

Avulsion mechanisms on the Okavango fan, Botswana: the control of a fluvial system by vegetation

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ABSTRACT

A study of the avulsion of a major distributory channel on the alluvial fan (22 000 km² in area) of the Okavango River in northern Botswana has revealed that channels serve as arterial systems distributing water which sustains large areas of permanent swamp. The channels are vegetatively confined. A primary channel, defined here as a channel which receives water and sediment directly from the fan apex, aggrades vertically as a result of bedload deposition. The rate of aggradation increases downchannel and may exceed 5 cm yr⁻¹ in the distal reaches. Rapid aggradation is associated with a decline in flow velocity. This initiates a series of feedback mechanisms involving invasion of the channel by aquatic plants which trap floating plant debris, further reducing flow rate and causing the channel water surface to become elevated, thereby increasing rate of water loss from the channel, accelerating blockage and aggradation. The channel ultimately fails. Enhanced water loss from the channel promotes the growth of flanking swamp vegetation, which confines the failing channel. Increased flow through the swamp erodes pre-existing hippopotamus trails, producing a secondary channel system which overlaps but does not connect directly to the failing reach of the primary channel. The region of failure of the primary channel migrates upstream, accompanied by headward propagation of the secondary channel system. The swamp distal to the failed primary channel desiccates and is destroyed by peat fires. Secondary channels are stable and not prone to blockage. Comparison with avulsions described in other river systems indicates that the influence of plants in the Okavango River system is exceptionally strong.

INTRODUCTION

The Okavango 'Delta' of northern Botswana (Fig. 1) is a large alluvial fan occupying graben structures within a south-westerly extension of the East African Rift system (Hutchins *et al.*, 1976; McCarthy *et al.*, 1988, 1991). The fan is about 22 000 km² in area and is characterized by very low gradients, averaging 1:3600 (Wilson & Dincer, 1976). It is situated on the fringe of the semi-arid Kalahari Desert, but the source of the Okavango River which debouches onto the fan lies within the subtropical highlands of central Angola. There is consequently a relatively large inflow of water (10.5 × 10⁹ m³ yr⁻¹; Dincer *et al.*, 1981) which is strongly seasonal (Wilson & Dincer, 1976; McCarthy *et al.*, 1991), but some 96% of this is apparently lost by evapotranspiration within the Delta and a further 2% by groundwater seepage (Wilson &

Dincer, 1976). All of the introduced sediment is deposited on the fan surface. The shallow gradient causes a large proportion of the fan to be inundated with water, either permanently (6000 km²) or seasonally (12 000 km²), resulting in extensive swamps. The fan surface can, therefore, be divided into four distinct subregions: (i) permanent swamps, (ii) seasonal swamps, (iii) the entry corridor or Panhandle (Fig. 1), and (iv) the distal areas which are permanently dry.

Water distribution through the permanent swamps is accomplished by flow in discrete channels and also by flow through the vegetated swamps. The vegetation consists of various emergent aquatic species, but *Cyperus papyrus* and *Miscanthus junceus* predominate (Smith, 1976). The channels serve as the principal conduits for the dispersal of sediment, which consists

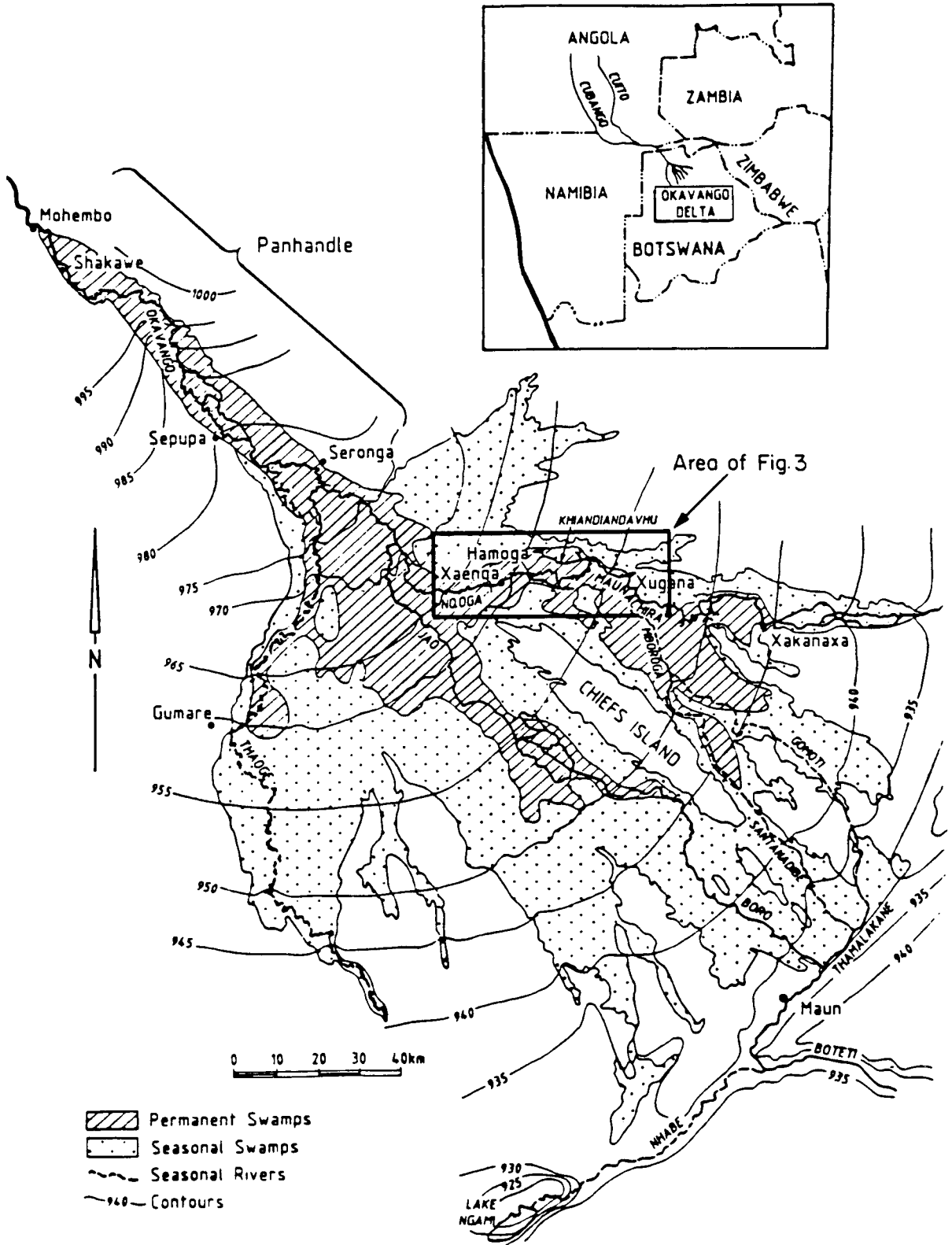


Fig. 1. Location and subregions of the Okavango Delta. Contours are in metres above sea level.

primarily of fine grained bedload sand (Wilson & Dincer, 1976; McCarthy *et al.*, 1991).

The low gradient of the Okavango fan contrasts with that of other fans in semi-arid to arid settings,

where debris flows are an important sedimentary process (Harvey, 1989), although the ratio of the catchment area (115 000 km²; Wilson & Dincer, 1976) to gradient is in accordance with other fans (Harvey,

1989). The general characteristics of the distributary system also differ substantially from other fans in arid environments. Channels in the permanent swamps are vegetatively confined and there is no evidence of braiding or debris flow deposition, two depositional styles commonly encountered on arid alluvial fans (Rachocki, 1981; Harvey, 1989). Channels vary from low to moderate sinuosity (1.2–1.9; mean 1.5), but their tendency to meander is very limited and they are stable over long periods (Wilson, 1973). In the Panhandle region, however, the Okavango River forms an active meander belt and there is evidence that this belt has prograded onto the fan in the past (McCarthy *et al.*, 1991).

Channel systems in the permanent swamps are subject to frequent avulsion in the sense of the definition of Smith *et al.* (1989): i.e. 'the diversion of a river channel to a new course at a lower elevation on its floodplain'. This causes major shifts in water distribution and ensures widespread distribution of sediment, which is typical of alluvial fans in general (Rachocki, 1981). The processes leading to avulsion on the Okavango fan are understood in general terms (McCarthy *et al.*, 1986; Ellery *et al.*, 1992)—vertical aggradation of channel systems occurs as a result of the accumulation of bedload within channels, causing avulsion. While this is usually the cause of avulsion on alluvial fans (Rachocki, 1981; Wells & Dorr, 1987a) and in other fluvial systems, the manifestation of the avulsion differs in that the Okavango channels show progressive failure proceeding up the fan from their distal ends. Moreover, the features characteristically associated with avulsion (such as crevasse splays; e.g. Smith *et al.*, 1989) are absent. This study of a channel currently undergoing avulsion was undertaken in order to obtain a comprehensive understanding of the avulsion mechanisms involved in this unusual fluvial system.

HISTORY OF RECENT AVULSION ON THE OKAVANGO FAN

The earliest accounts of the Okavango Delta by Anderson (1856), Chapman (1868) and Livingstone (Schapera, 1961) record a large Lake Ngami (Fig. 1), fed by the sinuous Thaoge River which was as much as 30 m wide at its mouth. The Thaoge River was connected to the Okavango River at the apex of the fan (Fig. 1), but during the early 1880s, it became prone to blockage by floating plant debris (mainly *C. papyrus*). These blockages extended over an increasing

length of channel and the river had ceased to flow into Lake Ngami by the early 1880s. Coincident with this, a new channel system developed to the north-east in what was formerly seasonal swampland. By the early 1900s, this channel, the Nqoga, had become the major distributary channel of the Okavango River (Stigand, 1923). It supplied water to the Mboroga and Santantidibe channels (Fig. 1) which discharged into the Thamalakane River at the foot of the Delta. In the early 1920s, the lower reaches of the Nqoga River also became prone to surface blockages and water ceased to flow into the Mboroga channel. Probably as a consequence of this the Maunachira River (Smith, 1976) and possibly the Boro channel (Fig. 1) began to receive more water.

The failure of the Nqoga channel has been progressive, starting at its distal end, and the process is continuing today. As the channel fails, the flanking swamps desiccate and the accumulated peat burns off, causing the area to revert to dry land or locally to seasonal swamp (McCarthy *et al.*, 1986, 1988b; Ellery *et al.*, 1989).

Aerial photography of the fan was first carried out in 1937, and was followed by photography at approximately 5 year intervals thereafter. These provide a record of the progressive demise of the lower Nqoga channel, as shown in Fig. 2, which was constructed from aerial photographs taken in 1937, 1951, 1969 and 1983.

According to measurements made by Stigand (1923) in 1921 the Nqoga channel at its lower end near the Mboroga channel was 36 m wide and 2.4 m deep, while south of Bokoro lake (Fig. 2) it was 32 m wide and 5.2 m deep. By 1951, some 30 km of channel had become blocked by floating debris and much of the flanking swamp and original channel had desiccated and been destroyed by peat fires. Between 1951 and 1969, a further 8 km became blocked and a considerable area of the swamp was destroyed by fire (Fig. 2). Between 1937 and 1951, widening of a narrow hippopotamus trail occurred, linking the Nqoga channel to a small lake (a in Fig. 2A). By 1969, this lake had become overgrown by emergent, aquatic vegetation (mainly *C. papyrus*), confining a distinct channel. A former narrow hippopotamus trail (b, Fig. 2B) linking this to the Bokoro lake had widened substantially, forming the Crosscut (or Letemetso) channel, and Bokoro lake had been reduced in size. Flow was very rapid in this channel during the 1970s, even generating standing surface waves (R. Oelofse, personal communication). By 1983, Bokoro lake had all but disappeared and major

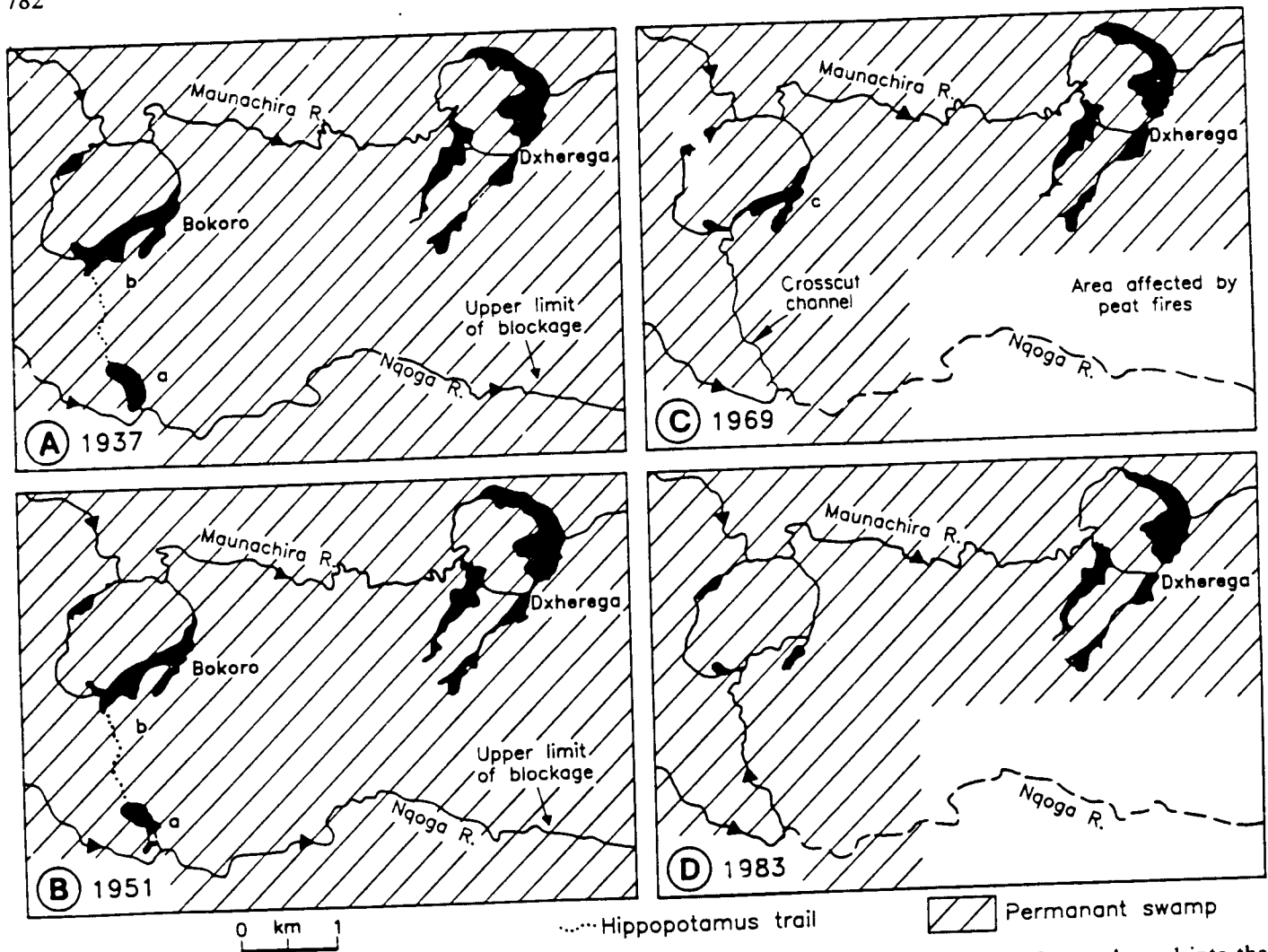


Fig. 2. A sequence of maps, based on aerial photographs, showing the apparent diversion of the Nqoga channel into the Maunachira channel. Lakes are in black.

shrinkage of the inlet of Dxherega lake had taken place. Diversion of the Nqoga into the Maunachira channel was now apparently complete.

A map of the area at the time of this study is shown in Fig. 3. The reach of the Nqoga channel between Letemetso island and Hamoga island is currently prone to severe surface blockage (Fig. 4), as is the Crosscut channel. A link between the headwaters of the Maunachira and the Nqoga channels was cut at Hamoga island by Mr P. A. Smith to facilitate boat passage. A difference in water level of approximately 1.5 m across this small island was evident at the time of excavation (P. A. Smith, personal communication) and upon opening, water from the Nqoga channel rushed through and eroded a wide channel. This channel still exists but has to be cleared regularly as vegetation growth tends to close it, the water dissipating in the dense aquatic vegetation. At the time of the

present study, the linking channel was closed although water was still passing through the vegetation in this area. The Khiandiandavhu channel, which flows parallel to the Maunachira, first appeared as a distinct channel in the 1951 aerial photographs and seems to be a component of the evolution of the channel system in this area.

Hydrographic records covering the reach illustrated in Fig. 3 are shown in Fig. 5. The seasonal fluctuations in water level in this region of the swamps are small (< 20 cm), for reasons discussed by McCarthy *et al.* (1991). More significant is the fact that the water level shows a steady rise over the recording period, especially at Xaenga Island (currently 2.1 cm yr^{-1}) and Hamoga Island (4.7 cm yr^{-1}). The rapid rise in water level at Hamoga Island (Fig. 5b) was accompanied by a corresponding decline in flow velocity (Fig. 5d).

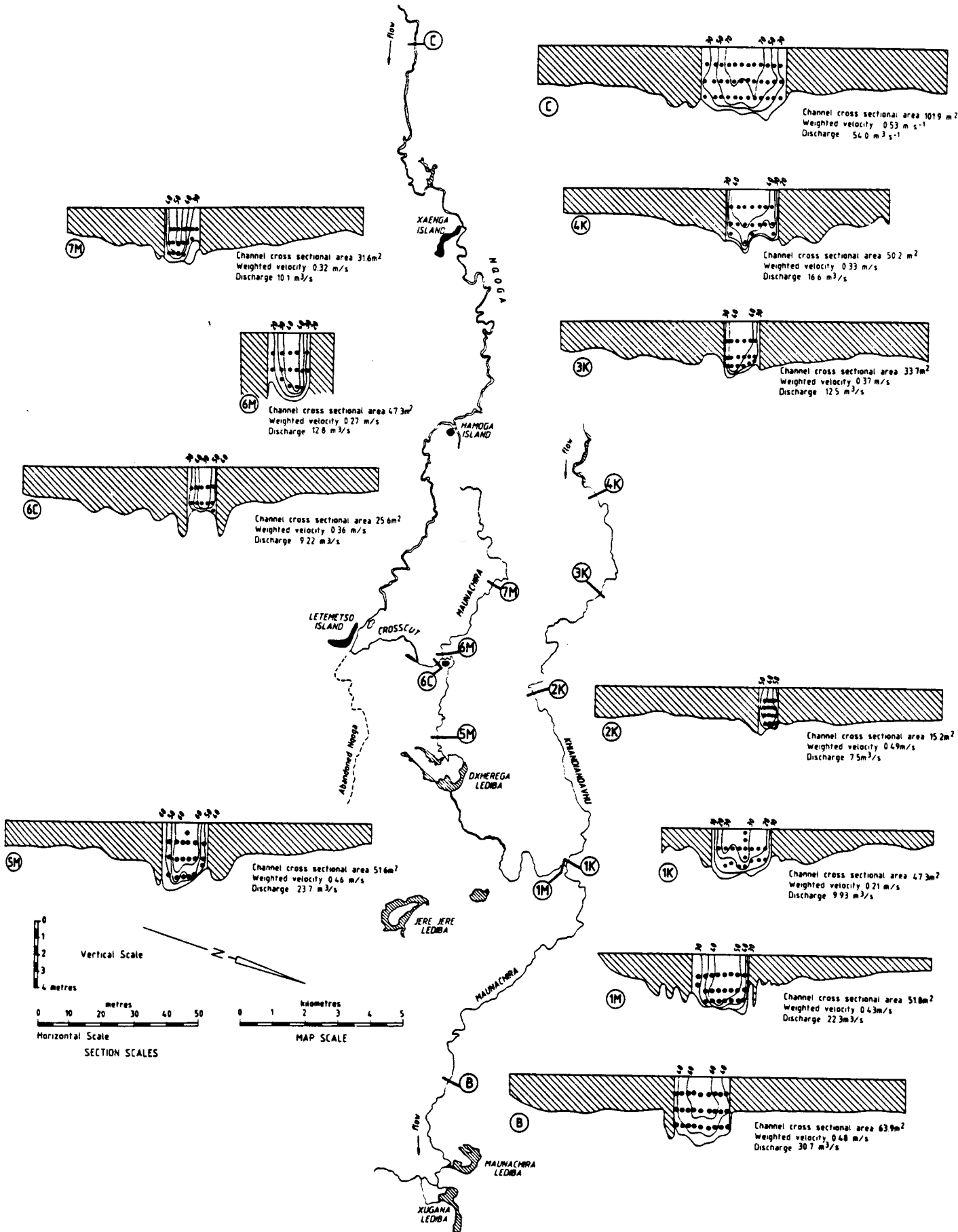


Fig. 3. Locations of the study sites and the channel profiles at these sites. The location of the river reach is shown in Fig. 1. Hatched areas on the main map consist of peat in which emergent aquatic plants are rooted.

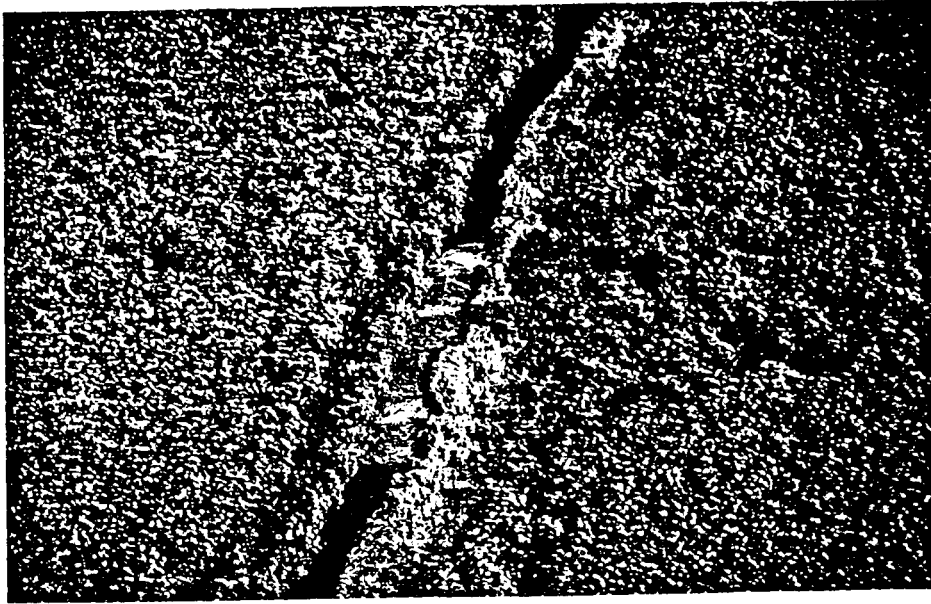


Fig. 4. Aerial photograph of a floating debris blockage (approximately 30 m in length) on the lower Nqoga channel.

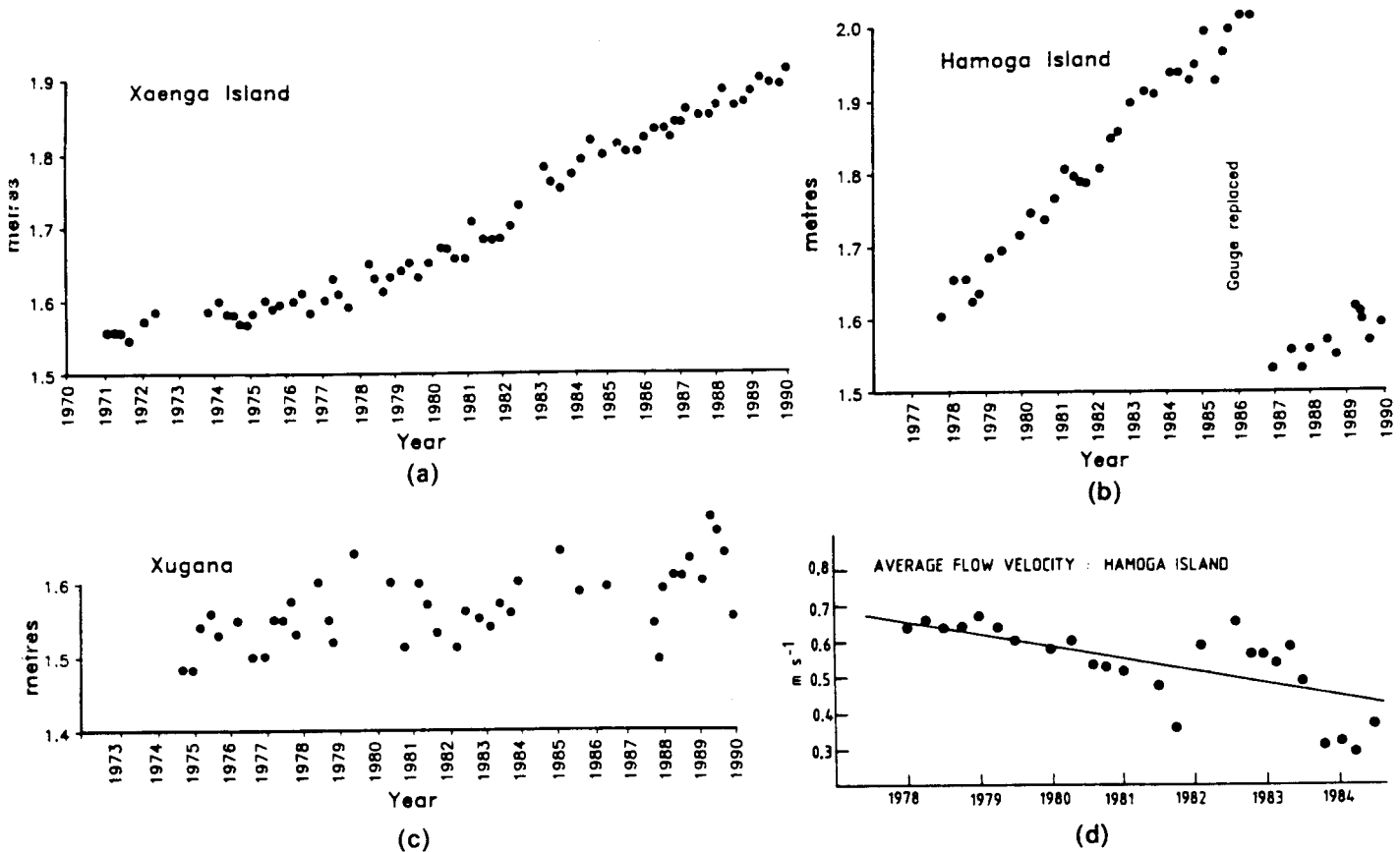


Fig. 5. (a) Hydrographic records for the Xaenga Island station. (b) Hydrographic records for the Hamoga Island station. (c) Hydrographic records for the Xugana lake station. (d) Flow velocity records for the Hamoga Island station.

METHODOLOGY

Full details of the methodology have been presented elsewhere (McCarthy *et al.*, 1991) and will only be briefly described here. The present study was carried

out during the period 28 December 1988 to 9 January 1989. Nine sites were selected for this study (Fig. 3). At each site, channel depth and flanking peat thickness profiles were determined using steel probes. Flow velocity profiles were measured in the channels using

a Watts current meter, measurements being made at 1 m depth intervals and variable distances across the channels. Isovels were interpolated and a weighted mean velocity calculated for each cross-section. Bedload sediment flux was measured using Helley-Smith bedload samplers. Between 40 and 70 measurements were made in a rectangular grid pattern at each study site and results were averaged. Swamp water levels were surveyed using a Kern GKO-A level. Water flow within the swamps was measured at several sites by placing fluorescein dye in the water. This was normally done far from the channel (50 m) to reduce the effect of the steep water surface gradients often encountered near the channels, thereby providing a maximum estimate of flow rate through the flanking swamps. In addition to the nine sites studied, two sites from a previous survey (B and C of McCarthy *et al.*, 1991) are included. As these were measured 1 year earlier, results for these sites will differ slightly from the other data. However, in this region of the Delta, seasonal water level and velocity fluctuations are small (UNDP, 1977; and Fig. 5) and hence hydrological and sedimentological parameters for the two data sets (turbidity excepted) are comparable.

RESULTS

A summary of the results is presented in Table 1 and Fig. 7.

Hydrology

The present hydrological relationships in the study area are illustrated diagrammatically in Fig. 6. Water

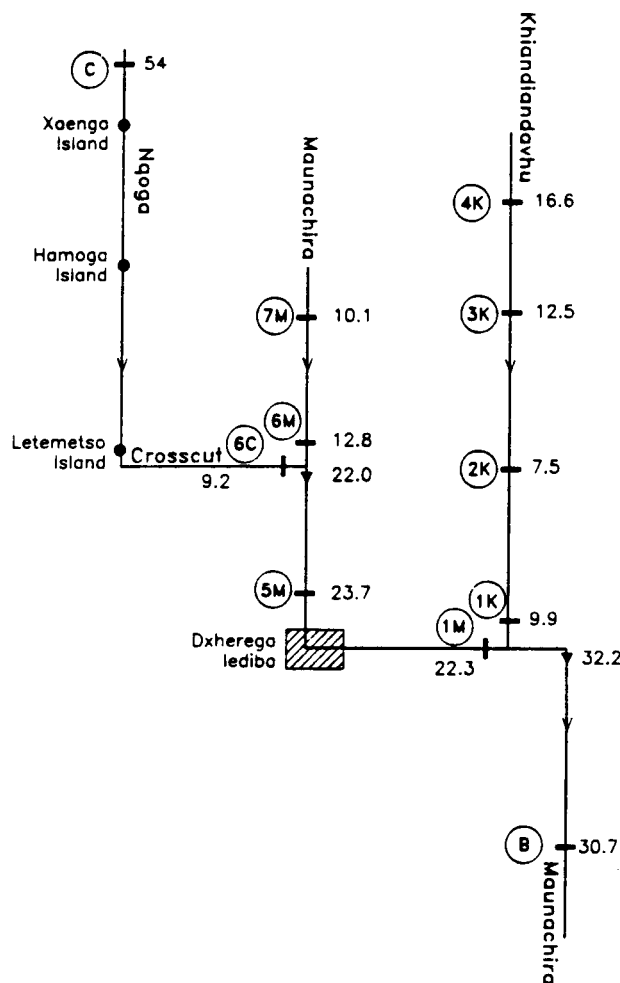


Fig. 6. Schematic diagram showing water distribution in the channels of the study area. Values shown are in $m^3 s^{-1}$. Locations of the measuring stations are shown in Fig. 3.

discharge into the area via the Nqoga channel is $54.0 m^3 s^{-1}$, but only $9.2 m^3 s^{-1}$ passes directly through the Crosscut channel, the remainder being

Table 1. Results of hydrological and sedimentological measurements.

Site	Width (m)	Mean depth (m)	Water discharge ($m^3 s^{-1}$)	Mean velocity ($m s^{-1}$)	Channel area (m^2)	Bedload discharge per unit width ($kg m^{-1} s^{-1}$)	Total bedload discharge ($kg s^{-1}$)	Turbidity (NTU)	Suspended load concentration ($kg m^{-3}$)	Total suspended load ($kg s^{-1}$)
C*	26	3.92	54.0	0.53	101.9	0.015	0.388	—	0.0117	0.630
6C	9	2.84	9.2	0.36	25.6	0.005	0.047	2.4	0.0026	0.024
7M	11	2.87	10.1	0.32	31.6	—	—	—	—	—
6M	13	3.64	12.8	0.27	47.3	0.001	0.022	1.2	0.0013	0.017
5M	14	3.04	23.7	0.46	51.6	0.009	0.126	2.2	0.0024	0.057
1M	17	3.05	22.3	0.43	51.8	0.007	0.122	1.6	0.0017	0.038
4K	16	3.14	16.6	0.33	50.2	0	0	0.5	0.0005	0.009
3K	11	3.06	12.5	0.37	33.7	0	0	0.5	0.0005	0.006
2K	6	2.53	7.5	0.49	15.2	0.014	0.019	0.4	0.0004	0.003
1K	18	2.63	9.9	0.21	47.3	0	0	0.2	0.0002	0.002
B*	17	3.76	30.7	0.48	63.9	0.015	0.254	—	0.0013	0.040

*Data from McCarthy *et al.* (1991).

lost through the flanking vegetation between Sites C and 6C. Some of this water undoubtedly exits via Smith's channel at Hamoga Island, but this channel is 'blind', rapidly losing its character as a channel, the discharge dissipating into the swamp vegetation. Water loss from the channel is by flow through permeable margins (McCarthy *et al.*, 1988a), driven by the elevated water level in the channel (Site C, Fig. 7).

The Maunachira River rises in the region below Hamoga Island (Fig. 3), gathering water downstream to $12.8 \text{ m}^3 \text{ s}^{-1}$ at its confluence with the Crosscut channel. The combined discharge at the confluence is thus $22.0 \text{ m}^3 \text{ s}^{-1}$ which rises to $23.7 \text{ m}^3 \text{ s}^{-1}$ at Site 5M situated upstream of the Dxherega lediba (Fig. 6). Below the confluence, the channel water surface is elevated relative to that in the surrounding swamps (Site 5M, Fig. 7).

In the uppermost site on the Khiandiandavhu River (Site 4K), a discharge of $16.6 \text{ m}^3 \text{ s}^{-1}$ was recorded (Fig. 6). This declines steadily downstream to Site 2K, but rises before its confluence with the Maunachira to $9.9 \text{ m}^3 \text{ s}^{-1}$, due to inflow of a minor channel. At the uppermost site (4K), swamp water surface slopes towards the channel, but downstream of this, water surface is either level with or slopes away from the

channel, becoming particularly steep at Site 2K (Fig. 7). At the confluence of the Maunachira and the Khiandiandavhu (Sites 1M and 1K) channels the combined discharge is $32.2 \text{ m}^3 \text{ s}^{-1}$, declining downstream to $30.7 \text{ m}^3 \text{ s}^{-1}$ at Site B. Across the entire region, therefore, some $23 \text{ m}^3 \text{ s}^{-1}$ or 43% of the channel flow is permanently lost to the swamps; this then undergoes evapotranspiration or seeps into the ground water system.

Bedload sediment

The nature of channel beds is dependent on flow velocity and to a lesser extent on depth and water clarity. Shallow, slower flowing channels tend to be vegetated, mainly by *Nymphaea* spp., *Ottelia* spp. and *Najas pectinata* (Ellery *et al.*, 1990), while deeper channels tend to support *Vossia cuspidata*. At higher flow velocities, bedload movement prevents plants taking root (Ellery *et al.*, 1990). Where the bed is unvegetated, the bedload consists of fine sand (McCarthy *et al.*, 1991) and bed roughness may be provided by ripples or sandwaves with ripples.

McCarthy *et al.* (1991) found that a relationship exists between bedload discharge and average flow velocity. The present data further refine and extend

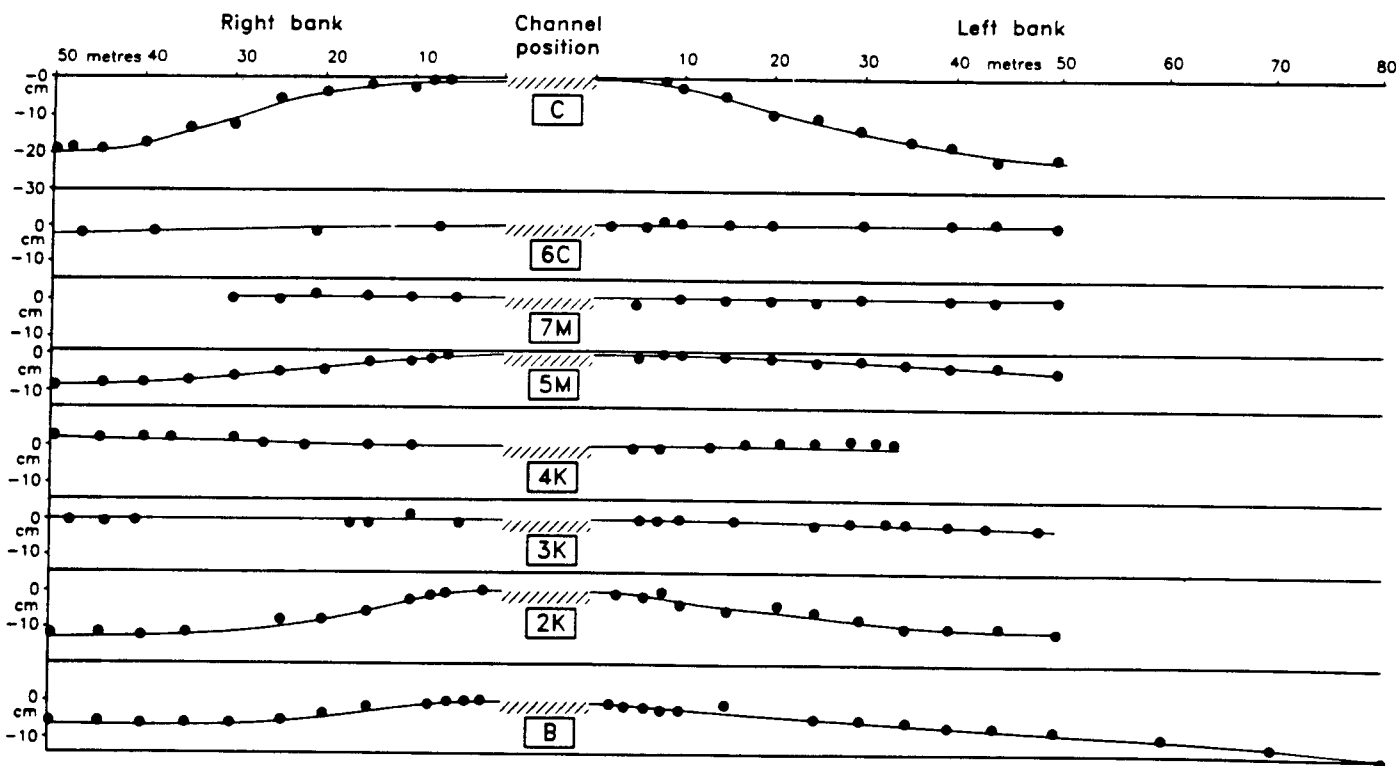


Fig. 7. Water level elevation in the swamps adjacent to the channels at the study sites (channel widths not to scale). Datum is channel water surface. Locations of the measuring stations are shown in Fig. 3.

this relationship (Fig. 8); the best fit line (excluding points G_N and H) has the equation:

$$Q = 0.154U^{3.40} \quad (1)$$

where Q is the bedload discharge per unit width ($\text{kg m}^{-1} \text{s}^{-1}$) and U is the flow velocity (m s^{-1}) ($r^2=0.97$).

Bedload discharges through the study area are shown diagrammatically in Fig. 9. At Site C on the Nqoga channel, sediment discharge is 0.388 kg s^{-1} , falling to 0.047 kg s^{-1} in the Crosscut channel at the Maunachira confluence. On average, therefore, approximately 0.34 kg s^{-1} of sand is being deposited on the channel bed along this reach.

Bed erosion is taking place in the upper reaches of the Maunachira channel and the combined bedload discharge at the confluence with the Crosscut channel is 0.067 kg s^{-1} . Downstream of this confluence,

further erosion must be taking place because sediment discharge rises to 0.126 kg s^{-1} upstream of Dxherega lake (Fig. 9). All bedload is, however, deposited where the Maunachira enters this lake in the form of a delta with a single, rapidly prograding mouth bar. Downstream of this lake, erosion again takes place, with bedload rising to 0.254 kg s^{-1} at Site B (Fig. 9). Consequently, the bed of the Maunachira channel tends to be incised into the substratum (Fig. 3). Downstream of Site B, the bed is vegetated, with no sediment movement (McCarthy *et al.*, 1991), indicating that this erosive reach passes downstream into a depositional reach. The bed of the Khiandiandavhu channel is largely vegetated, with only local sediment movement taking place.

Suspended load

The suspended load of the Okavango River at the apex of the Panhandle is 0.0085 kg m^{-3} , rising to 0.0117 kg m^{-3} (representing maximum values) at Site

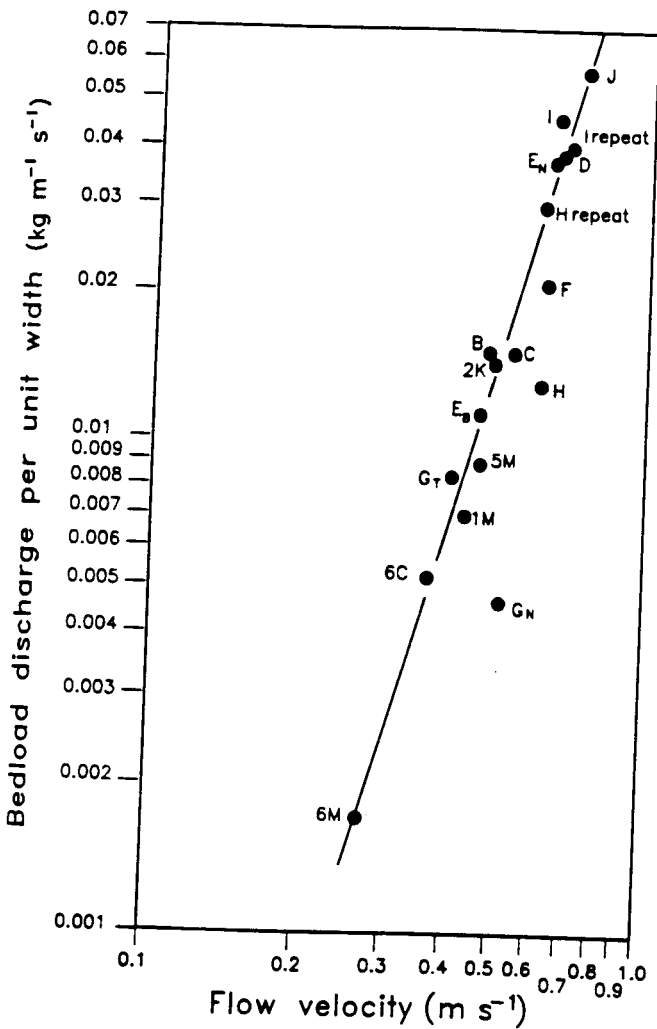


Fig. 8. Flow velocity against bedload discharge per unit channel width for the data of this work and McCarthy *et al.* (1991). Locations of the measuring stations are shown in Fig. 3.

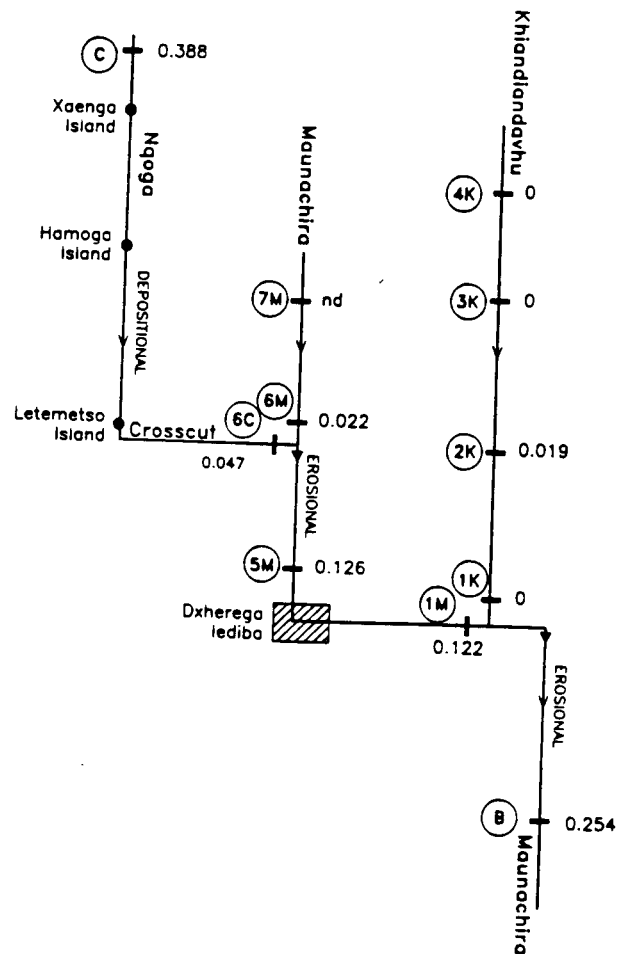


Fig. 9. Schematic diagram showing the bedload discharges (kg s^{-1}) in the study area. nd = not determined. Locations of the measuring stations are shown in Fig. 3.

C (McCarthy *et al.*, 1991), and is lower than any other major river of the world (Milliman & Meade, 1983). The data from Sites B and C, which were acquired in January 1988 (McCarthy *et al.*, 1991), are probably not directly comparable to the data for the remaining sites but are included for purposes of cross-reference. Bedload exceeds suspended load at almost all of the study sites (Table 1), a general feature of the Okavango Delta as a whole (McCarthy *et al.*, 1991). Suspended load (turbidity) is greatest in the Crosscut channel (Site 6C), which is directly connected to the external source of sediment (Fig. 10). Water in the Maunachira (Site 6M) channel has a turbidity of only 50% of that in the Crosscut channel. At Site 5M, which represents a mixture of these two flows, turbidity is higher than expected, possibly reflecting the fact that the reach upstream of Site 5M is erosional, as discussed earlier. Between Sites 5M and 1M the turbidity drops markedly, most probably due to settling of fine grained

sediment in the Dxherega lake. Turbidity of the water in the Khiandiandavhu channel is very low.

Water flow in the swamps

The permeable channel margins (McCarthy *et al.*, 1988a) permit water exchange between swamp and channel. Surface flow rates measured in the densely vegetated swamps varied between 0.010 and 0.025 m s⁻¹ (average of 0.015 m s⁻¹) in a direction oblique to the direction of the channel. It is probable that flow velocity decreases rapidly with depth because of the increasing density of roots and rhizomes.

DISCUSSION

The function of channels

Water flows down the Okavango fan both in channels and by slow flow through the swamps. At Site C, the swamp is about 10 km wide. Assuming that flow is negligible at 30 cm depth and that the average surface velocity is 0.015 m s⁻¹, it can be calculated that flow through the swamps across a section normal to the channel at Site C amounts to 11.3 m³ s⁻¹ (over 10 km of swamp width, compared to channel flow of 54 m³ s⁻¹ over 26 m). This figure is a maximum estimate because it is based on measurements made relatively near the channel and at the water surface. In the study area at least, channel flow dominates total flow down the fan.

The importance of channels is vividly illustrated by the demise of the lower Nqoga channel, which resulted in desiccation of the surrounding swamps and ultimately led to their destruction by peat fires. Evidently in the absence of the rapid water delivery system provided by a channel, large areas of permanent swamp cannot be sustained because flow rates in the swamp are too slow and evapotranspiration rates too high. In effect, therefore, the channels serve as an arterial system providing water to the permanent swamps.

The relationship of a channel to the surrounding swamps is conveniently portrayed schematically using elevation contours of the water surface (Fig. 11a). Water is lost from the swamps by seepage into the ground at the fringes of the swamp and by evapotranspiration and is supplied by leakage from the channel margins, creating the curved contours of the water surface.

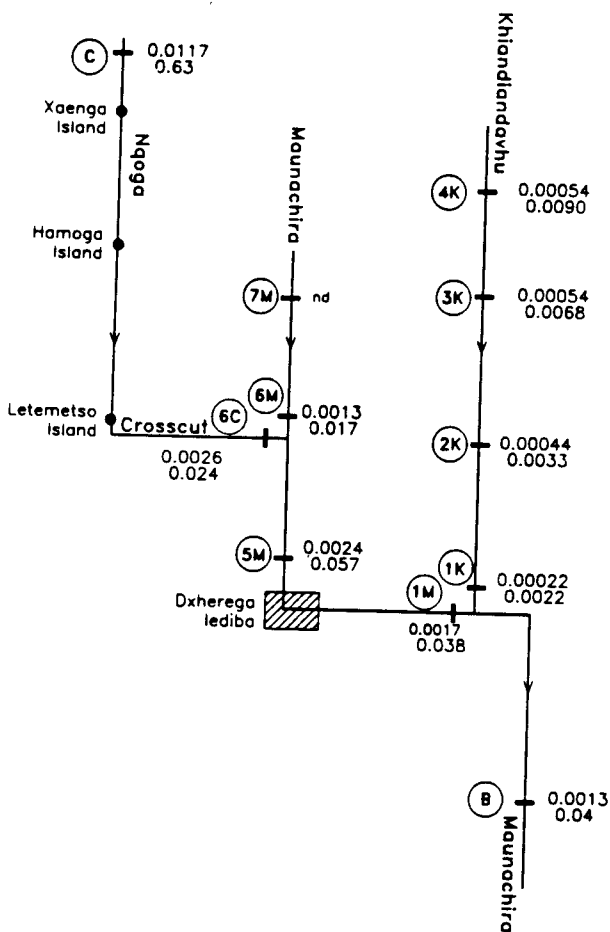
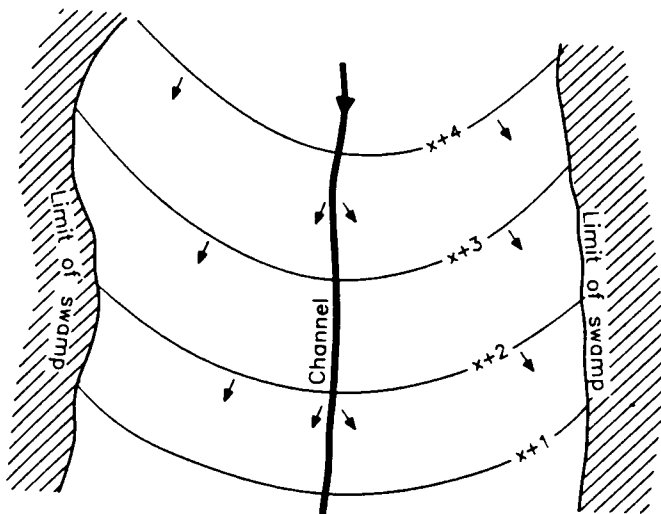
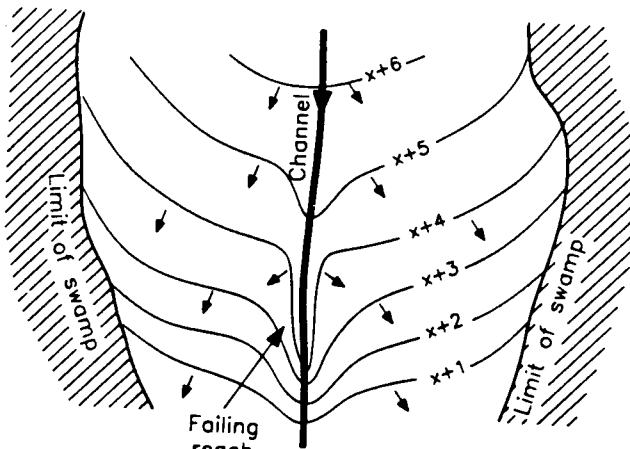


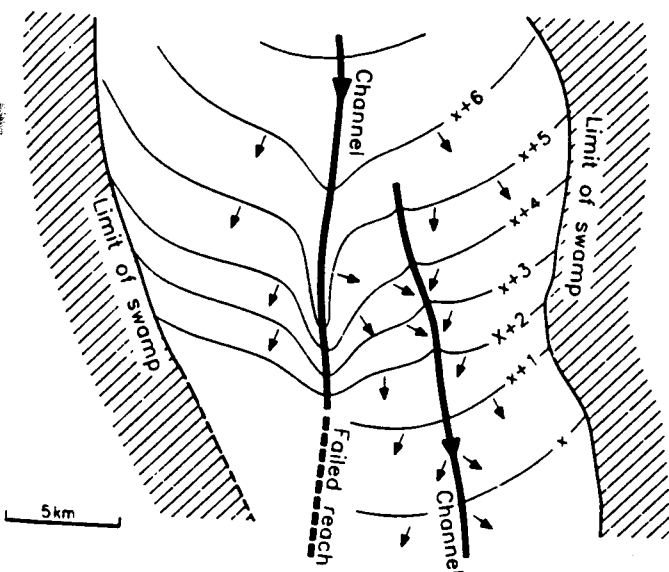
Fig. 10. Schematic diagram showing suspended load concentrations (above, kg m⁻³) and discharges (below, kg s⁻¹) in the study area. Locations of the measuring stations are shown in Fig. 3.



(a)



(b)



(c)

Fig. 11. Schematic diagrams illustrating the relationship of water surface elevation in swamps flanking channels. (a) A normal primary channel; (b) a failing primary channel; and (c) a failing primary channel and associated secondary channel. Arrows indicate water flow direction. Scale is approximate: contour intervals are in metres.

Channel bed aggradation

The Nqoga channel receives bedload sediment from erosion in the catchment of the Okavango River, and as such is referred to here as a primary channel. Continuous loss of water to the surrounding swamps causes aggradation (McCarthy *et al.*, 1991), but the absence of meandering indicates that deposition occurs only on the channel bed. The distribution of bedload deposition along the length of the Nqoga channel is central to this study and can be semi-quantitatively inferred using the data presented here and reported by McCarthy *et al.* (1991). The relevant data are compiled in Table 2. Sites D and E from McCarthy *et al.* (1991), located 29.9 and 49.5 km upstream of Site C respectively, are included in this analysis. In analysing bedload dispersal along the Nqoga channel, calculated values for bedload discharge (based on Eq. 1) are preferred because our measurements of bedload discharge are relatively imprecise due to the limitations of the Helley-Smith equipment, whereas flow velocity measurements are very precise. Although the differences between measured and calculated bedload discharges are small (Table 2), the calculated figures are standardized and hence between-site differences are more reliable.

Table 2. Bedload movement in the Nqoga channel.

Site	Velocity (m s ⁻¹)	Channel width (m)	Measured bedload (kg s ⁻¹)	Calculated bedload (kg s ⁻¹)†
E*	0.64	30	1.06	1.013
D	0.66	26	1.00	0.974
C	0.53	26	0.38	0.463
6C	0.36	9	0.047	0.042

*Data corrected for outflow via the Boro channel.

†Calculated using Eq. (1).

Table 3 shows the calculated bedload depositional rates and average aggradational rates along various reaches of the Nqoga channel. Data for the reach below Site C were calculated in two ways: (i) assuming uniform deposition along the entire reach between Sites C and 6C; and (ii) assuming that all deposition occurs between Site C and Hamoga Island (the reach downstream of Hamoga Island is severely constricted and is currently prone to blockage, hence flow velocities are greatly reduced). The actual aggradation rate for the reach below Site C lies between these extremes, probably closer to the latter. In either case, the data in Table 3 indicate a progressive downchannel increase in aggradation rate.

Table 3. Bedload deposition along the Nqoga channel.

Reach	Channel length (km)	Mean width (m)	Bedload deposition (kg s^{-1})*	Aggradation (cm yr^{-1})
E-D	19.6	28	0.039	0.127
D-C	29.9	26	0.511	1.17
C-6C	32.9	17.5	0.421	1.30†
C-Hamoga	19.0	23	0.421	1.72‡

*Based on calculated bedload discharges.

†Assuming a uniform deposition of bedload along this reach.

‡Assuming that all deposition occurs upstream of Hamoga Island.

Elevation of the water surface, as recorded on hydrographic gauges, shows an increase with time (Fig. 5) reflecting aggradation on the channel bed. These data, together with the aggradation rates calculated from bedload discharge (Table 3), are plotted as a function of channel distance in Fig. 12(a). Although the data are from fundamentally different

sources, there is nevertheless consistency and it is clear that aggradation rates rise towards the failing channel reach.

This relationship also reflects evolution in time at a particular point. This can be seen in the hydrographic records for Xaenga Island (Fig. 5a). During the early 1970s the rate of rise of water level was 0.7 cm yr^{-1} , increasing to 1.4 cm yr^{-1} in the late 1970s, while by the end of the 1980s the rate was 2.1 cm yr^{-1} . The aggradation rate at Xaenga Island can be expected to rise further in the manner shown in Fig. 12(b) as the region of channel failure moves further upstream.

Factors leading to avulsion

Localized aggradation of the channel bed is accompanied by a decrease in flow velocity (Fig. 5d). The effect of this decrease on the bedload transporting capacity is amplified because transporting capacity is a cubic function of flow velocity (Eq. 1). Aggradation on the channel bed causes a rise in channel water

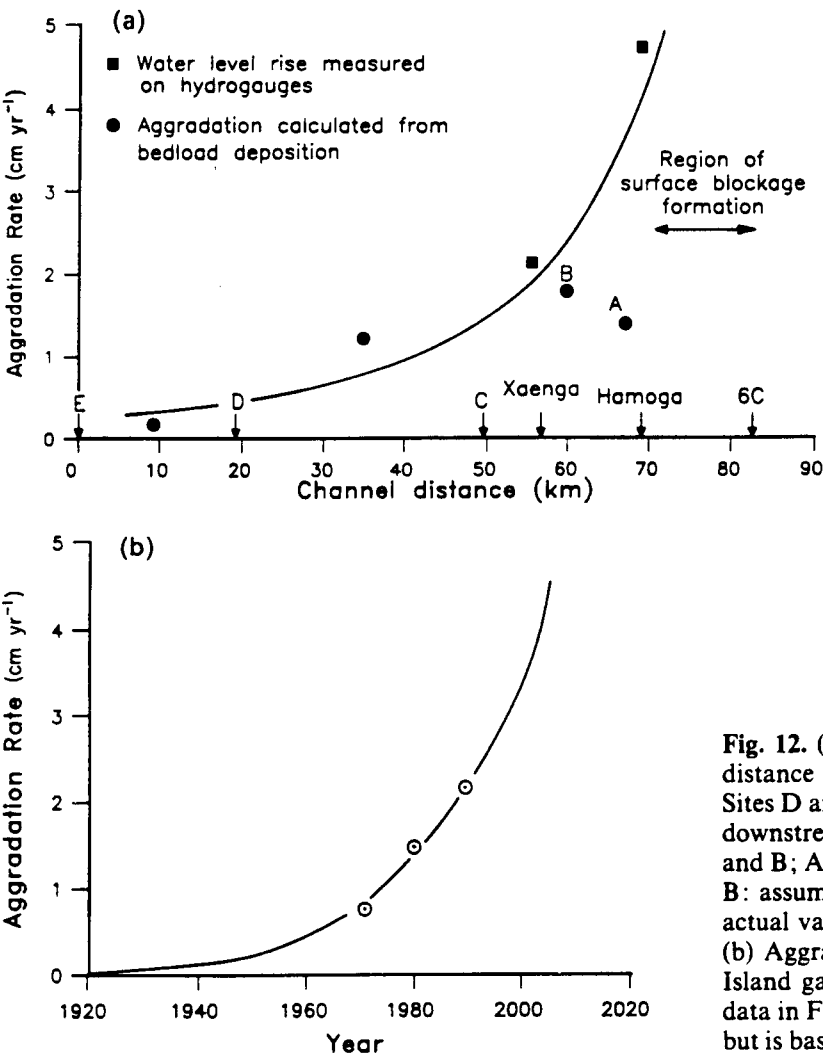


Fig. 12. (a) Channel bed aggradation rate as a function of distance along the channel taken arbitrarily from Site E. Sites D and E are from McCarthy *et al.* (1991). Aggradation downstream of C has been calculated in two ways (points A and B; A: assuming uniform deposition between C and 6C; B: assuming all deposition between C and Hamoga). The actual value lies between these points, probably close to B. (b) Aggradation rate as a function of time at the Xaenga Island gauging station. The three points are based on the data in Fig. 5(a); the remainder of the curve is hypothetical, but is based on aggradation rates shown in Fig. 12(a).

level, increasing the rate of water loss. Therefore, once started, positive feedback acts to accelerate aggradation.

Other factors further enhance this positive feedback. As flow velocity declines and bedload movement slows, bottom rooting plants, especially *Vossia cuspidata*, can become established. This species has an exceptionally strong, rope-like stalk which extends to the surface, where a cluster of long, narrow leaves emerges. It takes root along the margins of the failing reach of a channel, reducing the channel width (Fig. 13) and impeding flow. The stalks entrap floating plant debris drifting down channel (*c.* 2500 t yr⁻¹ in the study area; Ellery, 1988), producing vegetation blockages (Fig. 4). Although flow continues beneath these blockages, the volume of flow is reduced, accelerating channel demise. The overall effect is to increase aggradation rate and to accelerate rise of the channel water level. This increases the rate of water loss into the surrounding swamps, generating another important vegetation response involving *C. papyrus*, which is the dominant aquatic species along the main channels of the upper permanent swamps (Ellery *et al.*, 1990). Along primary channel reaches which are failing, the growth of *C. papyrus* becomes exceptionally vigorous and its thick rhizomes and culms constrain the rapidly aggrading channel. The combined effect of these various processes is suggested to cause the channel to fail progressively from its distal end and to prevent the formation of crevasse splays. It should be noted that silt and clay levées do not form adjacent to the failing channel because suspended

load concentration is too low (McCarthy *et al.*, 1988a).

Cyperus papyrus is unable to grow across open water because its rhizomes cannot support the weight of the culms. However, the flanking *V. cuspidata* and the floating debris blockages, which also contain living *C. papyrus* plants, provide a footing for *C. papyrus*, which overgrows the surface, ultimately obliterating the channel. Water continues to flow beneath the surface, but this soon ceases with the gradual retreat of the ground water system. Deprived of its arterial water supply, the swamp begins to desiccate and is ultimately destroyed by fire, creating a small increment of aggradation on the fan (McCarthy *et al.*, 1988b).

It is possible to reconstruct conceptually the water surface geometry around the failing channel from the nature of the lateral profiles (Fig. 7). Rising channel water level perturbs the water surface contours around the failing channel (Fig. 11b), producing the steep lateral gradients. The spacing of the regional water surface contours in the flanking swamps probably also decreases as leaked water piles up around the blocking end of the channel.

Formation of new channels

Any pre-existing lines of weakness through the flanking swamp lying perpendicular to the regional contours, such as hippopotamus trails, will accumulate more water, the most pronounced forming a channel which will propagate upgradient. Two such channels have developed in the present case, namely the Maunachira and the Khiandiandavhu. These chan-

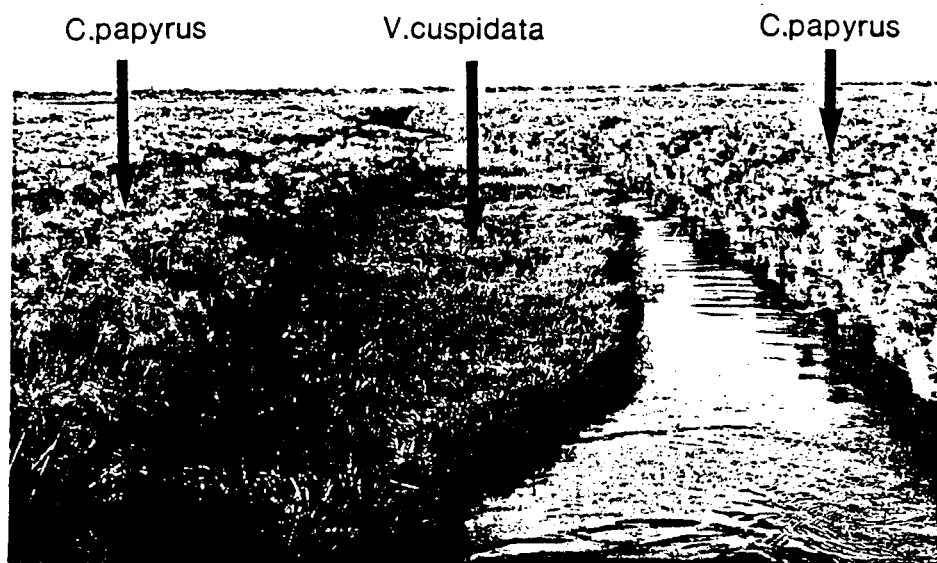


Fig. 13. Constriction of the lower Nqoga channel by *Vossia cuspidata*; *Cyperus papyrus* defines the original channel.

nels, referred to here as secondary channels, perturb the water surface gradient in the opposite sense to the aggrading channel, as shown schematically in Fig. 11(c), and the water surface rises away from the new channel (e.g. Site 4K, Fig. 7). The channel system is slightly erosional into the substratum (Figs 3 & 9), in this case the Maunachira being more so because, lying closer to the failing Nqoga channel, it gathers more water over a shorter reach than the Khiandiandavhu. The suspended load of the Maunachira is higher for the same reason (Fig. 10). There is a tendency for a developing channel to converge towards the failing channel (e.g. the Maunachira in Fig. 3), presumably because of the orientation of the water surface contours (Fig. 11c). Natural connection is unlikely, however, because of the vigorously growing papyrus that flanks the failing channel. Even artificial channels have to be maintained, as in the case of Smith's channel at Hamoga Island.

In detail, the course of secondary channels is moderately sinuous, following available lines of weakness, as the channels have only a limited capacity to erode the marginal vegetation. These channels are not subject to blockage for the reasons given below.

- (1) They do not have to contend with large volumes of externally derived sediment.
- (2) *Cyperus papyrus* growth is less vigorous, because the water has already passed through the thickly vegetated swamp—a so-called 'filter' (Wilson, 1973)—and is depleted in nutrients and fines; *Vossia cuspidata* does not thrive in these new channels (Ellery *et al.*, 1990), probably for the same reasons.

- (3) The rate of production of floating plant debris is less in these channels because of their restricted catchments (Ellery, 1988).
- (4) Plant species in these channels are generally less vigorous in their growth habits.

Complete failure of the Nqoga channel below Hamoga Island will deprive the head of the Maunachira of its inflow. As this happens, the rate of water loss from the Nqoga channel upstream of Hamoga Island will rise, increasing inflow into the Khiandiandavhu. In the long term, it seems likely that the Khiandiandavhu will take over as the dominant supply of water to the lower Maunachira channel. The development of the Khiandiandavhu over the last 50 years is probably the initial stage in this process.

The Crosscut channel

The Crosscut channel developed by widening of a hippopotamus trail, but is now also failing and appears to be aggrading. Evidence for the earlier erosive period is provided by the channel profile: the depressions flanking the present channel bed (Fig. 14a) reflect an older, wider and deeper channel (Fig. 14b). It is evident that this channel will not develop into a permanent link between the failing Nqoga and the Maunachira channels, and the Nqoga channel is already failing upstream of the Crosscut confluence. This is probably a general rule: the widening period of channels leading perpendicularly from a failing channel occurs only at an advanced stage of failure of the main channel, too late to remove the accumulated bedload in the main channel.

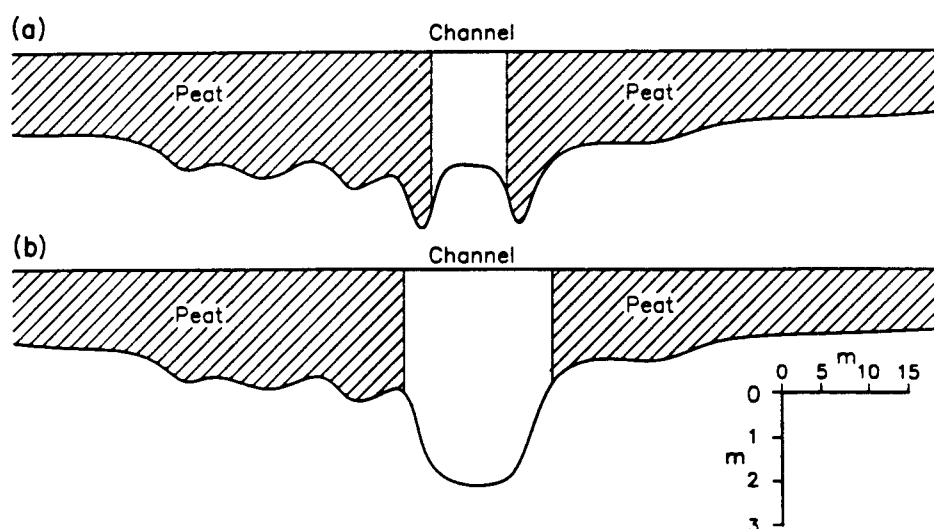


Fig. 14. (a) Profile across swamp and channel at Site 6C on the Crosscut channel. (b) Probable profile at this site during the rapid erosive period of the Crosscut channel.

Comparison with avulsion processes on other river systems

Studies of the mechanisms leading to river avulsion are rather rare (but see Smith *et al.*, 1989). It is appropriate, however, to compare the mechanisms described here with those reported from the Saskatchewan River of Canada (Smith & Smith, 1980; Smith & Putnam, 1980; Smith *et al.*, 1989) and the Kosi River of northern India (Gole & Chitale, 1966; Wells & Dorr, 1987a,b).

Saskatchewan River avulsions are different in their overall setting to those described here in that they occur on an alluvial plain rather than a fan. However, the association of avulsions with aggrading swamps makes them a natural candidate for comparison. The Saskatchewan River system is different from those dealt with here in the overwhelming component of fine grained sediment which it transports. As a result, levees comprise mainly silt and clay stabilized by rooted vegetation (Dirschl, 1972). Breaches through these levees develop crevasse splay systems which prograde over the surrounding wetland. In contrast, the Okavango fan river system has an extremely low proportion of fine grained sediment; levees consist almost totally of vegetation and peat (in volumetric terms) which so constrains the channel that crevasse splays are almost totally absent.

The processes leading to avulsion are also different. Saskatchewan River avulsion proceeds from a distinct levee breach which develops an avulsion node. The resulting crevasse splay continues to prograde over the low lying wetlands through distal deposition and aggradation. Ultimately, the system connects with the main channel further downstream. In contrast, channel avulsion on the Okavango fan propagates in a headward direction through a filter mechanism involving wetland vegetation, and no transfer of sediment takes place. The filter zone is not fixed but migrates upstream as channel erosion and complementary channel failure occur. This is facilitated by the unique characteristics of the Okavango fan wetland vegetation, which is permeable to water flow and yet sufficiently mechanically strong to confine the channel.

In both systems organic disturbance is important in breaching levee systems. On the Saskatchewan River the activities of man (canoe portages) and beavers play a significant role (N. D. Smith, personal communication), whereas hippopotamus trails represent potential channelways on the Okavango fan. Smith *et al.* (1989) relate the avulsion event to a trigger involving sudden flooding associated with an ice jam.

In contrast, the avulsion in the Okavango system appears to be continuous and autogenous.

The Kosi River of northern India is similar in its overall setting to that of the river systems described here, in that both systems are developed on a low gradient half-cone shaped fan. The Kosi River, however, has a large component of fine grained as well as coarse grained sediment (55% silt and clay; 16% coarse grained sand, 29% medium grained sand; Mahmood, 1987). The mechanism of avulsion in the Kosi fan also involves diversion into adjacent channel systems. Abandoning channels which are carrying the bulk of the discharge aggrade while the incipient channel develops to one side. During the waning flood stage, scour is enhanced particularly in the incipient channel. Ultimately, the topographic advantage afforded by the new channel causes avulsion during a subsequent flood. In contrast, the Okavango River channels are not reliant on a flood trigger for their avulsion. Lateral migration of the Kosi River proceeds progressively across the fan while the Okavango fan river systems are more radical in their change of water distribution and may supply water to totally different parts of the lower fan. In addition, the Kosi River system continuously supplies sediment to all its active channel systems, whereas the Okavango River system develops channels which may have no connection with an external sediment supply.

CONCLUSIONS

Distributary systems on alluvial fans serve a dual purpose—they transmit both sediment and water across the fan surface and these two processes are intimately interdependent. On the Okavango fan primary channels such as the Nqoga, which are connected to the external sediment supply provided by the Okavango River, serve this function. The lifetime of these channels is limited by virtue of the sediment load they carry. The avulsion characteristics of Okavango channels indicate, however, that the role of channels as major water conduits can be separated from their sediment dispersal role—in effect, the avulsion process described here locally produces this separation. A constant supply of water and sediment is delivered to the region of avulsion and the sediment accumulates, causing progressive primary channel failure, but dispersal of the water must continue. This need gives rise to secondary channels.

These secondary channels develop by headward propagation and, in the case of the Nqoga at least,

follow the dying primary channel, drawing water through the 'filter' or region of overlap. Events in the study area have shown that without the arterial water supply provided by a channel, the permanent swamps cannot survive, because water transmission directly through swamps is too slow to offset the high evapotranspiration rate and ground water seepage of the swampland. The secondary channels, which are stable over decades, are therefore important and sustain large areas of permanent swamp. It appears that the Maunachira/Khiandiandavhu secondary system may in time propagate the full length of the Nqoga as the latter progressively fails, thereby creating a 'pre-prepared' path. This path could eventually develop into a primary channel, possibly by direct connection to the main channel at the head of the fan where lateral water level gradients are particularly steep (McCarthy *et al.*, 1991).

The geological literature on sedimentation processes on alluvial fans tends to emphasize the interplay between water and sediment, but what emerges strongly from this study is the control that can be exerted by plants in certain settings. *Cyperus papyrus*, with its strong rhizomes and culms, contains the fast-flowing primary channels. It provides the bulk of the debris for surface blockage formation; dead rhizomes and culms provide the peaty substrate which forms the channel margins. Moreover, in those regions where a primary channel is starting to fail and is experiencing rapid aggradation, where breakout should occur and produce a more conventional avulsion, *C. papyrus* becomes exceptionally robust and confines the failing channel. *Vossia cuspidata* also thrives in these regions, providing a means of trapping floating debris as well as a substrate upon which *C. papyrus* can extend out and overgrow a failed primary channel. These plants, in effect, regulate the progressive upstream failure of primary channels.

Behind the fringe of robust papyrus, along a failing reach, aquatic vegetation is more open. In these areas, the network of hippopotamus trails provides lines of potential weakness, which are utilized in the generation of secondary channel systems. *Vossia cuspidata* and *C. papyrus* pose no threat to the slower flowing secondary channels, however, because they do not thrive in the water which has passed through the 'filter' regions which supply the secondary channels. Plant species which colonize the beds of secondary channels do not generate blockages. Clearly, in certain settings plants are well adapted to the regulation of water and sediment dispersal and it is evident that the Okavango Delta represents a fluvial system that has

been radically modified, if not totally subsumed, by life forms.

The fluvial systems of the Okavango fan differ from those of other fans in that the control exerted by vegetation is so strong. It is difficult to isolate the factors which contribute most to this unusual situation. Foremost amongst these must, however, be the regularity of water supply, the absence of sudden, catastrophic floods and the very low ratio of suspended sediment load to bedload.

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