

**Physical and Biological Processes  
Controlling the Okavango Delta -  
A Review of Recent Research**

by T. S. McCARTHY\*

**Abstract**

Over the last six years, a multidisciplinary team from the University of Witwatersrand has been carrying out research to establish the nature of the processes which underpin the Okavango Delta. From this work it has become evident that the environmental factors controlling the Delta can be divided into two broad categories. (i) External variables, which include graben faulting, which is the ultimate reason for the Delta's existence; the geology of the catchment area of the Okavango River, which controls water quality and the nature of particulate sediment; the semi-arid nature of the environment, which is responsible for the high evapotranspirational rate and the ground water leakage which prevents the accumulation of hypersaline ground water; (ii) Internal processes which operate within the constraints imposed by the external variables and have produced the present form of the Delta. Biotic processes dominate this latter category, with specialised plant communities fulfilling specific functions. These various communities regulate the dispersal of particulate sediment and water. They also control water loss through transpiration, thereby regulating chemical sedimentation, which is the dominant aggradational process in the Delta at present. The action of biological agencies induces even aggradation of the land surface and shapes the topography of the Delta, ensuring widespread distribution of water, and localising, and hence minimising the impact of, the accumulation of toxic salts. Far from being catastrophic, changes in water distribution are actually brought about by plant communities and constitute an essential self-renewal strategy in the system.

**Introduction**

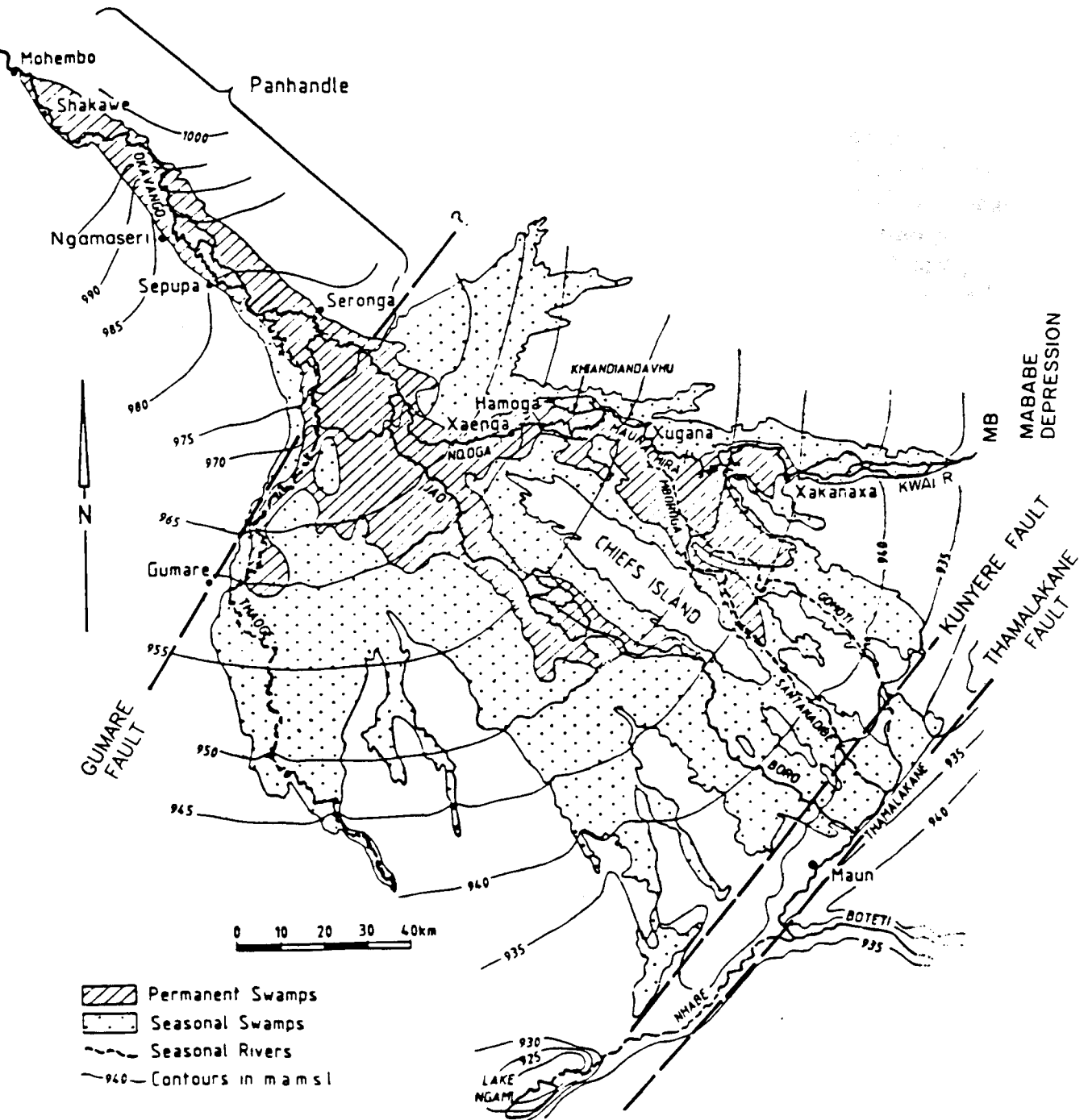
For its size, the Okavango Delta occupies a disproportionately important place in the cultural fabric of Botswana. It is historically important, having served as a refuge during politically troubled times in past centuries and as a guaranteed source of water in years of drought. It is ecologically important and a significant proportion of Botswana's wild life is located in the area. It is also economically important as it serves as a source of tourist revenue and of water for north-central Botswana. In a broader context, it is also important scientifically, being a rare association of abundant water in an otherwise arid environment. Moreover it contains a magnificent record of past climates of Botswana (Shaw, 1988).

The importance of the Delta has been recognised both nationally and internationally and many years of study by the Department of Water Affairs, together with major United

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Fig 1. The Okavango Delta. Contours taken from UNDP (1977); faults from Hutchins *et al.* (1976).



Nations and other smaller projects have provided a wealth of data and excellent maps of the Okavango region. These have served as a basis for more recent work carried out especially by groups from the University of Botswana and the University of the Witwatersrand. The latter group began work in the region in 1985, with a view to discovering the environmental controls which underpin and shape the Delta. The research is still continuing, but advances have been made on several fronts, and have been published in a wide variety of scientific journals. This review brings together and summarises the major findings of the group.

### **Geological Controls**

The Okavango River system is very old, perhaps dating back to pre-cretaceous times (Thomas and Shaw, 1988). It may once have linked to the Orange River (Lister, 1979; McCarthy, 1983) and perhaps later to the Limpopo (du Toit, 1926), but its course has been modified repeatedly over time by earth movements - by gentle warping of the earth's crust (du Toit, 1933) and more recently by fracturing in an extension of the great East African Rift Valley (du Toit, 1926; Scholz, 1975).

The entire Okavango River system lies within the Kalahari Basin, a great depression in the interior of southern Africa, partly filled with sediments of various types, notably by wind-blown desert sands, the so-called Kalahari Sands. These extend from the Cape Province to north of the Equator (Choubert and Faure-Muret, 1990). Most of the catchment area of the Okavango River is therefore underlain by Kalahari sand, although the headwaters of the Cubango River drain terrain underlain by basement granites. This simple geology of the catchment has important consequences for the Delta and contributes significantly to its uniqueness.

The course of the Okavango River has been interrupted by rifting, which has resulted in the collapse of a segment of the earth's crust along north easterly striking faults (Hutchins *et al.*, 1976; Cooke, 1980), notably the Kunyere and Thamalakane faults (fig.1). The concentration of seismic activity on the south-eastern boundary faults (Scholz, 1975) and the clear definition of these faults on satellite imagery (fig.2), indicates that the Okavango Delta lies within a half graben, with only minor faulting in the northwest (fig.3). This style of faulting is characteristic of rift settings (Rosendahl *et al.*, 1986; Frostick and Read, 1989). Sediment discharged by the Okavango River into the resulting depression has accumulated to form a gently sloping, curved alluvial fan (fig.1) which abuts against the south-eastern fault scarps in the vicinity of Maun. Two depressions result where the fan curves away from the Kunyere fault line (fig.2) - the Mababe Depression in the north-east and Lake Ngami in the south-west. While the Okavango deposits dominate the half-graben sediment fill, now dormant alluvial fans also occur adjacent to the Okavango fan both to the east and the west (Shaw and Thomas, 1992). The Okavango Delta is therefore not a delta in the strict sedimentological definition of the term (Bates and Jackson, 1987) as this requires discharge into a standing water body, but is a class of alluvial fan.

The term alluvial fan applies only to the region of the Okavango Delta below the Panhandle (fig.1). The origin of the Panhandle is enigmatic: it may represent a narrow graben perpendicular to the main rift (Mallick *et al.*, 1981) or it could represent an erosionally incised river segment on the upthrown side of the Gomare fault (fig.1 and 3). The flood plain of the Okavango River is confined by high shoulders of Kalahari sand in the Panhandle region, but is unconfined on the fan itself. This has important implications for the hydrology of the Delta.

It has been suggested that earth movements are responsible for changes in water distribution in the Delta, as the Boro system became active following a major earthquake in 1952 (Wilson, 1973). While this is possible, research has shown that such movements cannot be the major cause of shifts in water distribution.

### Hydrology

The hydrology of the Delta is well known as a result of regular monitoring of flows (Wilson and Dincer, 1976) and a hydrological model of the Delta has been developed (Dincer *et al.*, 1987). The seasonal flood peaks at Moheumbo in the period February to April, while outflow at Maun generally peaks between June and August (UNDP, 1977) (Fig.4). Annual inflow is 11000 million m<sup>3</sup> which is augmented by 5000 million m<sup>3</sup> of rainfall on the Delta. Of this, only 300 million m<sup>3</sup> leaves the Delta by way of the Boteti River (Wilson and Dincer, 1976) and it is estimated that no more than 300 million m<sup>3</sup> leaves by groundwater flow (Wilson and Dincer, 1976). Therefore, some 15400 million m<sup>3</sup> of water is lost to the atmosphere by evapotranspiration each year. This is a reflection of the semi-arid nature of northern Botswana, where evaporation is 3 to 4 times precipitation (Wilson and Dincer, 1976).

The arrival of the flood increases the water depth but the magnitude of this increase varies through the Delta. In the upper Panhandle, water depth varies by 1,7m between seasons (UNDP, 1977). This decreases to about 0,15m at the Jao/Boro take-off and remains low throughout the permanent swamp, but increases to around 2,7m at Maun (Wilson and Dincer, 1976). Base flow in the Okavango is sufficient to sustain about 6000km<sup>2</sup> of permanent swamp, but the area of swamp more than doubles during seasonal flooding.

Fig 2. Landsat image of the Okavango Delta (19-20 July, 1984).

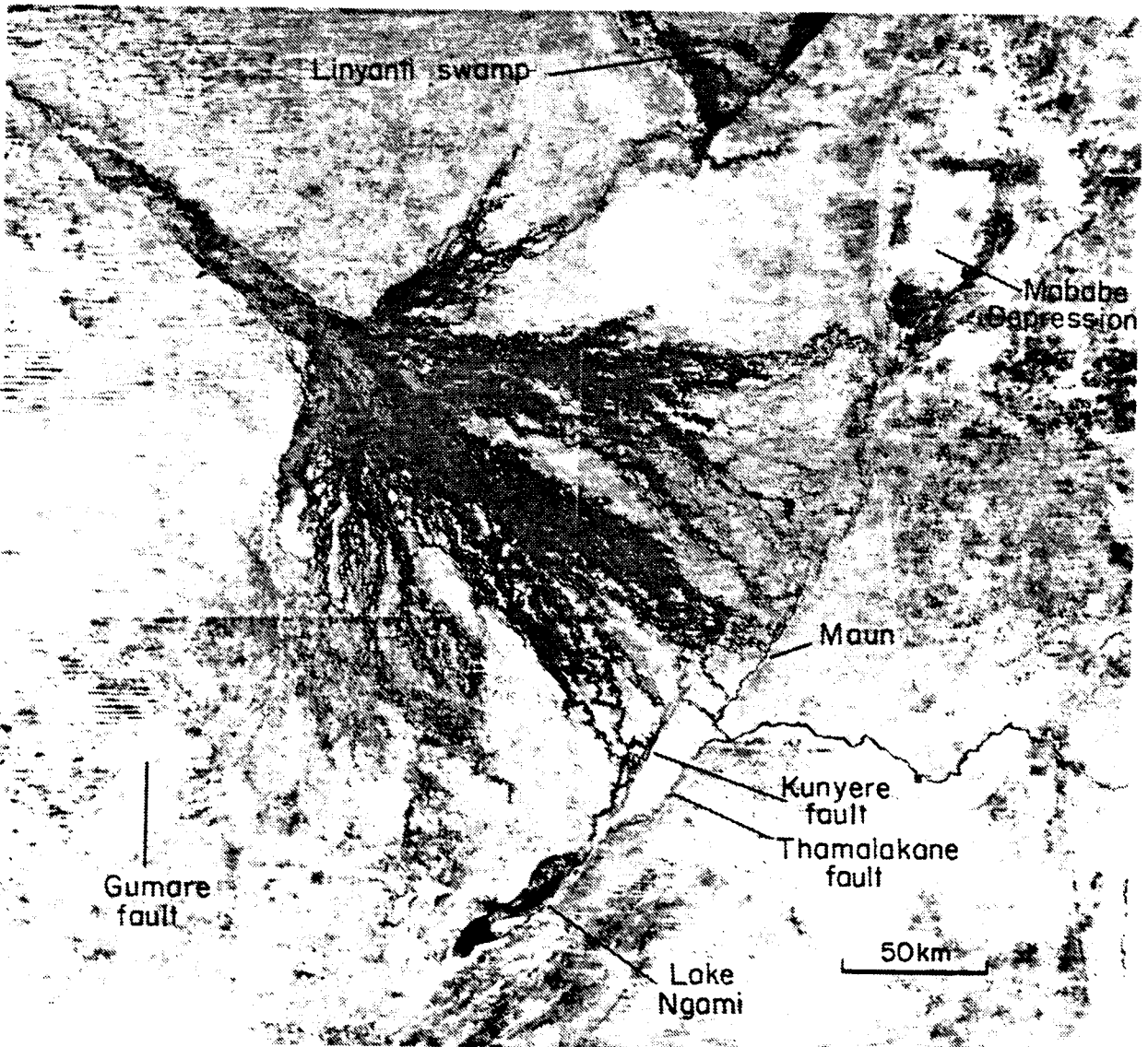


Fig 3. Schematic cross section through the Delta illustrating the half-greben form. Stippled area represents sediment deposited by the Okavango system.

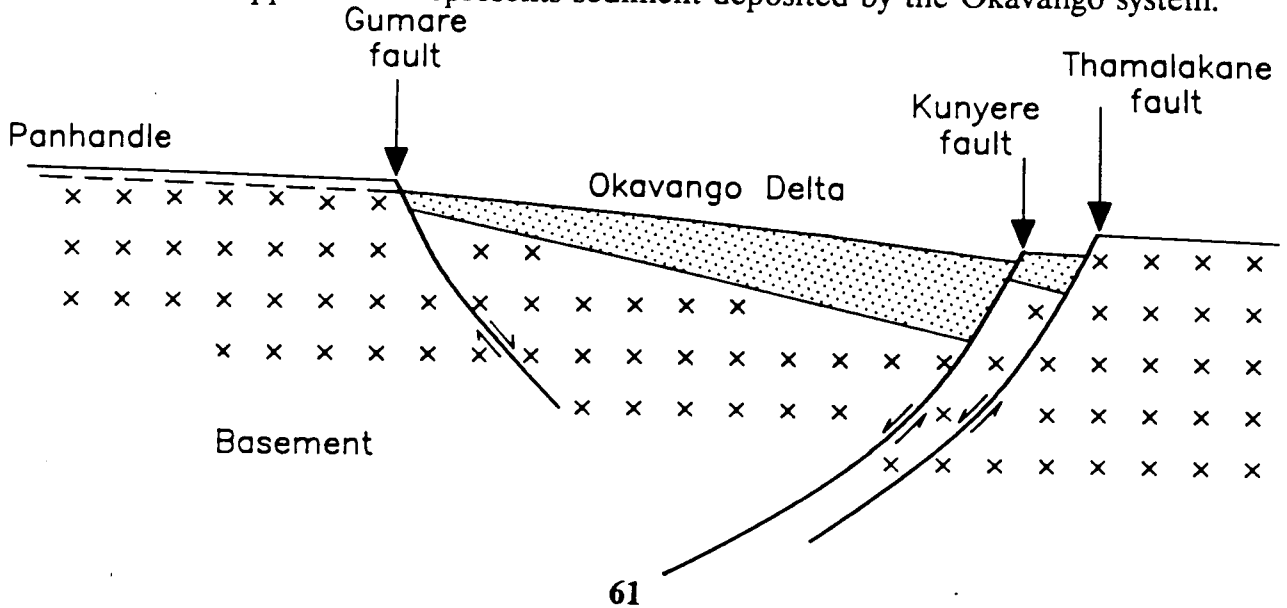
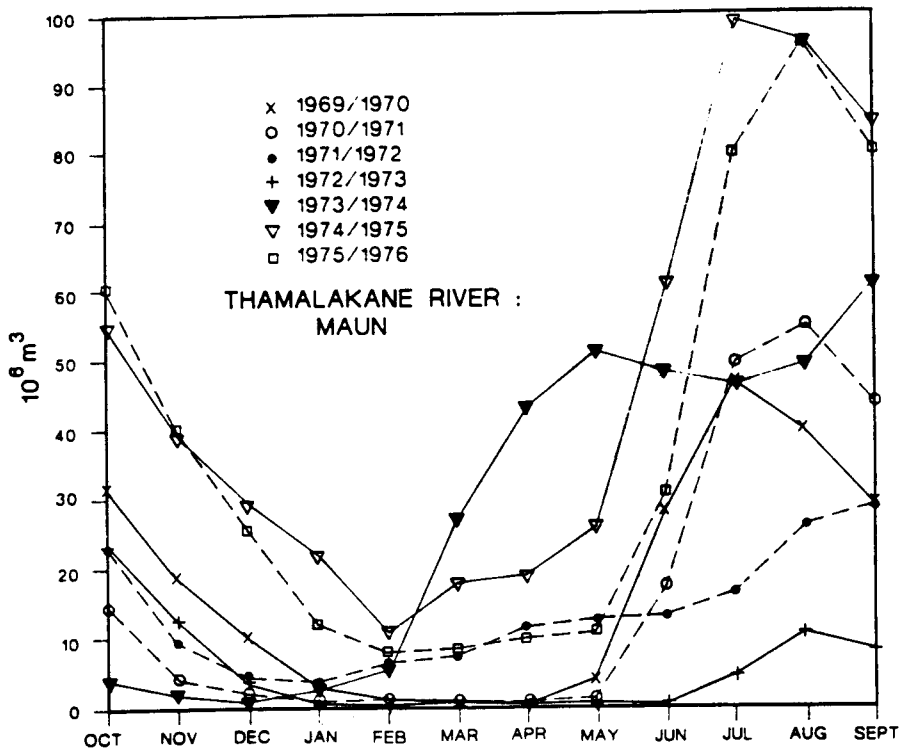
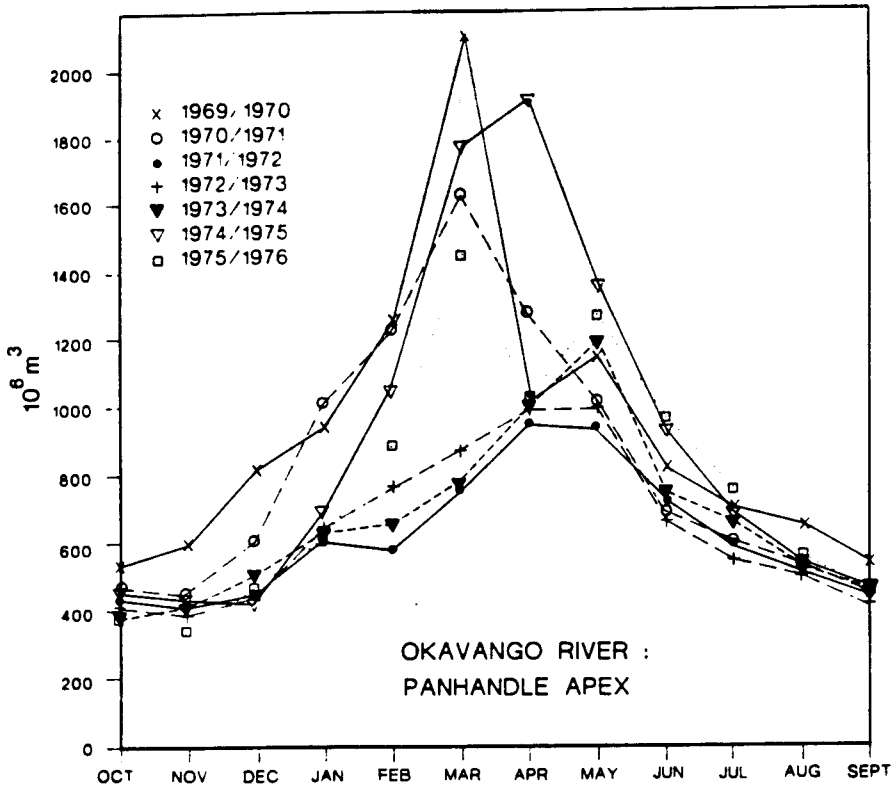


Fig 4. Inflow and outflow records for the period 1969 to 1976. Data from UNDP (1977).



### Channels of the Delta

Water is distributed through the swamps by a channel system. A single, meandering channel carries water through the upper part of the Panhandle. This divides at Ngamaseri but rejoins near Sepupa. In spite of the meandering form, Wilson (1973) noted that most of the meanders are stable, with some exceptions in the channels of the uppermost portion of the Panhandle.

The Thaoge and Jao/Boro distributaries leave the Okavango at the lower end of the Panhandle and carry water to the western and central regions of the Delta respectively. Wilson (1973) noted that both leave the main Okavango/Nqoga channel at peculiarly high angles (fig.5). The Nqoga channel, which is a continuation of the Okavango channel, carries water out towards the east. This channel formerly linked to the Mboroga (Stigand 1923; Wilson, 1973), but the link was broken as a result of vegetation blockage and failure of the lower Nqoga, a process which is still continuing today. The Nqoga supplies water to the Maunachira, which takes water out towards the Kwai River and now also supplies the Mboroga-Santantadibe system.

Wilson (1973) noted that water is frequently transferred from one channel to another by way of "filters", rather than by direct channel flow. Thus, the Mboroga obtains most of its water from the Maunachira by flow through a swamp filter as does the Khiandiandavhu from the Nqoga (McCarthy *et al.*, 1922b). The Maunachira obtains most of its water in a similar way from the Mqoga channel, although there is a narrow connecting channel. The same applies to the Jao/Boro (Porter and Muzilla 1989).

Channels throughout the permanent swamps are flanked by dense swamp vegetation which is rooted in peat, varying in thickness to a maximum of about five metres. The channel margins consist of root stabilised peat and are permeable to water, especially towards the water surface (McCarthy *et al.*, 1989a). This permeability allows water to flow from one channel system to another or to dissipate in the swamps.

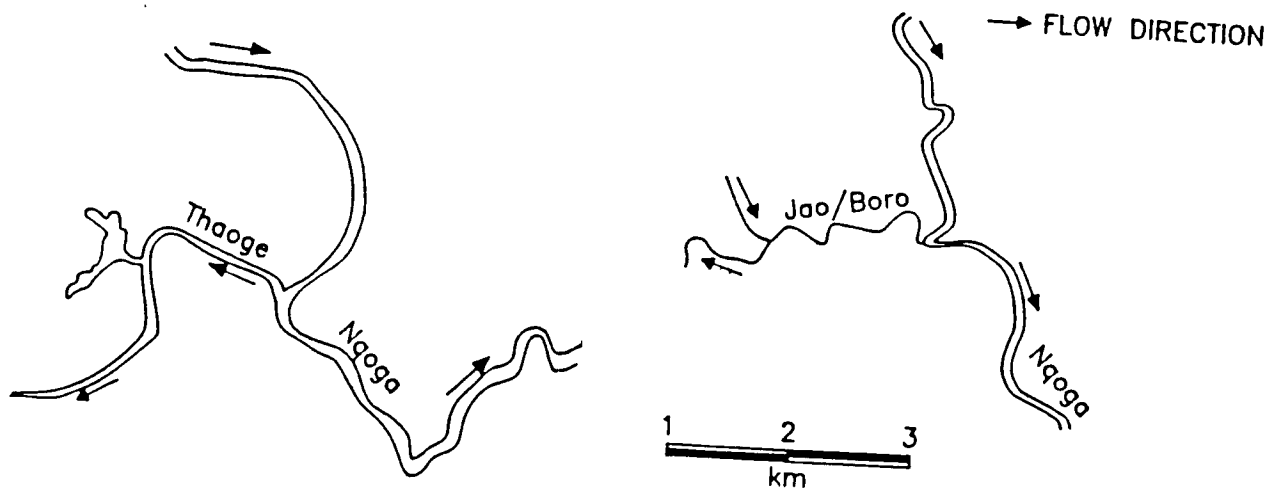
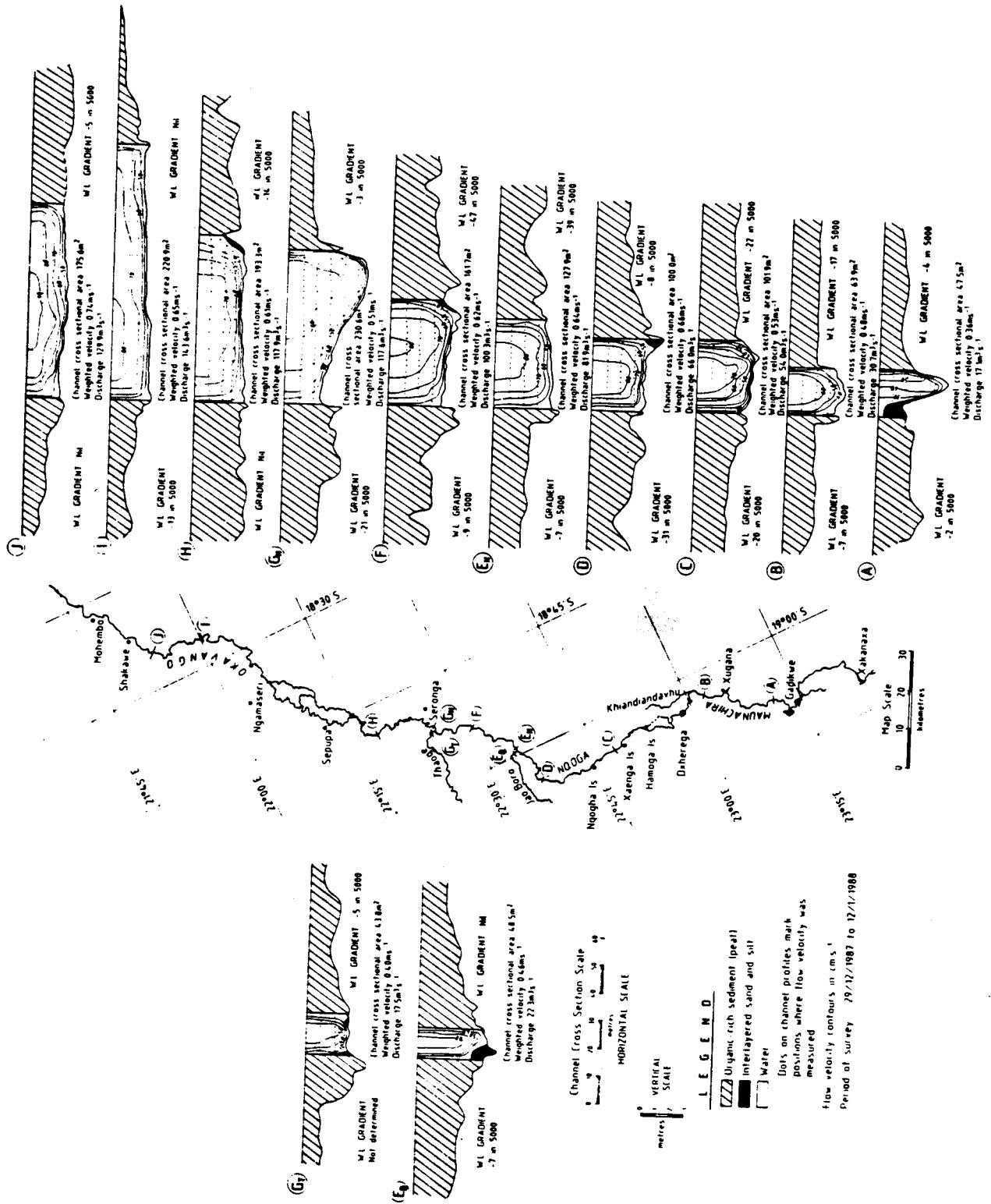


Fig 5. Maps showing the Thaoge and Jao/Boro take-offs. Arrows indicate flow direction.

Fig 6. Channel profiles at various points along the Okavango-Nqoga-Maunachira channel system (from McCarthy *et al.*, 1991a). Vertical exaggeration is 5:1.



The Okavango-Nqoga channel system is the major distributary of the Delta at present. This becomes progressively narrower downstream (McCarthy *et al.*, 1991a) and also decreases in width to depth ratio (fig.6). There is a particularly marked change in channel profile within the Panhandle. Upstream of Ngamaseri the channel is wide and shallow, but it becomes deeper and narrower at the lower end of the Panhandle (fig.6). Discharge in the channel system also decreases downstream (fig.7), reflecting loss of water to the swamp.

A survey undertaken along the Okavango and Nqoga channels revealed that the water surface in the channel is raised relative to that in the surrounding swamps (fig.8) (McCarthy *et al.*, 1991a). The difference in elevation is small in the upper Panhandle, but increases downstream, reaching a maximum at the head of the fan where the Thaoge and Jao/Boro distributaries separate from the Okavango-Nqoga channel. The relative elevation of the channel water surface declines downstream and is small in the lower reaches of the permanent swamp.

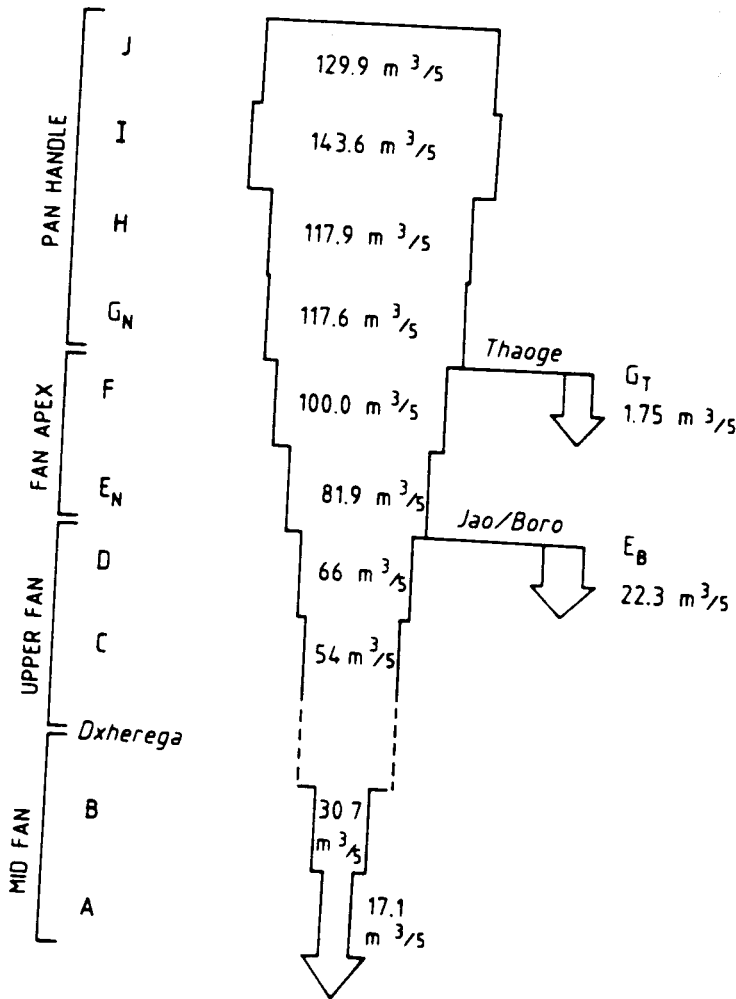
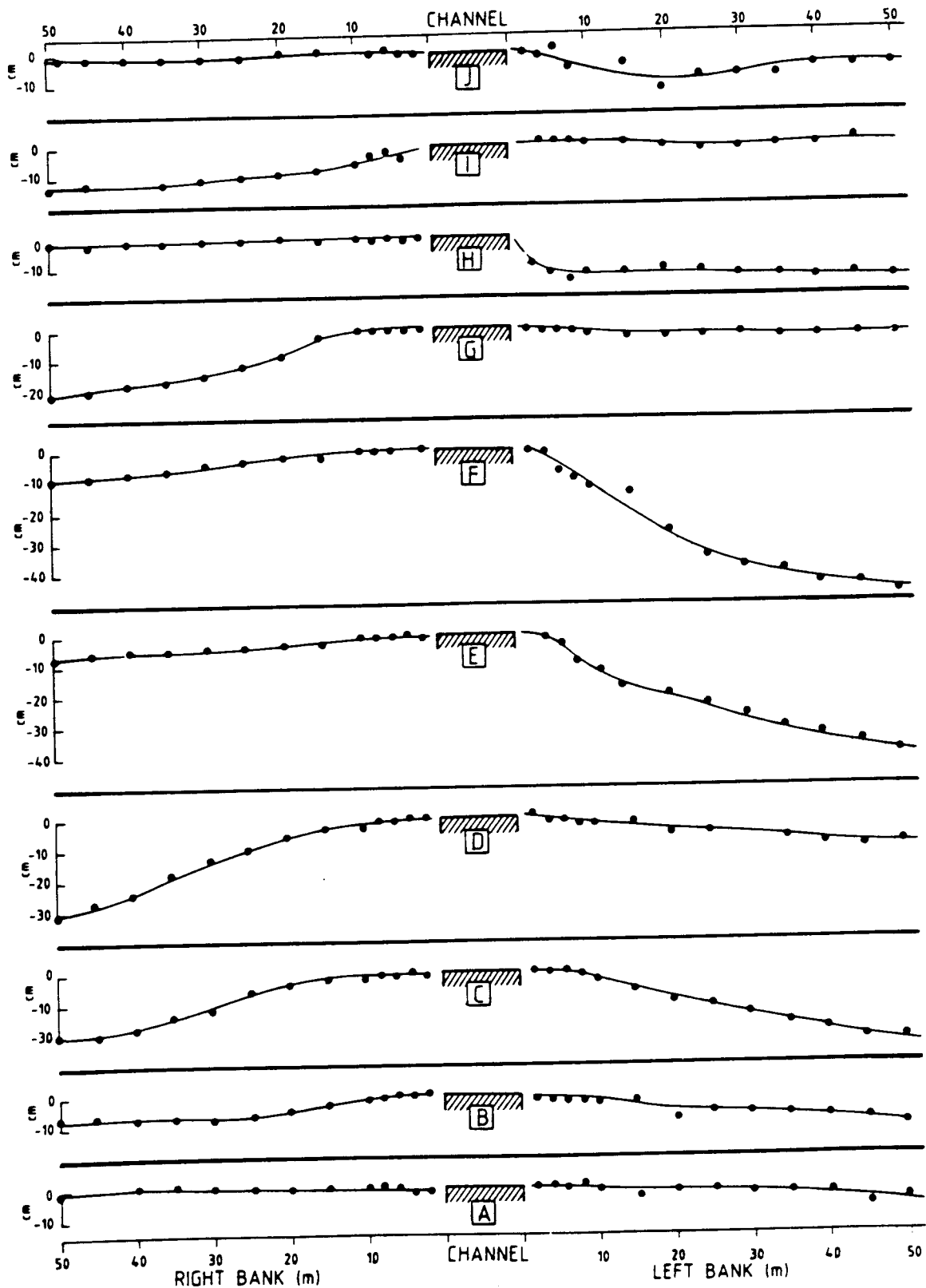


Fig 7. Discharge along the Okavango-Nqoga-Maunachira channel system. See fig. 6 for localities (from McCarthy *et al.*, 1991a).

Fig 8. Elevation of water surface in the swamps adjacent to the Okavango-Nqoga-Maunachira channel system. See fig.6 for localities. Datum is channel water surface; channel widths not to scale (from McCarthy *et al.*, 1991a).



The reasons for the change in relative channel water level elevation is not known but the observation provides an explanation for several features of the hydrology of the Delta. Significantly, the Thaoge and the Jao/Boro rise in the region where relative channel water surface elevation is at its highest. Moreover, the high take-off angles of the distributary channels (fig.5) probably reflect the direction of maximum slope of the water surface away from the main channel.

These observations also provide some insight into the variability of seasonal water level fluctuations across the Delta. As the seasonal flood arrives in the Panhandle, the channel water level rises and water floods into the surrounding swamp. The extent of this is however limited by the shoulders of the Panhandle, so water level fluctuations in this region are large. On the fan itself, however, there is no confinement. Moreover, channel water surface is significantly elevated, so any additional rise due to the arrival of the flood will result in a marked increase in water loss from the channel. Virtually all of the flood water therefore leaves the channels and flows into the surrounding swamp. Hence, seasonal water level fluctuations in this region are small. At the lower end of the Delta, flood water dams up against the fault scarps (especially the Kunyere fault, fig.2) so water level fluctuations are again large. During the waning flood, water drains back from the swamps of Panhandle into the channels, increasing the turbidity of the channel water (McCarthy *et al.*, 1991a). However, this does not occur on the fan itself, where water lost from the channel continues to spread outward across the gently sloping fan. Flow in the swamps is slow, accounting for the slow movement of the flood wave across the Delta. Had only channel flow been responsible for the movement of the flood across the Delta, its travel time between Mohembo and Maun would be about 10 days, rather than four months.

In spite of this, channels are important, as they serve as arteries, supplying water to outlying areas of permanent swamp. Each major branch of permanent swamp is served by a channel system - the Thaoge in the west, the Jao/Boro in the central Delta and the Maunachira-Mboroga-Santantadibe in the east. The importance of channels as arteries is dramatically illustrated by the failure of the lower Nqoga channel, which led to the progressive desiccation and destruction of a large area of permanent swamp (Wilson 1973; McCarthy *et al.*, 1988b). Without the arterial supply provided by a channel, permanent swamp cannot survive.

### Sedimentation

The sediment load of the Okavango River occurs in three discrete forms: bedload, consisting of Kalahari sand eroded from the catchment; fine particulate material held in suspension in the water, consisting of clays, organic matter and siliceous bodies of plant origin called phytoliths (McCarthy *et al.*, 1989; McCarthy *et al.*, 1992a); and various chemical compounds dissolved in the water. The annual inflow of these three types of sediment has been estimated to be 170000t of bedload, 30000t of suspended load and 456000t of dissolved load (McCarthy and Metcalfe, 1990).

Fig 9. Bedload discharge along the Okavango-Nqoga-Maunachira channel system. See fig. 6 for localities (from McCarthy *et al.*, 1991a).

Fig 10. Map showing the division in the main channel between Ngamaseri and Sepupa in the Panhandle region. I and H refer to measuring stations in fig.6.

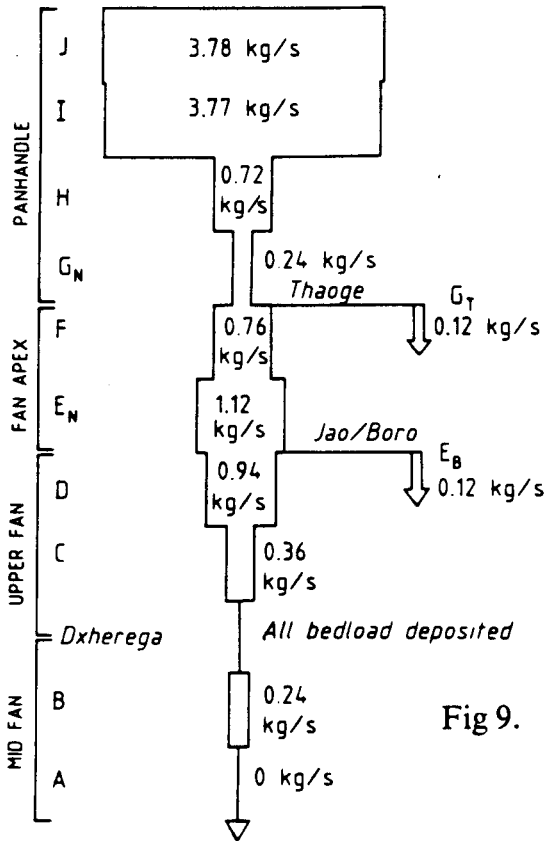


Fig 9.



Fig. 10

Fig 11. Aerial view of a floating papyrus blockage on the lower Nqoga channel.



The dissolved solid load seems large, but it must be emphasised that the concentration of dissolved solids is actually very low (40-50ppm, Wilson and Dincer, 1976; Hutton and Dincer, 1976). Moreover, the proportion of suspended material in relation to bedload is very low. The cause is undoubtedly related to the nature of the Okavango catchment area, which is dominated by aeolian sand, with minor granite. The aeolian sand is chemically stable and therefore produces little in the way of fine grained or soluble weathering products. Weathering of the granite in the catchment is responsible for the dissolved solids, but as the area of granite is small, the dissolved solid content is low. As is usual for rivers draining granite source rocks, the soluble salts are dominated by bicarbonates (Hutton and Dincer, 1976; Garrels and McKenzie, 1967). The nature of the catchment, i.e. dominated by siliceous sand and high silica granite, is probably also responsible for the relatively large quantity of dissolved silica in the water compared to most other major African rivers (Hutton and Dincer, 1976; Nkounkou and Probst, 1987).

Bedload discharge down the Okavango-Nqoga-Maunachira channel system during January 1989 is shown in fig. 9 (after McCarthy *et al.*, 1991a). It is evident from this figure that 90 percent of the bedload is currently being deposited in the upper reaches of the Panhandle above Ngamaseri. Measurements made during the flood stage (April) produced a similar result (McCarthy *et al.*, 1991a). Bedload discharge decreases further downstream, reaching a low near the Thaoge take-off, but rises slightly at the apex of the fan, decreasing thereafter. All remaining bedload is deposited in the Dxherega *lediba* (lake). Downstream of Dxherega, there is some bedload movement, reflecting local erosion in the Maunachira channel, but this is quickly deposited and in its lower reaches the bed of this channel is vegetated.

Although data are still being acquired, several lines of reasoning suggest that the massive loss of bedload in the Panhandle is the result of an avulsion which produced the split in the channel below Ngamaseri. The new channel, which lies to the east, is here referred to as the Eastern Channel. The main Okavango channel below Ngamaseri is characterised by broad, sweeping meanders typical of the upper Panhandle, but these are not present in the Eastern channel (fig.10). Wilson noted that unstable meanders occur in the upper Panhandle, while meanders downstream are very stable, even those with very convoluted shapes. Moreover, channel form differs above and below the division, with channels above Ngamaseri being generally shallow and wide compared to those in the lower Panhandle (fig.6).

The broad, shallow channels and unstable meanders of the upper Panhandle are the result of bedload deposition on point bars coupled with erosion on outer channel bends. Such a cut-and-fill process typically produces the broad meanders such as occur in the upper Panhandle and normally leads to the formation of a slightly elevated meander ridge on which the channel meanders. Avulsion periodically diverts flow away from such a ridge into the lower lying swamp beyond the limits of the meander ridge (Brizga and Finlayson, 1990). Such an event appears to have produced the Eastern channel. This evidently has had the effect of diverting water and bedload away from the main channel. Below the confluence of the Eastern and Okavango channels, the combined channel is starved of bedload and erosion of the channel bed is occurring. This appears to be the

Fig 12. Hydrogauge readings at the Hamoga Island station.

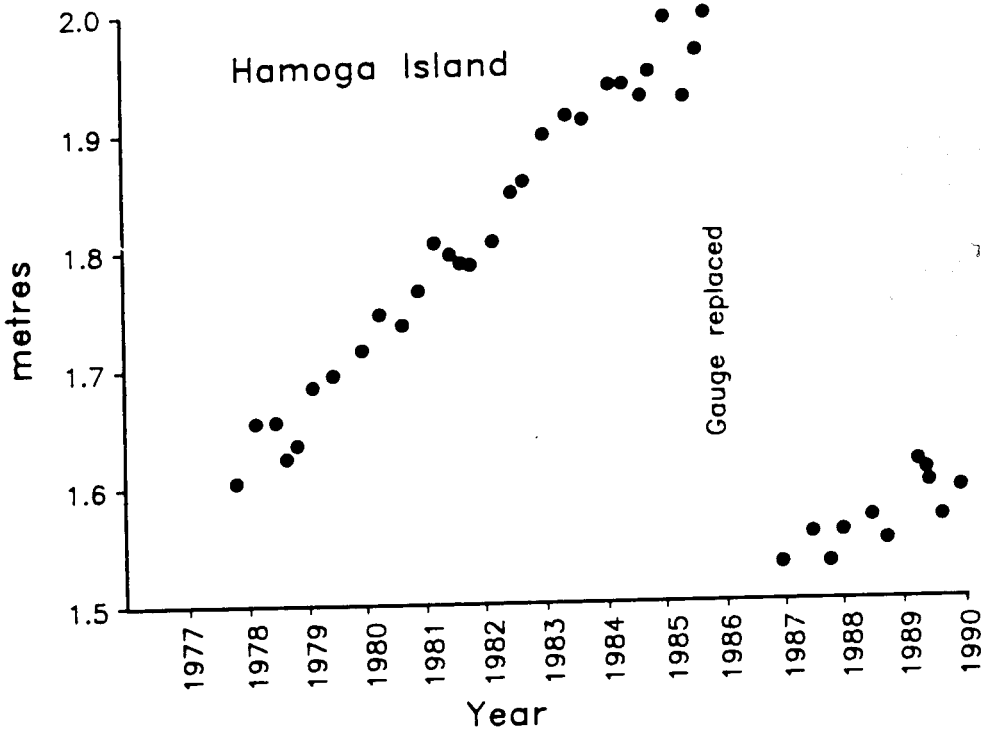
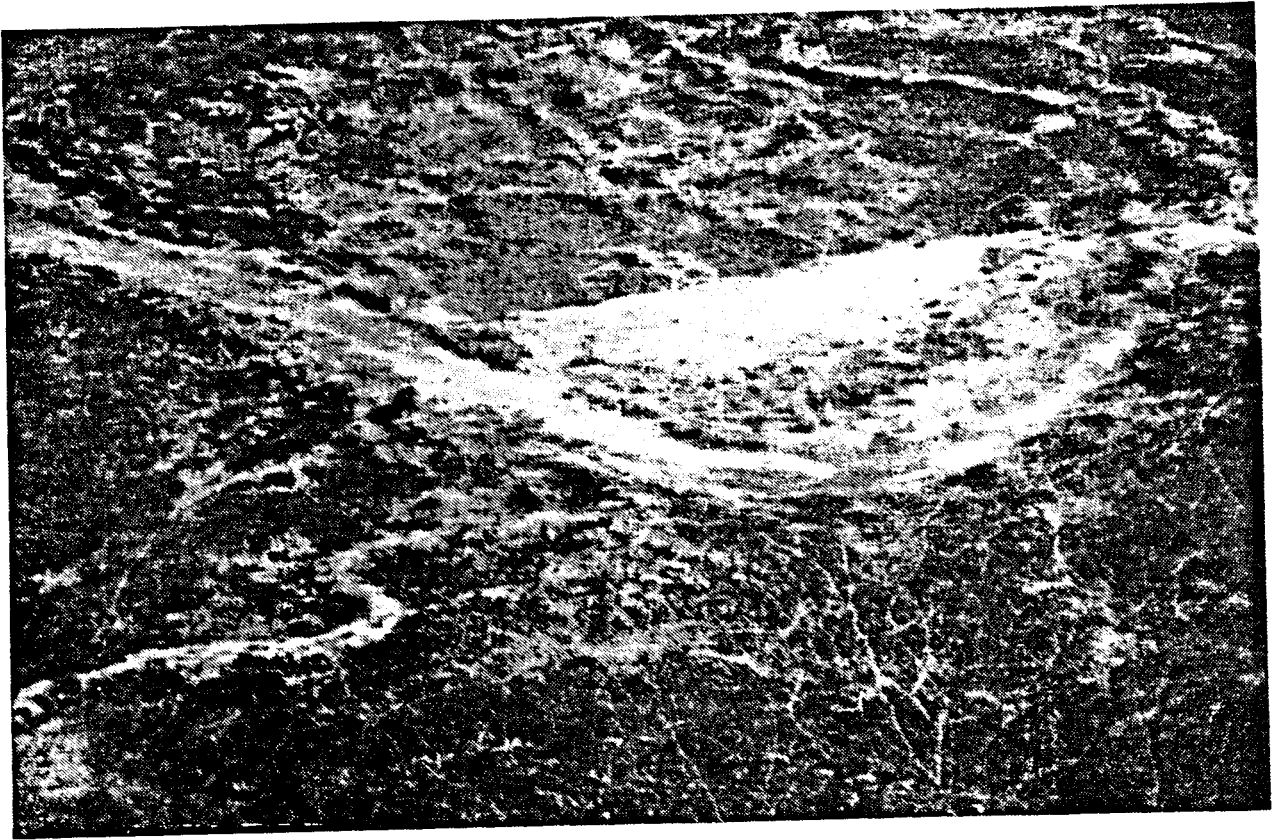


Fig 13. Aerial view of the burnt out swamp along the lower Nqoga. The former channel forms a sandy ribbon across a dry plain: small side channels form low ridges.



reason for the change in channel profile across the division in the channel (fig.6). The meanders downstream of the confluence are incised and hence stable.

The Thaoge and Jao/Boro channels receive very little bedload from the main channel, probably because of their peculiar take-off angles. There is strong evidence to suggest that, in the case of the Thaoge at least, this has not always been so. Historical records indicate that the Thaoge was the major distributary of the Delta in the last century (Shaw, 1984). Although the upper Thaoge is now substantially narrowed by vegetation growth, it displays the broad meanders typical of the Okavango River in the Panhandle. This suggests that the Thaoge, in its heyday, formed part of a continuous meander belt extending from the top of the Panhandle down the western side of the Delta. The Thaoge therefore probably also lies on a meander ridge.

The Nqoga channel has grown at the expense of the Thaoge and probably also owes its origin to an avulsion from the Thaoge meander ridge which diverted water to the east. This avulsion is probably older than that which gave rise to the Eastern channel. The blockages which have developed along the Thaoge (Wilson, 1973) result from loss of flow caused by this avulsion. In this context, the efforts to restore flow in the Thaoge by clearing blockages, so vividly described by Wilson (1973), can be seen to be totally futile. It seems that the Thaoge lies at a higher elevation than the younger Nqoga and is doomed.

The processes evident in the channels of the Panhandle are typical of the aggradational processes of meandering rivers (Smith *et al.*, 1989; Brizga and Finlayson, 1990). The overall, long term effect is the gradual outbuilding or progradation of the meander belt. The Thaoge evidently represented such a period of advanced progradation. As will be discussed below, there is evidence in the geomorphological record for other, older periods of advanced progradation of meander belts on to the fan.

The channels of the fan differ from the Okavango River in the Panhandle in that they are not meandering although they are sinuous. Deposition of bedload does not occur on point bars as in the upper Panhandle but rather on the bed of the channel. The cause seems to be the progressive loss of water from the channel, which reduces the capacity of the channel to transport bedload (McCarthy *et al.*, 1986a). The rate of bedload deposition increases downstream (McCarthy *et al.*, 1992b). The Nqoga channel typifies this condition. This channel originally connected to the Mboroga (Stigand, 1923) but has failed progressively (Wilson, 1973). The failing end of the Nqoga channel is characterised by the development of papyrus blockages (fig.11) (Wilson, 1973; Ellery, 1988). These are associated with a rapid rise in water level, as recorded on hydro-gauges (Fig.12) and a decline in flow velocity (McCarthy *et al.*, 1986a; McCarthy *et al.*, 1992b). This reflects rapid aggradation of the channel and the adjacent swamp in the failing reach. *Vossia cuspidata* (hippo grass) flourishes under these conditions and constricts the channel. It traps floating papyrus debris, forming surface blockages. However, water continues to flow beneath the blockage, scouring a depression in the bed of the channel (Ellery, 1988). Aggradation of the channel increases water loss to the surrounding swamp and as a result of increased flow, papyrus grows more prolifically. This is

important as it prevents the channel from avulsing. The increased flow through the swamps around the failing channel causes increased flow in hippo trails in the area and these become enlarged and lead to the formation of new channel systems (e.g. the Khiandiandavhu and upper Maunachira). These do not connect directly to the failing channel because of the vigorous growth of papyrus, but instead filter areas are created between the old and the new channel (McCarthy *et al.*, 1992b).

As vegetation blockages increase in frequency and density in the failing channel, flow is dramatically reduced. The flanking swamp, deprived of its arterial water supply, begins to desiccate and collapse. The peat catches fire and burns off (Ellery *et al.*, 1989). Such peat fires follow the channel as it progressively fails (Wilson, 1973; McCarthy *et al.*, 1986a). A peat fire reduces 4 to 5 metres of accumulated peat to a layer of ash typically less than 30cm thick (McCarthy *et al.*, 1988b), composed of relatively fertile, clay rich material. The former aggraded channel bed occurs as a sandy ribbon in this terrain, usually elevated (fig.13), but interspersed with depressions marking the former positions of debris blockages (McCarthy *et al.*, 1987; McCarthy *et al.*, 1988b; Cairncross *et al.*, 1988).

Peat fires are constantly burning in the Delta, and these areas are characterised by a pale brown colour, as opposed to the black colour of areas of normal surface fires. Dust devils rise continuously over these areas as heat generated by the slow burning peat lifts the fine ash into the air, but there is almost no smoke (fig.14). It must be mentioned that it is extremely dangerous to venture into these areas because the peat often burns underground beneath a hard crust of older ash and there is a risk of falling through into the fire below (Ellery *et al.*, 1989). Several lives have been lost in similar fires which occur in the Lichtenburg area of the Transvaal (de Beer, 1973). Chapman, who travelled to the Delta in 1852, relates how Chief Chapo of the Bakurutsie used his knowledge of these fires and the adjacent swamps to establish a refuge from the marauding Mandebele warriors - "..... a great danger is from the turfy earth, continually on fire and smouldering; men and animals sometimes fall in and are consumed" (Chapman, 1969, pg 58).

The failure of channels in this way is ecologically important because it creates large areas of clay rich, fertile soil. Grasslands which establish in these areas provide grazing for large herbivores (Ellery *et al.*, 1989). Stigand (1923) describes a similar transformation in the Lake Ngami - Tsau area, in this case related to the failure of the lower Thaoge channel. The former channels act as aquifers and often support larger trees or shrubs. Termites invade the abandoned, burnt-out swamp, raising termitaria. Areas of seasonal swamp characterised by mixture of sinuous islands (representing former channels) and small circular islands (representing ant hills) (fig.15) are, in part, the result of reflooding of abandoned burnt-out swamp. The life cycle of a channel from initial formation to final abandonment appears to be of the order of 150 to 200 years (McCarthy *et al.*, 1988b).

While bedload is important in channel evolution, fine particulates are ecologically possibly even more important. This material is carried into the swamp by channel

Fig 14. Aerial photograph showing floodwater invading an area in which a peat fire is burning on the lower Nqoga channel. Note the cloud of rising ash (dust devil).



Fig 15. Linear and ant-hill islands in the seasonal swamps.



outflow and together with dead plant material forms peat. The particulate material typically makes up between 30 and 90 per cent by mass of the peat, but only a few per cent by volume. This material makes up most of the ash left after a peat fire and provides the fine clays so essential for a good soil.

### Lakes

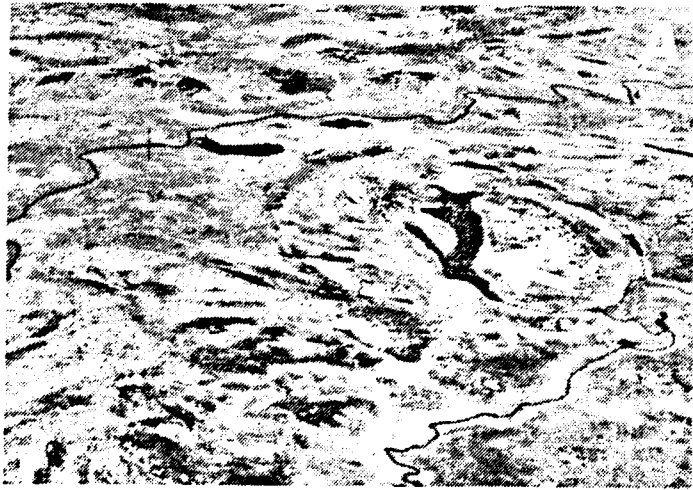
Numerous lakes or *madiba* occur throughout the Delta, predominantly in the permanent swamps. The largest lakes occur in the north-eastern region of the Delta along the Maunachira channel. Studies of aerial photographs of the lakes in this area have shown that some have remained stable while others have partially closed or even disappeared completely (fig.16).

Detailed study of the lakes along the Maunachira channel system (McCarthy *et al.*, 1992a) have shown that these are closely associated with a meander ridge. Some of the lakes are oxbows (fig.17) (e.g. Xugana, Gadikwe, Gobega), whilst others, especially in the very distal areas, are formed by water ponding against the meander ridge (e.g. Xakanaxa) (fig.18). The meander ridge and oxbows are not related to the present Maunachira channel but formed during a period of advanced progradation of the meander belt from the Panhandle region. The belt was active in the Maunachira area between 2000 and 3000 years ago. The Maunachira channel itself derives its water from the Nqoga channel and must be of a similar age, i.e. about 150 years (Stigand, 1923). The development of the Nqoga and Maunachira caused flooding of the old meander belt, including the oxbow depressions, giving rise to the lakes.

The oxbows and other lakes are connected to the main channel by way of hippo trails and occasionally, failure of a channel diverts flow into an oxbow. This sets in motion a complex sequence of events involving accumulation of sediment on the lake bed as well as prolific plant growth in and around the entry point to the lake, which eventually leads to closure (McCarthy *et al.*, 1992a). Dxherega (or Dobe) lake is currently filling in this way. As a lake fills, it is replaced by a typical channel, but occasionally, segments of a lake may be by-passed and these remain as irregular open water bodies, and can persist for long periods (fig.17). Most of the lakes in the Panhandle and upper fan probably formed in this way.

Lakes which are not connected to major channels also experience gradual filling, but at a much slower rate. Fine organic detritus collects on the lake bed and over time considerable thickness can accumulate. Bacterial decomposition causes a build-up of gas within this material, rendering it buoyant and large lumps tear away and float to surface, to form free floating or partially attached rafts or "sudds". These rafts become colonised by various plant species, especially *Pycreas nitidis* (K. Ellery *et al.*, 1990). Lakes in the lower reaches of the swamps which are filling in this way have a very "patchy" appearance, due to the variety of ages of floating rafts (fig.19). Such rafts in the upper swamps may be colonised by papyrus (Child and Shaw, 1990). The lake will eventually be replaced by a densely vegetated swamp.

Fig 16. Sequence of aerial photographs taken in 1937 (A), 1969 (B) and 1983 (C) showing the progressive closure of Bokoro *lediba* (indicated by larger arrow). The lake marked with a smaller arrow has remained unchanged in this period. The lake to the left of Bokoro in A had disappeared by 1969.



## Islands

Islands are a characteristic component of both the seasonal and the permanent swamps. They range in size from a single anthill to large land masses such as Chiefs Island. They vary in shape, from round to sinuous to irregular. Islands evidently form in a variety of ways. Chiefs Island may have been formed by tectonic uplift. Some islands are almost certainly anthills, which formed during periods of swamp abandonment (fig.15). Most long, sinuous islands are probably former channel beds or point bar deposits formed on meander bends. These become elevated during channel abandonment when fires destroy the surrounding peat. Reflooding of such areas makes islands of what were former channel beds. Islands also result from the drowning of former sand dunes formed by wind action during arid periods (fig.20). These occur only along the lower reaches of the Boro channel between the Thamalakane and Kunyere fault lines.

The most common type of islands are irregular in shape. They have formed as a result of the local, subsurface precipitation of calcium carbonate (calcite) and silica, which causes the land surface to rise (McCarthy and Metcalfe, 1990). Localised precipitation is caused by transpiration especially by broad leaf, evergreen trees (McCarthy *et al.*, 1991b). The trees transpire water into the atmosphere, leaving dissolved salts behind in the groundwater. The water table beneath the islands becomes depressed by as much as 50cm relative to the surrounding swamp, with diurnal fluctuations of as much as 7cm (Ellery *et al.*, 1992). Fresh swamp and ground water flows in beneath the island under the hydraulic head provided by the swamp and a steady state is achieved between inflow and transpiration. The salinity of the ground water increases steadily and it eventually saturates in calcite and silica, which precipitate between the soil grains, forcing them apart and causing the land surface to rise. Saturation occurs in the centre of small islands but towards the margins of larger islands. This results in larger islands having a slightly raised margin and a gentle interior depression, which may sometimes fill with rain water, which is usually saline and black in colour due to dissolved lignin (McCarthy *et al.*, 1991b).

The groundwater beneath the interior of the islands eventually becomes toxic due to accumulation of salts and the trees start to die. The less salt tolerant species die first, but ultimately all trees in the interior die. Capillary action brings the saline groundwater to surface where it evaporates leaving a crust of sodium bicarbonate (trona) (McCarthy *et al.*, 1986b). Trona is a characteristic end product of evaporation of water derived from granitic terrains (Eugster and Jones, 1979). At this stage, the soils are highly alkaline and cannot support any vegetation. In contrast, fresh water continues to flow beneath the islands from the margins so salinities remain low around the island fringes. This gives rise to distinct vegetation zonation on the islands - from a densely vegetated margin dominated by broad leafed evergreens and phoenix palms, passing inward to ivory palm which are more salt tolerant (Ellery *et al.*, 1992) and finally giving way to a barren interior (fig.21). The transformation from a fully vegetated island to one with an atoll-like appearance with a salt encrusted, barren interior, takes of the order of 200 years (McCarthy *et al.*, 1992c).

Fig 17. Aerial photograph of Xugana *lediba*, an oxbow lake along an old meander belt. Note the traces of former channels to the south of the lake.

Fig 18. Aerial photograph of Xakanaxa *lediba*. The former meander belt passes to the south of the lake.



Fig. 17



Fig 18.

Fig 19. Open water body undergoing filling by colonisation of floating rafts of organic debris.



Islands of this type probably nucleate on some original topographic irregularity such as an anthill or the raised bed of a former channel. The nature of the nucleus tends to express itself in the shape of the island. The common occurrence of elongated islands and chains of these islands indicates that former channel bed deposits constitute important nuclei for island growth.

As discussed previously, water distribution on the fan is constantly changing due to channel failure. Swamp abandonment deprives the islands of a continuous water supply and the water table falls. Rain flushes out the surface salts, regenerating the island soils. However, calcite and silica have very low solubilities so these remain in the soil, maintaining the form of the island. Reflooding starts the process anew. Repeated cycles of flooding and drying have, in this way, produced the hummocky topography of the swamps. Similar processes probably operate in the seasonal swamps but these are still being studied.

As mentioned earlier, the Okavango Delta fan has been constructed from material deposited by the waters of the Okavango River. This is made up of some 200 000t per annum of particulate material (bedload and suspended load) and about 457 000t of dissolved load. Some of the dissolved load is probably carried away by ground water outflow from the Delta. Nevertheless, it is clear that chemical precipitation is the dominant process by which the Okavango fan has been constructed (McCarthy and Metcalfe, 1990). Sedimentation of this type tends to be more evenly spread over the surface, especially in the lower reaches of the fan, where little particulate sedimentation occurs. It is probably this process which causes the low gradient on the fan as a whole and facilitates the wide distribution of seasonal flood water.

### Evapotranspiration

Some 96 per cent of the inflow into the Delta is lost to the atmosphere by evapotranspiration, amounting to some 15400 million m<sup>3</sup> per annum. This massive loss of water causes only a doubling of the salinity in the lower swamps (Hutton and Dincer, 1976) and saline surface water is very rare in the Delta, confined mainly to rainwater pans in depressions on highly saline islands, which usually result from rainwater dissolving surface trona accumulations.

Dincer *et al* (1982) estimated the relative contributions of evaporation and transpiration in the Delta (using changes in isotopic and chemical compositions of the swamp water). They came to the conclusion that during winter, evaporation dominates while during the summer evaporation and transpiration are about equal. However, their analysis is based on samples collected in channels and assumes that water which has been affected by transpiration has the same probability of occurring in channels as water which has been affected by evaporation. Plants take up water from their root zones where the water is not free to circulate, which is not the case for evaporation. Very saline water generated by transpiration from vegetated islands is confined to the groundwater regime and does not appear on surface, but probably seeps away from the Delta by groundwater flow. Accordingly, the method of analysis used by Dincer *et al.*, (1982) greatly underestimates

Fig 20. Flooded dune streets among windblown sand dunes between the Kuyere and Thamalakane faults.

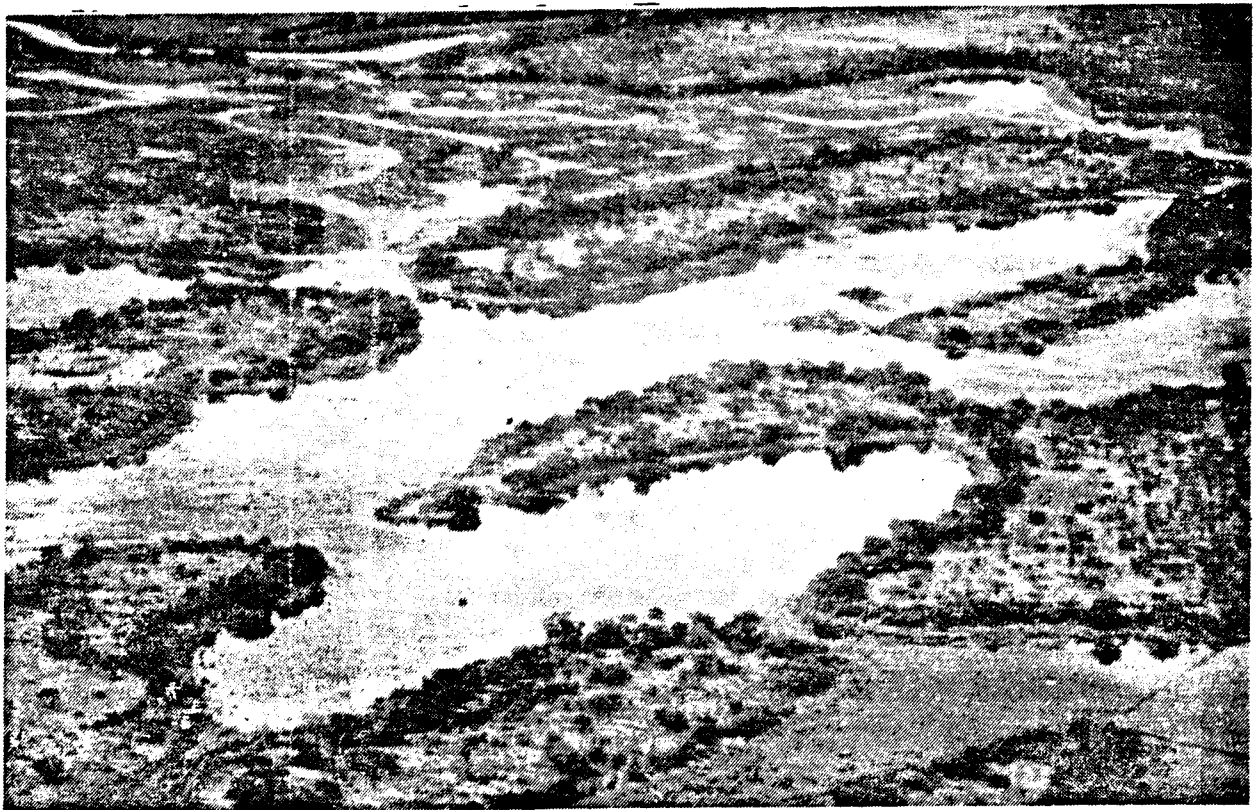
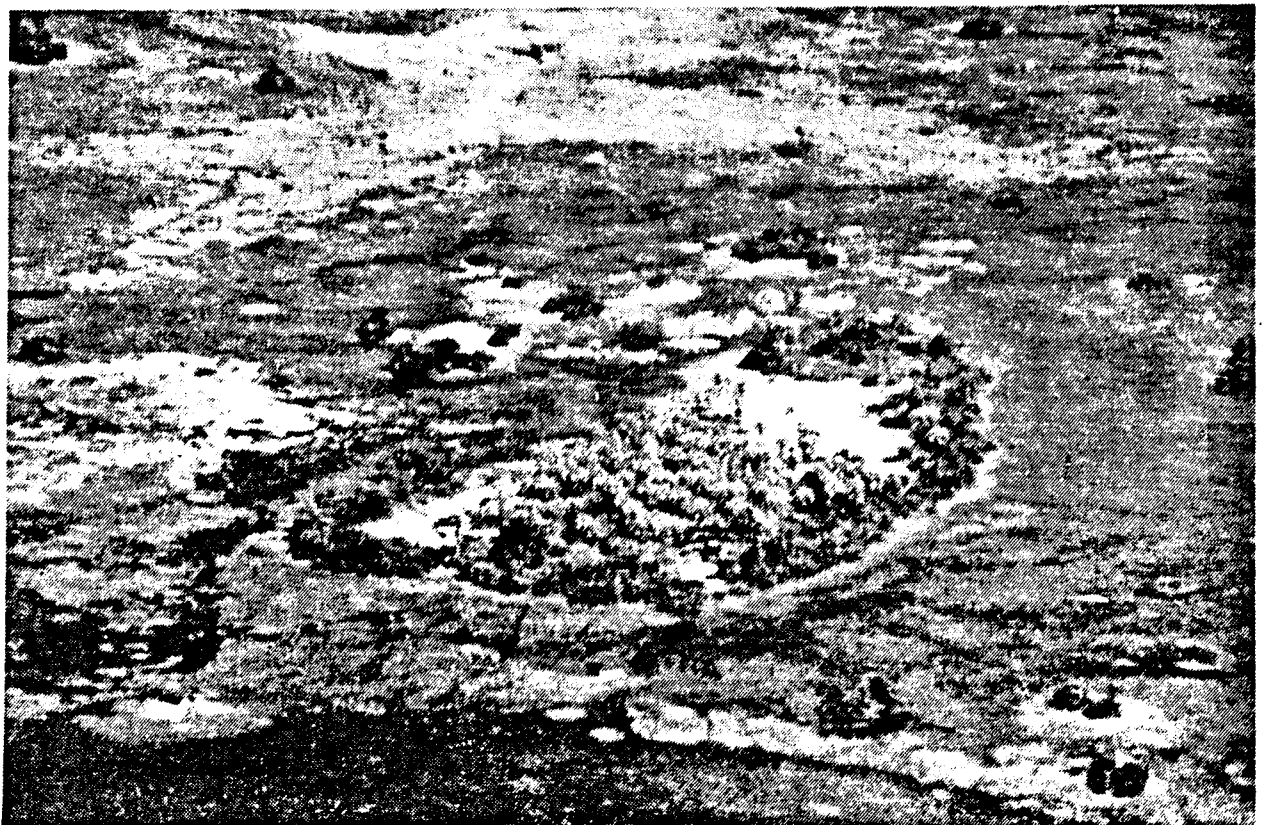


Fig 21. Vegetation zonation on an island in the permanent swamp.



the effects of transpiration. It is probable that transpiration is the dominant means of water loss and islands play an important part in this process as discussed above.

It is likely that in the permanent swamps, transpiration by aquatic plants also greatly exceeds evaporation (Migahid, 1947). Salt accumulation in the water in these areas is partly offset by bacteria growing in the peat which absorb salts from solution (McCarthy *et al.*, 1989). The overall effect of the dominance of transpiration is to prevent the formation of saline surface water, which is why it is so rare in the Delta.

### The Role of Vegetation

Vegetation has been mentioned in a variety of contexts in the preceding sections but its role in shaping the Delta is so important that it needs to be specifically discussed. While geological and hydrological factors are ultimately responsible for the existence of the Delta, the most remarkable finding of our research is the way in which the biota regulate the environment. Far from being passive spectators it appears that plants have taken control and regulate the physical environmental variables in such a way as to prevent stagnation and to maximise biological diversity. Indeed, without the biotic influence, there is little doubt that the Okavango Delta would consist of a saline lake with a sandy river delta, like so many saline lakes in the more arid regions of the East African Rift Valley (e.g. Frostick and Reid, 1986).

Biotic control is evident at a variety of levels in the ecosystem. Channel flanking plants such as *Cyperus papyrus*, *Phragmites australis* and *Miscanthus junceus* form permeable channel margins and facilitate the widespread distribution of water, but at the same time regulate and localise the deposition of sediment. *Vossia cuspidata* grows prolifically in failing channels, entrapping floating papyrus debris and facilitating channel failure. Yet this plant does not grow in the slower flowing channels of the lower Delta, where its vigorous growth habit would cause channel obstruction (Ellery *et al.*, 1990). Papyrus also grows luxuriantly in failing, rapidly aggrading channels, preventing avulsion and causing the formation of filter areas. This ensures that new channels which form do so at some distance from the failing channel and as a consequence the swamp area ahead of the failing channel desiccates and is destroyed by peat fires. This, in turn, creates fertile grassland and leads to an increase in biological diversity. Herbivores, net importers of nutrients, migrate into these areas. Termites and burrowing animals are also attracted and plough the fertile peat ash into the subsoil. Moreover, islands in the area which have become enriched in iron and hence poisoned are able to recover as a result of swamp abandonment.

Papyrus does not flourish in the distal swamp areas, where its thick rhizomes could potentially block channels. Here miscanthus becomes dominant. This plant has very short rhizomes and cannot extend over open water, thus posing no threat to the existence of channels, but it is an important stabiliser of channel margins (McCarthy *et al.*, 1988a). The important arterial channels of the distal swamps therefore remain unobstructed.

In the semi-arid environment of the Delta, evaporation could potentially lead to the development of saline surface water, which is inimical to higher life forms. That this does not happen is due to the dominance of transpiration over evaporation. Salinity increases resulting from transpiration by aquatic plants are corrected by bacteria living in the peat substrate. Moreover, transpiration by trees on islands localises salt accumulation to islands. These islands have concave centres so that rainwater which dissolves surface salts collects in the island centres and does not pollute the swamps. Saline ground water is more dense than fresh water so it is probably that these islands act as sinks, funnelling salts into the subsurface below the biosphere. Salt accumulating in the shallow ground water beneath islands does impact on the vegetation but this is temporary, because vegetation induced swamp abandonment enables them to recover.

Hippos also seem to play a role in the functioning of the ecosystem. Their movements through the swamps probably contribute to the maintenance of the narrower channels, but perhaps even more important, their paths provide loci for the development of new channel systems.

### **Conclusions**

The Okavango Delta is tightly constrained by several external environmental variables: (i) by the nature of the catchment, which produces a sediment load dominated by bedload, and water with low total dissolved solids; (ii) by tectonic forces which have created a depression across the course of the Okavango River; (iii) by the semi-arid nature of the environment, which ensures that 96% of incoming water is lost to the atmosphere; and (iv) by the limited, but nevertheless important, quantity of ground water outflow.

Biota operating within these external constraints have shaped the Okavango Delta into what we see today. It is a system undergoing constant change, but far from being catastrophic, this change is an essential characteristic of the system as it is the basis of self-renewal of the ecosystem. Without this constant change, the system would become stagnant and moribund. Moreover, while apparently random, change is orchestrated by plant communities specifically adapted to force change. Although it is difficult to envisage altruistic behaviour amongst plants, plant communities of the Delta appear to fulfil specific functions, to the benefit of other communities in the system. In this sense, the Okavango Delta encapsulates the spirit, if not the letter, of James Lovelock's (1988) "Gaia". Our six years of research have yielded considerable insight into the functioning of the Okavango Delta and the broad picture is emerging, but much still needs to be learned.

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