ISOTOPES, OF FLOW DISTRIBUTION, SURFACE-GROUNDWATER RELATIONS AND EVAPOTRANSPIRATION IN THE OKAVANGO SWAMP, BOTSWANA

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Abstract

STUDY, USING STABLE ISOTOPES, OF FLOW DISTRIBUTION, SURFACE-GROUNDWATER RELATIONS AND EVAPOTRANSPIRATION IN THE OKAVANGO SWAMP, BOTSWANA.

Stable isotope data collected in the Okavango Delta have confirmed that the central distributary system is more active at present than the peripheral systems. The data also show that there is no groundwater outflow at the western and southern margins of the delta. A salinity-isotope model of the deltaic swamp has been developed to study the relation between the salinity and isotopic composition of the swamp waters. An attempt has been made to separate the atmospheric losses from the swamp into its evapotranspiration components. The results indicate that in winter, when high water levels prevail, these losses are almost entirely due to evaporation, whilst in summer, when the water levels are low, evaporation and transpiration contribute almost equally to the total atmospheric losses.

INTRODUCTION

The Okavango Delta is where the Okavango River deposits all its sediment load and where at least 95% of its water is lost to the atmosphere through evapotranspiration. The delta lies over Recent to Tertiary Kalahari deposits consisting of layers of fine sand, silt, calcrete and silcrete, averaging a thickness of 200–300 m. Beneath these superficial deposits lies a sequence of Karroo rocks

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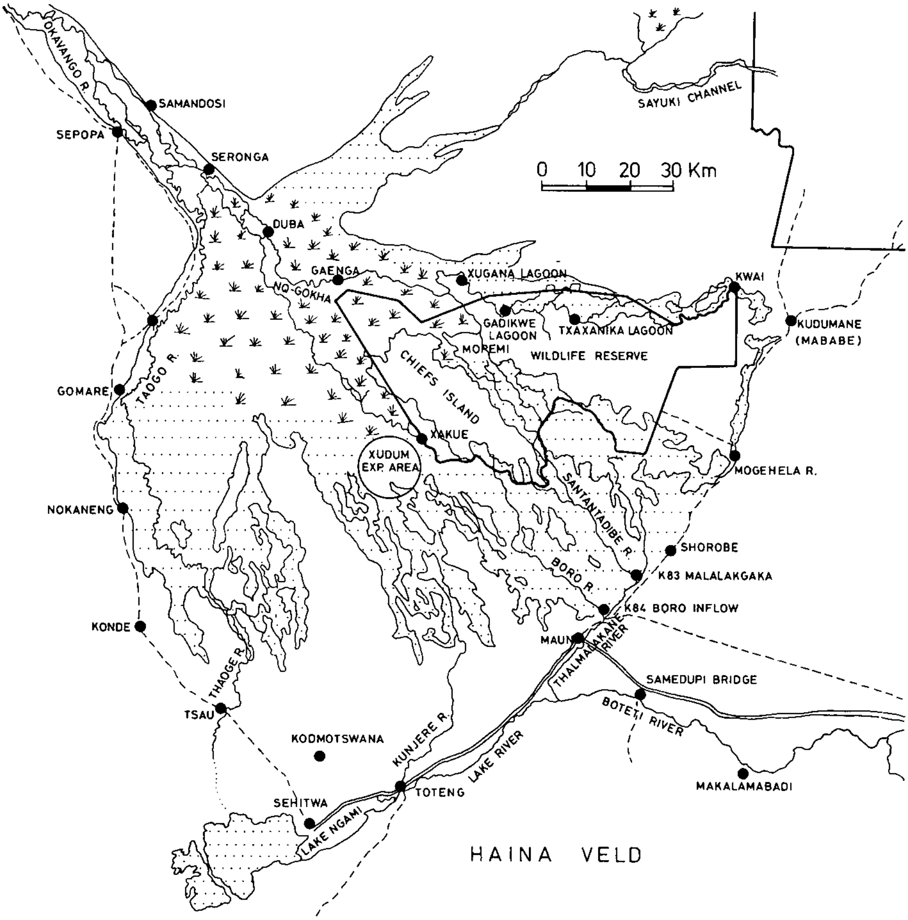

FIG. 1. Okavango Delta sampling locations.

faulted against Precambrian crystalline basement [1]. The mean annual precipitation over the delta is 500 mm but there is a large variability of 170 to 1200 mm. Precipitation occurs during the warm summer months and winters are extremely dry.

The catchment basin of the Okavango River, which covers an area of 180 000 km^2, lies in the Angolan Highlands. The river has no significant tributaries in Botswana, and its mean annual flow at the location where it enters the Okavango Swamp is 10.5 X 10^9 m^3. It is important to note here that, although the words swamp and delta are interchanged to indicate the same area

TABLE I. MAJOR MORPHOMETRIC AND HYDROLOGICAL PARAMETERS OF THE OKAVANGO SWAMP

Mean area of the swamp	10 000 km^2
Max. area of the swamp	13 000 km^2
Min. area of the swamp	6 000 km^2
Mean active storage	4×10^9 m^3
Max. active storage	7×10^9 m^3
Min. active storage	1×10^9 m^3
Input	
Inflow	10.5×10^9 m^3/a
Precipitation	5×10^9 m^3/a
Output	
Evapotranspiration	14.9×10^9 m^3/a
Outflow (surface)	0.3×10^9 m^3/a
Outflow (groundwater)	0.3×10^9 (?) m^3/a

the swamp occupies only approximately 50% of the total area of the Okavango Delta which is 20 000 km^2. The swamp area continuously shifts over the very gently sloping delta in an unpredictable way causing a highly variable flow pattern at the surface and also possibly the groundwater régime at the boundaries of the swamp (Fig. 1).

The Okavango Delta owes its existence to a series of fault lines which blocked its ancient channel in the fairly recent geological past. At present, the old channel reappears at the base of the delta and continues some 280 km until it reaches the Makgadikgadi salt pans where the ancient river used to spread over a vast plain. The ancient channel of the Okavango River between the delta and the Makgadikgadi salt pans is now called the Boteti River which, during recent years, had a mean annual flow volume of 300×10^6 m^3, barely 3% of the mean annual inflow to the swamp.

The chemical composition of the Okavango Swamp waters indicates that the major ionic species are sodium and bicarbonate with significant amounts of silica. The total dissolved solids in the inflow waters are about 35 mg/l, which

TABLE II. THE RELATION BETWEEN THE ^{14}C and ^{18}O CONTENT OF GROUNDWATERS IN BOTSWANA

Range of ^{14}C values per cent of modern carbon	Mean tritium content (T.U.)	Mean $\delta^{18}O$ (‰)	Error of the mean $\delta^{18}O$
86.2–120.2	7.03 ± 1.69	− 5.38	± 0.44
52.6–78.4	0.78 ± 0.16	− 5.17	± 0.62
3.1–48.3	1.22 ± 0.34	− 6.37	± 0.16

gradually increase downstream to reach 120 mg/l at the swamp outlet. This shows that most of the salts entering the swamp are deposited in the swamp or removed by groundwater. Similarly, there is a gradual enrichment of stable isotopes along the main flow systems in the swamp.

Table I shows the major components of the Okavango Swamp water balance calculated by using a mathematical model of the Okavango Swamp [2]. Evapotranspiration from the swamp was found, using the mathematical model and satellite imagery, to be approximately 1500 mm/a, which is 85% of the open-water evaporation calculated by the Penman for mula. This information is a basis for an overall understanding of the hydrological conditions in the swamp.

1. STABLE ISOTOPE STUDIES

1.1. Previous studies

A survey of the isotopic composition of groundwaters in Botswana including tritium, ^{14}C, ^{13}C, D and ^{18}O has been made by Mazor et al. [3]. This study has given a good idea of the variability of water-related isotopes in Botswana.

A few samples collected in the vicinity of the Okavango Swamp showed extensive isotopic enrichment of the swamp and related groundwaters. An interesting feature of this study is the variation of the stable isotope content of groundwaters with the age of the water. This has not been emphasized by the authors. Table II gives the ^{14}C, ^{18}O and tritium content of groundwaters in Botswana classified according to the decreasing values of ^{14}C. It can be seen that three statistically significant ranges of ^{18}O and D values correspond to the three groups of ^{14}C values. Thus, the age of groundwater can be roughly inferred from the stable isotope data. This point has been used advantageously in subsequent studies of the groundwater in the vicinity of the Okavango Swamp.

Text continued on p. 14

TABLE III. STABLE ISOTOPE DATA FOR THE OKAVANGO SWAMP AND RELATED WATERS

Sample	Location	Type	Date	Depth (m)	EC (μmho/cm)	TDS (ppm)	^{18}O (‰)	D (‰)	Remarks
1	Xudum	Pool	24-04-75	0.2	5500	4900	+ 7.49	26.3	Stagnant water
2	Xudum	Pool	24-04-75	0.2	340	350	+ 1.29	− 2.2	Stagnant water
3	Xudum	Pool	28-04-75	0.10	1000	850	+ 0.09	− 6.9	Stagnant water
4	Xudum – Pontoon	Channel	27-04-75	1.00	70	84	− 0.14	− 11.7	
5	Mohembo (Okavango)	River	29-05-75	.....	32	32	− 3.89	− 29.7	
6	Duba (Nggokha)	Channel	13-05-75	.....	..	28	− 3.79	− 28.9	
7	Xakue (Boro)	Channel	10-05-75	.....	47	40	− 2.02	− 19.4	
8	Txatxanika KQ2 (Khwaai)	Channel	15-05-75	.....	58	76	− 0.36	− 11.1	
9	Malalakgaka K.S3 (Santantadibe)	Channel River	17-05-75	.....	86	92	+ 0.69	− 4.2	
10	Boro Junction KB4 (Boro)	River	05-05-75	.....	..	84	− 0.80	− 13.0	
11	Kondo	DW	12-05-75	32	350	320	− 0.04	− 11.5	
12	Maun	Rain	15-04-75	..	...	28	− 5.60	− 25.8	
13	Mohembo (Okavango)	River	06-04-75	..	43	48	− 4.42	− 30.8	
14	Seronga (Okavango)	River	26-02-75		40		− 3.98	− 30.6	
22	Kondo	DW	06-09-75	35			+ 0.10	− 14.8	
23	Kodmotswana	BH	02-09-75		3150	1676	+ 0.72	− 11.1	

TABLE III (cont.)

Sample	Location	Type	Date	Depth (m)	EC (μmho/cm)	TDS (ppm)	^{18}O (‰)	D (‰)	Remarks
24	Gumare	BH	03-09-75		200	176	− 2.44	− 23.9	
25	Tsau	BH	06-09-75		430	412	− 1.54	− 22.4	
26	Maun Met. station	A-Pan	19-09-75				+ 13.94	+ 46.3	
27	Toteng (Kunyere R.)	River	02-09-75				+ 3.71	+ 8.1	
28	Tsau (Thaoge R.)	River	02-09-75		65 (30)		+ 4.78	+ 13.0	
29	Experimental area (outlet)	Swamp	12-09-75	0.80	53		+ 164	− 2.9	
30	Experimental area (inlet)	Swamp	13-09-75	1.60	53		+ 0.92	− 6.1	
31	Experimental area	AH	13-09-75	0.80	550		+ 2.71	+ 1.2	Shallow G.W.
32	Xudum	Swamp	12-09-75	80	55		+ 1.02	− 5.5	Bekkers bridge
33	Maun Bridge (Thamalakane R.)	River	08-09-75				+ 1.86	− 1.6	
34	Nokaneng	BH	03-09-75		275		− 2.84	− 27.4	
35	Shakawe (Okavango R.)	River	06-09-75				− 4.79	− 36.2	
36	Gaenga (Nggokha R.)	River	22-09-75		36		− 4.02	− 31.2	
37	Xugana Lagoon	Lagoon	23-09-75		42		− 2.32	− 21.3	Monachira R.
38	Duba (Okavango R.)	River	22-09-75		35		− 4.12	− 32.8	

Sample	Location	Type	Date	Depth (m)	EC (μmho/cm)	TDS (ppm)	^{18}O (‰)	D (‰)	Remarks
39	Txatxanika (Khwaai)	River	24-09-75		48		− 0.84	− 14.4	
40	Malalakgaka (Santantadibe)	River	25-09-75		120		+ 5.88	+ 19.7	
41	Boro Junction KB4				55		+ 2.46	− 0.5	
42	Xakue (Boro R.)	River	19-09-75		45		− 0.92	− 13.1	
43	Experimental area (outlet)	Swamp	03-10-75		68	68	+ 2.22	+ 1.6	
44	Experimental area (inlet)	Swamp	03-10-75		55	52	+ 1.50	− 3.1	
45	Gadikwe Lagoon	Lagoon	21-09-75				− 1.47	− 17.3	
46	Chobe Road (Mogohelo R.)	River	20-09-75				+ 4.91	+ 16.9	
47	Bodumatu B. (Moremi G.R.)	Swamp	20-09-75				+ 0.74	− 5.1	
48	TFC Barrier Borehole	BH	20-09-75			320	+ 2.38	− 1.80	at Shorobe
49	Maun Borehole	BH	03-11-75	(10)	(350)		+ 4.50	+ 7.0	
50	Experimental area (outlet)	Swamp	04-11-75				+ 4.72	+ 14.6	

TABLE III (cont.)

Sample	Location	Type	Date	Depth (m)	EC (μmho/cm)	TDS (ppm)	^{18}O (‰)	D (‰)	Remarks
51	Experimental area (inlet)	Swamp	04-11-75		55		+ 4.12	+ 9.3	
52	Toteng (Kunyere R.)	River	08-11-75				+ 8.74	+ 31.7	
53	Experimental area (outlet)	Swamp	13-11-75		80		+ 5.24	+ 19.9	
54	Experimental area (inlet)	Swamp	13-11-75		75		+ 3.49	+ 10.1	
55	Boteti R. (Rakops)	River	26-11-75				+ 6.78	+ 20.6	
56	Mopipi Res.	Reservoir	26-11-75		1800		+ 7.68	+ 33.4	
57	Mabe I (Haina Velt)	BH	26-11-75		3100		− 7.62	− 51.6	
58	Mabe II (Haina Velt)	BH	26-11-75				− 6.22	− 42.0	
59	Boteti R. (Mopipi inlet)	River	26-11-75		600		+ 8.00	+ 29.6	
60	Thaoge R. BE/17	River	29-11-75				+ 9.66	+ 38.9	
61	Experimental area (outlet)	AH	03-12-75	0.40			+ 1.09	− 3.5	
62	Experimental area (inlet)	Swamp	05-12-75				+ 5.70	+ 18.8	

Sample	Location	Type	Date	Depth (m)	EC (μmho/cm)	TDS (ppm)	^{18}O (‰)	D (‰)	Remarks
63	Boteti R. (Rakops)	River	15-12-75				+ 6.08	+ 20.0	
64	Mopipi Res.	Reservoir	07-02-76			1123	+ 6.65	+ 28.5	
65	Boteti R. (at Mopipi)	River	07-02-76			666	+ 4.78	+ 17.7	
66	Boteti (Rakops)	River	07-02-76				+ 4.52	+ 12.5	
67	Boteti R. (at Tsoi)	River	07-02-76			115	+ 4.04	+ 9.8	
68	Boteti R. (at Dikwalo)	River	07-02-76			102	+ 4.04	+ 10.6	
69	Boteti R. (at Samedupi)	River	07-02-76			84	+ 2.60	+ 4.8	
70	Thamalakane (at Maun)	River	20-02-76				+ 2.76	+ 4.2	
71	Haina Velt 5001	BH	07-04-76				− 6.52	− 46.7	
72	Haina Velt 5004	BH	08-04-76				− 6.82	–	
73	Haina Velt 5008	BH	08-04-76				− 6.80	− 46.7	
74	Haina Velt 5010	BH	09-04-76				− 7.22	− 48.1	

TABLE III (cont.)

Sample	Location	Type	Date	Depth (m)	EC (μmho/cm)	TDS (ppm)	^{18}O (‰)	D (‰)	Remarks
75	Haina Velt 5012	BH	09-04-76			2210	−6.15	−42.6	
76	Haina Velt 5013	BH	09-04-76				−6.78	−45.3	
77	Haina Velt 5022	BH	10-04-76			5640	−6.64	−44.4	
78	Haina Velt	BH					(−5.05)	−35.2	
79	Haina Velt 5026	BH	13-04-76				−7.15	−47.1	
80	Haina Velt 5028	BH	13-04-76				−6.60	−42.5	
81	Haina Velt 5031	BH	13-04-76				−6.28	−40.3	
82	Haina Velt 5032	BH	14-04-76				−6.68	−43.3	
83	Machaba (L. Ngami) 5200	DW	18-04-76				(+0.36)	−10.2	
84	Xhabaxwa (L. Ngami) 5213	DW	19-05-76				+0.86	−7.4	
85	Motopi pan (L. Ngami) 5222	DW	20-05-76				−4.92	−26.5	

Sample	Location	Type	Date	Depth (m)	EC (μmho/cm)	TDS (ppm)	^{18}O (‰)	D (‰)	Remarks
86	Maigo (L. Ngami) 5228	DW	20-05-76				− 7.37	− 47.0	
87	Hitoto (L. Ngami) 5239	DW	21-05-76				− 7.48	− 54.1	
88	Masalanyane (L. Ngami) 5262	DW	21-05-76				− 7.83	− 54.4	
89	Matlabologa (L. Ngami) 5263	DW					− 7.74	− 54.0	
90	Kara (L. Ngami) 5269	DW					− 0.33	− 13.1	
91	Patane I (L. Ngami) 5255	DW?					+ 1.76	− 0.2	
92	Khwaai Lodge	BH					+ 2.56	2.1	
93	Mababe Village	DW					+ 1.92	− 2.2	
94	Kodmotswana	BH					+ 0.47	− 11.6	

NOTE: DW = dug well; BH = Borehole; AH = Augerhole.

1.2. The purpose of the present study

The collection of the stable isotope data is particularly useful in hydrological situations where evaporation is a major component of the water balance since evaporation modifies the stable isotope content of the water. The basic purposes of the present study were:

(a) To determine the significance of the groundwater outflow from the delta. This point was of extreme importance in formulating the water balance of the Okavango Swamp and the mathematical model.
(b) To determine the conveyance efficiency of major distributary swamp and channel systems. It was assumed that high isotopic enrichment would be related to more or less stagnant swamp areas.
(c) To determine the past and present flow conveyance status of the distributary swamp systems. This is based on the hypothesis that the isotopic composition of shallow groundwater is related to the past conveyance status of the system whereas the isotopic composition of surface waters represents the present conditions.
(d) Detection of direct precipitation recharge to shallow groundwater, particularly in ancient swamp areas.
(e) Partitioning of the total atmospheric losses into their evaporation and transpiration components.

1.3. Data collection

Ninety-four stable isotope samples were collected, including both surface and groundwater samples (Table III). As the annual flood of the Okavango River starts in April and there is practically no precipitation over the swamp until the end of October, samples collected at the end of the southern winter should be free of the contaminating effect of the precipitation and represent the isotopic variability resulting only from evaporation. Samples were also collected at the end of the rainy summer season to compare with the samples collected at the end of the winter. A parallel survey was also made of the chemistry and electrical conductivity of water in order to obtain a better understanding of the chemistry of the waters and of the relationship between evaporation and transpiration.

1.4. General pattern of variability of stable isotopes on the Okavango Swamp and related groundwaters

The stable isotope content of swamp waters is determined by various factors which can be summarized as follows:

(a) The importance of the flow-rate in the swamp system – if the conveyance efficiency of the system is high there is less time for the water to evaporate and

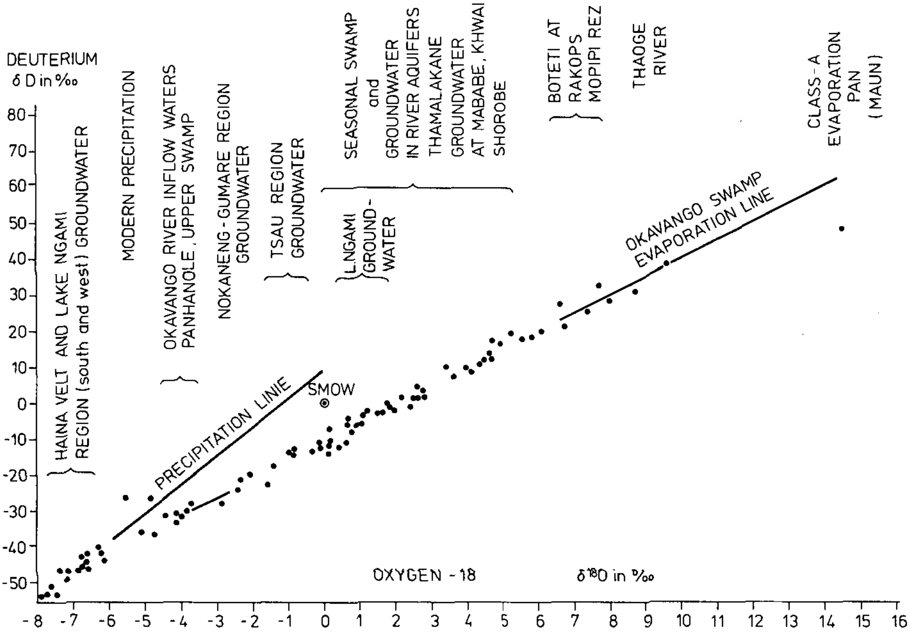

FIG. 2. ^{18}*O-D relation in the Okavango Swamp and groundwaters in the same region.*

consequently the isotopic enrichment is less compared with the stagnant swamp areas;

(b) The addition of isotopically lighter rain-water to the isotopically enriched swamp water; and

(c) The ratio of the evaporation to transpiration along a given flow line or distributary swamp system. The isotopic enrichment of swamp waters is less in seasons or along the flow lines where the major portion of the atmospheric losses occurs as transpiration which, unlike evaporation, does not cause the isotopic enrichment of the source water.

Figure 2 gives the ^{18}O and D graph of the water samples collected in the Okavango Delta and its vicinity. The correlation between ^{18}O and D values of the samples is very high and the information content of the stable isotope data is thus duplicated. The only exception is the sample collected from the Class-A pan at Maun meteorological station which shows that care should be exercised while extrapolating artificial conditions, not only in estimating evaporation but also in evaluating the isotopic composition of the evaporating water.

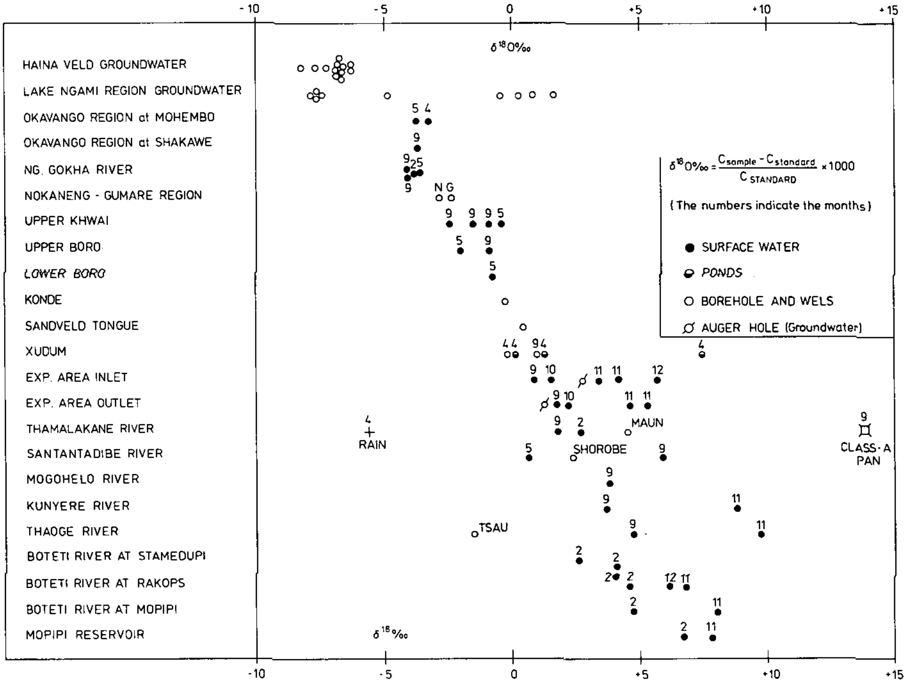

FIG. 3. Classification of Okavango Delta waters with respect to ^{18}O.

Figure 3 shows the range of ^{18}O values in the delta waters. The inflow waters as represented by samples collected at Shakawe and Mohembo fall within the range of −4.9 to − 3.9‰. There is an indication of a small seasonal variation, since the September 1975 sample from Shakawe, representing the base flow period, is 1% lower than the sample collected at Mohembo in May, which represents the flood flow. According to these results the typical ^{18}O value of the inflow waters can be taken as −4.0‰.

The second distinct group of waters with respect to ^{18}O is from the central part of the swamp, such as the Boro channel at Xakue, Xugana Lagoon, Gadikwe Lagoon and Txatxanika, which have ^{18}O values of between −2.3 and −0.3‰, which show that extensive evaporation losses are already taking place between Mohembo and these locations. The range of the ^{18}O values is some 2‰, about twice the range observed in the upper part of the swamp.

The third group of samples is related to the lower part of the swamp, which as a whole fluctuates seasonally in extent, and to the outlets of the swamp. Not only is there a wide variation among samples collected at various distributaries, but also a wide variation at a given location among samples collected at different times of the year. This variability can be explained by the addition of the rainwater and the different evapotranspiration ratios.

1.5. Determination of relative conveyance efficiencies of distributary swamp systems

The determination of relative conveyance efficiencies of different distributary swamp systems could be made using either the salinity or the stable isotope content of swamp waters, with the difference that the isotopic enrichment is related to the evaporation and the increase in salinity to the total atmospheric losses, i.e. to evapotranspiration.

When the waters at the various outlets of the Okavango Swamp are compared on the basis of their ^{18}O content in September 1975, which is the period of maximum discharge at these locations, it is seen that the waters which are less enriched isotopically are found at the Boro channel near the base of the delta, followed by the Kunyere channel on the west. The waters of the Santantadibe, Mogohelo and Thaoge channels are significantly enriched compared with the Boro and Kunyere channels. There is also a significant isotopic enrichment in all these outlet channels from September to October as a result of the very dry and windy atmospheric conditions during October. These results are in good agreement with the present flow distribution and flow conveyance status of the different distributary swamp systems as inferred from hydrological records.

The stable isotope content of the Boteti River and Mopipo Reservoir, where the water of the Boteti River is pumped to supply the Orapa diamond mine, discloses further evaporative losses. Samples collected along the Boteti River from its source at the base of the delta clearly show a gradual isotopic enrichment from Samedupi (+ 2.6‰) to Dikwalo and Tsoi which are at the upper reaches of the Boteti River (+ 4.1‰) and then to Rakops (+ 4.6‰) and to the Mopipi Reservoir itself (+ 6.7‰), in agreement with a considerable decrease in flow rates along the river.

1.6. The stable isotope content of the groundwaters

Owing to the limited number of wells and boreholes in the sparsely populated region of the Okavango Delta and its surroundings from which samples could be collected, the hydrological information obtained from the stable isotope content of the groundwater is tentative although of great value in determining the significance of the groundwater outflow from the delta, the recharge through direct infiltration of rain, and in evaluating historical hydrological conditions in some distributary swamp systems. The basic findings of this study are:

(a) The groundwater at the western periphery of the delta consists mainly of runoff rain-water with no significant contribution from the swamp (wells and boreholes at Nokaneng, Gumare and Tsau). Thus, there is no groundwater outflow from this area of the swamp, which is in agreement with the admittedly scarce piezometric and topographic data.

(b) Lake Ngami groundwaters on the western and southern borders of the lake, as well as the groundwater in Haina Velt south of the Thamalakane faultline, have no swamp origin, which excludes the possibility of groundwater outflow from the swamp in this region and shows that the faultline is an effective barrier against groundwater movement. Moreover, the isotopic composition of these waters is similar to group 3 waters in Table II, showing that their ^{14}C content is most probably less than 50% of the modern carbon, and consequently these waters are not of recent origin. Nevertheless, the groundwater samples collected at the north of the lake clearly show that these waters have swamp origin.

(c) Groundwater at Konde and at Sandvelt Tongue in the southwest part of the delta consists of mixtures of swamp and directly infiltrated rain-waters.

(d) Groundwater at Maun, immediately north of the Thamalakane faultline, is of pure swamp origin, obviously recharged through the Thamalakane River. It is significantly more enriched than the flood waters of the Thamalakane, indicating that in the past the river water was subject to more extensive evaporation than today, i.e. the Boro swamp feeding this river was more stagnant. The same conclusion also holds for the groundwater in the experimental area established in the lower Boro system.

(e) Groundwaters at Shorobe, Mababe and Khwai on the southeast of the delta are less enriched than swamp waters, indicating either a more active flow condition in the source Nggokha system in the past or the contribution of rain-water infiltration. The hydrological data on the Nggokha system favour the first hypothesis.

1.7. A stable isotope-salinity model of deltaic swamps and partitioning of the atmospheric losses into their evapotranspiration components

An important feature of the deltaic swamps is their divergent flow pattern which results in limited mixing of waters. Lateral mixing occurs rarely and most flow systems are independent of each other. In this respect, a deltaic swamp functions as an irrigation system where water is distributed to the consumptive areas. In such hydrological systems the physical, chemical and biological properties of water at a given location are determined not by local conditions but by the history of water between the source area and that location, although there may be exceptions to this rule. This is a most useful point in interpreting any particular property of water as the information is not local but integrated along a flow line.

Let us consider a large cell of water, similar to a tracer cloud, moving from the source downstream. It will be assumed, as is the case from April to October in the Okavango Delta region, that no rain-water is added to the cell during its travel. Such a cell will be split into smaller cells as the flow is distributed and redistributed over the delta. The water balance of this cell along any flow line and any period t can be written as:

$$\frac{\Delta V}{\Delta t} = I - E - T - O - Q \qquad (1)$$

where V is the volume change of the cell during t and I, E, T, O, and Q are the mean rates of inflow, evaporation, transpiration, outflow and losses to groundwater, respectively.

The salt balance of the cell is given by:

$$V\frac{\Delta C}{\Delta t} + C\frac{\Delta V}{\Delta t} = C_iI - CO - CQ \qquad (2)$$

where C is the salinity of the water in the cell and C_i is the salinity of the inflow to the cell. It is assumed that the losses to groundwater and surface outflow from the cell have the same salinity as the water in the cell. It should be noted that Eq.(2) is more applicable for ionic species with good tracer properties than the total salinity of water. Finally, the stable isotope balance of the cell can be expressed as:

$$V\frac{\Delta R}{\Delta t} + R\frac{\Delta V}{\Delta t} = R_iI - R_eE - RT - RO - RQ \qquad (3)$$

where R is the stable isotope content of the water in the cell expressed as isotope ratio, R_i and R_e the isotopic composition of the inflow and evaporated water, respectively. It is assumed that the water transpired by swamp vegetation has the same isotopic composition as the cell water, since a plant functions essentially as a pipe and the swamp vegetation has shallow root systems. It is worth mentioning that R_e is a value which is calculated from the molecular exchange of swamp water with the atmospheric moisture and has no physical meaning itself. As in the case of salinity of water it is assumed that the losses to groundwater and surface water outflow from the cell have the same isotopic composition as the water in the cell.

Eliminating the term $\frac{\Delta V}{\Delta t}$ between Eqs (1), (2) and (3) one obtains:

$$\frac{\Delta C}{\Delta t} = \frac{I}{V}(C_i - C) + \frac{C}{V}(E + T) \qquad (4)$$

and

$$\frac{\Delta R}{\Delta t} = \frac{I}{V}(R_i - R) - \frac{E}{V}(R_e - R) \tag{5}$$

It should be noted that, on the right side of these equations, the term related to the inflow is negligible compared with the terms related to evaporation and transpiration because the salinity and the isotopic composition of the inflow to the cell from neighbouring cells are similar to the salinity and the isotopic composition of the cell water itself.

Neglecting the terms related to the inflow and then taking the ratio of the left and right sides in Eqs (4) and (5), one obtains

$$\frac{\Delta R}{\Delta C} = \frac{E\,(R_e - R)}{(E + T)\,C} \tag{6}$$

which gives the differential relation between the salinity and the isotopic composition of the cell. It is seen that this relation is independent of the volume of the cell, the losses to groundwater and the surface water outflow from the cell.

Writing the hypothetical isotopic composition of the evaporated water [4], expressed in its physical components of molecular exchange of cell water with the atmospheric moisture, one has:

$$R_e = \frac{R}{\alpha\alpha'} \cdot \frac{1}{1-h} - \frac{R_a}{\alpha'} \cdot \frac{h}{1-h} \tag{7}$$

where h is the relative humidity of the atmosphere with respect to the surface water temperature, and the equilibrium and kinetic fractionation factors and R_a the stable isotopic composition of the atmospheric moisture. Inserting R_e from Eq.(7) into Eq.(6) and integrating with respect to R and C, one finally obtains the relation:

$$R = (R_i - R_f)\left(\frac{C}{Ci}\right)^{-\frac{E}{E+T}\,\frac{(1-h)\,\alpha\alpha' - 1}{(1-h)\,\alpha\alpha'}} + R_f \tag{8}$$

where R_i and C_i are the initial values of the stable isotope content and the salinity in the source region and R_f the final equilibrium stable isotope content of the cell water, which depends only on the relative humidity of the atmosphere and the isotopic composition of the atmospheric moisture. Since the equilibrium and kinetic fractionation factors α and α' are close to unity, Eq.(8) can be further reduced to:

$$R = (R_i - R_f)\left(\frac{C}{C_i}\right)^{-\frac{E}{E+T}\frac{h}{1-h}} + R_f \qquad (9)$$

in which the isotope ratios can be replaced by δ values for ease of calculation.

Relation (9) is somewhat similar to the relations found earlier by Craig and Gordon [5] and Fontes and Gonfiantini [6], who studied stable isotope variations in isolated evaporating water bodies. However, in addition it includes a term which has hydrological significance, namely the evaporation/evapotranspiration ratio.

When there is a large number of samples the evaporation/evapotranspiration ratio can possibly be estimated by maximizing the coefficient of correlation between the stable isotope content and salinity of swamp water together with the measured values of the atmospheric moisture. It should also be stressed that the proposed method cannot be used in estimating evaporation or evapotranspiration but only their ratio. Another possible way of estimating this ratio is to estimate R_f – or δ_f – the final equilibrium isotopic composition of swamp water. If this can be estimated from the isotopic data the evaporation/evapotranspiration ratio can be determined using Eq.(9). In the final interpretation it is important to see whether the salinity and isotope variations are caused by evaporation and transpiration processes. There are, for example, samples with high salinity and low stable isotope content (samples 2 and 3 and possibly the Mopipi Reservoir samples in the present study), where the salinity and isotopic composition of the water are not determined either by evaporation or by transpiration, but by mixing, which is mathematically a linear process, or by solution of salt crusts by isotopically light water. The addition of the rain-water is also a mixing process, which makes the interpretation of the salinity and isotope data difficult along the lines proposed here, unless the amount of rain is small compared with the depth of the water in the swamp, or its isotopic composition and the salinity of the rain are known.

1.8. Application of the isotope-salinity model to the Okavango Swamp

From the meteorological records at Maun the relative humidity of the atmosphere is estimated to be 45% for winter and 60% for summer months. According to the short-term measurements in the experimental area in the swamp, the relative humidity in the swamp is higher than at the peripheral stations such as Maun, which results in the evaporation/evapotranspiration estimates being on the higher side when Maun records are used. For the initial values of the ^{18}O content a delta value of −4.0‰ and, for the initial salinity one of 35 ppm TDS have been assumed according to the consistent values observed in the source area. As there is a good correlation between salinity and

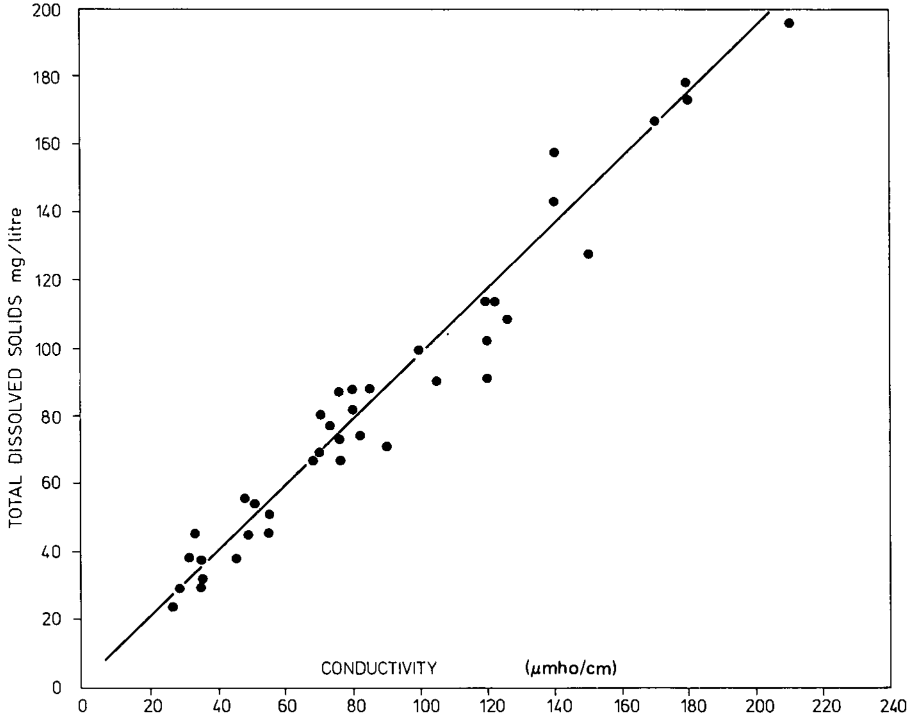

FIG.4. Relation between the salinity and electric conductivity of swamp waters.

the electrical conductivity of water, salinity values have been replaced by electrical conductivity for which there is more information.

Although the correlation between salinity, expressed in EC units, and the isotopic composition of swamp waters is high at the end of winter months ($r = 0.95$ for 16 samples) it is not possible to determine the evaporation/evapotranspiration ratio using this statistical approach because, for a wide range of this ratio, the coefficient of correlation remains high and does not have a well-defined maximum. Therefore, it is necessary to use the second approach based on the estimation of the final isotopic composition δ_f of swamp waters, which would be in isotopic equilibrium with atmospheric moisture.

From Table III it can be seen that the δ_f value cannot be less than + 10.0‰ for end-winter samples as there are few samples with ^{18}O values near that figure. According to the class-A pan data it can be as high as + 14‰ but, as was mentioned earlier, this cannot be very reliable. For end-summer samples the best indication of δ_f is given by the sample collected from an isolated pool at Xudum which has an ^{18}O content of + 7.49‰. Using these values together with the initial salinity

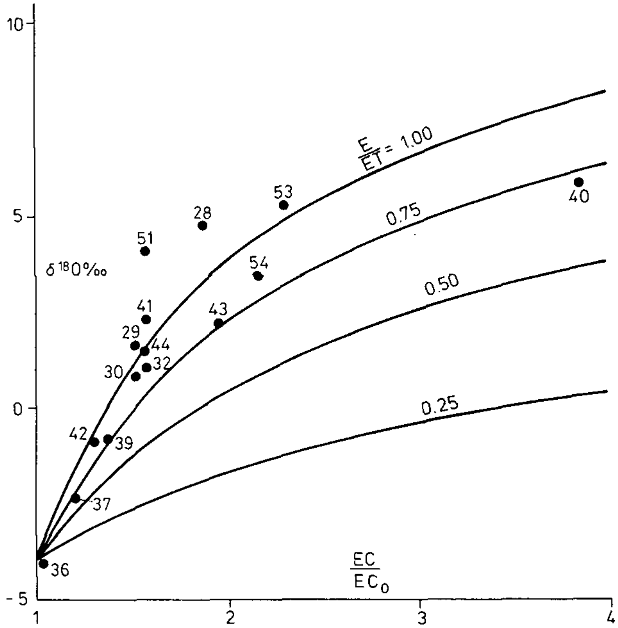

FIG. 5. Equal evaporation/evapotranspiration ratio curves for winter with data points.

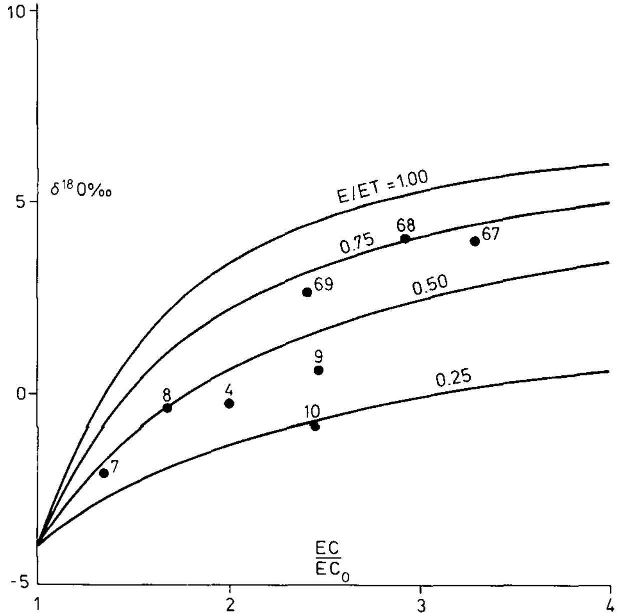

FIG. 6. Equal evaporation/evapotranspiration ratio curves for summer with data points.

and isotopic composition of swamp waters, two families of curves were calculated for winter and summer periods for different values of the evaporation/evapotranspiration ratio as a parameter in Eq.(9). These curves are given in Figs 4 and 5 with the isotope and salinity data for the respective periods.

It is seen from Figure 4 that in winter, when high water levels prevail in the swamp the evaporation/evapotranspiration ratio is near unity for most flow lines, although there are significant differences among these ratios, possibly reflecting different plant types and plant density conditions. The points having evaporation/evapotranspiration ratios higher than unity indicate that the δ_f value has to be corrected to avoid ratios higher than unity.

In this case the evaporation/evapotranspiration ratios would be all lower than unity but still remain high. In summer months the evaporation/evapotranspiration ratio never reaches unity but has a wide range between 25 and 75% showing the increasing part of the transpiration versus evaporation (Fig.6). In addition to the plant type and density along the flow lines this large variation is probably caused by the addition of rain-water to the swamp in summer months when water levels are low.

2. CONCLUSIONS

The results of the stable isotope survey of the Okavango Swamp and the groundwater in the same region have shown that the stable isotopes could be very helpful in swamp-water balance studies and surface and groundwater relations. The method proposed on the partition of evapotranspiration losses into its evaporation and transpiration components can easily be improved by a regular periodic sampling programme including precipitation and atmospheric moisture and using Eq.(9) in its differential form. It should be stressed that the interpretation of the results depends largely on the clarity of the hydrological model to be adopted. Finally it is hoped that the proposed method will contribute to the study of the transpiration in emergent aquatic plants both in swamps and in agricultural areas.

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DISCUSSION

B.Th. VERHAGEN: You warn against the use of evaporation pan data, yet you assume a value for δ_f of 14‰ on the basis of pan data.

T. DINÇER: A δ^{18}O-δD plot for these swamp waters indicates that the isotopic composition of the Class A evaporation pan is not reliable for estimating δ_f. When δ_f is plotted against the exponent of Eq.(9), one sees that the exponent is not very sensitive to variations in δ_f. This means that a reasonable estimate of δ_f based on highly enriched samples could be useful for calculating a reliable evaporation-evapotranspiration ratio. A frequency study of all δ values would perhaps also be helpful.

B.Th. VERHAGEN: You use stable isotope data on groundwater in swamps to make deductions about past water regimes in the swamps. Would not some age measurements help to elucidate this question?

T. DINÇER: Age measurements of the shallow groundwater within the swamp would certainly be useful when studying the past conveyance status of the distributary swamp systems. However, in the present study this point was not considered important enough to warrant additional tritium or ^{14}C measurements.

A. ZUBER: Was your Eq.(5) used to calculate any component of the water balance?

T. DINÇER: The water balance for the Okavango Swamp was established by means of a mathematical model based on Eq.(5), with some additional parametric relations between the volume, area and discharge of the swamp.

A. ZUBER: What kind of average values for humidity and temperature did you use in Eq.(9)?

T. DINÇER: The relative humidity and temperature values used in this study were obtained from the Maun meteorological station on the periphery of the swamp. Our measurements indicated that the relative humidity in the swamp was significantly higher than at the peripheral meteorological station. Maun records were used because the meteorological records obtained in the swamp itself related to too short a period. It was assumed that the temperature of the evaporating water would be similar to the atmospheric temperature. This assumption was not far from the truth according to the measurements, although there is a certain lag between the atmospheric and water temperatures. The average values used for relative humidity relate to the six months preceding each sampling period. To get better estimates of the evaporation-evapotranspiration ratio it is necessary to use Eq.(9) in the differential form and to sample swamp waters on a regular basis.

J.Ch. FONTES: Did you observe variations in pH which would indicate that a fraction of the total dissolved carbon is contributed by atmospheric CO_2?

L.G. HUTTON: In the flowing swamp waters total dissolved solids (TDS) increase from 35 mg/l at the inlet to about 200 mg/l at the outlet. The relationship with conductivity of bicarbonate, calcium, sodium, sum total and TDS at 120°C are linear up to a conductivity of 250 μS/cm. The flowing waters are continually in contact with the atmosphere and with plants which also produce CO_2. Thus, any imbalance of the HCO_3^-/CO_3^{--}/pH system would be buffered naturally.

In stagnant swamp waters we observed an increase in pH as the TDS increased. The main ionic components were sodium and bicarbonate with the carbonate species appearing only as evaporation proceeded. pH values of 8.1 and 9.9 were measured in samples from stagnant pools adjacent to "soda" deposits.

More in-situ pH and Eh determinations should be carried out in future investigations of the Okavango Delta. At the time of the study the difficulty of analysing such low TDS waters was not fully appreciated. It would in fact be preferable to choose a single chemical species which is not involved in other interactions, e.g. chloride, to study the relationship with evaporation. Details of the chemical analyses are available in UNDP/FAO Technical Report AG:DP/BOT/71/506, Gaborone 1977 (The Investigation of the Okavango Delta as a Primary Water Resource for Botswana).