

The fluvial dynamics of the Maunachira Channel system, northeastern Okavango Swamps, Botswana

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Abstract

This study was undertaken to investigate the role and function of secondary channels (those that arise within the swamps and carry no externally derived bedload sediment) in the Okavango Delta, and focused on the Maunachira Channel of the north-eastern swamps. Three reaches were identified: an erosive upper reach; a depositional middle reach; and a stable lower reach where no sediment movement is occurring and the channel bed is vegetated. The erosive reach is confined to the most proximal section of the channel and is associated with inflow into the channel from tributaries and from the surrounding swamp. Downstream of this reach, the channel becomes aggradational. The aggradational reach is associated with a marked rise in the channel water level relative to the surrounding swamps, which promotes water loss from the channel. Some of the water leaked from the channel supplies the Mboroga Channel to the south. *Cyperus papyrus* grows vigorously along the aggrading reach, and partially constricts the channel. Aggradation results in a decrease in channel gradient and flow velocity declines to below 0.4 m/s, when bottom-rooted vegetation is able to colonise the channel bed, terminating sediment movement. Channel margins in these lower reaches are characterised by *Miscanthus junceus*, a non-invasive plant species, which promotes long-term stability. The zone of aggradation is migrating upstream at about 170 m/a. The study suggests that secondary channels arise due to local oversteepening of the regional gradient, and their role is to redistribute sediment down this gradient.

Introduction

The Okavango Delta of northern Botswana (Fig. 1) is a large alluvial fan situated in a north-easterly striking graben structure, which is an extension of the East African Rift System (UNDP 1977; McCarthy et al., 1993a). Water is supplied by the Okavango River, which rises in the highlands of central Angola. The river enters the Okavango Delta by way of the Panhandle, a narrow, north-westerly trending subsidiary graben structure, and divides at the south-eastern end of the Panhandle into a number of distributary channels. Overflow from the channels inundates up to 18 000 km², to form Southern Africa's largest wetland. At present the Nqoga Channel is the major distributary, and diverts water to the eastern portion of the Delta (McCarthy et al., 1991).

Distribution of water on the fan is constantly shifting (Ellery and McCarthy, 1994), and in the early part of this century, the Nqoga Channel directly

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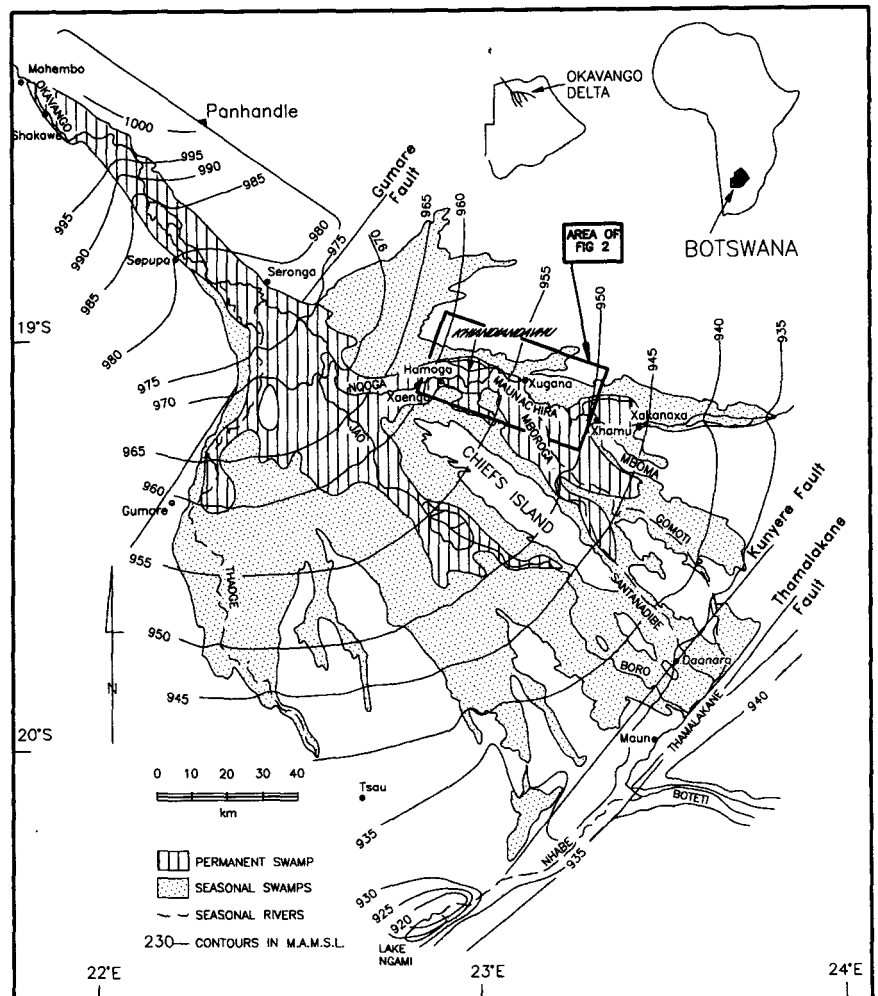


Figure 1
Map of the Okavango Delta showing the location of the study area

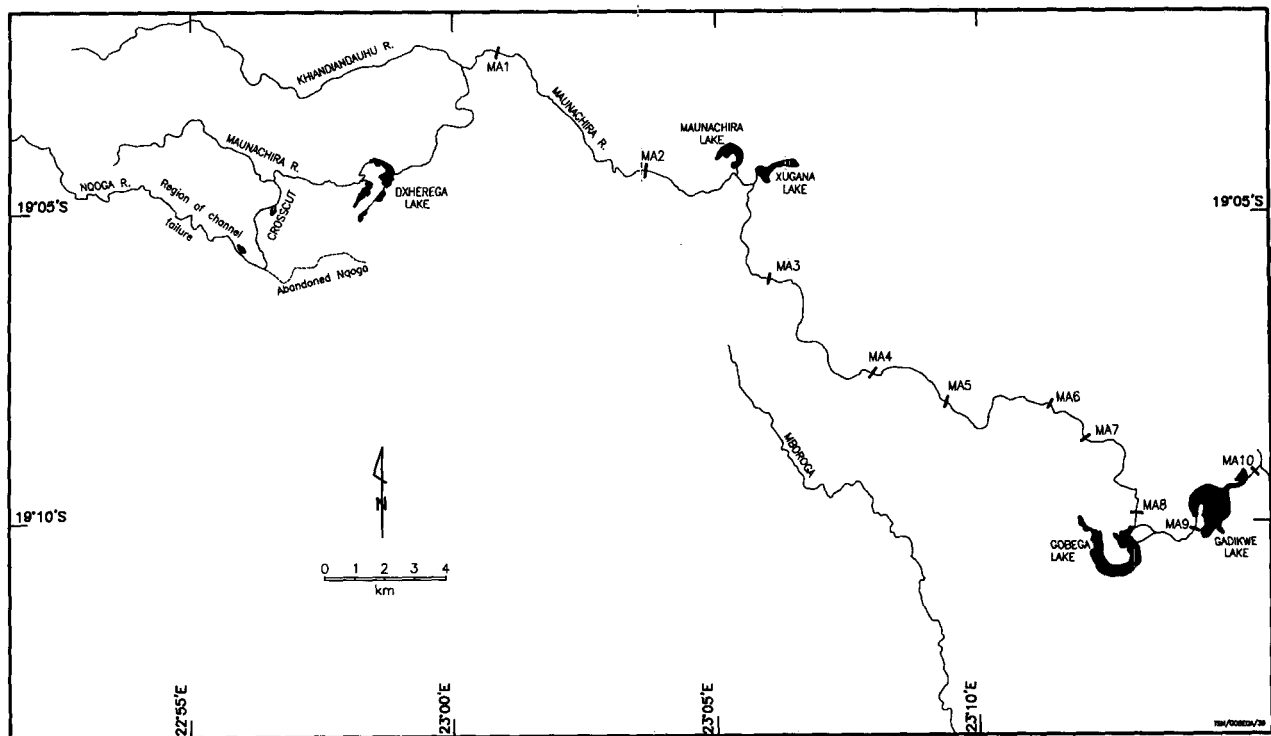


Figure 2
Map of the study area showing the location of study sites

supplied the Mboroga-Santantidibe Channel system (Fig. 1). The lower reaches of the Nqoga Channel began to fail in the 1920s (Wilson, 1973) and the link to the Mboroga was broken. The Nqoga Channel has continued to fail progressively from its distal end. The history of this failure and the processes involved have been documented by Wilson (1973) and McCarthy et al. (1992), and was recognised by the latter authors to be due to aggradation as a consequence of sedimentation.

Concomitant with this failure, the Maunachira Channel and its tributary, the Khiandiandavhu Channel, have developed by headward erosion, and water is currently transferred from the failing reach of the Nqoga Channel to these channels. At one time, the Maunachira was connected to the Nqoga Channel, but this link has become overgrown by aquatic vegetation (McCarthy and Ellery, 1995), and water is now transferred entirely by leakage through the flanking vegetation. The Maunachira Channel has succeeded the Nqoga as the main supplier of water to the Mboroga Channel system, and as such, fulfils an important ecological function in the Delta.

The Maunachira is an example of a secondary channel, i.e. one not connected directly to an external supply of sediment (McCarthy et al., 1992), several of which exist on the Okavango fan. Water transfer is not accompanied by sediment transfer, and an expanding secondary channel can therefore be expected to be erosional in its upper reaches. Sediment generated by erosion in the headwaters of such a secondary channel is confined to in-channel areas, and is likely to be deposited further downstream. Furthermore, there is a strong feedback between hydrology, sedimentation and vegetation processes (Ellery et al., 1990; 1993). The aim of this study was to establish the hydrological, sedimentological and biological processes along the Maunachira Channel with a view to obtaining insight into the role and function of secondary channels in the Okavango wetland.

Methods

Channel characteristics

The study was carried out between 11 and 17 August 1992. The methods used are similar to those documented by McCarthy et al. (1991), and will only be briefly described here. Ten study cross-sectional sites were selected along the Maunachira Channel in the reach from the confluence of the Khiandiandavhu to the outlet channel of Gadikwe Lake (Fig. 2). At each site, channel cross-sectional area, discharge and lateral water surface slope were measured. Channel depth profiles were measured using steel depth probes. Flow velocity was measured using a Watts vane-type flow meter, flow velocity being measured at 1 m depth intervals at variable distances across the channel. Velocities were contoured, areas between contours integrated and a weighted average velocity was calculated. Peat thicknesses in the swamp flanking the channels were also measured with steel depth probes. The water surface adjacent to the channel was surveyed along cutlines perpendicular to the channel using a Kern level and staff. Site MA2 was chosen to be close to Site B of McCarthy et al. (1991) so as to provide a link with previous surveys in the area. Bedload was not measured, but was calculated from the average velocity using the formula of McCarthy et al. (1992).

Vegetation

At each study site, the species composition of vegetation was determined on each bank at 5 m and 50 m from the channel margin, in sample plots 5 m x 5 m in size. Within each sample plot ($n = 40$), the species present were listed, and an estimate of cover was made using a cover scale with intervals between 1, 2, 5, 10, 20, 50 and 100%. The samples were classified using a polythetic

divisive cluster analysis (TWINSPAN; Hill, 1979). Major groupings are provided with diagnostic, or indicator species, which are those with a distribution (or a particularly high abundance) that is restricted to the samples in one group of the division, and are absent (or have low abundance) in the other group (Hill, 1979).

Satellite imagery

A SPOT 2 satellite image of the study area, recorded on 8 October 1991, was available for this study. This was processed using a Transformed Vegetation Index (TVI), as this has been found to be particularly useful in studies of the Okavango wetland. Details of the processing techniques and the advantages of the method have been described by McCarthy et al. (1993b). In addition, conventional panchromatic aerial photographs of the study area were also used.

Results and discussion

The headwaters of the Maunachira Channel

The headwaters of the Maunachira and Khiandiandavhu Channels (Fig. 2) had been the focus of a detailed investigation by ourselves in January 1989 (McCarthy et al., 1992). At that time, the Crosscut or Letemetso Channel linked the failing Nqoga Channel to the Maunachira, and supplied 9.2 m³/s to this channel. However, a greater proportion of the Maunachira's discharge (12.8 m³/s) was derived from the swamps adjacent to the failing reach of the Nqoga, this being obtained from lateral leakage from the Nqoga Channel through the flanking vegetation. Total discharge in the Maunachira Channel immediately downstream of the Crosscut confluence was 22.0 m³/s. A small quantity of bedload was supplied to the Maunachira Channel via the Crosscut, but the bulk was derived by erosion, particularly in the reach below the Crosscut confluence. All of this bedload was being deposited in Dxherega Lake (McCarthy et al., 1993c). Additional inflow to the Maunachira Channel occurred via the Khiandiandavhu Channel, and downstream of the confluence of these two channels, total discharge was 32.3 m³/s. The Khiandiandavhu Channel also obtained its water from leakage from the Nqoga Channel. The Khiandiandavhu supplied no bedload, however, while bedload discharge in the Maunachira at its confluence with the Khiandiandavhu was 0.12 kg/s, all of which was being derived by bed erosion downstream of Dxherega Lake.

Although this study embraced an area of swamp which is undergoing very rapid change (Ellery et al., 1990; McCarthy et al., 1992; McCarthy and Ellery, 1995), conditions during the present study were similar to those existing in January 1989, total discharge downstream of the confluence of the Khiandiandavhu and Maunachira Channels being 36.9 m³/s. Discharge at Site MA2 (close to Site B of McCarthy et al. (1991)) was 29.0 m³/s in the present study, while McCarthy et al. (op. cit.) reported a discharge of 30.7 m³/s at Site B in September 1987. It should be noted that seasonal fluctuations in water level and discharge in this region of the swamps are very small (McCarthy et al., 1992).

Channel profiles

Channel margins are identical to those described by McCarthy et al. (1988a) and consist of muddy peat, which is stabilised by roots and rhizomes of the plant communities living on the peat. These communities consist mainly of *Cyperus papyrus* and *Miscanthus*

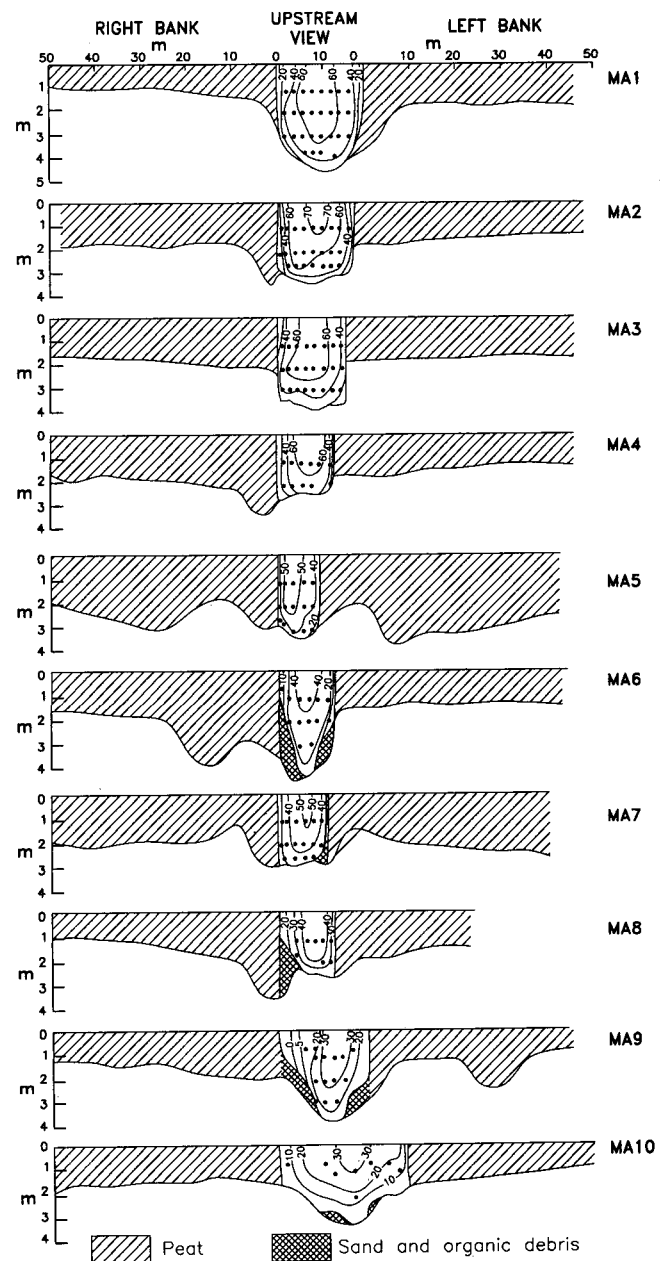


Figure 3
Depth profiles across the channels and flanking peat at the study sites. Dots within the channel indicate flow velocity measuring positions. Isovelocity contours are in cm/s.

juncus (Ellery et al., 1990). Margins are near vertical or may have overhanging papyrus rhizomes. Rhizomes of the channel-fringing communities are submerged, and moreover, the peat itself is permeable to water, so that exchange of water between channel and flanking swamp may occur. Channel width decreases downstream from a maximum at MA1 (19 m) to a minimum at MA5 (9 m), whereafter it rises to about 12 m. In the vicinity of the lakes (MA9 and MA10), the channel is 20 m and 28 m wide respectively (Table 1).

The channel profiles indicate that the channel is incised into the substratum at most sites (Fig. 3). The substratum consists of sand to clay-rich sand. Incision is particularly marked in profiles

Site	Width m	Depth m	Area m ²	Velocity m/s	Discharge m ³ /s	Lateral gradient* right bank	Lateral gradient* left bank
MA1	19	4.0	75.9	0.49	36.9	-5	+3
MA2	17	3.2	54.3	0.53	29.0	-12	-6
MA3	15	3.6	54.6	0.50	27.1	-22	-17
MA4	12	2.6	31.6	0.46	14.5	-9	-20
MA5	9	3.5	31.7	0.44	13.8	-5	-1
MA6	12	3.4	40.9	0.26	10.7	0	0
MA7	11	2.9	31.8	0.35	11.2	-1	-2
MA8	12	2.4	29.2	0.34	9.9	0	-12
MA9	20	2.6	52.5	0.21	11.0	-4	-1
MA10	28	2.5	71.0	0.20	14.4	-10	-3

*Difference in elevation of water surface between the channel and the swamp 50 m from the channel

MA1 to MA3, less so in MA4 and least in MA5. The form of the substratum surface in most of the profiles, but especially at sites MA4 to MA8, suggests that the channel was much wider in the past, particularly in the lower reach, and has been narrowed by encroachment of the peaty margins and by the accumulation of organic material together with sand on the channel bed. This is particularly evident in profile MA6, in which the channel appears to have been at least 35 m wide and has incised at least 2 m into the substratum. These distal sites currently exhibit flow velocities of below 0.4 m/s, which are insufficient to prevent colonisation by submerged, aquatic vegetation (Ellery et al., 1990), and hence experience no bedload movement.

Hydrology

Maximum discharge occurs at Site MA1 (36.9 m³/s, Table 1). This declines downstream, slowly at first, so that at MA3, discharge is 27.1 m³/s, but rapidly between MA3 and MA4, where 50% of discharge is lost. Thereafter, discharge remains relatively uniform between 10 m³/s and 14 m³/s.

The lateral water surface gradient at MA1 is asymmetric (Fig. 4), sloping gently away from the channel on the right (south) bank, but towards the channel on the left bank, indicating inflow into the channel from the swamps to the north of the channel. Downstream of this site, water surface in the channel rises above that in the surrounding swamps, reaching maximum elevation at MA3. Thereafter, relative elevation of the channel water surface declines, but rises again slightly at MA8.

The region of maximum relative elevation of the water surface coincides with the region of maximum rate of water loss

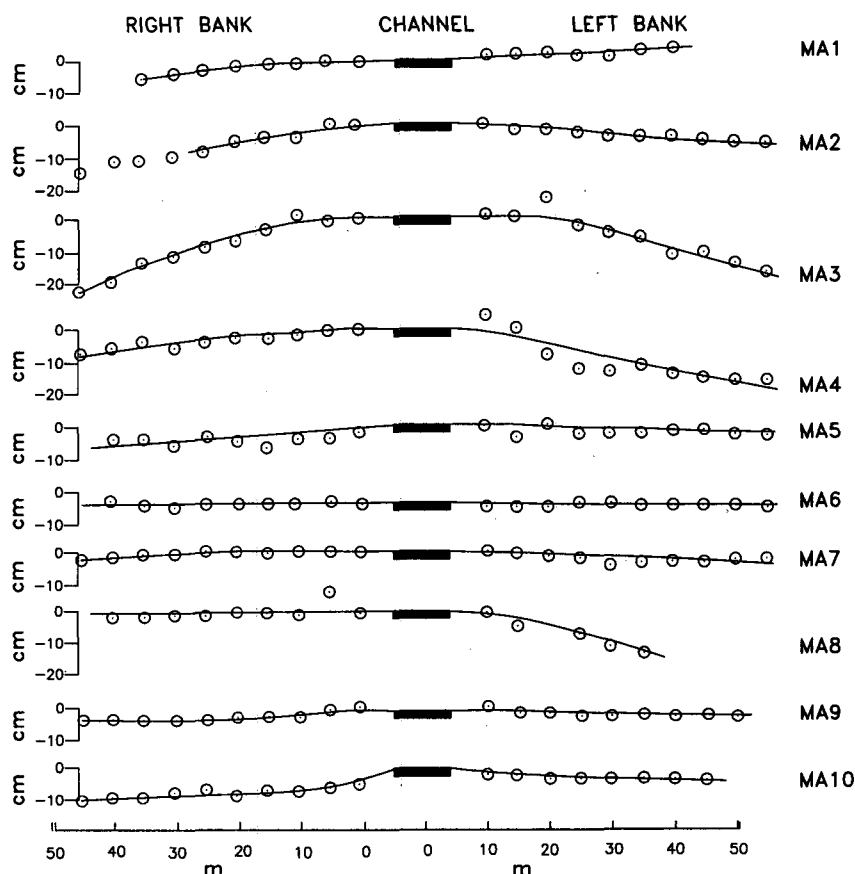


Figure 4
Water level elevation in the swamps adjacent to the channels at the study sites (channel widths not to scale). Datum is channel water surface.

from the channel, indicating that water loss occurs through the channel margins under the influence of the hydraulic head provided by the channel. It is significant that the Mboroga Channel rises adjacent to this reach in the swamps on the right (south) bank of the Maunachira Channel (Fig. 2). The two

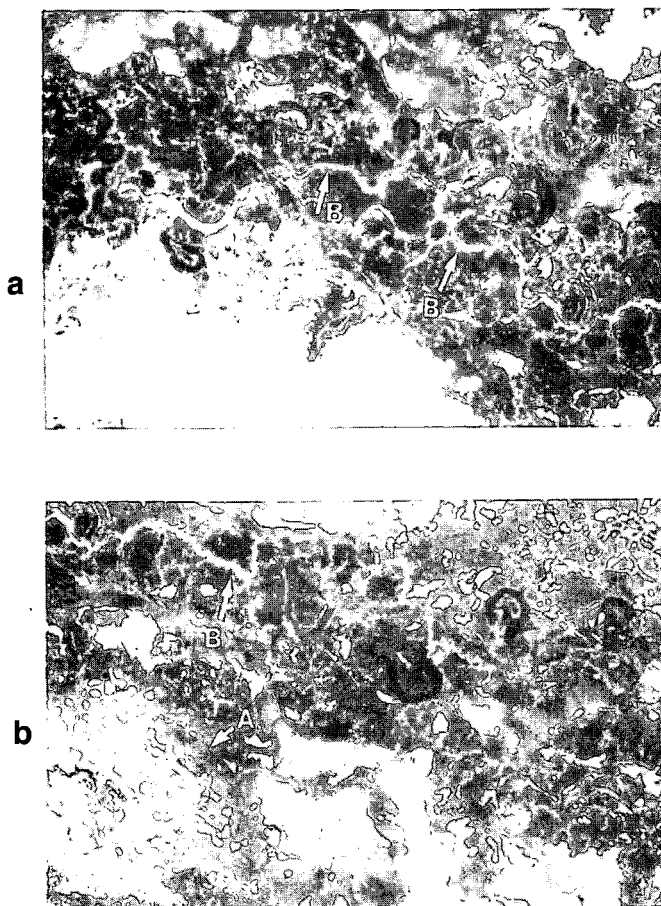


Figure 5
 SPOT satellite images of the upper Maunachira Channel (a) and of the Middle Maunachira and upper Mboroga channels (b). The letters A and B indicate the Mboroga and Maunachira Channels respectively. Colour versions of these images may be found in McCarthy et al. (1993b).

channels are not connected directly, but flow sub-parallel to each other for some distance, separated by vegetated swamp. It is likely that the Mboroga derives its water from outflow from the Maunachira Channel through this swamp. Wilson (1973) termed these areas of vegetated swamp separating channel systems "filter areas", an apt description, because while water is able to discharge from one channel to the other across the filter, sediment is not.

A SPOT scene processed as a TVI image has been shown to provide a synoptic view of water loss from channels in the Okavango swamps (McCarthy et al., 1993b). The reason for this is that channel-flanking vegetation tends to become more luxuriant when growing in rapidly through-flowing water, because flow provides a steady supply of nutrients in this generally nutrient-deficient environment. This results in high values of the TVI, which are rendered visible on the image. SPOT scenes covering the study area are shown in Fig. 5. The upper reaches of the Maunachira Channel are indistinct on the image, but towards Xugana Lake a bright fringe develops on the right bank (vicinity of Site MA2), indicating water loss through this bank. The water surface gradient at site MA2 is steeper on the right bank (Fig. 4),

in agreement with the inference made from the satellite image. Downstream of Xugana Lake as far as Site MA5, the fringe becomes particularly bright, indicating significant water loss from the channel. Thereafter, the fringe is variable, but generally not particularly pronounced. The Mboroga Channel has no fringe at all, indicating that it is experiencing inflow from the flanking swamps.

Vegetation

Based on the study by Ellery et al. (1990), the vegetation of channel margins in the present study area was expected to have both *Cyperus papyrus* and *Miscanthus junceus* as dominant species, whereas *Ficus verruculosa* would be absent, or present in low abundance. Vegetation within the channel was expected to be present throughout the study area. The observed patterns in the more regional study (Ellery et al., 1990) were related to differences in patterns of sediment movement, hydrology (source of water), and the degree of confinement of channels.

The present classification offers a more detailed assessment of the interrelationships between vegetation distribution, sediment movement and hydrology (Appendix A). Forty samples were classified into three major groups (Fig. 6). The samples in the positive group at the first level of division were characterised by the indicator species *Drosera madagascariensis*, *Ellocharis dulcis*, *Erlochrysis pallida* and mosses such as *Hypnum* spp. *Pycnurus nitidus* with a high cover (>20%) was also an indicator species of this group, although it was present with a cover of less than 20% in samples in the negative group. The samples in the negative group were indicated by the presence or high cover of *Cyperus papyrus* and *Miscanthus junceus*, which were either absent from samples in the positive group, or were present with low cover.

The vegetation characteristics of the samples in the positive group were not encountered in the study of channel vegetation by Ellery et al. (1990), but were described in a study of backswamp vegetation by Ellery et al. (1991), being equivalent to the "dense emergent community with a homogeneous substratum". These samples were restricted to sites in the lower reach of the study area, including Sites MA6, MA9 and MA10, and they were all 50m from the channel. They thus appear to be uninfluenced by the channel itself, either hydrologically, or by receiving a supply of nutrients from the channel.

The samples in the negative group at the first level of division were further subdivided into two groups at the second level of division (Fig. 6). Samples in the positive group were indicated by the presence of *Ficus verruculosa* with a cover of greater than 2%, while those in the negative group had a cover of less than 2%, with the species being absent from many samples. Furthermore, *C. papyrus* was present with a cover of less than 20% in the samples in the positive group, while it generally had a cover greater than this in the samples in the negative group. *Miscanthus junceus* was present with a high cover (>20%) in all samples.

This division separates samples in the upper half of the study area (negative group) from samples in the lower half of the study area that were not in the positive group at the first level of division. There are four exceptions: two samples (out of 20) in the upper half of the study area were classified into the positive group, while the same number of samples in the lower half of the study area were classified into the negative group at the second level of division. Despite these minor inconsistencies, there is a clear separation between sites of the upper reaches of the study area (Sites MA1 to MA5), and those of the lower reaches (Sites

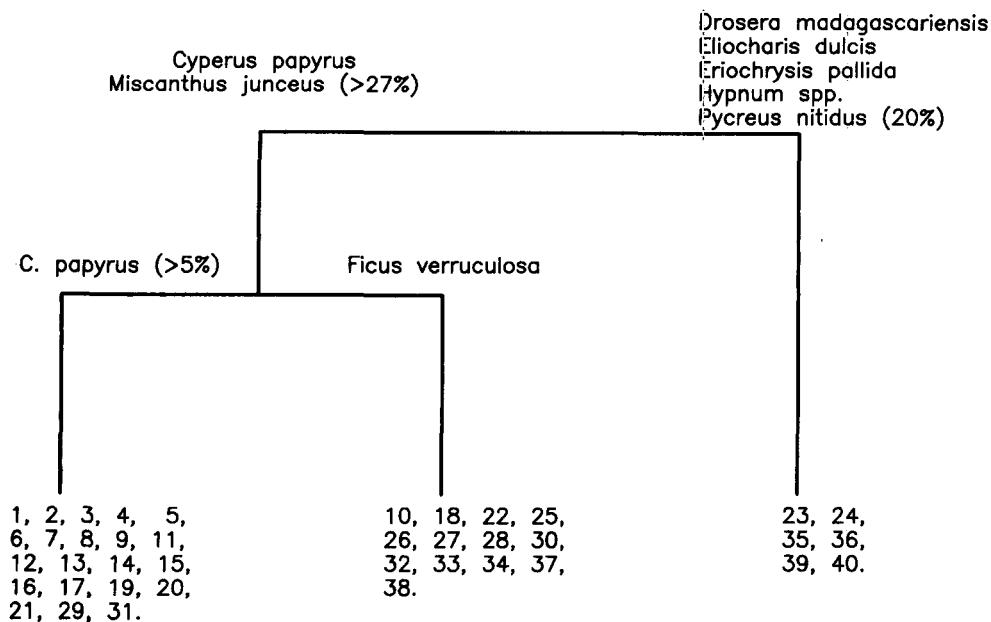


Figure 6
 Hierarchical classification
 of stands derived from the
 TWINSpan analysis,
 showing sample numbers
 and indicator species for
 each division.

MA6 to MA10), based on overall species composition. The division of sites based on channel margin was also reflected in the absence of in-channel vegetation in the upper five sites and its presence in the lower sites.

While *M. junceus* has a high cover at all sample sites, *C. papyrus* is more variable. In the sites along the upper reaches of the Maunachira Channel, it is subordinate to *M. junceus*, but its relative abundance increases downstream, and in the reach between MA3 and MA5, papyrus is the dominant species (**Appendix A**).

Although not reflected in the present data, due to local variation in vegetation distribution, as well as the manner in which the data were collected (use of cover abundance), the vigour of papyrus (reflected in the standing crop) increases downstream from the upper reaches of the Maunachira Channel, where it is absent, reaching a maximum standing crop between MA5 and MA6. Downstream of Site MA6, its cover abundance is, however, low.

The presence of *C. papyrus* with a high cover in the channel margin, together with the absence of in-channel vegetation, has been associated with channel aggradation (Ellery et al., 1990). In this study, the samples with the highest cover of papyrus were in the middle region of the study area, where channel aggradation is taking place (see below). In the lower half of the study area, there is no sediment movement, channel beds are vegetated, and papyrus occurs at lower abundance. Papyrus is able to survive a situation where the water level rises gradually, as it exists as a semi-floating mat and is not rooted in the substratum sand which underlies the peat. Throughout its distribution range in Africa, it has been known to exist both growing in peat resting on the substratum, or else it may exist as a floating mat above the column of water (Thompson, 1976). In contrast, the other dominant species in the study area, *Miscanthus junceus*, is rooted in the substratum beneath the peat deposits (Ellery et al., 1991) and for this reason it is flooded by a gradually rising water level. In this situation, it is out-competed by *C. papyrus*.

Sediment movement

The Maunachira Channel carries very little suspended load (McCarthy et al., 1991), and all bedload derived from the Nqoga Channel is deposited in Dxherega Lake. Consequently, the bedload which is carried in the middle reaches of this channel is derived

by erosion, primarily of the channel bed, because flow power appears to be insufficient to modify the course of the channel. The reason for this is the binding effect which *M. junceus* and papyrus have on channel banks (McCarthy et al., 1988a). The channel is not meandering (sinuosity is about 1.2) and point bars characteristic of this fluvial style are generally uncommon. The channel bed is vegetated downstream from a point approximately mid-way between MA5 and MA6, where sediment movement effectively ceases. This discussion on sediment movement will therefore focus on the reach upstream of MA6.

Calculated bedloads are shown in Fig. 7b, and rise to a maximum at Site MA2, declining steadily thereafter, to zero at MA6. In effect, sediment which is being eroded from the bed in the upper reaches of the channel is being transferred downstream and deposited in its lower reaches, also on the channel bed. The degree of incision of the channel bed at the upper sites is consistent with this finding. The channel at Sites MA1, MA2 and MA3 is strongly incised, but less so at Sites MA4 and MA5 (Fig. 3).

It is possible to use the bedload data to calculate the aggradation rate, because bedload is deposited on the channel bed. Between Sites MA2 and MA3, bedload decreases by 0.08 kg/s. The average channel width between these sites is 16 m, and the channel length 9 km. Therefore, the channel bed in this reach must be aggrading at a rate of 0.98 cm/a. As discussed by McCarthy et al. (1992), the channel margins and the flanking swamp aggrade in sympathy with the aggrading channel, and a rise in water level might therefore be expected in this area. A hydrogauge is maintained at Xugana Lake, between Sites MA2 and MA3 (Fig. 2). The records for this gauge are shown in Fig. 8, and reveal a steady rise in water level in this region of the swamp of 0.75 cm/a over the recording period, consistent with the calculated result.

Similar calculations were performed for successive intervals between Sites MA3 and MA6, and for the erosive reach between Sites MA1 and MA2. These calculations reveal a steady increase in aggradation rate between successive sites downstream of MA2, with a maximum of 3 cm/year between Sites MA5 and MA6 (Fig. 7c). The actual rate in this last reach may be higher because sediment movement ceases some distance before MA6. The progressive downstream increase in aggradation rate is similar to that recorded for the lower Nqoga Channel by McCarthy

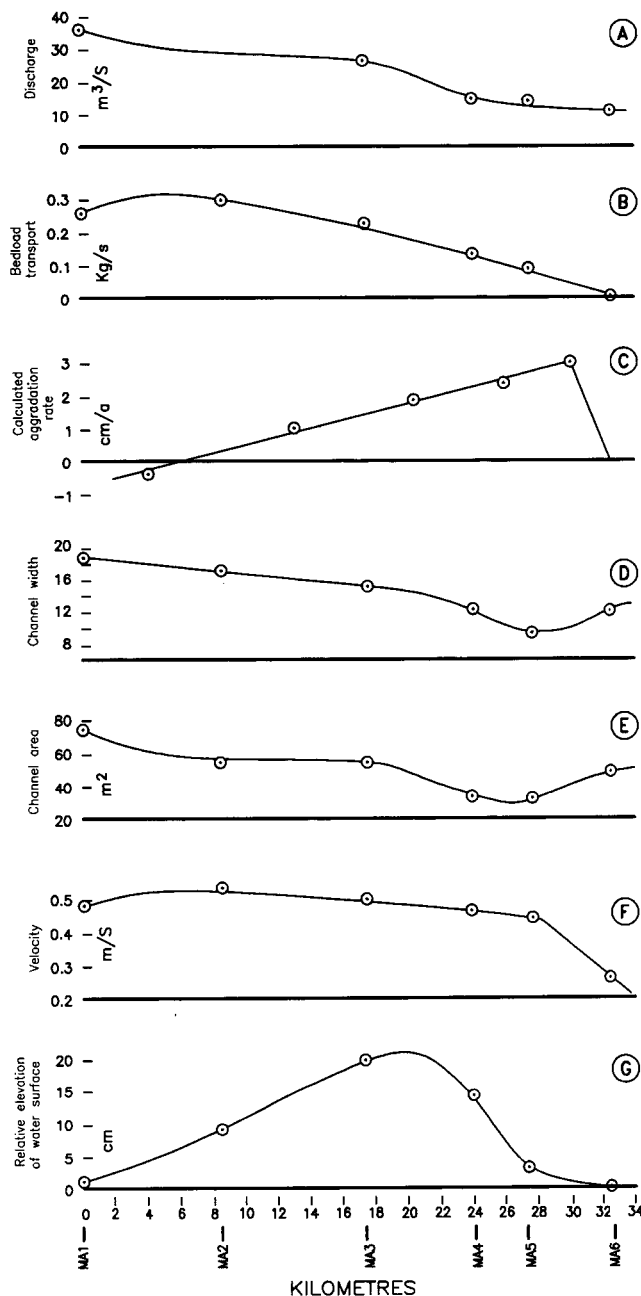


Figure 7
Hydrological and sedimentological parameters in the reach between sites MA1 and MA6.

et al. (1992).

Information pertinent to channel aggradation is summarised in Figs. 7 a-g. The channel is constricted by the flanking vegetation in the vicinity of MA5 (Fig. 7d,e). Flow velocity declines towards this constriction (Fig. 7f). Water accumulates upstream of the constricted reach, raising the relative channel water surface (Fig. 7g), and rapid loss of water occurs (Sites MA3 to MA5, Fig. 7a). The result is a decrease in the ability of the channel to transport bedload (Fig. 7b), which results in bed aggradation (Fig. 7c).

An important variable that was not recorded in the present study is the down-channel gradient. It is likely that aggradation will cause a decline in the gradient, although the rate of change

will be slow, because aggradation rate increases linearly with distance along the channel (Fig. 7c). Some indication of the change in gradient brought about by bed aggradation is provided by down-channel water surface slope measurements made by McCarthy et al. (1991). These data can only be regarded as semiquantitative, but nevertheless provide insight into the process of bed aggradation. In the vicinity of Site MA2, gradient was 1:2630, while near MA6 gradient was 1:3330. It is probable that the gradient flattens gradually between these sites. The flattening of gradient and the presence of channel bed vegetation would both contribute to lowering the flow velocity in the lower channel, and would therefore contribute to aggradation between Sites MA2 and MA6.

As sediment accumulates on the channel bed, gradient is reduced and flow velocity declines, to the point where no further sediment movement occurs. It follows, therefore, that rather than remaining static, the region of maximum aggradation must be migrating upstream over time, as is illustrated in Fig. 9a. This implies that at a particular place and time, the channel bed may be eroding into the substratum, but at a later stage, deposition will occur on the bed at that position. Cross-channel profiles shown in Fig. 3 provide evidence to support this conjecture, in that Sites MA5 to MA8 show a complex topography beneath the peat adjacent to the channels, suggesting that in former times a wider and deeper channel existed at these sites. In effect, material is being eroded from the upper reaches of the channel and deposited in the lower reaches, causing regrading of the channel profile.

It is possible to estimate the rate of upstream advance of the zone of aggradation. At Site MA2, the channel is incised about 2 m into the substratum (Fig. 3), and aggradation at this site has just started (Fig. 7c). If we assume that aggradation will cease when the incised section has been filled, and further, that aggradation occurs at a rate equal to the average over the aggrading reach, i.e. 1.5 cm/a, then site MA2 will be fully aggraded (equivalent to Site MA6) in 133 years. The end of the aggrading reach will thus have moved upstream from its present position to Site MA2, a distance of 22 km, in 133 years. The aggrading reach must therefore be migrating upstream at about 170 m/a, or possibly faster, because incised portions of channels are seldom filled completely (e.g. Sites MA6 to MA8, Fig. 3).

The aggrading reach is relatively long, extending from just upstream of MA2 to a point downstream of Site MA5 (Fig. 7c), a distance of about 24 km. However, it terminates very abruptly, with aggradation rate falling from 3 cm/a to zero over a distance of no more than three or four kilometres (Fig. 7c). This region coincides with a marked decrease in current velocity (Fig. 7f). These changes suggest that a critical threshold is passed, which radically alters conditions in the channel. The most likely cause is a decrease in velocity below 0.4 m/s, which enables extensive vegetative colonisation of the channel bed to become possible (Ellery et al., 1990). Once established, such vegetation will increase bed roughness, further reducing flow rate, and more importantly, inhibiting sediment movement. The reduced flow rate thus created contributes to the piling-up of water immediately upstream, and other features discussed above. The resulting increase in water loss from the channel promotes vegetation growth in the channel fringes, which constricts the channel, and accelerates channel bed aggradation.

The relative importance of vegetation and gradient in causing the decrease in flow velocity between MA2 and MA6 can be determined using the data of McCarthy et al. (1991) (their Sites B and A respectively) in conjunction with Manning's equation. In the vicinity of MA2, Manning's roughness is 0.077, while near

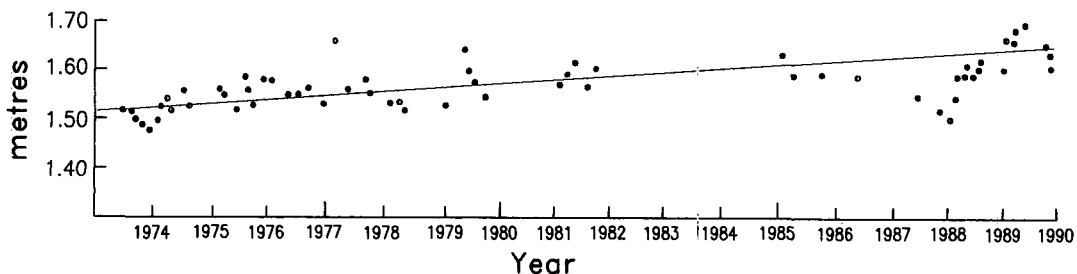


Figure 8
Hydrogauge
records at
Xugana Lake.
See Fig. 2 for
location.

MA6 it is 0.079. This implies that the decrease in flow velocity is mainly due to change in slope, with vegetation playing only a minor part. It appears therefore that the most important contribution of the vegetation is to stabilise the channel bed, preventing sediment movement.

The distal channel

Downstream of the rapidly aggrading reach, discharge remains relatively uniform at about $10 \text{ m}^3/\text{s}$, flow velocity remains below 0.4 m/s (Table 1), and the channel bed is vegetated. Channel depth is, on average, less than upstream of MA6 (2.8 m and 3.4 m respectively). The relative elevation of the channel water surface is variable, but at almost all sites there is a slight tendency for channel water surface to be elevated relative to the surrounding swamps (Table 1), indicating that the channel system is an important supplier of water to the swamps. On the SPOT image, these channels therefore have a bright fringe (Fig. 5b), although not as pronounced as along the aggrading reach.

The channels also supply water to the large lakes which occur in this region of the swamps, notably Gobega and Gadikwe (Fig. 2). Evaporation in the Okavango region is high (1.6 m/a , Wilson and Dincer, 1976), but the total evaporative loss of water from these lakes is unlikely to exceed $0.14 \text{ m}^3/\text{s}$, a small proportion of the channel discharge.

Although the Maunachira Channel feeds directly into Gadikwe Lake, there is no evidence of any change in the lake margins at the channel mouth. This contrasts markedly with the situation at Dxheraga Lake upstream on the Maunachira Channel (Fig. 2), where discharge of the channel into the lake has induced rapid closure (McCarthy et al., 1993c). The reason for this is that the Maunachira Channel in these lower reaches carries no bedload, so sandy deltas do not form, and moreover, invasive plant species, especially *Vossia cuspidata* and papyrus, do not thrive in this region of the swamps.

In spite of the relatively low flow velocity in the channel downstream of Site MA6, there is little tendency for the channel to become constricted by vegetation. In fact, the channel appears to be very stable. The reason for this is evidently the differences in plant communities, which appear relatively unproductive and benign.

The reason for the downstream decline in plant productivity appears to be related to decreased concentrations of plant-available nutrients in water within the channels. Water flowing down the Maunachira Channel downstream of Dxheraga Lake is a mixture of source water and water which has passed through a "filter area", which removes suspended sediment and dissolved nutrients as well. Immediately downstream of the confluence of the Crosscut and Maunachira Channels, source water contributes approximately 40% of the total discharge (McCarthy et al., 1992). This water flows through Dxheraga Lake, and into the upper reaches of the Maunachira Channel. At the confluence of the Khiandiandavhu and the Maunachira Channels this diluted source water is further diluted by 25%, by discharge from the Khian-

diandavhu Channel (McCarthy et al., 1992) which also originates in a filter area. As dilution continues, the concentration of plant-available nutrients in the channel water declines, and vegetation productivity appears to decline concomitantly.

Reference to the channel profiles in Fig. 3 indicates that the lower Maunachira Channel was wider in the past, but has become reduced in width and probably also in depth. This is partly due to the upstream migration of the zone of channel bed aggradation, as discussed above. However, this cannot alone be responsible. For example, at Site MA6, the form of the substratum adjacent to the channel suggests that the channel at this site was about 35 m wide and 5 m deep in the past. Assuming a conservative flow velocity of 0.4 m/s , this implies a discharge of the order of $70 \text{ m}^3/\text{s}$, far greater than anywhere along the Maunachira at present. Clearly, the Maunachira was a much larger river in the past.

In the early part of this century, following the demise of the Thaoge Channel system in the west of the Delta (Fig. 1), the Nqoga Channel became the major distributary channel, and supplied water to the Mboroga-Santantidibe Channel, which in turn supplied the Thamalakane River. Since the 1950s the Jao-Boro Channel system in the central region of the Delta has become increasingly important, indicating another shift in water distribution (Wilson and Dincer, 1976). The larger channel indicated by the form of the channel bed of the lower reaches of the Maunachira discussed above may well relate to these earlier times when far more water was supplied to the eastern region of the swamps.

Comparison of the aggrading reaches of the Nqoga and Maunachira Channels

The lower reach of the Nqoga Channel is currently failing (McCarthy et al., 1992) and consequently water is being diverted to the headwaters of the Maunachira. As the Nqoga Channel fails progressively upstream, so the Maunachira and its tributary, the Khiandiandavhu, extend by headward erosion. Water is supplied between the failing channel and the eroding channel through a "filter area". In the same way, the aggrading reach of the Maunachira is supplying water to the Mboroga Channel. These situations are remarkably similar, and emphasise the importance of this process in the Okavango Delta. The origin of this phenomenon lies in the sensitivity of vegetation to water flow. Because of the low nutrient status of swamp water, plants growing in standing water consume the limited supply of nutrients and tend to become moribund, but in flowing water, the availability of nutrients is increased, and aquatic species under these conditions grow more vigorously. Regions of rapid aggradation are associated with an elevated channel water surface, and hence lose water rapidly to the surrounding swamp. The flanking swamp vegetation grows more vigorously as a result, confining the channel and preventing avulsion from taking place. The enhanced leakage associated with rapid aggradation encourages the development of secondary channels in the immediate vicinity of the zone of

aggradation (McCarthy et al., 1991).

While there is clearly a similarity between the aggrading reaches of the Maunachira and the Nqoga Channels, there are also important differences. The most important difference is the end result of the phase of rapid aggradation. In the case of the Nqoga Channel, this is complete abandonment, and the channel and the surrounding areas revert to dry land or seasonal swamp (McCarthy et al., 1992). In the case of the Maunachira Channel, this does not appear to be the case. Instead, a stable channel system, free from the destabilising influences of sediment dispersal, is produced. This difference in response seems to be related to regional changes in vegetation species distribution and behaviour. In the distal reaches of the Okavango Delta, the general level of biological productivity seems to be lower than in the proximal reaches, as gauged by satellite imagery (McCarthy et al., 1993b), probably due to a decline in nutrient levels, as discussed above. Species which play a key role in the failure of the Nqoga Channel, notably *V. cuspidata* and *C. papyrus*, are at the limits of their range in the lower Maunachira Channel, and they are unable to invade the channel. Both of these species can be considered "guerilla species" (Hutchings and Bradbury, 1986), as the distance between ramets (connected modules of a clonal plant) is large (>10 cm). These species therefore have the ability to colonise areas rapidly (one to several metres per annum). Therefore, although the Maunachira Channel has become constricted by *C. papyrus* in its rapidly aggrading reach, little *V. cuspidata* grows, and complete constriction is not accomplished. Instead, the channel bed becomes vegetated, and channel margins become colonized by non-invasive *M. junceus*, which is a "phalanx" species, having short distances <1 cm between successive ramets, and the channel remains intact.

The relationship between the Mboroga and Maunachira Channels is also different from that between the Nqoga and Maunachira in that the Mboroga is an old extension of the Nqoga and may not be propagating by headward erosion in the same way as the Maunachira. In fact, satellite imagery of the area around the headwaters of the Mboroga Channel suggests that a new channel may be forming between the Mboroga and Maunachira Channels (Fig. 5b). If this channel continues to develop, it could deprive the Mboroga Channel of much of its water.

The role of secondary channels

The continued existence, and indeed, the continued headward propagation of the Maunachira Channel and its tributary, the Khiandiandavhu, raises an important issue in swamp hydrology, namely, what is the function of channels? Wilson and Dincer (1976) suggested that the main reason for the existence of channels is the dispersal of sediment. This appears to be an important function of those channels connected directly to the Okavango River, such as the Nqoga Channel, which disperse

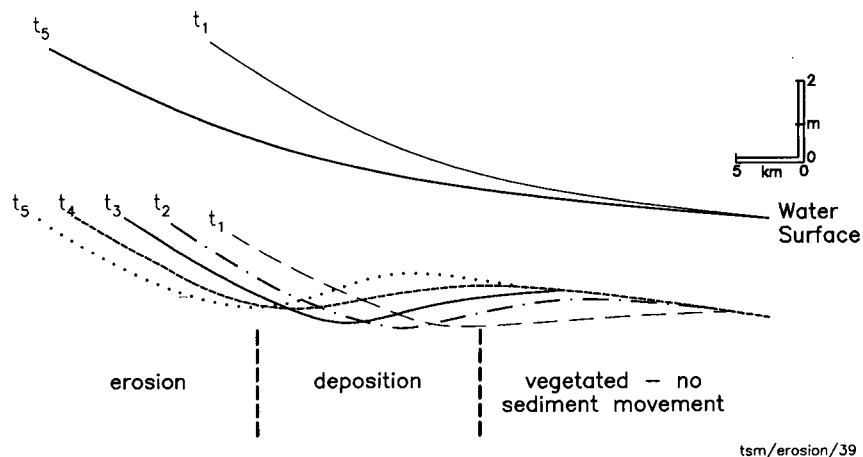


Figure 9a
Schematic diagram illustrating the movement of erosive and depositional reaches over time (t_1 to t_5)

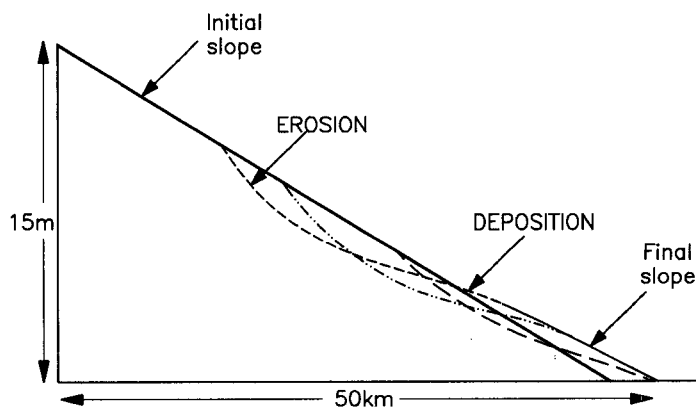


Figure 9b
Schematic cross-section illustrating how redistribution of sediment could contribute to decreasing the gradient on the Okavango fan

sediment derived external to the swamp system. The same cannot apply to the Maunachira Channel, as it exists entirely within the swamp, and generates its sediment load autogenously in its upper reaches, while its distal reaches carry no sediment. Moreover, there are extensive areas of swamp which are not served by channel systems at all, so the view that channels serve as rapid water delivery systems to sustain the permanent swamps (McCarthy et al., 1992) is also not universally valid.

The development of the Maunachira Channel suggests that channel systems internal to the permanent swamps arise as a result of a combination of water availability and local water surface gradient. If sufficient water is locally available and local gradient sufficiently steep, water flow will concentrate in whatever zones of weakness are available (usually hippopotamus trails) and a channel system will be created. If velocity is above the threshold of 0.4 m/s, the channel bed will erode and sediment will be transported downstream, thereby reducing the gradient. As long as gradient remains favourable and water supply is maintained, the channel will continue to propagate headwards. The implication is that channels like the Maunachira are the system's means of flattening gradients (Fig. 9b) which have become locally too steep, either because of sedimentation on the proximal fan, or because of neo-tectonics. In effect, such channels function as sediment redistributors, but their efficiency in this regard must be

very low, because they can only derive sediment from within the channel, and not from the catchment, as with normal rivers. Moreover, the suspended load in the water is very low, so the aggradational increment on the fan surface (McCarthy et al., 1988a) associated with such a channel would be small. Consequently, many generations of channel would be required to alter gradient in a particular region of swamp. This may be the reason an aggrading channel such as the Nqoga is paralleled and overlapped by a new, eroding channel system, such as the Maunachira and Khiandiandavhu Channels, or the aggrading reach of the Maunachira by the Mboroga Channel.

Conclusions

The Maunachira Channel system exists entirely within the swamps. It can be divided into three discrete reaches on a basis of sediment movement:

- the catchment system, which derives its water from the failing Nqoga Channel by way of a "filter area"; a small amount of sediment is derived from the Nqoga, and this together with that eroded from the bed of the upper Maunachira is deposited in Dxherega Lake;
- a middle reach in which there is significant bedload movement, which is being eroded in the upper section and deposited in the lower; and
- a stable reach in which the channel bed is vegetated and no sediment movement occurs.

Channel bed aggradation is associated with a marked rise in water surface of the channel relative to the surrounding swamps, which induces water loss and promotes the growth of the flanking vegetation, particularly *C. papyrus*, which, in turn, partially constricts the channel. Some 50% of the channel's discharge is being lost along the aggrading section of the middle reach, and some of this water is supplying the headwaters of the Mboroga Channel. The aggrading zone is migrating upstream at about 170 m/a. The distal end of the aggrading zone is characterised by a drop in flow velocity to below 0.4 m/s, which appears to be primarily due to a decrease in down-channel gradient, and by the consequent appearance of bottom-rooted vegetation. Channel margins become vegetated by *M. junceus*, a non-invasive species. This results in a stable channel, which is extending upstream. The long-term stability of the lower channel is to a large extent due to the scarcity of channel invading species in the distal areas of the swamp.

There is strong evidence suggesting that the Maunachira Channel was far larger in the past. The decline in discharge is most likely due to the regional shift of water to the central regions of the fan, along the Jao-Boro Channel system. In spite of this, the Maunachira remains an important distributary channel, as it supplies water to the Mboroga-Santantadibe system to the east of Chief's Island and to the distal swamps around Xaxanaka.

This study suggests that secondary channels such as the Maunachira Channel arise due to local oversteepening of the gradient on the fan surface and their role is to redistribute sediment down the fan. Their efficiency is, however, probably very low, because both erosion and deposition of sediment is confined largely to in-channel areas.

Plant species flanking the secondary channels are very sensitive to hydrological conditions within the channels. Where aggradation is taking place, papyrus becomes the dominant species in the channel margin. However, in erosive reaches, or reaches which have attained grade, papyrus is replaced by the non-invasive phalanx species *M. junceus*. Channels are thus able to survive for

long periods, and no doubt fulfil a valuable function as water and nutrient delivery systems to the very distal swamp areas.

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References

- ELLERY WN and McCARTHY TS (1994) Principles for the sustainable utilization of the Okavango Delta, Botswana Biol. Conserv. **70** 159-168.
- ELLERY WN, ELLERY K, ROGERS KH, MCCARTHY TS and WALKER BH (1990) Vegetation of channels of the northeastern Okavango Delta, Botswana. *Afr. J. Ecol.* **28** 276-290.
- ELLERY K, ELLERY WN, ROGERS KH and WALKER BH (1991) Water depth and biotic insulation: Major determinants of backswamp plant community composition. *Wetlands Ecol. and Manage.* **1** 149-162.
- ELLERY WN, ELLERY K, ROGERS KH, McCARTHY TS and WALKER BH (1993) Vegetation, hydrology and sedimentation processes as determinants of channel form and dynamics in the north-eastern Okavango Delta, Botswana. *Afr. J. Ecol.* **31** 10-25.
- HILL MO (1979) TWINSpan - A FORTRAN programme for arranging multivariate data in an ordered, two-way table by classification of the individuals and attributes, Cornell University, Ithaca, N.Y.
- HUTCHINGS MJ and BRADBURY IK (1986) Ecological perspectives on clonal perennial herbs. *Biosc.* **36** 178-182.
- McCARTHY TS and ELLERY WN (1995) The failure of the Nqoga channel between Hamoga and Letenetso Island, northeastern Okavango Delta. *Botswana Notes and Records* **27** 129-150.
- McCARTHY TS, ROGERS KH, STANISTREET IG, ELLERY WN, CAIRNCROSS B, ELLERY K and GROBICKI TSA (1988a) Features of channel margins in the Okavango Delta. *Palaeoecol. Afr.* **19** 3-14.
- McCARTHY TS, STANISTREET IG, CAIRNCROSS B, ELLERY WN, ELLERY K, OELOFSE R and GROBICKI TSA (1988b) Incremental aggradation on the Okavango Delta-fan, Botswana. *Geomorphol.* **1** 267-278.
- McCARTHY TS, STANISTREET IG and CAIRNCROSS B (1991) The sedimentary dynamics of active fluvial channels on the Okavango fan, Botswana. *Sedimentol.* **38** 471-487.
- McCARTHY TS, ELLERY WN and STANISTREET IG (1992) Avulsion mechanics on the Okavango fan, Botswana: The control of a fluvial system by vegetation. *Sedimentol.* **39** 779-795.
- McCARTHY TS, GREEN RW and FRANEY NJ (1993a) The influence of neo-tectonics on water dispersal in the northeastern regions of the Okavango swamps, Botswana. *J. Afr. Earth Sci.* **17** 23-32.
- McCARTHY TS, FRANEY NJ, ELLERY WN and ELLERY K (1993b) The use of SPOT imagery in the study of environmental processes in the Okavango Delta, Botswana. *S. Afr. J. Sci.* **89** 432-436.
- McCARTHY TS, ELLERY WN and STANISTREET IG (1993c) Lakes of the northeastern region of the Okavango swamps, Botswana. *Z. Geomorph. N.F.* **37** 273-294.
- THOMPSON K (1976) Swamp development in the headwaters of the White Nile. In: Rzoska J (ed.) *The Nile, Biology of an Ancient River*. W. Junk, The Hague. 177-196.
- UNDP (1977) Investigation of the Okavango Delta As a Primary Water Resource for Botswana. United Nations Development Programme. Food and Agriculture Organization DP/BOT/71/506.
- WILSON BH (1973) Some natural and man-made changes in the channels of the Okavango Delta. *Botswana Notes and Records* **5** 132-153.
- WILSON BH and DINCER T (1976). An introduction to the hydrology and hydrography of the Okavango Delta. In: *Symposium on the Okavango Delta*. Botswana Society, Gaborone, Botswana.

