Observations on the hydrology and geohydrology of the Okavango Delta

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The Okavango Delta is situated within two major grabens, one containing the Panhandle and the other the Delta itself. The main graben is underlain by between 200 m and 300 m of largely unconsolidated medium to fine sand. The Delta is an alluvial fan, which is divided longitudinally into two by horsts which form Chief's Island and the Duba Island cluster. Permanent swamp, sustained by base flow of the Okavango River, is developed in the Panhandle, upper fan, and portion of the fan to the east and northeast of Chief's Island. Seasonal flood water enters the Panhandle via the Okavango River, but because of the permeable nature of channel margins and the elevated water surface in the channels, especially at the apex of the fan, it is rapidly leaked from the channels. Most of the seasonal flood water flows to the west of Chief's Island where the bulk of the seasonal swamps are located. The extent of annual inundation is variable, and is strongly influenced by the magnitude of flood discharge and local rainfall, and to a lesser extent by antecedent conditions and evapotranspiration. Seasonal flooding has created a recharge mound beneath the Delta, but analysis of ground water chemistry and isotopic characteristics indicates that the Delta is essentially hydrologically closed, with no ground water outflow, and only limited surface water outflow. There is no large-scale lateral flow of ground water and water movements in the system are essentially vertical. Recharge occurs through the flood plains, and water is lost to the atmosphere by evaporation and especially by transpiration, particularly from islands. Soluble salts are accumulating in the deep ground water. This study has emphasized the need for more data on the aerial extent of seasonal flooding, on the ground water recharge, and on the contributions of evaporation and transpiration to water loss.

Die Okavango Delta is tussen twee hoofgrabens geleë. Een bevat die Pypsteel en die ander die Delta self. Die hoofgraben word onderlê deur tussen 200 en 300 m grootliks ongekonsolideerde medium tot fyn sand. Die Delta is 'n alluviale waaier wat longitudinaal in twee verdeel word deur horste wat Chief's Eiland en die Duba Eiland-tros vorm. Permanente boommoeras, onderhou deur basiese vloei van die Okavangorivier, is in die Pypsteel, die bo-waaier, en gedeelte van die waaier oos en noordoos van Chief's Eiland, ontwikkel. Seisoenale vloedwater kom die Pypsteel binne via die Okavangorivier, maar as gevolg van die deurlatende aard van die kanaalwande en die opgehewe watervlak in die kanale, veral by die punt van die waaier, lek dit vinnig uit die kanale uit. Die meeste van die seisoenale vloedwater vloei na die weste van Chief's Eiland, waar die meerderheid van die seisoenale boommoerasse geleë is. Die omvang van jaarlikse oorstroming varieer, en word sterk beïnvloed deur vloedafsetting en plaaslike reënval, en in 'n mindere mate deur voorafgaande gebeure en evapotranspirasie. Seisoenale oorstromings het 'n aanvullingsheuwel benede die Delta geskep, maar analise van grondwaterchemie en isotoop-eienskappe dui daarop dat die Delta hoofsaaklik hidrologies gesluit is, met geen uitvloei van grondwater nie, en slegs beperkte uitvloei van oppervlak water. Daar is geen grootskaalse laterale vloei van grondwater nie, en die beweging van water in die stelsel is hoofsaaklik vertikaal. Aanvulling geskied deur die vloedvlaktes, en verlies van water met betrekking tot die atmosfeer geskied deur verdamping en veral deur transpirasie, veral vanaf die eilande. Oplosbare soute is besig om in die diep grondwater op te hoop. Hierdie studie het die behoefte aan meer data oor die verbreiding van seisoenale oorstromings, oor die grondwateraanvulling, en oor die bydrae van verdamping en transpirasie tot waterverlies, beklemtoon.

Introduction

The existence of the Okavango wetland was first drawn to the attention of the developed world through the travels and writings of David Livingstone. Following his visit in 1849, numerous travellers ventured to the area, primarily to Lake Ngami (see Kokot, 1948, for a comprehensive review of the writings of these early travellers). During the early decades of this century, an interest in the hydrology of the Okavango began to develop. Schwarz (1918; 1920) proposed to recreate the great lakes of central Botswana using the waters of the Chobe and Okavango Rivers in the belief that evaporation from these lakes would improve rainfall over all of southern Africa. After field investigation, Du Toit (1927) deduced that all of the Okavango water was lost by evapotranspiration, yet the local climate remained semi-arid. The far smaller Chobe River was unlikely to alter this, and certainly both together were incapable of sustaining the proposed lakes. Nevertheless, support for Schwarz's scheme continued into the 1940s (Mackenzie, 1946; Kokot, 1948). Alternatives were also proposed: to irrigate the Mababe Depression by diverting water from the Chobe River along the Savuti channel (Du Toit, 1927); and to convert the entire area west of Chief's Island to irrigation using Okavango water diverted at Popa Falls (Wellington, 1948). Regional interest in the area waned, but several local schemes were implemented to modify flows with a view to improving local water supply (Wilson, 1973).

Following the independence of Botswana in 1966, and especially after the discovery of its mineral potential, renewed interest began to develop in the Okavango region as it is one of only two sources of perennial water in this land-locked, semi-arid country. Major water projects were formulated for the region (Standish-White, 1972) and limited dredging was carried out on the Boro channel in the Okavango in an attempt to increase supply to Orapa Mine (Standish-White, 1972; Ellery & McCarthy, in press). In addition, two major investigations were carried out, focusing particularly on the hydrol-

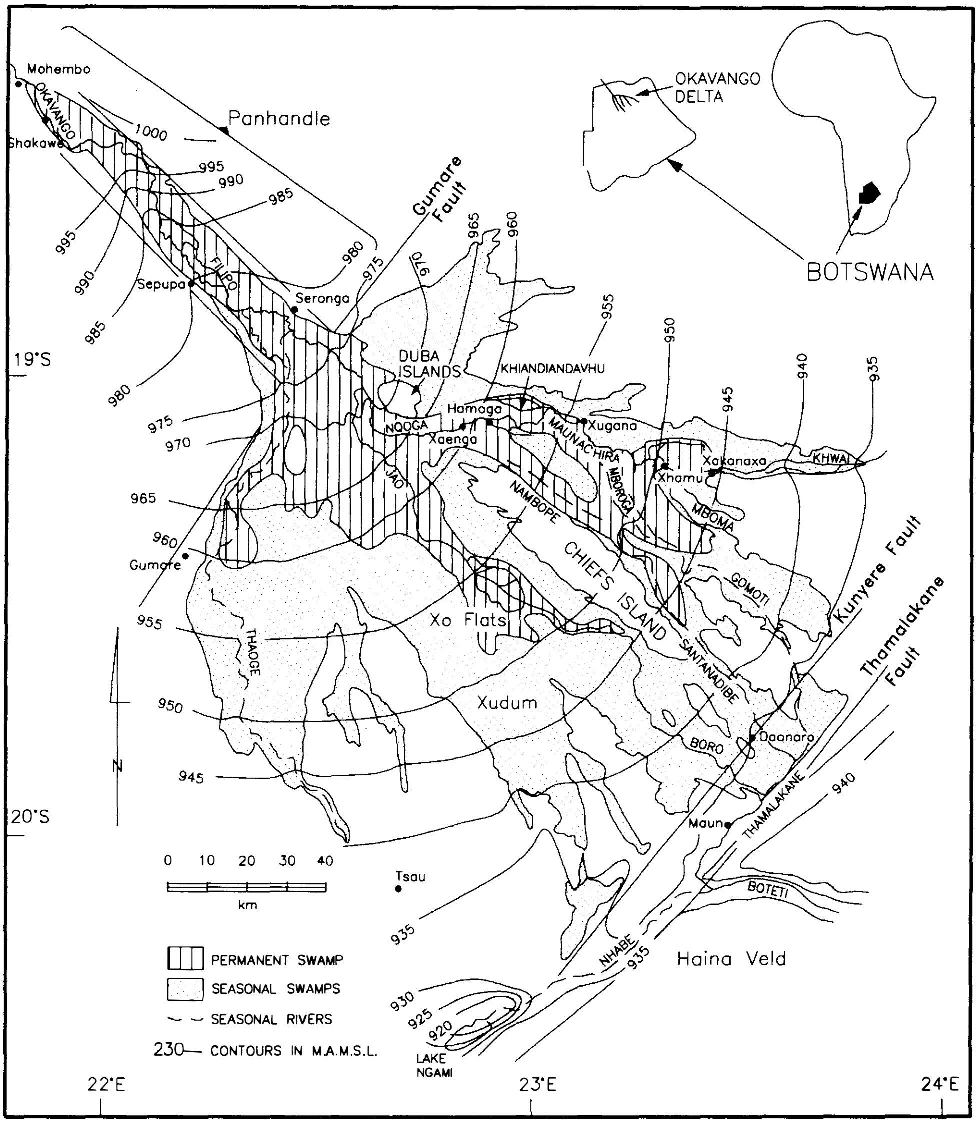

Figure 1 The Okavango Delta.

ogy of the Okavango, by the United Nations in the early 1970s (UNDP, 1976) and a private firm of consultants (Snowy Mountain Engineering Corporation, SMEC) in the late 1980s. The latter project resulted in proposals to extend the dredging on the lower Boro channel. The ensuing outcry from conservation groups (Greenpeace, 1991) led to a government sponsored investigation by the IUCN (1993), and subsequently, the shelving of dredging plans. Several smaller studies have been undertaken in the Delta by university groups, consultants, and by government agencies. These various studies have provided a large amount of data and insight into the hydrology and geohydrology of the Okavango Delta.

This investigation was prompted by the rapidly growing need for water both within Botswana and in neighbouring Namibia and Angola. Although several hydrological models have been developed for the Okavango region (see below), these are narrowly focused and are unsuitable for predicting the full extent of environmental impacts likely to be created by development projects in Namibia and Angola. Moreover, the models have been formulated using a conceptual framework of the Delta which is incomplete. In this paper, the authors propose to integrate available data with recent satellite information in order to provide an overview of the hydrological functioning of this important wetland ecosystem, and to highlight deficiencies in the database. It is hoped thereby to provide a basis for both future research and for the development of more complete hydrological models.

Methods and data sources

A variety of data sets were used in this syntheses. Hydrological records for the Okavango River at Mohembo and the Thamalakane River at Maun, rainfall records from Shakawe and Maun, and evaporation data from Maun, for the period 1969 to 1995, were used to examine hydrological aspects of the Delta. Depth to water table in 167 boreholes drilled between 1960 and 1985, and chemical analyses on 251 samples from these boreholes, provided information on the geohydrology and hydrochemistry of ground water in the region. This was augmented by stable isotope data for both surface and ground water which were extracted from the literature. Limited information on ground water recharge was obtained from unpublished United Nations reports. Results obtained in a study currently in progress by one of the authors (TSM) of shallow ground water in the Xudum area were also utilized, as were LANDSAT (TM and MSS) and NOAA 11 satellite imagery. Processing methods for this imagery have been described elsewhere (McCarthy *et al.*, 1997).

Okavango Delta

Introduction

The Delta consists of two broad regions: the Panhandle, and Delta proper (Figure 1), which is a large alluvial fan (Stanistreet & McCarthy, 1993). Both are situated in graben structures related to the East African Rift system (Du Toit, 1927; Hutchins *et al.*, 1976; Mallick *et al.*, 1981). Little is known of the sediment fill in these grabens. Geophysical studies suggest a thickness in excess of 300 m close to the Thamalakane fault (Reeves, 1978). A borehole drilled at Tsau revealed a thickness of Delta sediments of 257 m, most of which (231 m) consisted of unconsolidated or semi-consolidated, medium to fine sand; the remainder being weakly cemented sandstone (Dr R. Key, pers. com., 1997). Two boreholes drilled to the northeast of the Delta encountered in excess of 200 m of poorly consolidated, medium-grained sand with increasing carbonate cement, and marls and silcrete towards the base. The thickness of the Kalahari sequence in the two boreholes was 218 m and 307 m. Core recovery was very poor due to the unconsolidated character of the sandy sediment (Meixner & Peart, 1984).

The two regions of the Okavango may be subdivided on a basis of duration of flooding. The Panhandle has a gradient of 1:5500 (McCarthy *et al.*, 1997) and is dominated by a meandering river system flanked by permanent swamps. Towards its southern end, a number of distributaries develop which carry water to the western (Thaoge), central (Jao-Boro), and eastern (Nqoga) regions of the fan. The gradient on the fan is 1:3300 (McCarthy *et al.*, 1997) and is remarkably uniform. The character of its channels differs from those in the Panhandle in that they are not meandering and are flanked by extensive permanent swamps. Along its distal fringes, the permanent swamp gradually gives way to seasonal swamp, and the duration and frequency of flooding decreases distally. Seasonal swamps may be associated with channel systems, such as the Boro, but mostly they are not supplied by clearly defined, persistent channels. The southern margin of the Delta is defined by the scarps of the Thamalakane and Kunyere faults. Surface water reaching the southern extremity of the Delta flows along these scarps, especially in the Thamalakane River, some of which leaves the Delta via the Boteti River.

Panhandle

The Okavango River, which arises in central Angola, enters the Panhandle at Mohembo where the floodplain is relatively narrow, and thence meanders down a widening flood plain into the Panhandle proper, which exists southwards from about the latitude of Shakawe. In this upper section, the floodplain is primarily underlain by sand and meander-related features such as scroll bars are prominent. Vegetation indicative of prolonged flooding is generally absent.

From Shakawe southwards, permanent swamp environments become more prevalent and increase in area downstream. The channel continues to meander, but unlike the reach above Shakawe, the banks consist not of sand, but of peat impregnated with fine clastic material and stabilized by vegetation. Meandering occurs over nearly the full width of the Panhandle, and a meander ridge has developed in the vicinity of Sepupa. An avulsive channel, the Filipo, has developed which forms part of a complex zone of anastomosis in this section of the Panhandle. About 55% of the Okavango River's discharge is currently being diverted into the Filipo system (Smith *et al.*, 1997). Seasonal swamp environments occur beyond the permanent swamps, which fringe the channels of the middle Panhandle.

Towards the southern end of the Panhandle, the water surface in the Okavango River is substantially elevated relative to that in the surrounding swamps (McCarthy *et al.*, 1991a). Recent measurements (unpublished) have shown that the channel water surface can be as much as 60 cm higher than the water surface in the swamp 100 m from the channel margin. These steep gradients are maintained by dense vegetation and peat which forms semi-permeable levees, allowing a slow leakage of water from the channel. In the backswamp areas, by contrast, vegetation is more open, allowing a rapid dissipation of water emanating from the channel. It is within this region of marked relative channel water surface elevation that the major distributaries arise which supply water to the fan.

Upper Fan

The main channel of the lower Panhandle and upper fan is the Nqoga; a continuation of the Okavango River. The Thaoge and Jao–Boro distributaries discharge from its right bank. For much of its length, water surface in the channel is raised relative to the backswamp (McCarthy *et al.*, 1991a; unpublished data), and water is continually lost from the channel. McCarthy *et al.* (1991a) showed that of the water entering the Panhandle, the Thaoge, Jao, and Nqoga account for 60% of the discharge, the remainder having leaked through the channel margins. An important consequence of the raised channel water surface in this area is that the hydrograph shows only minor seasonal fluctuations (Wilson & Dincer, 1976), as the seasonal flood simply dissipates through the channel margins.

The Thaoge supplies water to the western portion of the fan. In the last century, this was the major distributary channel (Shaw, 1984), but experienced progressive failure from its distal end and is currently only a minor channel. The vast swamp which used to be associated with this channel has desiccated and the peat has burnt off, leaving extensive grasslands.

The Jao–Boro channel removes about 25% of the discharge of the Nqoga, but according to Porter & Muzila (1989), this is augmented downstream by water leaked through the margins of the Nqoga. In its upper reaches, the Jao is a well-defined channel, but this gives way to extensively flooded areas downstream, known as 'Xo flats', in which the channel is poorly developed or not developed at all (McCarthy *et al.*, 1997). This extensive flooding is due to neo-tectonic activity in this region of the fan. South of this area, the Boro becomes essentially a seasonal channel.

The Nqoga channel carries water to the north of Chief's Island, a tectonic uplift which divides the fan into two halves. The channel exists only as far as Hamoga Island, beyond which it has been subject to failure in the same manner as the Thaoge (McCarthy *et al.*, 1992; McCarthy & Ellery, 1995b).

Water leaks from the Nqoga to supply the Maunachira and its tributary, the Khiandiandavhu (McCarthy *et al.*, 1992). The Maunachira is an important secondary channel. It receives a steady supply of water from the Nqoga and hence experiences only minor seasonal variation (McCarthy & Ellery, 1997). It is flanked by extensive permanent swamps which extend as far as Xaxanaka in the east. The seasonal Khwai River and its associated swamps are supplied by the Maunachira channel. Water leaked from the Maunachira in its middle reach is a major source for the Mboroga–Santantidibi–Gomoti system to the east of Chief's Island (McCarthy & Ellery, 1997). Earlier this century, the Nqoga was linked directly to the Mboroga (Stigand, 1923), and as a consequence, the Santantidibe was the major distributary system. This changed with the failure of the lower Nqoga. Water leaked from the right bank of the Nqoga flows along extensive swamps to the northeast of Chief's Island, which contains the poorly developed Nambope channel (Wilson & Dincer, 1976). This system also supplies water to the Santantidibe channel.

The Upper Fan is an extremely important region in terms of wetland function, for it is here that primary water dispersal takes place. As alluded to above, water distribution has changed in historic times, from the west (Thaoge) to the east (Santantidibe) to the centre (Boro). The underlying reason for this is apparently the failure of the primary supply channels, which originate in the lower Panhandle and at the apex of the fan. These channels fail as a result of bedload accumulation in them, caused by loss of water through the channel margins (McCarthy *et al.*, 1992). In effect, shifts in water distribution across the fan are driven by clastic sediment loads in the channels, and especially by bedload. It is possible that channel abandonment may be aided by neo-tectonic activity.

The Lower Fan

The lower fan is characterized by seasonal swamps, dry grassland, and woodland. The topography is gently undulating, with a local relief seldom more than 1.5 m. During flood periods, the higher ground forms islands. The frequency and duration of seasonal flooding decrease distally across the lower fan. The boundary between the permanent and seasonal swamps is very diffuse as it is constantly shifting in response to short-term climatic variations, which expand or contract the area of permanent swamp. In a similar way, and for the same reason, the distal extremities of the seasonal swamp are also poorly defined.

Several studies have shown that wooded islands in the seasonal swamps fulfil a valuable function in the Okavango ecosystem as they act as transpirational pumps, releasing ground water into the atmosphere. In the process, they confine potentially toxic salts to locations beneath island centres (Ellery *et al.*, 1993; McCarthy *et al.*, 1993; McCarthy & Ellery, 1994; 1995a).

Hydrology

Hydrological functioning of the wetland

The basic hydrology of the Okavango Delta is now fairly well understood, at least qualitatively, largely as a result of the pioneering work of Wilson & Dincer (1976). Several hydrological models of increasing complexity and sophistication have been developed over a number of years (UNDP, 1976; Dincer *et al.*, 1987; SMEC., 1987, cited in Gieske, 1996; IUCN, 1993; Gieske, 1996). These models are narrowly focused on predicting the outflow in the Thamalakane River, which is the primary water source for Maun, and offer little insight into the regional hydrology, and particularly patterns of seasonal flooding. In the analysis presented here, hydrological models as such are avoided, and instead the physical processes involved, and the way each of the hydrological variables contributes to the overall hydrology of the Delta system, are examined.

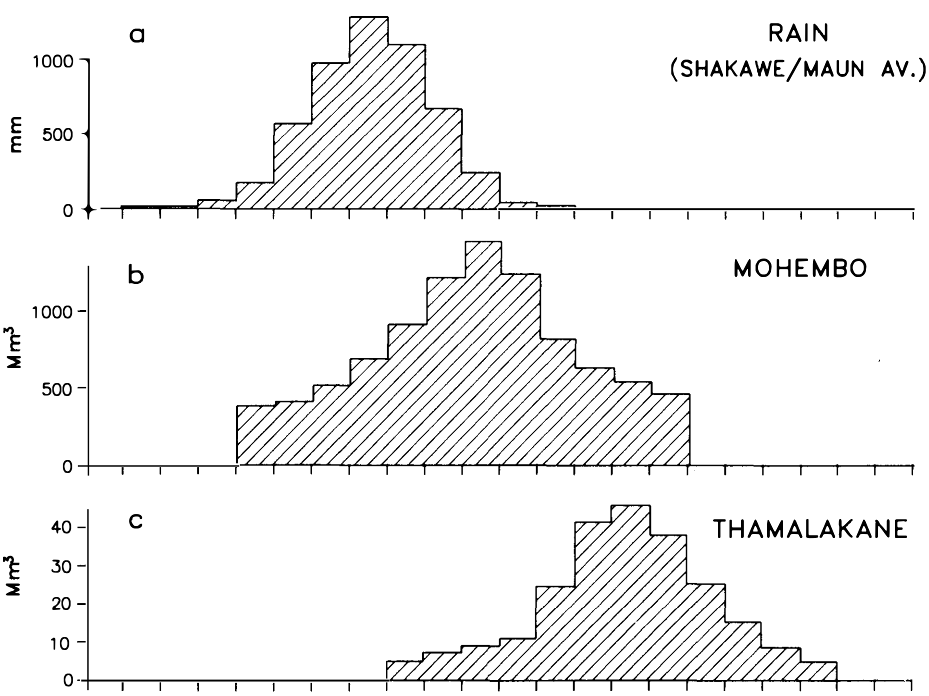

Figure 2 Monthly average (**a**) rainfall, (**b**) discharge in the Okavango River at Mohembo, and (**c**) discharge in the Thamalakane at Maun, for the period 1969 to 1994.

Summer rainfall in the catchment area collects in the Okavango River and discharges into the Panhandle at Mohembo, where the hydrograph shows a steady rise from a low in November to its seasonal peak in April (Figure 2b), whereafter it falls to the following seasonal low. The mean annual discharge (November to the following October) at Mohembo is 9195 Mm^3 for the period 1969 to 1994. The flood wave enters the Panhandle and moves downstream, where leakage occurs through the channel margins as described above. The flood water spreads outward, expanding the area of inundation and flooding the seasonal swamps. This pulse of water finally reaches the distal regions of the seasonal swamp some four months after the peak at Mohembo. This is illustrated by the hydrograph for the

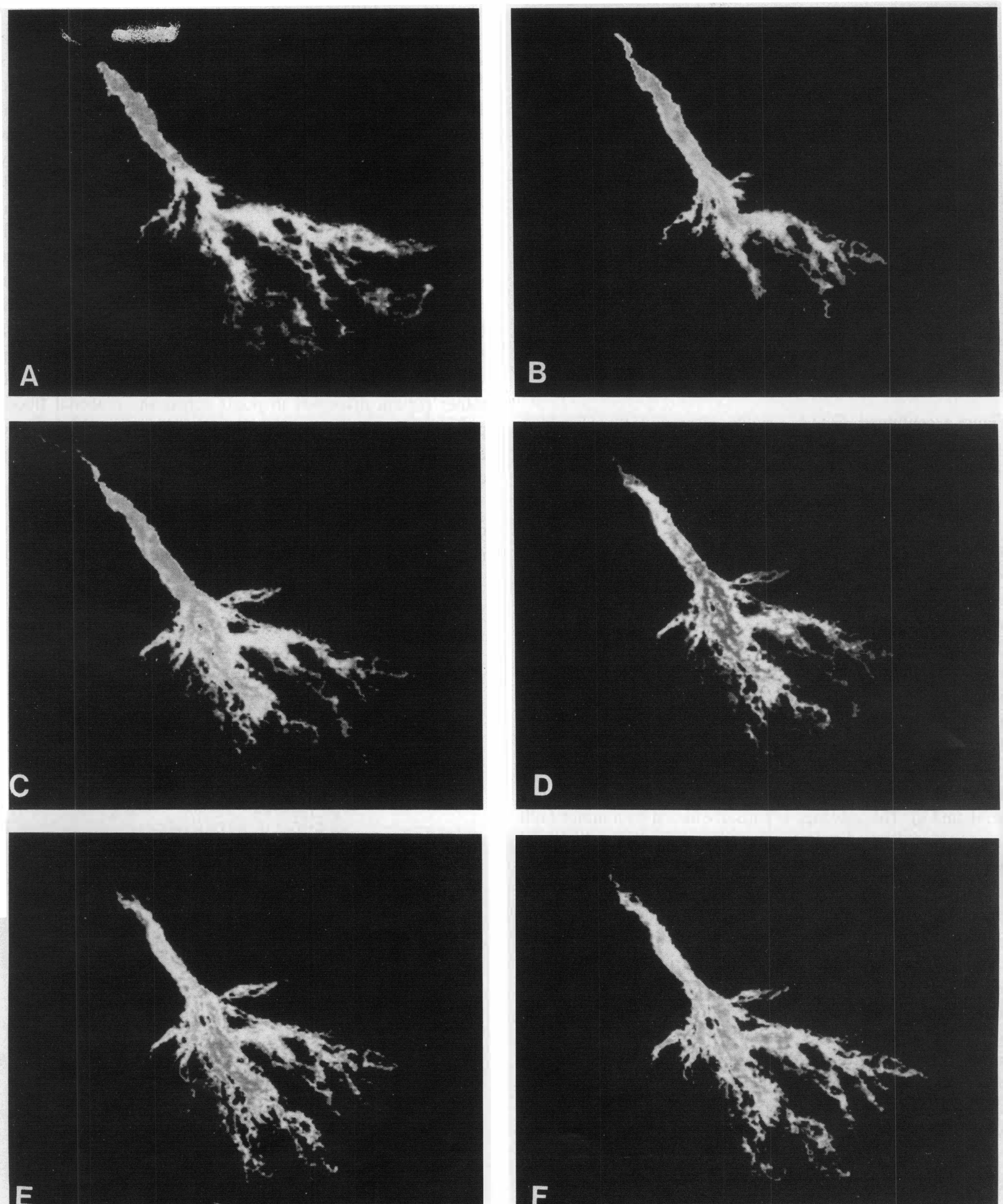

Figure 3 NOAA satellite images of the Okavango recorded during 1992 showing the advance of the seasonal flood: **(a)** 28 January; **(b)** 8 March; **(c)** 7 May; **(d)** 18 June; **(e)** 7 August; **(f)** 12 October.

Thamalakane River at Maun (Figure 2c), which is at its seasonal low in February and peaks in August. Mean annual discharge (February to January of the following year) in the Thamalakane River is 236 Mm^3. Maximum flow coincides with maximum area of inundation of the seasonal swamp.

The advance of the flood is illustrated by a series of NOAA satellite images, recorded at various times in 1992 (Figure 3). In January (Figure 3a), the inundated area is confined to the

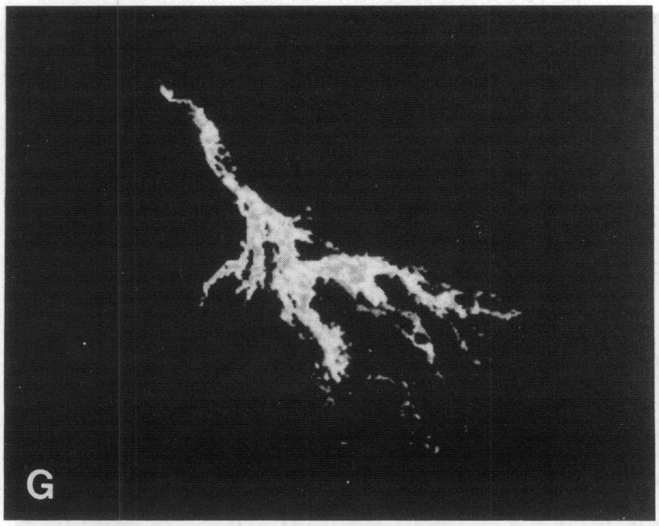

Figure 3 continued NOAA satellite images of the Okavango recorded during 1992 showing the advance of the seasonal flood: **(g)** 10 December.

middle and lower Panhandle, and to the Nqoga–Nambope–Maunachira–Mboroga–Santantidibe system to the north and northeast of Chief's Island. These areas are effectively permanently inundated, and are sustained by the base flow of the Okavango River. Isolated surface water bodies are scattered across the Delta area as a result of the summer rains, which peak in January (Figure 2a). By March (Figure 3b), these have disappeared and the flood wave has entered the Panhandle. As the flood wave passes down the Panhandle, the area of swamp expands outwards from the fan apex, particularly into the area to the west and northwest of Chief's Island (Figures 3c, d, and e). This advance is partially halted by a minor fault scarp across the centre of the fan to the west of Chief's Island to produce the extensively flooded area of Xo flats (Figure 3c and d). Some water crosses the scarp via the incised Boro channel, which leads to local inundation down towards the southern margin of the Delta (Figure 3e), and ultimately discharges into the Thamalakane River. During the months following peak flood in August (Figure 3e), the area of inundation shrinks, leaving isolated areas of flood water (Figure 3f), and in December–January attains its seasonal minimum (Figure 3g). It should be noted that the greatest area of permanent swamp lies in the Panhandle, fan apex, and especially to the northeast of Chief's Island along the Nqoga, Maunachira, Nambope, and Mboroga channels.

Although the spatial resolution of NOAA images is low (1 km^2), it nevertheless appears that the flood advances across a broad front by overland flow, with leaders forming a radial, dendritic pattern (Figures 3 and 4). The Boro channel is somewhat different in that it arises across a minor fault scarp south of Xo flats, through which it has incised (McCarthy *et al.*, 1997), and its discharge causes local inundation to the south (Figures 3c, d, e, and 4b).

Local rainfall is a potentially important contributor to the overall hydrology of the Delta. Rain which falls on an inundated area will behave in the same way as inflow. Rain falling on dry areas could contribute to the ground-water reservoir, and hence have an indirect impact on the extent of flooding. There is very little rain in the winter months and peak rainfall occurs in January (Figure 2a) when the area of inundation is at its minimum. The mean annual rainfall over the Delta is 513 mm (average of Maun and Shakawe stations, 1969 to 1994). It is difficult to translate the rainfall into a meaningful volume so that it can be compared with inflow and outflow discharges, because rain falls over the entire Delta. Some may fall on inundated areas, whilst the rest falls on dry ground. Assuming a potential wetland area of 12 000 km^2, the annual contribution of rain to the Delta amounts to 6144 Mm^3, which is substantial and of a similar order of magnitude to the inflow. It has been noted that rain may sustain or even increase discharge in the Thamalakane river (Wilson & Dincer, 1976). This is largely a local effect. The Delta has a broad, conical form, so that runoff in areas of seasonal swamp will not gather together as in a normal catchment, but will rather remain dispersed in pools across the seasonal floodplain. Only storms precipitating directly on the Boro, and especially on the incised reach, are capable of contributing directly to outflow.

The total annual input of water into the wetland is in the order of 15 339 Mm^3, whilst annual outflow is 236 Mm^3, that is only 1.5% of input. Wilson & Dincer (1976) suggested that

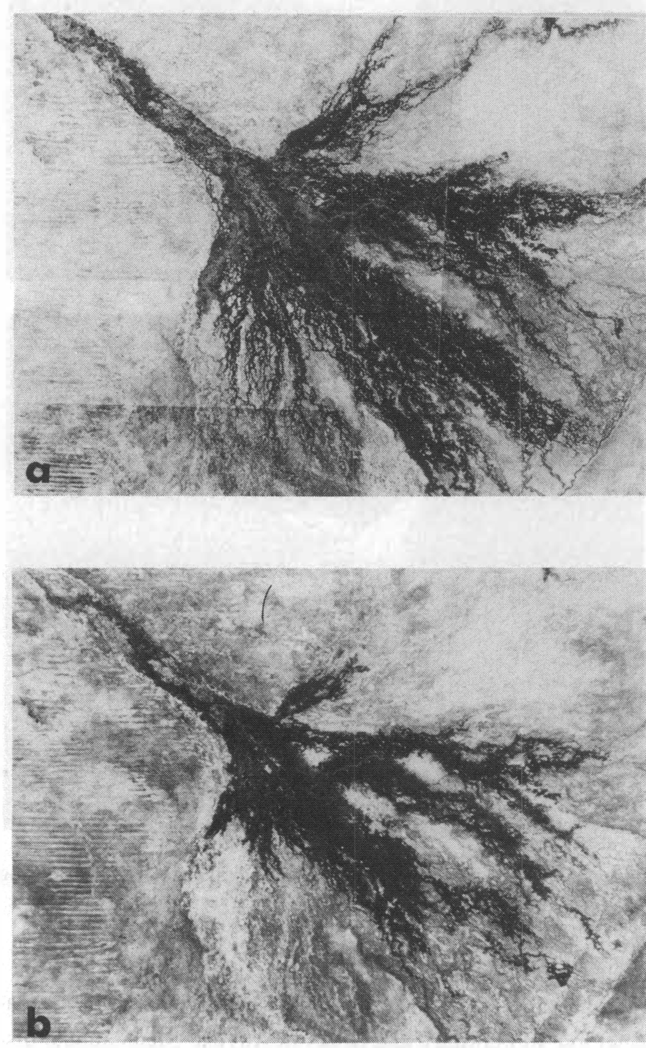

Figure 4 a) LANDSAT MSS image of the Okavango recorded in July 1984; **b)** LANDSAT TM image of the Okavango recorded in July 1995

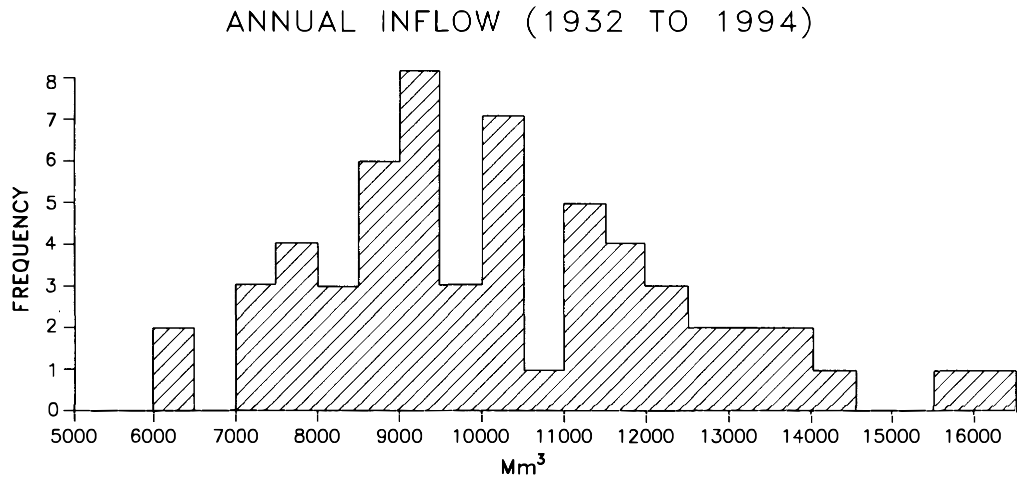

Figure 5 Annual discharge in the Okavango River, 1932 to 1994, measured near Mohembo.

not more than 2% leaves as ground-water flow, while Gieske (1995) believes it may be less. The rest is lost to the atmosphere by evapotranspiration. Mean annual evaporation measured at Maun is 2172 mm, so this huge loss of water is not surprising, and is promoted by the broad, flat form of the Delta which maximizes the area of inundation and, hence, evapotranspiration loss.

Effects of inflow, rainfall, and evapotranspiration on area of inundation and outflow

The area of inundation varies widely from year to year, as can be seen by comparing the two LANDSAT images in Figure 4, both recorded in late July, but 11 years apart. Unfortunately, there is a lack of annual records of the area inundated. However, outflow, as recorded on the Thamalakane River, can be used as a proxy for area of inundation, at least during the period of maximum inundation, because the greater the area flooded, the higher will the stage be in the Thamalakane, and hence, the greater will be the discharge. In July 1984 some 10 600 km^2 were flooded (Figure 4a), and discharge recorded in the Thamalakane for that month was 61.7 Mm^3. In July 1995, the flood had inundated 6200 km^2 (Figure 4b), but the flood water had not yet reached the Thamalakane and no discharge was recorded.

In assessing the contributions of rain and surface inflow to outflow, cognisance must be taken of the different phasing of the input and output components. Thus, rain falling in December to February combines with the flood peak from April to July to produce outflow in the Thamalakane from June to October (Figure 2). In the following analysis, therefore, a different hydrological year will be used for each of the variables: rain from July to June, inflow from November to October, and outflow from February to January. This is a departure from convention, which uses a single hydrological year extending from October to September for both inflow and outflow. Because of the slow passage of the flood wave, the use of the single hydrological year means that outflow for any given year is actually a combination of the current year's and the previous year's inflow and rainfall. For this reason, separate hydrological years are used in this analysis.

Inflow

Annual inflow is highly variable (Figure 5) and ranges from a low of around 6000 Mm^3 to a high of over 16 000 Mm^3, with an average of 9195 Mm^3. Annual outflow is similarly variable, with an average of 236 Mm^3 and a range from 6 to 880 Mm^3. Given the similarly shaped hydrographs of inflow and outflow (Figure 2b and c), albeit out of phase and of very different magnitude, one might anticipate a high degree of correlation between a season's inflow and the corresponding outflow. In fact, the correlation between them is poor (Figure 6), with a correlation coefficient of only 0.592. Low inflow generally corresponds to low outflow, but intermediate to high inflows produce erratically variable outflows.

Rainfall

Annual rainfall is highly variable, and in the period 1969 to 1994 ranged from a low of 288.3 mm to a high of 1144.5 mm. The mean (average of Maun and Shakawe) is 513 mm. Rain

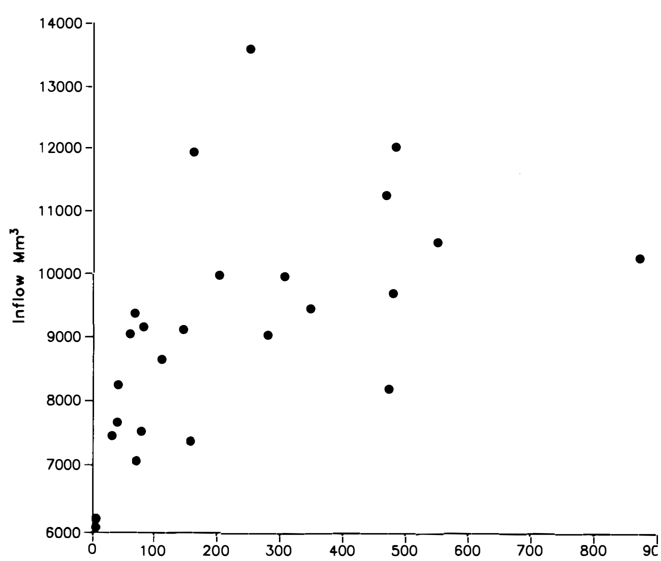

Figure 6 A plot of annual discharge in the Okavango River between November and October (inflow) against annual discharge in the Thamalakane River at Maun between February and January (outflow). Note the poor correlation between inflow and outflow.

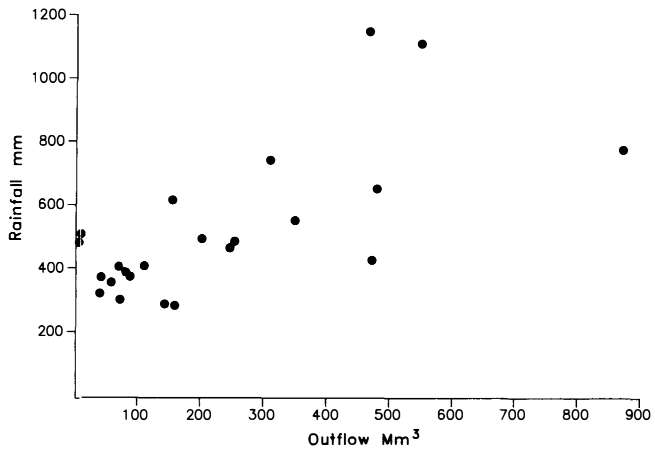

Figure 7 A plot of annual rainfall (average of Maun and Shakawe stations, July to June) against annual discharge in the Thamalakane River between February and January (outflow).

which falls on the dry, seasonal swamps could potentially have an important influence, mainly by raising the water table. As discussed above, the annual flood advances by overland flow. In order to progress, it is necessary that the water table be raised to the surface, which is accomplished by infiltration of flood water into the ground. If rain has raised the water table, less infiltration of flood water will occur and a greater area of inundation may be expected. Hence, outflow might be expected to correlate with rainfall (Figure 7). The correlation coefficient between outflow and rainfall is 0.637, somewhat better than with inflow.

To investigate the combined effect of rain and inflow on outflow, a first-order equation was fitted to the annual inflow, rainfall, and outflow, using standard regression techniques. Outflow was then computed from this equation, and calculated outflow compared to measured outflow. The correlation coefficient between calculated and measured outflow is 0.857.

It would appear that rain and seasonal inflow contribute approximately in equal proportions to outflow. Rain has little influence on the shape of the outflow hydrograph, however, because it is uniformly distributed over the Delta, and the shape of the hydrograph is determined primarily by the seasonal flood.

Evaporation and antecedent conditions

While the combined effects of rainfall and inflow account for much of the outflow, there are clearly other factors involved. The higher the water table, the less the infiltration losses, and hence, the greater the expected area of inundation. A factor which could influence the level of the water table is the extent of the previous season's flood. A large flood will raise the water table, so that in the following year a smaller inflow and lower rainfall may, nevertheless, still produce a large area of inundation. Such antecedent conditions were investigated by fitting an equation to inflow, rainfall, the previous season's outflow (as a measure of the antecedent conditions), and outflow, with outflow the dependant variable. As before, outflows were computed from the fitted equation and compared to measured outflow. The resulting correlation coefficient is 0.951, indicating the importance of antecedent conditions.

Evapotranspiration is an important factor in swamp hydrology, because it is so large. Evaporation averages 2172 mm per annum (A class pan, Maun). The pan coefficient for Maun is 0.66 (Wilson & Dincer, 1976), and potential evaporation is therefore 1433 mm. Evaporation varies through the year, but is not as variable from year to year as are rainfall and inflow, and hence, will contribute less to the annual variability of outflow. An equation was fitted to outflow, inflow, rainfall, the previous season's outflow, and measured evaporation. Outflow was calculated from this equation, as before. The correlation coefficient between calculated and measured outflows is 0.965 (Figure 8). The fitted equation is as follows:

$$\text{Outflow} = 42.76 + 0.406 \times \text{rainfall} + 0.0442 \times \text{inflow} + 0.444 \times \text{previous outflow} - 0.248 \times \text{evaporation}$$

where units of inflow and outflows are in Mm^3 and evaporation and rainfall in mm.

The good correlation obtained suggests that all of the major variables in the hydrology of the Delta have been accounted for.

Geohydrology

Introduction

As discussed above, ground water plays an important part in the hydrology of the Okavango Delta. Ground-water recharge consumes seasonal flood water and hence influences the extent of inundation and outflow. In order to carry out this regional investigation of the ground water in the Okavango area, data on 167 boreholes were extracted from the records of the Botswana Geological Survey in Lobatse. Full water chemistry was obtained for each borehole, as well as depth to the water table. Multiple samples had been analysed from several of the boreholes, making a total of 251 analyses. The boreholes are located mainly to the west, south, and south-

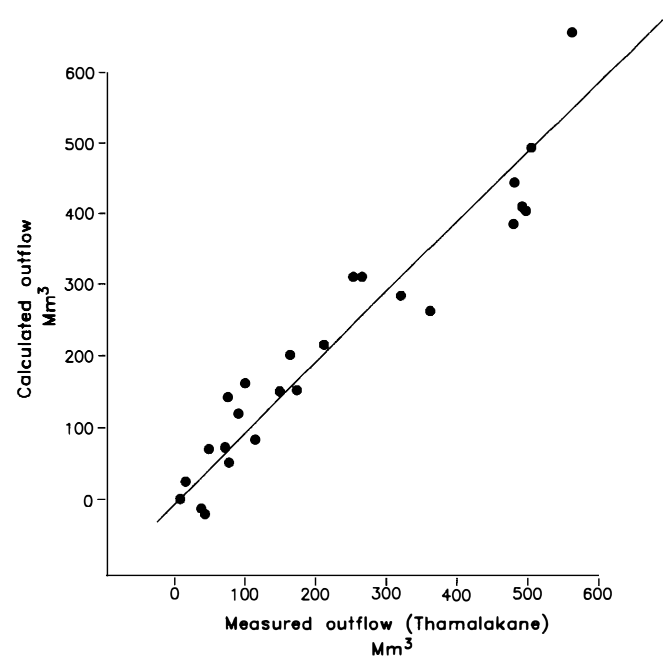

Figure 8 Calculated annual discharge in the Thamalakane River, determined using a fitted equation (see text for details), plotted against measured discharge.

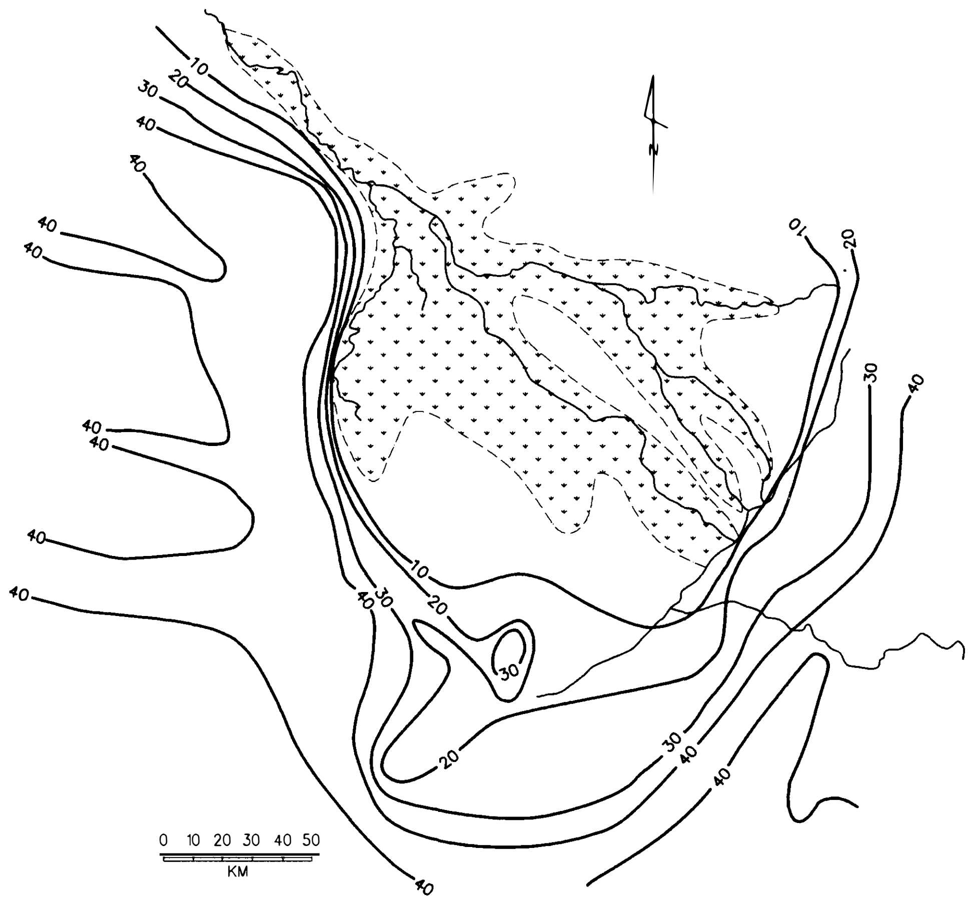

Figure 9 Map showing the depth to the water table (in metres) recorded in 167 boreholes in the Okavango region.

west of the Delta, with very few to the east, a refection of the distribution of human habitation in the region.

Piezometric surface

Depths to the water table are shown in Figure 9. No borehole collar elevations are available, but because the terrain is relatively flat with a gentle regional slope (Figure 1), these depths give an indication of the shape of the piezometric surface. The data used represent measurements made over several decades, and include both wetter and drier years. The piezometric surface shown in Figure 9, therefore, reflects a long term average.

The water table within the Okavango Delta is close to the surface, but it is generally far deeper to the west and south of the Delta (Figure 9). The gradient on the piezometric surface is particularly steep on the western and southeastern margins of the Delta, and there appears to be a trough extending along the western margin of the Delta, a feature also recorded by Gabaake (1989). Along drainage lines in this area, the water table is somewhat closer to surface. The slope of the piezometric surface in the area north of Lake Ngami is generally flatter and there is a prominent depression in the surface in this area. The overall appearance of the piezometric surface suggests a recharge mound related to the swamp system of the Okavango Delta.

Ground-water chemistry

Okavango River water has a very low total dissolved solid (TDS) content (typically about 40 ppm), most of which is silica (about 20 ppm). Major cations are Ca and Mg, while bicarbonate is the only anion of significance, chloride and sulphate typically being below 1 ppm (Hutton & Dincer, 1976; Sawula & Martins, 1991; Cronberg *et al.*, 1995). TDS of outflow water is typically double that of inflow. Exceptions occur in small saline pans occasionally encountered on islands, where ground water has come to the surface during the seasonal flood and has experienced extreme evaporative concentration. Water in these pans very occasionally attains saturation in trona (McCarthy *et al.*, 1991b). Apart from these rare exceptions, surface water in the Okavango is generally of very low TDS. It is this water which is responsible for ground-water recharge during advance of the seasonal flood. The water is chemically distinctive in that the anion assemblage is dominated by carbonate and bicarbonate, even to the point of saturation in trona (McCarthy *et al.*, 1991b), and chloride and sulphate concentrations remain relatively low. In contrast, relative proportions of cations change radically as various mineral species precipitate from the water as salinity increases (McCarthy *et al.*, 1991b). Anion proportions, therefore, provide a potentially useful means for distinguishing ground water from this source from other ground water types.

The anion proportions of borehole water from the Okavango region are shown plotted on a ternary diagram in Figure 10. Samples scatter widely and have been classified into carbonate-, chloride-, and sulphate-dominated end members. The field boundary of each end member was arbitrarily

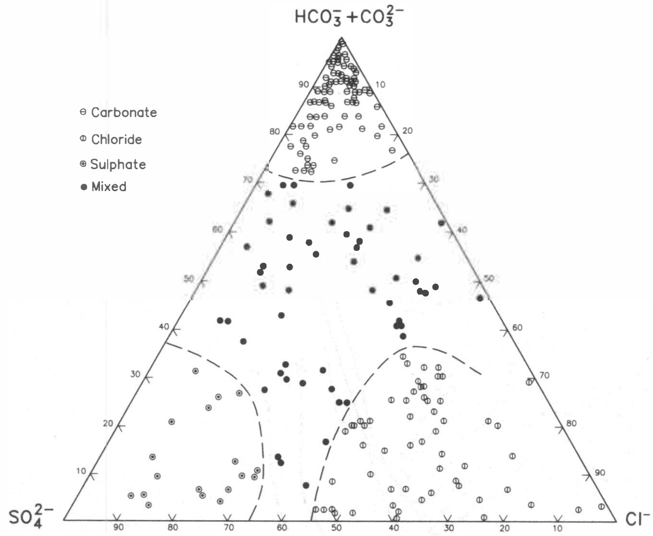

Figure 10 Ternary diagram showing the proportions of chloride, sulphate, and carbonate in ground water in the Okavango region. Three end member types are evident. The boundaries have been arbitrarily drawn.

selected. A number of samples fall outside of these end-member fields, and these are considered to represent mixtures between end members. Two component mixtures seem to predominate, and the centre of the ternary diagram is unpopulated.

The distribution of water types is shown in Figure 11. Carbonate-dominated water is confined almost entirely to the area of the Okavango Delta. This region is surrounded by chloride-dominated water, except along the western margin of the Delta where sulphate-dominated water tends to be concentrated in three apparently isolated areas. Neither the chloride- nor sulphate-dominated waters could have originated from the Okavango Delta, and most probably have some other provenance. Water classified as mixed generally occurs in fringe areas between types, particularly along the western and southwestern edge of the Delta. In contrast, the boundary between carbonate- and chloride-dominated waters along the southeastern margin of the Delta is abrupt, with little mixing. There are a few widely scattered, mixed water samples involving carbonate as an end member. These probably represent meteoric water which has dissolved pedogenic calcrete and are probably unrelated to Okavango water.

The salinity of ground water is shown in Figure 12. Only very general comments can be made regarding these data for several reasons: there is evidence of mixing of different water types; there is likely to be a bias towards lower salinity water; and several studies have shown that lower salinity water frequently overlies water of higher salinity (Aquatec, 1982; BRGM, 1986), so that the salinity in the collected samples may be a function of borehole depth and screen placement.

The carbonate-dominated ground water of the Delta shows a gradual but irregular increase in salinity from the apex of the fan towards its extremities, particularly the southwest. In the Maun area, salinity is generally low, but nevertheless is always significantly greater than swamp water in the region

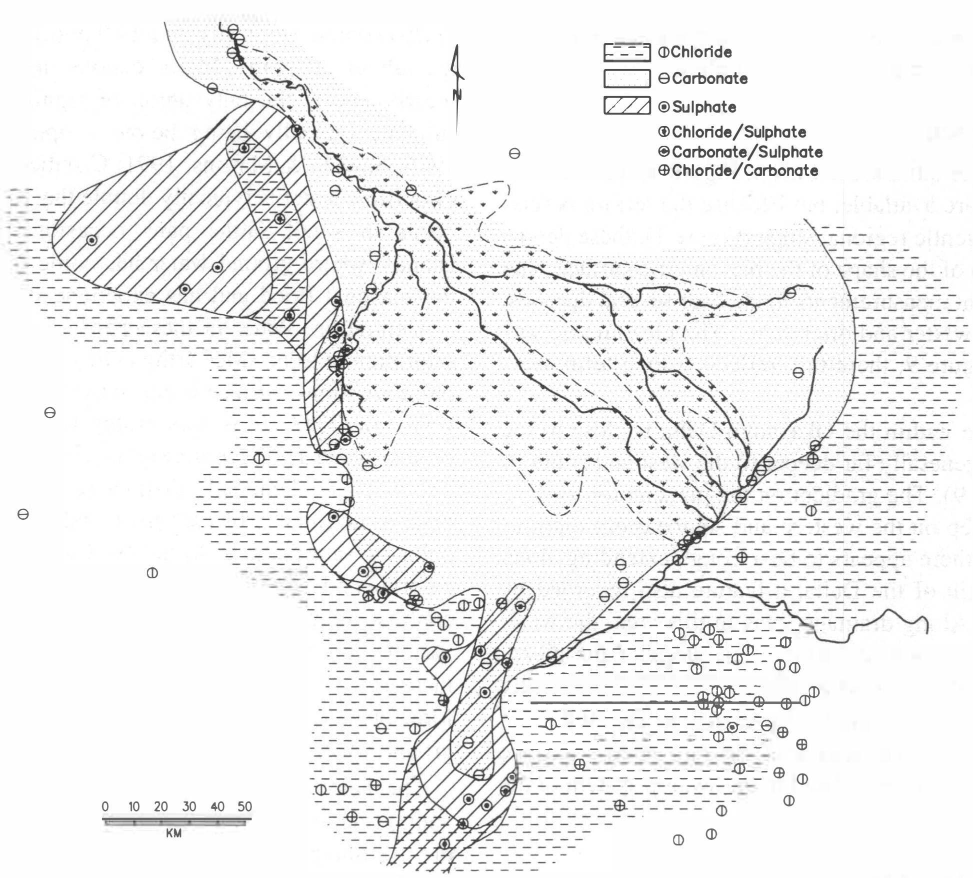

Figure 11 Map showing the distribution of the three ground water types in the Okavango region.

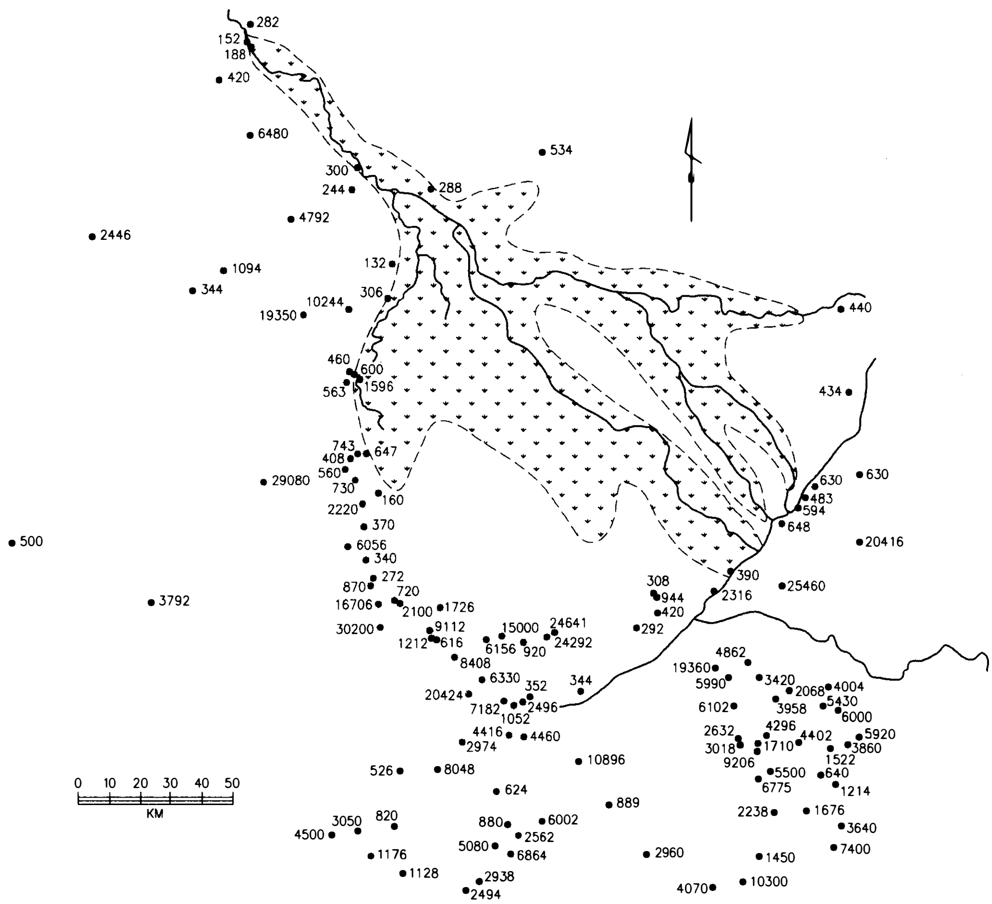

Figure 12 Map showing the total dissolved solid concentrations in ground water from the Okavango region.

(*c*. 70 ppm TDS). The chloride-dominated water to the southeast and south of the Delta generally has high salinity.

Detailed studies of shallow ground water within the Okavango Delta have shown that salinity is spatially extremely variable, and that salinity may change by up three orders of magnitude over a horizontal distance of a few tens of metres. High salinity ground water generally occurs beneath islands (Ellery *et al.*, 1993; McCarthy *et al.*, 1993). This is well illustrated by results from a study in progress in the Xudum area (Figure 13), where the localization of saline water beneath an island can be seen clearly.

Stable isotope studies

Several isotope studies of ground and surface water have been carried out in the Okavango region (Mazor *et al.*, 1974; 1977; Dincer *et al.*, 1978; Gabaake, 1989; McCarthy *et al.*, 1991b; Smith, 1996), the most comprehensive being that of Dincer *et al.* (1978). All available results are shown plotted on a $\delta^{18}O$–δD diagram in Figure 14.

Local rain water has a $\delta^{18}O$ of about –5 per mil, while surface water in the region lies along an evaporation line, with the water from the distal reaches of the Boteti River and from local saline pans within the swamps showing extreme enrichment in ^{18}O. In general, there is an increase in $\delta^{18}O$ with distance from Mohembo, the rate of increase varying as a function of the transport efficiency of the swamp (Dincer *et al.*, 1978), with the Boro system being the most efficient.

Ground water is also variable in its isotope chemistry. Water from the Haina Veld is isotopically light, with $\delta^{18}O$ less than –6 per mil, while to the west of the Delta, ground water is generally less than –7 per mil. Ground water from these areas lies on the meteoric water line. This light isotopic signature corresponds to the sulphate- and chloride-dominated water. Measurements of ^{14}C in this water suggests that it is of some considerable age (Dincer *et al.*, 1978; Gabaake, 1989). In contrast, ground water from within the swamp area lies along the swamp evaporation line, indicating recharge from surface swamp water. An exception occurs along the western margin of the swamps where the isotopic signature defines a mixing line between the isotopically light chloride ground water and isotopically enriched swamp water.

The light isotopic signature of the ground water surrounding the Delta appears to be a regional characteristic, and has been interpreted by Mazor *et al.* (1977) to be the result of recharge by infrequent, heavy storms. In contrast, the isotopic signature of ground water in the Delta reflects recharge by the annual flood. Limited mixing does occur on the western margin of the Delta, but there is no evidence for large-scale outflow of ground water from the Okavango (Dincer *et al.*, 1978). The isotopic data, like the water chemistry, suggest that the Okavango is hydrologically closed except for surface outflow via the Boteti River.

Ground-water recharge

As discussed previously, it is necessary that the water table be raised through infiltration before significant flood advance can occur. The quantity of flood water thus consumed will depend on the depth of the water table below surface. This, in turn, will depend on several factors, the most important of which are location, antecedent conditions, and the density of islands.

At the boundary between the permanent and seasonal swamps, the water table is at the surface, but it becomes progressively deeper with distance from this boundary. Therefore, as the flood advances, more water will be required to raise the water table with increasing travel distance. A large flood in the previous season, or higher than average rainfall, will generally reduce the depth to the water table, and hence less flood water will be consumed through infiltration in the subsequent year. During flood advance, water infiltrates the ground, raising the water table beneath both the flood plain and islands on the plain (e.g. McCarthy & Ellery, 1995b), and, hence, the greater the proportion of islands to flood plain, the more water will be consumed during flood advance.

Very little quantitative data is available regarding the amount of infiltration which occurs during flood advance, and only one study has been undertaken (Dincer *et al.*, 1976). The results obtained in that study will be recounted here in some detail because the report is not readily available, and the results are considered important. Dincer *et al.* (1976) isolated an area of seasonal swamp between two islands (Beacon and Lion Islands, Figure 15) in the Xudum area using bunds, and measured the inflow and outflow across the area over two flood seasons (1975 and 1976). A weather station was established at the site, recording both rainfall and evaporation. The results obtained are summarized in Table 1. The context of the study is also important: there had been a drought preceding the study which was broken in 1974 (Table 2), when discharge in the Thamalakane amounted to 476 Mm^3, well above

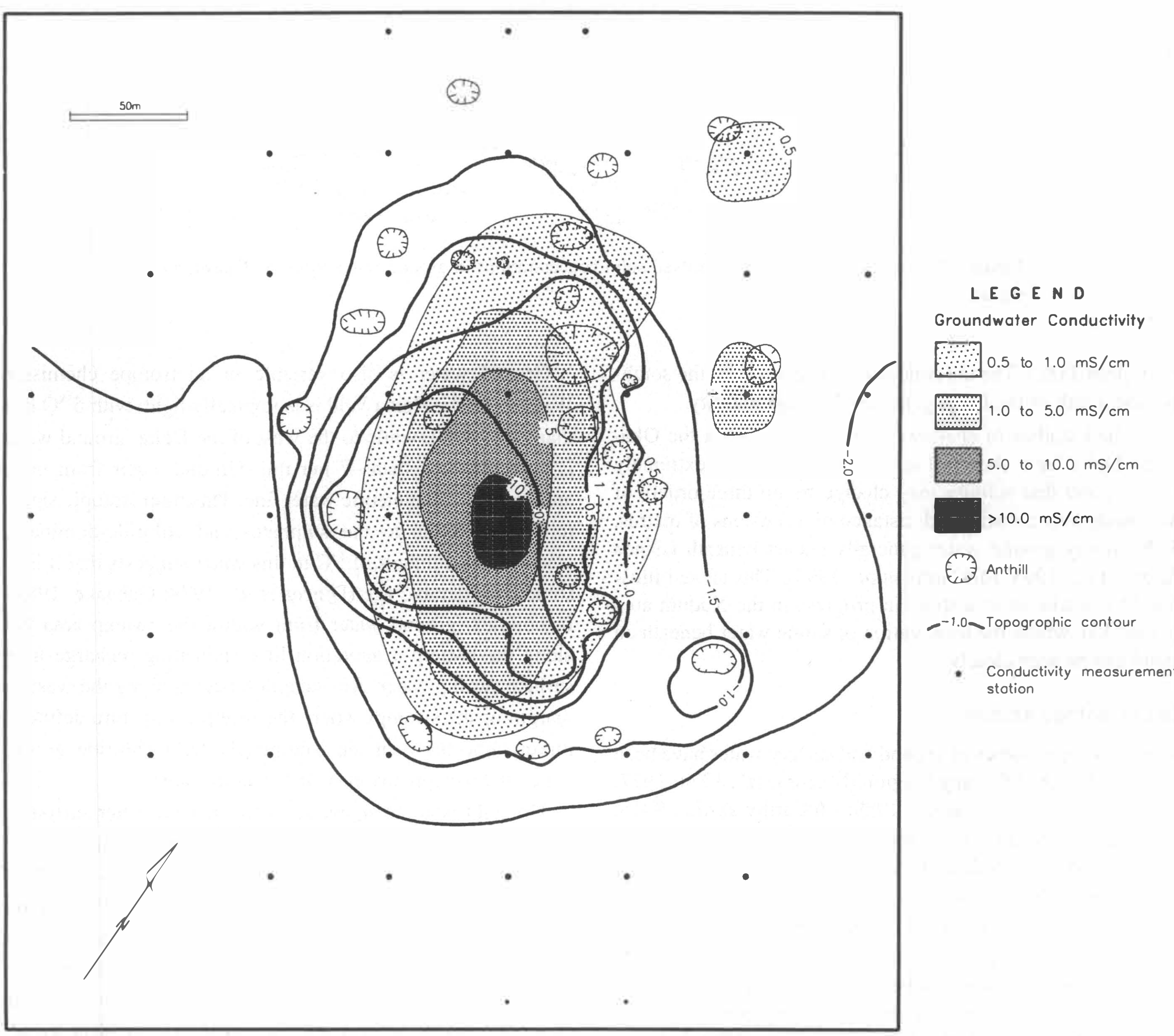

Figure 13 Map showing the relationship between the topography of a small island in the Xudum area and the electrical conductivity of the underlying ground water. The conductivity spans almost three orders of magnitude, and the high conductivity zone is located close to the island centre. Topographic contours are expressed in metres relative to an arbitrary datum.

the annual average of 236 Mm^3. The flood was also well above average during the two seasons that the study was conducted. It is therefore likely that water tables were generally rising over the two years of the study.

In both years, the quantity of flood water lost to ground water recharge exceeded evaporation by a significant margin: in 1975, ground water recharge was 4.7 times evaporation, while in 1976, recharge was 3.8 times evaporation. It is clear from these results that in the relatively distal areas of the seasonal swamp, the quantity of flood water lost as a result of ground water recharge is substantially larger than that lost by evaporation.

Table 1 Summary of results from the experimental area in the seasonal swamps at Beacon Island

Period	11/4/75 to 21/11/75	21/4/76 to 1/9/76
Inflow	31.4 Mm^3	19.6 Mm^3
Outflow	10.9 Mm^3	7.2 Mm^3
Groundwater recharge	17.7 Mm^3	9.0 Mm^3
Evaporation	3.8 Mm^3	2.4 Mm^3
Flood plain area	5.8 km^2	
Half area of islands	11.5 km^2	
Duration	224 days	133 days

Discussion

Distribution of permanent and seasonal swamp, and the advance of the seasonal flood

The role of channels

The role of channels in conveying water through the permanent swamps has been quantitatively examined in several studies. Porter & Muzila (1989) noted that the role of channels as water conveyors was significant. They cite a case in which 35% of the water flowing through a 325-m-wide region of swamp between two islands was carried in a channel 7 m wide and 0.9 m deep. Similarly, McCarthy *et al.* (1992) estimated that in the area north of Chief's Island, where the swamp is about 10 km wide, the Ngoga channel carries about 90% of the discharge. However, the downstream decrease in channel width has been well documented (Porter & Muzila, 1989; McCarthy *et al.*, 1991a), and it is clear that substantial quantities of water do leak through channel margins, particularly during the advance of the seasonal flood. This water dissipates through the back swamp areas, and it is likely that hippopotamus trails play an important role in this regard (McCarthy *et al.*, in press).

During the seasonal expansion of the swamp, advance of the flood is initiated along leaders which form a dendritic pattern on the fringes of the swamp (Figures 3 and 4). These appear to be nucleated along hippo trails, which follow low ground because of hippos' preference for travelling in water. It can only be speculated how they form, but it is suggested that terrestrial animals, through their movements, transfer soil towards the hippo trail, while the hippos transfer this down-

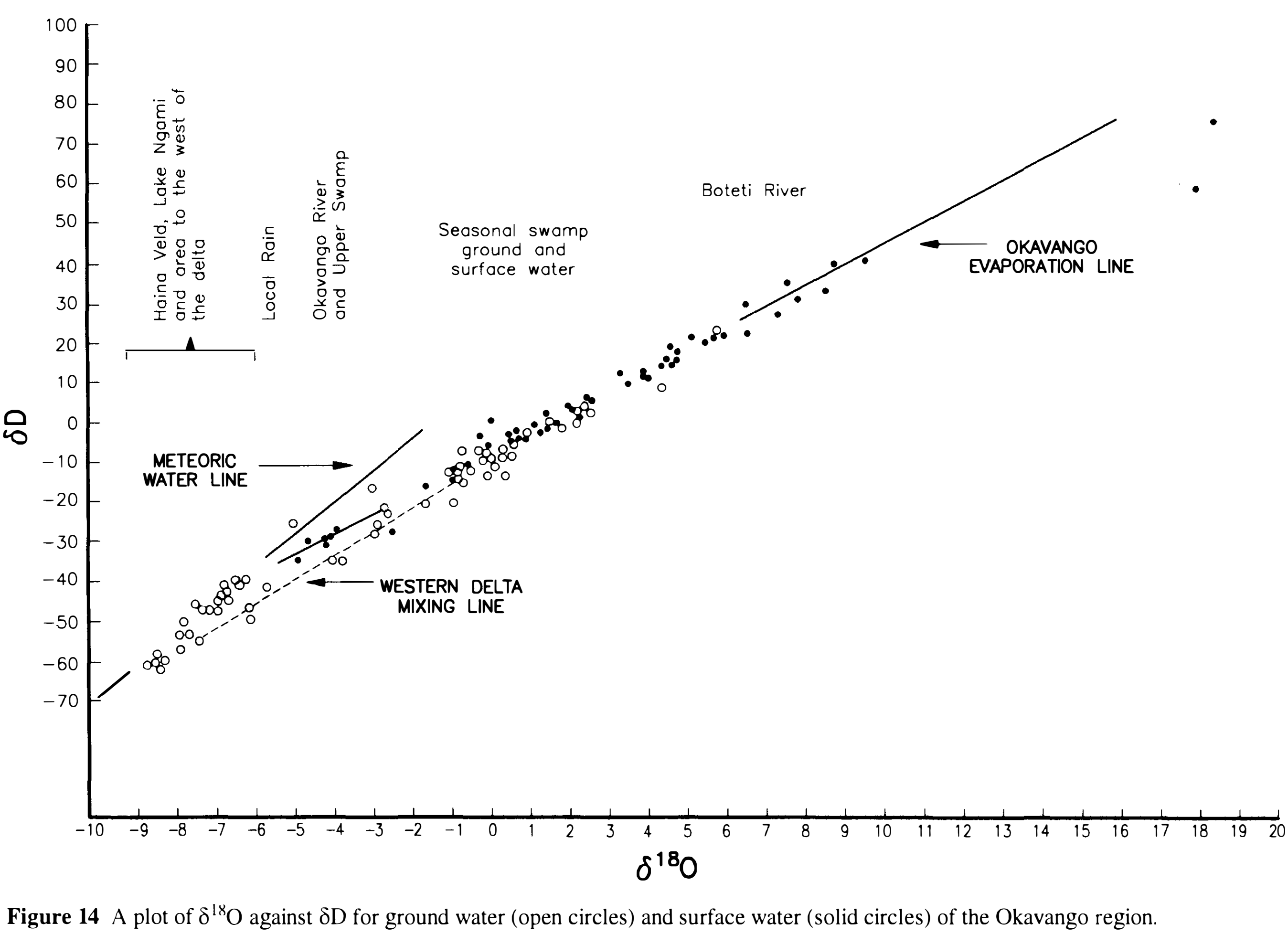

Figure 14 A plot of $\delta^{18}O$ against δD for ground water (open circles) and surface water (solid circles) of the Okavango region.

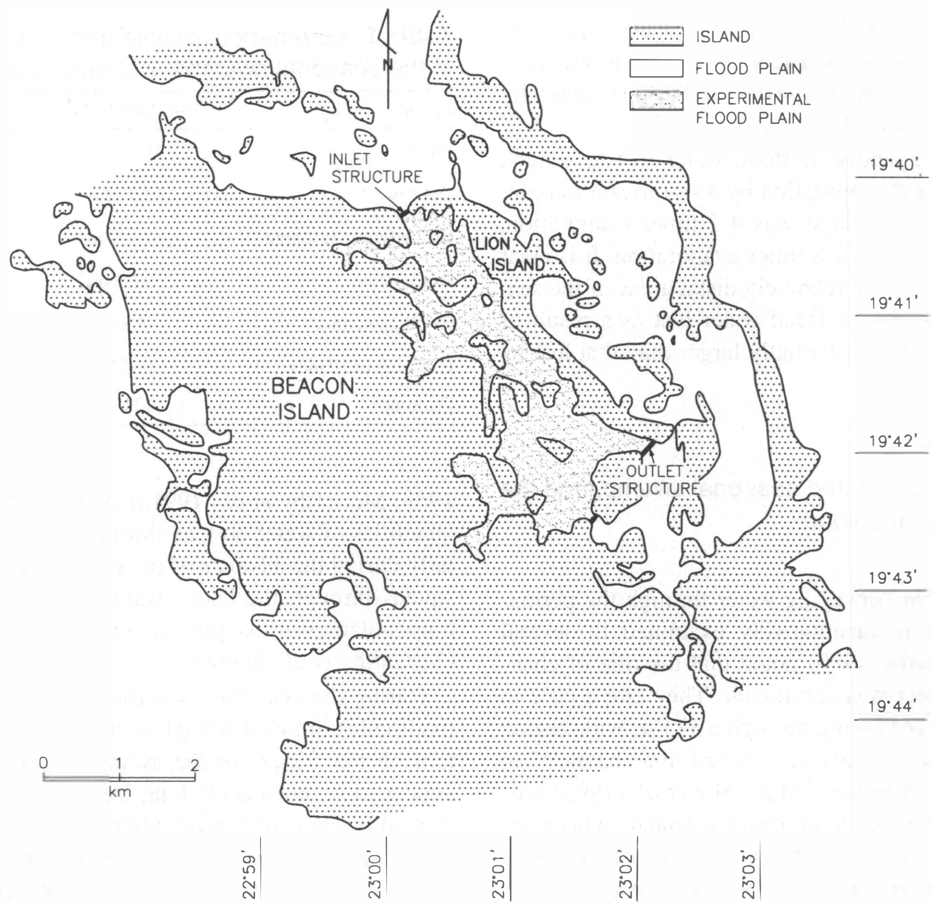

Figure 15 A map of the United Nations study area in the seasonal swamps at Beacon Island in the Xudum area. The maximum area of swamp was 5.8 km^2, while the half area of the surrounding islands was 11.6 km^2.

stream. The resulting topographic low focuses water and attracts grazing animals, which further enhance the process. Over time, these trails develop into extended topographic lows, albeit with gentle lateral slopes which serve as nuclei for flood advance.

Swamp distribution

Satellite imagery reveals that the permanent swamps are situated mainly in the lower Panhandle, the fan apex, and an extensive area to the north and northeast of Chief's Island (Figures 3a and b). In contrast, the seasonal swamps are concentrated mainly to the west of Chief's Island (Figures 3d and e), with far less seasonal swamp to the east and northeast of the island. However, in years of particularly large floods, the area east of Chief's Island also develops extensive seasonal swamps (Figure 4a).

The lack of extensive seasonal swamps to the east of Chief's Island appears to be related to the nature of water supply to this region, which is primarily by the Nqoga channel. The satellite image in Figure 4b shows that the Nqoga channel flows between Chief's Island and what appears to be a tectonic uplift which forms the Duba Island cluster. Seasonal stage variations on the Nqoga to the east of this region (e.g. at Xaenga and Hamoga Islands) are small, in the order of a few centimetres (McCarthy *et al.*, 1992). Seasonal stage variations increase to the west and northwest of Duba Islands, however, becoming progressively larger into the Panhandle (Wilson & Dincer, 1976). As the seasonal flood wave debouches onto the fan, the channel stage rises and the water leaks from the channel. It appears from the small stage variation on the lower Nqoga that most of the flood wave has left the channel before it reaches the Duba Island cluster. Under normal circumstances, the leaked water will extend the area of swamp, as can be seen to the west of Chief's Island. However, Chief's Island and the Duba Island cluster prevent much of this surface water from spreading to the east, reducing the extent of seasonal flooding in this region. In years of high flood, or after particularly heavy rains, the Duba Island cluster becomes largely submerged (Figure 4a), and is less effective as a barrier to surface flow. Moreover, flood water bypasses the cluster around its northern edge. In such years, more extensive seasonal flooding occurs east of Chief's Island.

In essence, the confining effects of Chief's Island and the Duba Island cluster, and the long river length upstream of these islands ensures that the area to the northeast and east of Chief's Island receives a very steady supply of water, with

Table 2 Annual discharge (Mm^3) in the Thamalakane River around the time the Beacon Island experiment was conducted

Year	1971	1972	1973	1974	1975	1976
Discharge	205	160	33	476	553	476

Long term average 236 Mm^3

only limited seasonal variation. Transfer of water from the Nqoga to the Mboroga and Maunachira channels, and leakage from the right bank of the Nqoga into the Nambope system, as described above, ensures that this effect is propagated to the limits of the eastern and southeastern Delta. As a result, the distal areas of the swamps in the east and southeast, such as the lower Santantidibe and Xaxanaka regions, have far smaller areas of seasonal swamp compared to the area to the west of Chief's Island. The Nqoga supplies essentially the same volume of water to the area north and east of Chief's Island throughout the year. Hence, a large area of permanent swamp is sustained in this region.

Ground water regime

The shape of the piezometric surface beneath the Okavango Delta suggests a recharge mound (Figure 9). However, the inorganic and isotope chemistry of the surrounding ground water indicates that this is not of swamp origin and is old water which experiences recharge by local rainfall (Dincer *et al.*, 1978). The Okavango groundwater system appears to be closed, with no sub-surface outflow occurring.

Detailed studies of near-surface ground water in both the permanent (McCarthy *et al.*, 1993) and the seasonal swamps (McCarthy & Ellery, 1995a) have shown that the ground water is laterally very heterogeneous in composition. Ground water beneath island centres can have a salinity as much as three orders of magnitude higher than swamp or flood-plain ground water (e.g. Figure 13). This saline water remains fixed beneath islands and shows no indication of lateral movement in spite of the regional gradient on the piezometric surface (Figure 13). It appears therefore that no regional, lateral ground water flow occurs in the Okavango Delta.

Saline ground water develops beneath islands as a result of transpiration by trees, which are confined almost exclusively to islands. Numerical modelling suggests that it may take several centuries for this saline ground water to develop (McCarthy *et al.*, 1993). Increase in salinity induces precipitation of minerals in the soil, which causes island growth. Transpiration lowers the water table beneath islands, forming, in effect, a diffuse cone of depression which shows diurnal fluctuations of up to 7 cm (McCarthy & Ellery, 1994). Recharge occurs from the ground water or swamp flanking the islands. Numerical modelling by Gieske (1995) suggests that the central, saline brine may sink under gravity, and accumulates at deeper levels in the Kalahari sediment which underlies the Delta. This may account for the observation that deep ground water in the area is frequently saline (BRGM, 1986; Aquatec, 1982).

The water table beneath the seasonal swamp rises due to rain infiltration (McCarthy & Ellery, 1994), and to the arrival of flood water (McCarthy & Ellery, 1994; 1995a). Since there is no lateral flow, the lowering of the water table after the rainy and flood seasons must be entirely due to transpiration. While surface water is still present, evaporation is active, but once the water surface falls below ground level, transpiration becomes dominant. Initially both flood plain and island plants contribute to transpiration, but as the water table falls, the shallow-rooted flood-plain plants contribute less and less to water loss. The cone of depression beneath islands ensures a steady movement of ground water towards islands, and the water table over wide areas is thus lowered. As the water table approaches the rooting depth of the trees, the cone of depression becomes progressively shallower, and eventually disappears completely (McCarthy & Ellery, 1995a). In the absence of recharge, further lowering of the water table will occur by capillary supply to the root zone, and ultimately by vapour transfer. The rate of fall of the water table in the absence of flood recharge is not inconsequential: measurements reported by Gieske (1996) from the Xudum area record a fall of 3.5 m over a period of 3 years.

Available evidence suggests that ground-water movement in the Okavango Delta is predominantly vertical. The form of the piezometric surface, therefore, simply reflects the local balance between flood recharge and transpiration loss. The interior of the Delta experiences regular recharge, and hence, the water table is shallow and ground water is of low salinity, at least beneath the flood plains where most recharge occurs. As recharge becomes less frequent towards the periphery of the Delta, the water table deepens and ground-water salinity generally increases because of the more uniform distribution of trees.

Evaporation versus Transpiration

As discussed above, transpiration is an important process in water loss to the atmosphere. However, the flooded area may at times exceed 10 000 km^2, and hence evaporation must also be an important process. Dincer *et al.* (1978) attempted to estimate the ratio of evaporation to transpiration by using a combination of salinity and isotopic composition. Their calculations indicated that in winter the ratio was about unity, while in summer evaporation was between 25% and 75% of total water loss. These calculations provide minimum estimates because they assume that swamp water is equally exposed to the effects of both evaporation and transpiration. In reality, this is incorrect. Most of the aquatic plants in the Delta are bottom rooted, particularly those in the seasonal swamps, and the effects of their transpiration will therefore occur in the shallow ground water and will in general not be communicated to the overlying swamp water. Consequently, the calculations will tend to overestimate the effects of evaporation.

The experiment in the Xudum area carried out by Dincer *et al.* (1976) showed that ground-water recharge consumed large quantities of flood water. The results in Table 1 show that in 1975 the recharge through the flood plain averaged 13.4 mm/day, compared to an average evaporation rate of 2.92 mm/day. During 1976, recharge amounted to 11.7 mm/day, while evaporation was 3.1 mm/day. The recharge would have served to raise the water table beneath both flood plains and islands (e.g. McCarthy & Ellery, 1994; 1995a). If recharge is calculated over the entire area (i.e. flood plain and half of the area of flanking islands), the recharge rates are 4.5 mm/day (1975) and 3.9 mm/day (1976). Since large-scale lateral flow of ground water does not occur, much of this water must ultimately be lost to the atmosphere by transpiration. These results indicate that in the seasonal swamps the proportion of water lost to the atmosphere by transpiration is substantially larger than is lost by evaporation.

However, it is probable that the relative effects of transpiration and evaporation vary throughout the swamp, and quantitative data is in general very sparse. Current hydrological models consider only the effect of evaporation (although it is usually referred to as 'evapotranspiration'), but it is evident that substantial quantities of water are lost through transpiration alone from what is essentially dry land. This is a subject which urgently needs investigation using a variety of methods, for example, those which were used at the Beacon Island experiment, numerical modelling, and lysimeter measurements in different swamp settings.

Area – volume relationships

Hydrological models developed for the Okavango focus on predicting outflows using measured inflows, but very little is known about the relationship between inflow and the area of inundation. Dincer *et al.* (1976) derived a relationship between volume and area for the experimental area at Beacon Island (Figure 15), which has the following form:

$$V = 0.16\ A^{1.75}$$

where V is volume in Mm^3 and A is area in km^2. This equation, or modifications of it, have been used in hydrological models by Dincer *et al.* (1987) and Gieske (1996) in order to calculate water losses due to evaporation.

This form of equation implies a bowl-shaped swamp, and while valid for small areas such as at Beacon Island, tends to underestimate swamp area if applied to large areas. This is a consequence of the fact that the Delta cannot be regarded as a single 'bowl'. Rather it consists of many small 'bowls', perhaps only a few square km in extent, each governed by an area – volume relationship such as the one above. If these are integrated, the area – volume relationship reduces to a simple expression of

$$\text{volume} = \text{area} \times \text{average depth}$$

In reality, area – volume relationships are extremely complex, and are governed by the same principles as were discussed in regard to inflow – outflow. Observational data on the area of inundation are urgently needed to establish an inflow – area model for the Delta. These data can be obtained from satellite images such as shown in Figure 3. Moreover, by using satellite data in constructing such a model, cognisance can be taken of the uneven distribution of the annual flood.

Conclusions

The Okavango is increasingly being viewed as a source of water for development, not only by Botswana, but by Namibia and Angola as well. The nature of the impact of schemes these latter countries are likely to, or have already proposed, will differ radically from those of the earlier dredging schemes. Projects undertaken by these countries will impact primarily on the area of the swamp. Hydrological models based on outflow records, which were developed to assess impacts on the lower Delta, will not be sufficient to evaluate these new schemes. What is required is a thorough understanding of the hydrological functioning of the wetland, which can serve as a basis for more comprehensive numerical models of the hydrology of the system. These new models need to focus on the total area and spatial distribution of inundation. In this paper, the authors have synthesized available data as a first step towards this goal.

The data indicate that rainfall and inflow probably contribute more or less equally to the area of inundation. Unlike inflow, rainfall is spread uniformly over the Delta and its effect is to either raise or to reduce the rate of fall of the water table. Antecedent conditions also contribute significantly to inundation through their effect on residual ground and surface water in the system.

Evapotranspiration, while contributing little to the seasonal variability of inundation, is nevertheless important in the overall hydrological functioning of the system. The Okavango system is apparently hydrologically closed, except for a small (1.5%) surface discharge via the Boteti River. It is surrounded by old ground water of different provenance. Annual recharge has created a ground-water mound, but there is no detectable large-scale lateral ground-water flow. Water movement is essentially vertical; recharge occurs through the flood plain and water is lost to the atmosphere mainly by transpiration, especially through tree-covered islands. Much of the dissolved sediment load precipitates around these islands, but the most soluble salts are confined to island centres by this process. The resulting brines apparently settle to deeper levels in the sub-surface, driven by density flow. The closed nature of the system implies that these toxic salts must be steadily accumulating in the deep ground water.

Satellite imagery has revealed that the seasonal flood is not distributed uniformly over the Delta. The permanent swamp is developed in the lower Panhandle, fan apex, and especially in the area to the north and northeast of Chief's Island, as these areas receive a steady supply of water from the Okavango River, its continuation, the Nqoga channel, and various secondary distributaries. However, the seasonal flood largely dissipates through the channel margins before passing to the north of the island, so that the main area of seasonal swamp lies to the west of the island. This asymmetry is caused by tectonic uplifts which have produced Chief's Island and the Duba Island cluster. This high ground prevents water leaked from the channel from spreading to the east, except in years of exceptional flooding. The annual flood wave, released through the channel margins in the permanent swamps, advances by overland flow, and preferentially along leaders which are probably the product of animal movements, especially hippos. This advance creates the dendritic pattern characteristic of the fringes of the swamp.

The Okavango Delta is a dynamic system and is undergoing constant change, and it is known from historical evidence that the rate of change is rapid, even in human terms. The hydrological pattern described above represents a snapshot in time, and it will change in the future. A comprehensive understanding of the Okavango system will enable the likely directions that future changes will follow to be predicted, and therefore place us in a better position to assess anthropogenic impacts on the Delta.

References

Aquatec (1982). *Watering point survey: Ngamiland cattle trek route.* Aqua Tech Groundwater Consultants, Gaborone, 132 pp.

BRGM (1986). Maun water supply hydrogeological survey. *Bur. Rech. Geol. Mineres*, Orleans, France. 86-BWA-022-EAU. Vols 1 and 2, 99 pp.

Cronberg, G., Gieske, A., Martins, E., Nengu, J. & Stenström, I-M (1995). Hydrobiological studies of the Okavango Delta and Kwando/Linyanti/Chobe River, Botswana. I. Surface water quality analysis. *Botswana Notes Rec.*, **27**, 151–225.

Dincer, T., Heemstra, H.H. & Kraatz, D.B. (1976). The study of hydrological conditions in an experimental area in the research swamp. *Tech. Note 2, UNDP/FAO,* **BOT/71/706**, 11 pp.

----, Hutton, L.G. & Kupee, B.B.J. (1978). Study, using stable isotopes, of flow distribution, surface groundwater relations and evapotranspiration in the Okavango Swamp, Botswana. *IAEA. Proc. Ser.*, **SM-228/52**, 3–25.

----, Child, S. & Khupe, B.B.J. (1987). A simple mathematical model of a complex hydrolgical system: Okavango Swamp, Botswana. *J. Hydrol.*, **93**, 41–65.

Du Toit, A.L. (1927). Report on the Kalahari reconnaissance of 1925. *Dept. Irrig., Un. S. Afr.*, 79 pp.

Ellery, W.N. & McCarthy, T.S. (in press). Environmental change over two decades since dredging and excavation of the lower Boro River, Okavango Delta, Botswana. *Biogeography*.

----, Ellery, K. & McCarthy, T.S. (1993). Plant distribution on islands in the Okavango Delta: determinants and feed back interactions. *Afr. J. Ecology*, **31**, 118–134.

Gabaake, G. (1989). *A report on an investigation of the hydrogeological and hydrochemical conditions in northwest Ngamiland, Botswana.* M.Sc. thesis (unpubl.), Univ. College, London, 85 pp.

Gieske, A. (1995). Vegetation driven ground water recharge below the Okavango Delta (Botswana) as a solute sink mechanism — an indicative model. *Ext. Abstr. Conf. on Groundwater Recharge and Rural Water Supply*, Johannesburg, 119–124.

---- (1996). Modelling surface outflow from the Okavango Delta. *Botswana Notes Rec.*, **28**, 165–192.

Greenpeace (1991). *Okavango—Delta or desert? A question of water.* Greenpeace International, Amsterdam, 5 pp.

Hutchins, D.G., Hutton, L.G., Hutton, S.M., Jones, C.R. & Loenbert, E.P. (1976). A summary of the geology, seismicity, geomorphology and hydrogeology of the Okavango Delta. *Bull. Botswana geol. Surv.*, **7**, 27 pp.

Hutton, L.G. & Dincer, T. (1976). Chemical and stable isotope composition of Okavango Delta waters. *Tech. Note 23, UNDP/FAO. BOT/71/706*, 18 pp.

IUCN (1993). *Review of the southern Okavango integrated water development project.* Scudder, T. (Ed.), IUCN, Switzerland, 543 pp.

Kokot, D.F. (1948). An investigation into the evidence bearing on recent climatic changes over southern Africa. *Mem. Dept Irrig., Un. S. Afr.*, 160 pp.

Mackenzie, L.A. (1946). *Report on the Kalahari expedition. 1945.* Un. S. Afr., **UG 28/1946**, 35 pp.

Mallick, D.I.J., Hapgood, F. & Skinner, C.A. (1981). A geological interpretation of landsat imagery and air photography of Botswana. *Inst. geol. Sci., Overseas Geol. Miner. Res.*, NERC, 35 pp.

Mazor, E., Verhagen, B.Th., Sellschop, J.P.F., Robins, N.E. & Hutton, L.G. (1974). Kalahari groundwaters: their hydrogen, carbon and oxygen isotope. *IAEA Proc. Ser.*, **SM-182/18**, 203–223.

?----, ----, ----, Jones, M.T., Robins, N.E., Hutton, L.G. & Jennings, C.M.H. (1977). Northern Kalahari groundwaters: hydrologic, isotopic and chemical studies at Orapa, Botswana. *J. Hydrol.*, **34**, 203–234.

Meixner, H.M. & Peart, R.J. (1984). The Kalahari Drilling Project. *Bull. geol. Surv. Botswana*, **27**, 240 pp.

McCarthy, T.S. & Ellery, W.N. (1994). The effects of vegetation on soil and groundwater chemistry and hydrology of islands in the seasonal swamps of the Okavango fan, Botswana. *J. Hydrol.*, **154**, 169–193.

---- & ---- (1995a). Sedimentation on the distal flood plain of the Okavango fan, Botswana, and it bearing on calcrete and silcrete (ganister) formation. *J. sedim. Res.*, **A65**, 77–90.

---- & ---- (1995b). The failure of the Nqoga channel between Hamoga and Letenetso Islands, northeastern Okavango Delta. *Botswana Notes Rec.*, **27**, 129–150.

---- & ---- (1997). The fluvial dynamics of the Maunachira channel system, northeastern Okavango Swamps, Botswana. *Water SA*, **23**, 115–126.

----, Stanistreet, I.G. & Cairncross, B. (1991a). The sedimentary dynamics of active fluvial channels on the Okavango fan, Botswana. *Sedimentology*, **38**, 471–487.

----, McIver, J.R. & Verhagen, B.Th. (1991b). Groundwater evolution, chemical sedimentation and carbonate brine formation on an island in the Okavango Delta swamp, Botswana. *Appl. Geochemistry*, **6**, 577–596.

----, Ellery, W.N. & Stanistreet, I.G. (1992). Avulsion mechanisms on the Okavango fan, Botswana: the control of a fluvial system by vegetation. *Sedimentology*, **39**, 779–796.

----, ---- & Alar, K. (1993). Vegetation induced subsurface precipitation of carbonate as an aggradational process in the permanent swamps of the Okavango (Delta) fan, Botswana. *Chem. Geol.*, **107**, 111–131.

----, Barry, M., Bloem, A., Ellery, W.N., Heister, H., Merry, C.L., Ruther, H. & Sternberg, H. (1997). The gradient on the Okavango fan, Botswana, and its sedimentological and tectonic implications. *J. Afr. Earth Sci.*, **24**, 65–78.

----, Ellery, W.N. & Bloem, A. (in press). Some observations on the geomorphological impact of hippopotamus in the Okavango Delta, Botswana. *Afr. J. Ecology*.

Porter, J.W. & Muzila, I.L. (1989). Aspects of swamp hydrology in the Okavango. *Botswana Notes Rec.*, **21**, 73–92.

Reeves, C.V. (1978). The gravity survey of Ngamiland, 1970–71. *Bull. geol. Surv. Botswana*, **11**, 77 pp.

Sawula, G. & Martins, E. (1991). Major ion chemistry of the Lower Boro River, Okavango Delta, Botswana. *Freshwater Biology*, **26**, 481–493.

Schwarz, E.H.L. (1918). *The desiccation of Africa: the cause and the remedy.* W.E. Hortor & Co, Johannesburg, 43 pp.

---- (1920). *The Kalahari or Thirstland Redemption.* W.E. Hortor & Co, Johannesburg.

Shaw, P.A. (1984). A historical note on the outflow of the Okavango Delta system. *Botswana Notes Rec.*, **16**, 127–130.

Smith, M. (1996). *A stable isotope study of water and soil carbonate from an island in the Okavango swamps, Botswana.* B.Sc. Hons diss. (unpubl.), Univ. Witwatersrand, 15 pp.

Smith, N.D., McCarthy, T.S., Ellery, W.N., Merry, C.L. & Ruther, H. (in press). Avulsion and anastomosis in the Panhandle regions of the Okavango fan, Botswana. *Geomorphology*, **20**, 49–65.

Standish-White, D.W. (1972). Watch on the Okavango. *Optima*, **22**, 167–181, Anglo American Corp S. Afr..

Stanistreet, I.G. & McCarthy, T.S. (1993). The Okavango fan and the classification of fan systems. *Sedim. Geol.*, **85**, 115–133.

Stigand, A.G. (1923). Ngamiland. *Geog. J.*, **62**, 401–419.

UNDP (1976). Investigation of the Okavango as a primary water resource for Botswana. *Tech. Report UNDP/FAO,* **BOT/71/506**, 3 Vols.

Wellington, J.H. (1948). The food-producing possibilities of the Okavango Delta. *S. Afr. Sci.*, October, 1948, 65–67.

Wilson, B.H. (1973). Some natural and man-made changes in channels of the Okavango Delta. *Botswana Notes Rec.*, **5**, 132–153.

---- & Dincer, T. (1976). An introduction to the hydrology and hydrography of the Okavango Delta. *In: Symposium on the Okavango Delta.* Botswana Soc., Gaborone, 33–48.

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