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The role of *Cyperus papyrus* L. in channel blockage and abandonment in the northeastern Okavango Delta, Botswana

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Summary

Channel blockage and abandonment in the Okavango Delta has been considered to be caused by either a combination of encroachment of *Cyperus papyrus* from the channel banks into the channels, or the development of papyrus debris blockages in the lower reaches of major distributary channels. This has been investigated in the present study by measuring rates of encroachment of papyrus from the banks into the channels, rates of debris production from the channel fringes, quantities of debris flowing along different channel sections, as well as the dimensions, colonization, decomposition and overall spatial dynamics of debris blockages along the lower reaches of the major distributary channel of the Okavango Delta. Results do not support suggestions that papyrus growth and/or debris production cause channel blockage and abandonment. First, encroachment is inversely related to current velocity within the channel fringe, and current velocities in the fringes of those distributary channels that are considered to be prone to blockage and abandonment are amongst the highest in the study area. Secondly, channel cross-sectional area is maintained by erosion of the channel bed beneath floating debris blockages. Thirdly, there is no evidence for the gradual upstream development of debris blockages in the lower reaches of major distributary channels. Data on hydrological aspects on the lower reach of a major distributary channel system suggest that sedimentation processes, leading to aggradation of the channel bed and to a decline in current velocity may be the cause of channel decline. This appears to be accompanied by encroachment of the channel from the margin by papyrus and by the development of more permanent blockages than were observed in the present study. This sequence of events (encroachment and blockage) is therefore considered to be a symptom and not the cause of channel decline and abandonment.

Key words: Botswana, *Cyperus papyrus*, encroachment, papyrus, Okavango

Résumé

On a considéré que l'obturation et l'abandon du canal dans le Delta de l'Okavango avaient été causés par soit l'envahissement des canaux à partir des berges par *Cyperus papyrus*, soit par de développement de barrages faits de

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débris de papyrus dans les parties basses des principaux canaux défluents. La présente étude a analysé cela en mesurant le taux d'envahissement des papyrus à partir des berges, le taux de production de débris des rives des canaux, les quantités de débris qui flottent le long de différentes sections de canal, ainsi que les dimensions, la colonisation, la décomposition et la dynamique spatiale générale des barrages de débris le long des parties basses du principal canal défluent du Delta de l'Okavango. Les résultats ne corroborent pas les suggestions selon lesquelles la croissance et/ou la production de débris de papyrus causent l'obturation et l'abandon du canal. D'abord, l'envahissement est inversément proportionnel à la vitesse du courant au bord du canal, et la vitesse actuelle du courant au bord de ces canaux défluents que l'on considère être les plus enclins à s'obstruer et à être abandonnés est parmi les plus élevées dans toute la région de cette étude. Ensuite, la zone du canal qui traverse se maintient grâce à l'érosion du lit du canal sous le niveau des barrages de débris flottants. Troisièmement, il n'y a aucune preuve d'un développement progressif vers l'amont des barrages de débris dans les parties basses des principaux canaux défluents. Des données sur des aspects hydrologiques de la partie basse d'un des principaux canaux défluents suggèrent que le processus de sédimentation, conduisant à un rehaussement du lit du canal et à une diminution de la vitesse du courant, pourrait être à l'origine du déclin du canal. Ceci semble s'accompagner de l'envahissement du canal à partir du bord par les papyrus et par le développement de barrages plus permanents que la présente étude a constatés. Cette séquence des événements (envahissement puis blocage) est dès lors considérée comme un symptôme et non une cause du déclin et de l'abandon du canal.

Introduction

Major distributary channels of the Okavango Delta have a history of blockage and abandonment leading to large-scale changes in the distribution of water (Wilson, 1973). These changes have important implications for the nature and long-term success of any development schemes for the region, which generally involve the use of water. The importance of channel blockage and abandonment as an ecosystem process within the Okavango Delta was recognized by Smith (1976), who suggested that '. . . an understanding of most of the changes occurring in the Delta today lies within the investigation of the causes of channel blockages'.

The significance of channel abandonment is illustrated by a brief consideration of their occurrence during the past 150 years. When the explorer David Livingstone reached Lake Ngami at the southern end of the Delta (Fig. 1) in 1849, it appears that the Lake received its water supply from the Thaoge River (Schapera, 1971). Three years later, Lake Ngami was visited by the Swedish explorer Andersson, who travelled up the Thaoge River for 10 days. He estimated that he travelled approximately 15 miles a day, a total distance of approximately 240 km (Andersson, 1857). At the time he described the river as deep, wide, and having moderate flow. Today, the Thaoge River does not reach the lake, and extends for approximately one-third of its former length. Its abandonment was accompanied by the development of two vegetation

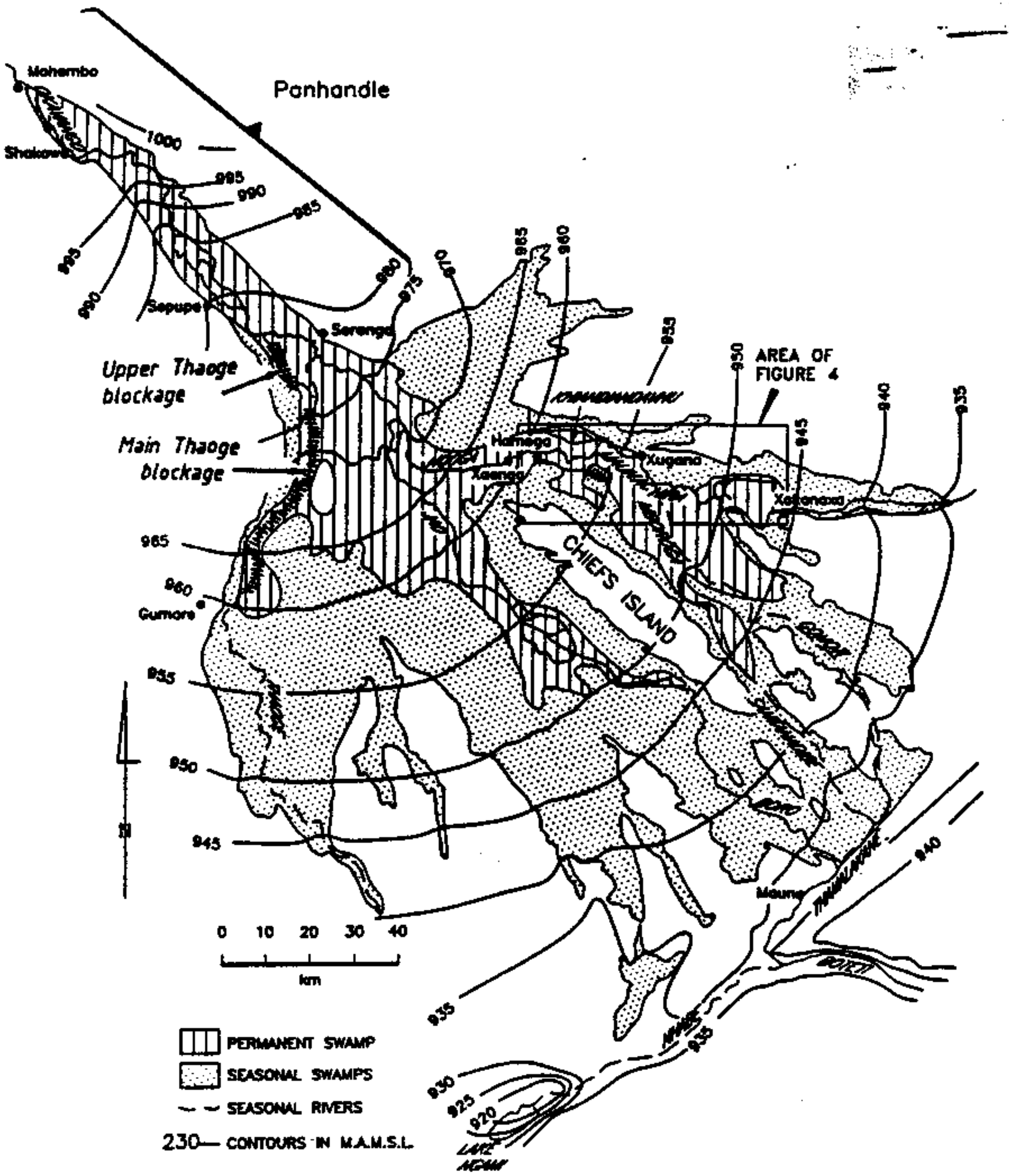

Fig. 1. Map of the Okavango Delta showing the positions of major papyrus blockages that have been recorded in historic time, and showing the main study area.

blockages, the upper and main Thaoge blockages (Fig. 1). Their development was accompanied by an increase in flow along the northern fringe of the Delta, primarily along the Nqoga River. The lower reaches of the Nqogo River system have, in turn, become progressively blocked and abandoned since the 1920s (Fig. 1; Wilson, 1973; Smith, 1976; Wilson & Dincer, 1976), and based on past patterns of channel decline, this is expected to propagate upstream. Presently, papyrus blockages are observed upstream of the area that has been abandoned, an example of which is illustrated in Fig. 2.

Fig. 2. An aerial view of a typical vegetation debris blockage (DB) along the lower Nqoga River immediately downstream of Hamoga Island (HI). Flow is clockwise around the bend illustrated, and the man-made channel at Hamoga island can be seen on the left of the bend.

A number of different processes have been proposed as causes of channel blockage and abandonment in the Okavango Delta:

(a) Encroachment of the giant sedge, *Cyperus papyrus* L., from the channel banks into the channels, leading to a reduction in channel width, and ultimately to channel decline and abandonment.

(b) The formation of vegetation (mainly *C. papyrus*) debris blockages which develop progressively upstream and lead ultimately to channel decline and avulsion. The use and later abandonment of man-made papyrus rafts by the local people in the Delta has been considered to be a possible cause. A combination of blockage and encroachment has been described along the Thaoge and lower Nqoga Rivers and is considered to have been a possible cause of the decline and abandonment of these river systems (Stigand, 1923; Pole Evans, 1948; Brind, 1955; Grove, 1969; Wilson, 1973). During the colonial period, considerable effort and money was spent in attempting to clear these blockages, without success (Wilson, 1973).

(c) The deposition of sediment along the channel floor, leading to channel aggradation, and ultimately to channel decline (McCarthy *et al.*, 1986).

(d) Tectonic activity within the graben in which the Okavango Delta is confined (Pike, 1970; Wilson, 1973; Scholz, 1975; McCarthy, Green & Franey, 1993b).

The aim of the present study was to investigate the relationships between *C. papyrus* growth from the channel bank into the channel, debris production and the formation and dynamics of papyrus blockages, in attempt to evaluate the importance of vegetation processes in channel blockage and abandonment. Two working hypotheses were formulated based on the observation that the lower Nqoga River is in the process of blockage and abandonment (McCarthy, Ellery & Stanistreet, 1992):

(1) papyrus vigour and encroachment into the channel from the bank would be highest along the lower Nqoga River than elsewhere in the study area, and/or

(2) papyrus debris blockages would be actively forming and propagating upstream along the lower Nqoga River.

The growth characteristics of *Cyperus papyrus*

The giant sedge, *Cyperus papyrus*, grows clonally to a height of 3 to 4 m. Each ramet comprises a portion of rhizome, with a basal sheath of leaves that protects the terminal and axillary buds of the rhizome (Fig. 3a). The axillary bud grows to form the culm, which supports an umbel, the primary photosynthetic organ, but also bearing the inflorescence when this is produced. Generally, papyrus is rooted in peat submerged below the level of permanent flooding. In situations where papyrus occurs at the margins of open water, shoots (rhizomes) extend from the peat into the area of open water (Fig. 3b). It is therefore able to colonize areas of open water as a floating mat of entangled rhizomes, culms and umbels. In cases where it colonizes open water, mats of floating papyrus may be broken off from the fringe, to form floating rafts. These are common in areas of the Nile River and on lakes supplying the Nile with water. Historically these papyrus rafts have been referred to as 'sudd', derived from the Arabic meaning 'obstacle' or 'blockage'.

The study area

The Okavango Delta forms part of an internal drainage system, the Kalahari Basin. The bulk of its water supply is from summer rainfall (December to March) in the catchment in the highlands in central Angola. The catchment is largely on unconsolidated Kalahari sand. The Okavango River at its point of entry into Botswana at the top of the panhandle (Fig. 1) is one of the largest rivers in southern Africa (Hutchinson & Reiner, 1973). It contains low concentrations of dissolved substances and sediment introduced into the Delta from source areas is mainly fine sand which is transported as bed-load, with a small quantity of suspended load (Wilson & Dincer, 1976; McCarthy, Stanistreet & Cairncross, 1991).

The study area is in the northeastern region of the Okavango Delta, and includes the lower reaches of the Nqoga river upstream of the region that has

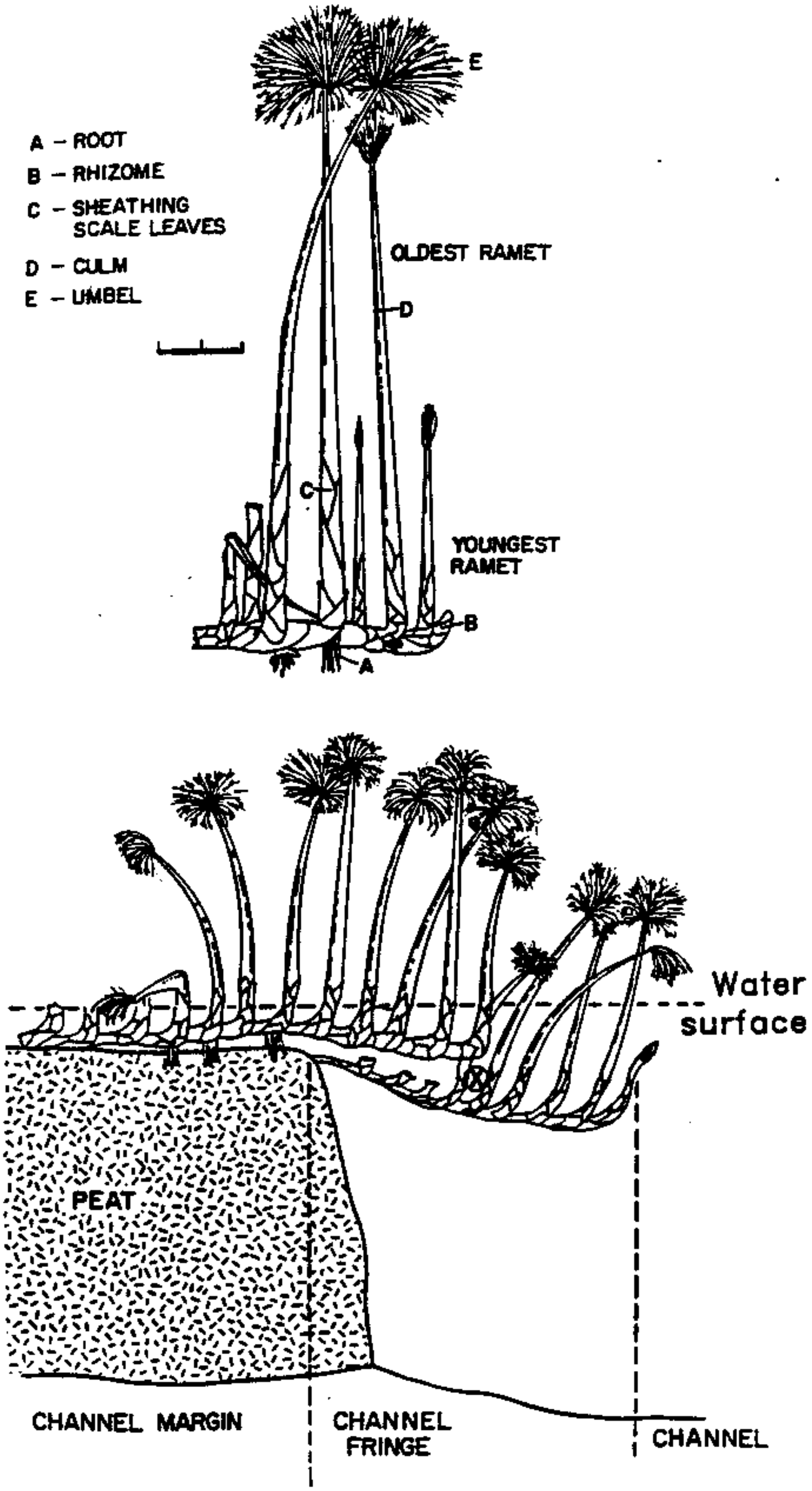

Fig. 3. (a) The growth form and plant parts of the giant sedge *Cyperus papyrus*, and (b) of its growth habit in the channel fringe of channels in the study area. The position within the fringe at which current velocities were measured is shown ⊗.

become abandoned since the 1920s (Fig. 4). It also includes the upper and middle reaches of the Maunachira river which is receiving increased water flow as a

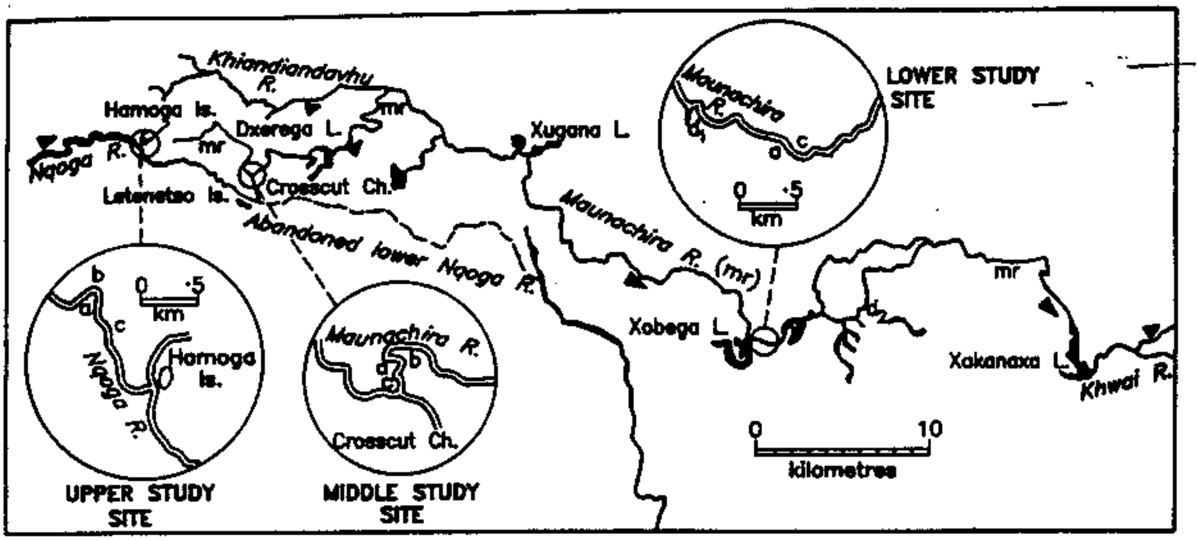

Fig. 4. The study area showing rivers, lakes, the former course of the abandoned lower Nqoga River and the locations of plots in three study sites in the study area.

result of the decline in flow along the lowermost (abandoned) Nqoga and Mboroga Rivers (Fig. 4). The abandonment of the lower Nqoga River has been progressive (Wilson, 1973) and is evidently continuing. This is indicated by the apparent encroachment of the channel downstream of Hamoga Island (Fig. 4) by *C. papyrus* and *Vossia cuspidata* (Ellery *et al.*, 1990), and by frequent occurrence of papyrus debris blockages along the same section of river. Vegetation growth and demography in the channel fringes, and the dynamics of debris blockages in this region of the Delta, were determined to provide an indication of the role of vegetation processes in channel blockage.

Methods

Papyrus vigour and encroachment from the bank into the channel

The growth of papyrus rhizomes, by the production of new ramets, enables it to colonize new areas. Encroachment of the channel by papyrus growing from the bank into the channel would lead to a reduction in channel width. Its rate of encroachment would be expected to be related to the rate of rhizome extensional growth. The growth of papyrus was measured in the channel fringe in 10 plots spread over three study sites in the study area (Fig. 4), one on each of the concave, straight and convex bends of the Nqoga River above Hamoga Island (upper study site) and on the Maunachira River, immediately downstream of the Crosscut Channel (middle study site). At the lower study site on the lower reaches of the Maunachira River, plots were placed on convex and straight sections only due to the absence of papyrus on concave banks (Ellery *et al.*, 1990). A further two plots were placed on minor distributary channels of the lower Maunachira River, both with a very slow flow.

At each plot, permanent markers were placed at intervals along the interface of the channel and the channel bank. The position of this interface was marked using nylon chord pulled taught between these markers. Sufficient length of channel was marked to include a minimum of 25 rhizomes extending from the bank into the channel. The youngest culm on each rhizome was tagged at the beginning of the study period and its distance from the margin was measured. The depth of the rhizome was measured at the position of the youngest ramet, as was the height of the culm. Subsequently, at approximately 2-month intervals, plots were revisited and newly produced culms were tagged. The depth of the rhizome and the distances of the youngest and of the first-tagged culms from the margin were measured, as was the distance between these two culms on the rhizome. The latter measures provided a basis for comparing the rate of encroachment and the rate of extensional growth of rhizomes within the channel fringe. The heights of all rhizomes produced from inception of the study were also measured. The length of each plot was known and was used to calculate rhizome density per unit length of channel margin.

Using an allometric relationship between culm height and biomass determined from ramets collected throughout the study area (Ellery, 1988), it was possible to estimate the biomass of papyrus being produced by each rhizome and thus per unit length of the channel fringe. The loss of rhizomes from each plot was recorded during the study period and provided a basis for estimating the amount of debris generated from the channel fringes.

At the time of each visit, the current velocity in the channel fringe was measured using a calibrated current velocity meter at four intervals down the length of the plot.

Blockage formation and dynamics

During the course of the study several blockages were seen to form, grow and then disintegrate. The aggregation of debris to form floating rafts was examined at a single site by measuring the size and shape of a marginal debris accumulation from shortly after its initiation to its final disintegration, covering a period of six months. It was the only example of such a marginal debris accumulation to be seen in the study area, although similar accumulations have been observed on the Nqoga River upstream of the study area.

The quantities of vegetation debris floating down the Nqoga river at Hamoga Island and on the Crosscut channel immediately upstream of its confluence with the Maunachira River were measured by stringing gill nets across the channel for between one and six hours, depending on the quantity collected. The mass of debris was measured and the proportions contributed by different species was estimated visually.

The dynamics of debris blockages within the study area were determined by recording their positions and dimensions over the study period (1 year). Colonization of these blockages was recorded by counting the mean shoot density of each species in six randomly placed 2 × 2 m quadrats.

The rate of decomposition of papyrus debris (contributing by far the greatest proportion to debris blockages) was measured by placing known quantities (wet mass) into litter bags with a mesh size of 2 mm. Larger holes (5 mm) were punched into the bags to enable small invertebrates access to the plant material. The bags were placed in a debris blockage in the lower Nqoga River. Three samples were removed immediately and air dried, and three samples were removed on three subsequent occasions over a period of 26 weeks. Each was air dried and weighed.

Table 1. The mean maximum culm height per rhizome (Culm hght; m), mean number of culms produced per rhizome per annum (Culm prod; number. a^{-1}), rhizome density in the channel fringe (Rhiz dens; number. m^{-1}), mean annual biomass produced per rhizome per annum (Mass per rhiz; g.rhizome^{-1}.a^{-1}), annual biomass produced in the channel fringe per unit channel margin length per annum (Mass per metre; g.m^{-1}.a^{-1}), proportional rhizome loss per annum (Rhiz loss), estimated annual debris production per unit channel margin length (Debris prod; g.m^{-1}.a^{-1}), flow rate (m.s^{-1}) and sample size (N) in the channel fringe in ten plots in three study sites within the study area (cf. Fig. 4). Where relevant, standard deviations are supplied below the mean values. The estimated biomasses ar given as a dry mass

Study site	Bank	Culm hght	Culm prod	Rhiz dens	Mass per rhiz	Mass per metre	Rhiz loss	Debris prod	Flow rate	N
Upper	Concave	2·82	5·42	2·29	526	1203	0·24	286	0·41	38
		0·39	2·61		262					
	Straight	2·79	6·15	2·03	578	1174	0·25	293	0·40	26
		0·44	2·55		262					
	Convex	2·89	4·17	1·03	491	506	0·23	116	0·11	21
		0·31	3·44		207					
Middle	Concave	2·23	5·58	2·14	314	673	0·22	149	0·38	26
		0·45	2·40		161					
	Straight	2·39	5·68	1·95	324	632	0·25	158	0·35	25
		0·22	2·29		130					
	Convex	3·01	4·74	1·08	598	646	0·16	103	0·11	22
		0·37	3·28		307					
Lower	Straight	2·09	5·84	1·51	267	403	0·16	64	0·14	42
		0·45	2·97		168					
	Convex	1·94	6·88	2·11	231	487	0·17	81	0·28	43
		0·31	2·40		101					
	Straight	1·78	8·24	1·49	219	327	0·14	47	<0·03	28
		0·27	1·47		116					
	Straight	2·42	6·31	1·27	373	473	0·16	74	<0·03	32
		0·22	1·04		95					

The effect of a single debris blockage on channel morphology was determined by measuring the thickness of the blockage and the depth to the channel bed at intervals of 4 m down the length of the blockage and for a distance of 20 m downstream of the blockage.

Results

Papyrus vigour and encroachment

There is a downstream decline in the vigour of *C. papyrus* in the channel fringe, as indicated by the downstream decline in the mean height of the tallest culm on each rhizome (an indication of the height of mature culms), the density of rhizomes in the channel margin and the estimated mean biomass produced by each rhizome, as well as per unit channel margin length (Table 1). The number of culms produced per rhizome per annum however increases downstream.

If encroachment from the channel margin is important in promoting channel blockage, data on overall vigour suggest that this would be most likely in the

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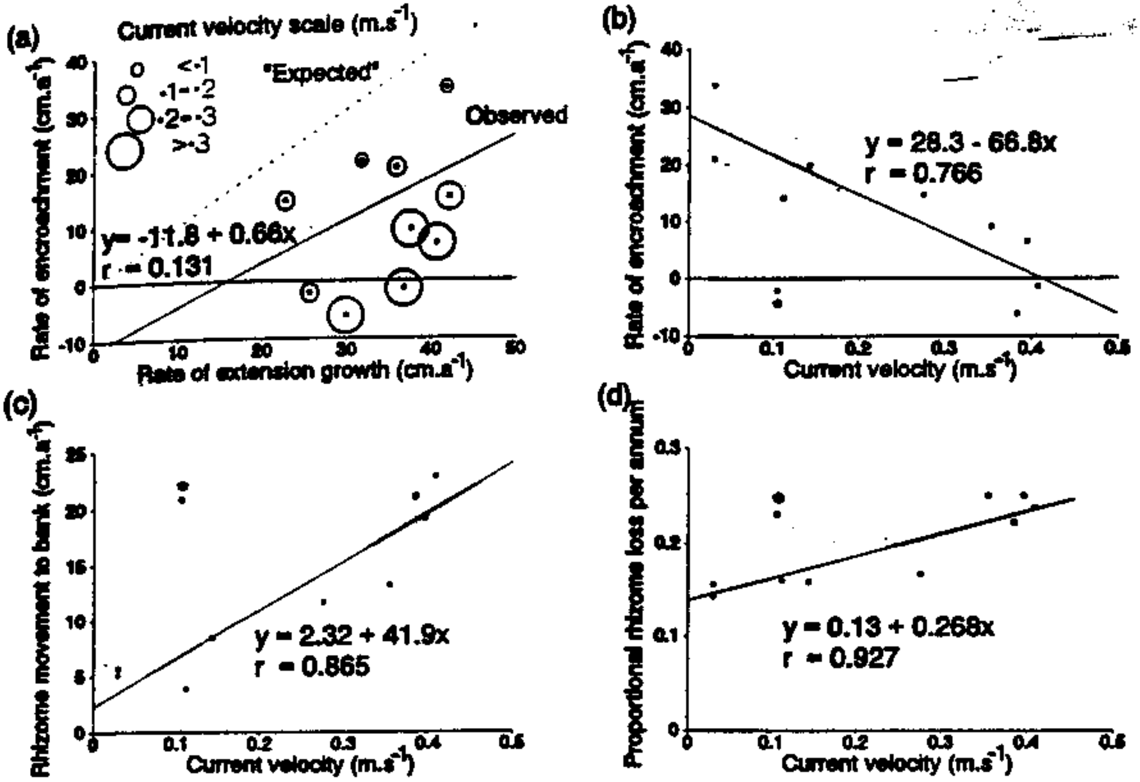


Fig. 5. The relationships between: (a) the rates of encroachmnent of the channel by papyrus and extension growth (circles around points indicate current velocities in the channel margin); (b) the rate of extension growth and current velocity; (c) the rate of movement of rhizomes towards the bank and current velocity; and (d) the loss of rhizomes from the channel fringe and current velocity. Solid lines were calculated by linear regression omitting the points indicated by asterisk, all from a single plot.

upper study site. The rate of encroachment of the channel by papyrus would be expected to be a linear function (passing through the origin) of the rate of extension growth of papyrus, with a maximum rate of encroachment equal to the rate of extension growth. However, not all rhizomes extend into the channel at right angles to the bank, and the mean rate of encroachment would be expected to be slower than the mean rate of extension growth. Data comparing the rates of extension growth and encroachment show no significant relationship (Fig. 5a). Of particular interest is that the relationship does not pass through the origin. The effect of current velocity on the rate of encroachment is illustrated by superimposing current velocity on the figure (Fig. 5a) and in the negative correlation between encroachment and current velocity (Fig. 5b).

In the channel margin papyrus exists as a floating, unconsolidated mat. The current appears to reduce encroachment by both moving rhizomes towards the bank (Fig. 5c) and by removing rhizomes from the channel fringe (Fig. 5d), presumably by breaking the older, decomposing end of the rhizome closest to the bank and causing it to float downstream (cf. Fig. 3). Indeed, some of the rhizomes that had been tagged during the study were found downstream, broken off at the end of the rhizome closest the channel margin. Rates of encroachment are lowest in those plots at the upper study site due to the current velocities there being higher than elsewhere in the study area, suggesting that encroachment of the channel may not be the mechanism by which channels become blocked and abandoned.

This interpretation is supported by aerial photographic evidence which illustrates the effect of current velocity on channel planform geometry. A man-made channel was excavated away from the Nqoga River at Hamoga island (Fig. 6). This resulted in a reduction in flow in the Nqoga river downstream of this point, which was accompanied by a reduction in the width of this section of channel. Upstream of this point where flow rates remained virtually constant, no reduction in channel width has been observed. A consequence of reduced encroachment under increased current velocities is the increased generation of papyrus debris. This could lead to the formation of debris blockages, which have also been implicated in channel blockage and abandonment.

Debris production

Current velocity appears to be important in removing rhizomes from the channel fringe. Other factors that would affect the rate of debris production are related to the growth characteristics of papyrus in the channel fringe. These include the density of rhizomes in the channel fringe and the rate of biomass production per rhizome. Rhizome density within the channel fringe varied between 1·08 and 2·29 rhizomes per metre (Table 1), and biomass production per rhizome from approximately 220 to 600 $g.a^{-1}$ (Table 1). Taken together these provide an estimate of biomass production per unit channel fringe length of 325 to 1200 $g.m^{-1}.a^{-1}$ (Table 1). When this is considered together with the proportional loss of rhizomes from each stand over the study period, the quantity of debris produced per unit channel fringe length varied from approximately 50 to 300 $g.m^{-1}a^{-1}$ (Table 1), with upper study sites producing the greatest quantities of debris and the lower study sites producing far less. The large quantities of debris that were produced from the channel fringes of the upper channels, which appear most susceptible to blockage and abandonment, suggests that papyrus debris blockages may well be important in promoting channel blockage and abandonment, as has been described in the case of the Thaoge and lower Nqoga Rivers.

Using these figures it is possible to estimate an annual rate of debris (dry weight) for the lower Nqoga River (the upper study site). If 400 g of papyrus debris are produced per metre per annum (200 g from each side of the channel) along the 150 km Okavango/Nqoga river system, the annual total quantity of debris that reaches Hamoga Island may be expected to be in the region of 60 tons. This translates to a figure of over 150 kg per day.

The quantity of debris carried along the lower Nqoga River just upstream of Hamoga Island, but downstream of its confluence with the man-made channel at Hamoga Island, is not inconsistent with this amount (Table 2). Figures are tabulated as wet weight. If this quantity is converted to an annual amount, it is estimated that nearly 400 tons of debris enters the Nqoga River downstream of the man-made channel at Hamoga Island. Debris includes papyrus rhizomes, senesced, dead culms and other species, but papyrus makes up over 80% of the total. Expressed as a dry mass it is similar to the figure of 60 tons per annum estimated in the growth and demographic studies. This suggests that there is no removal of papyrus debris by any of the distributary channels along the course of the Okavango/Nqoga River system, which fits the description of the Thaoge

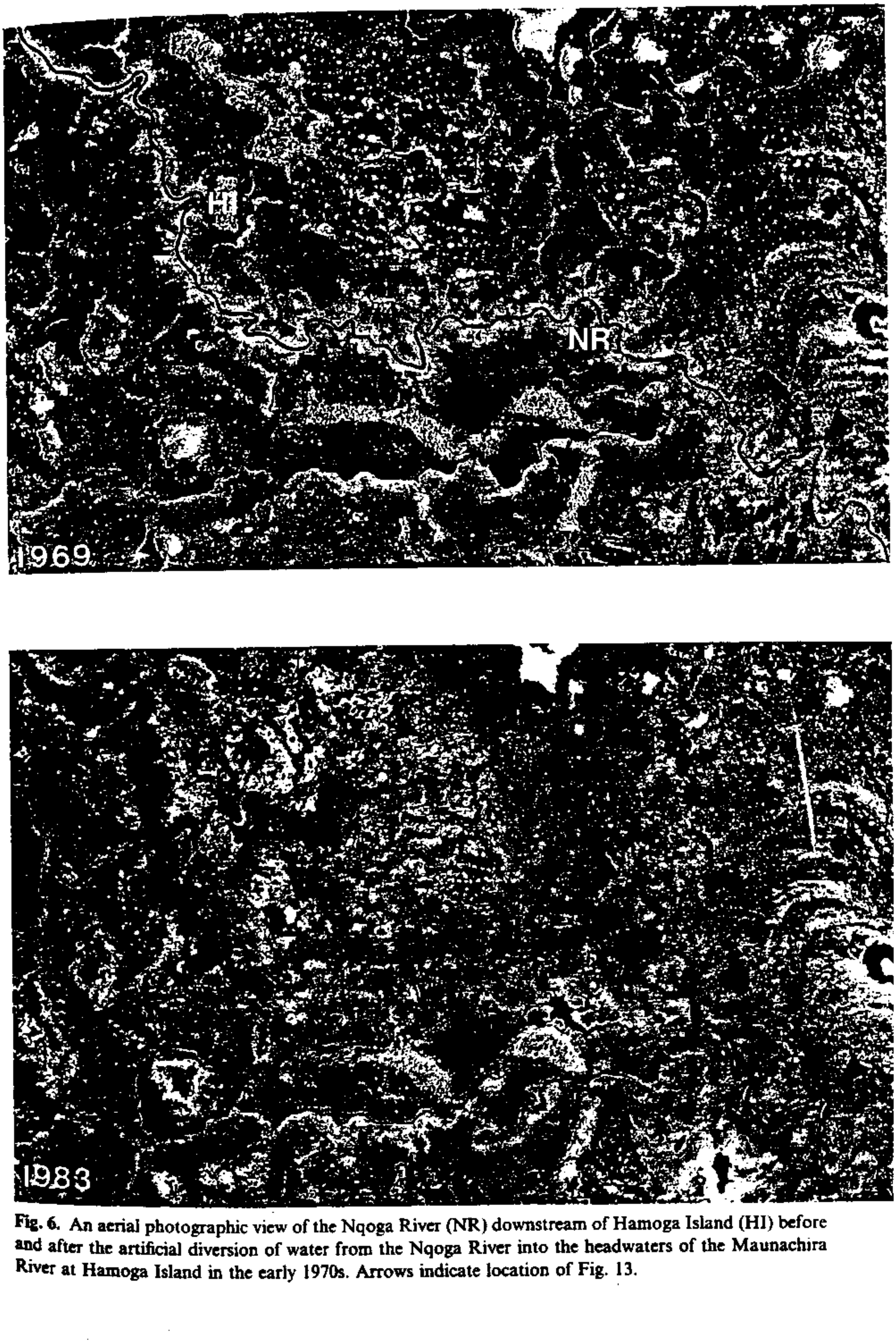


Fig. 6. An aerial photographic view of the Nqoga River (NR) downstream of Hamoga Island (HI) before and after the artificial diversion of water from the Nqoga River into the headwaters of the Maunachira River at Hamoga Island in the early 1970s. Arrows indicate location of Fig. 13.

Table 2. Rates of debris flow expressed as wet weights (kg.h^{-1}) along the Nqóga River at Hamoga Island (NQOGA) and the Crosscut Channel just above its confluence with the Maunachira River (CROSSCUT) on sampling occasions during the study period. At the time of sampling in July at the lower study site (***), a large number of rafts greater than 4 m in diameter drifted into the sampling station and destroyed the sampling nets, representing several tons of material that passed the station in less than 15 minutes

Locality	March	May	July	Sept	Dec
NQOGA	88·6	48·4	20·7	28·2	94·6
CROSSCUT	8·3	1·9	***	1·4	5·3

and Boro River offtakes as ‘restricted offtake’ channels (Wilson, 1973), in that they do not remove debris from the primary channels themselves.

By far the bulk of the material carried downstream along the Nqoga River at Hamoga Island is accumulating along the stretch of river between Hamoga Island and the Crosscut Channel, immediately above its confluence with the Maunachira River (Table 2). This is a continuous section of channel, uninterrupted by the presence of either lakes or of any distributary channels. The presence of at least one vegetation debris blockage along this channel section throughout the study period accounts for this accumulation of vegetation debris along this channel section. At the time of sampling in July at the lower study site, several tons of debris drifted into the sample net over a period of 15 minutes, destroying the sampling device. Part of a blockage further upstream (cf. following section) had become dislodged, and a large number of rafts 3 to 4 m in diameter drifted into the sampling station.

The origin and dynamics of debris blockages

The effect of a blockage on flow conditions was investigated in a qualitative way by examining a profile of a blockage and of the channel bed upstream of, underneath, and downstream of a blockage (Fig. 7). It is evident that the channel bed is scoured out beneath the blockage and that some of the scoured material is deposited on the downstream side. The presence of a sand bar on the downstream side of blockages was invariably observed during aerial surveys, and is evidence that scouring of the channel bed takes place to compensate for the reduced cross-sectional area that results from blockage formation.

Debris is generated as individual culms, or as individual rhizomes with the living culms attached. Along the lower Nqoga river, individual items of debris continually drift downstream with the current. Some mechanism must lead to the aggregation of these items into rafts sufficiently large to form a blockage. A marginal debris accumulation was observed to form on the convex (slow flowing) bank of one channel bend in the study area. It developed gradually by the addition of individual pieces of debris that became caught in an eddy current. One such marginal debris accumulation was observed over a period of six months (Fig. 8). Initially it comprised a small floating raft of unconsolidated debris with an area of approximately 10 m^2, which gradually increased in size by the addition of individual fragments, mainly of papyrus debris, but also by the

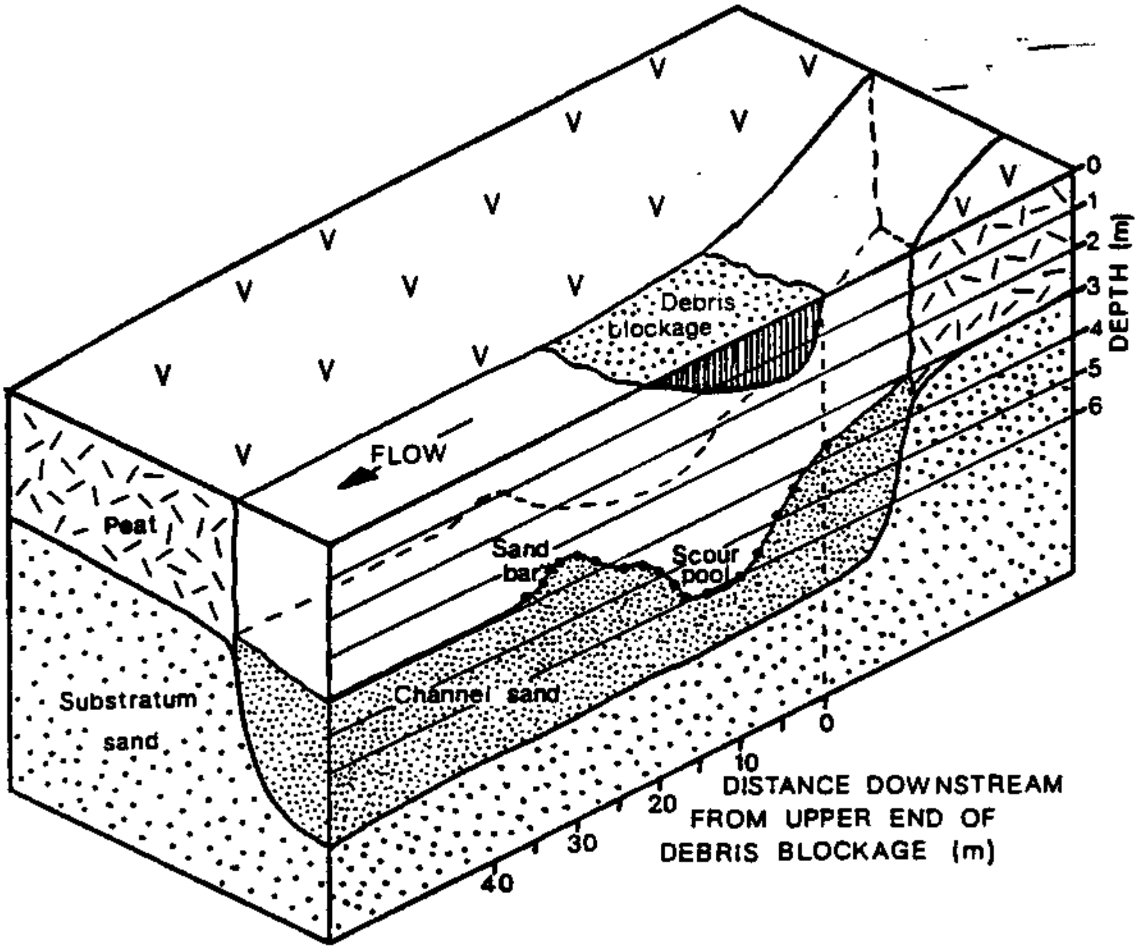


Fig. 7. A longitudinal section of a blockage and of the channel bed beneath and downstream of a blockage.

addition of smaller quantities of *Vossia cuspidata* and *Phragmites australis*, usually in small floating rafts. After a month the marginal debris accumulation had increased to 21 m^2, and after a further 2 months to 43 m^2. Two months later, the entire debris accumulation had disappeared, presumably as a single floating raft of debris. A circular raft with a surface area of 43 m^2 would have a diameter of approximately 7·4 m, which is similar to the width of sections of the Crosscut Channel. Many such rafts of debris have been observed floating downstream along the lower Nqoga and Crosscut channels during the study period, and could lead to the formation of a surface debris blockage.

The longevity and dynamics of debris blockages is considered to be the outcome of four main processes: the addition of debris to the upstream side of the blockage; the removal of debris from the downstream side of the blockage; the colonization of the blockage by plants (which would increase blockage stability); and the decomposition of the dead plant matter within the blockage, which would reduce blockage stability.

The importance of debris addition and removal to the upper and from the lower ends of blockages respectively, is illustrated by the comparison of two blockages, the first of which (blockage 1; Fig. 9) developed shortly before an additional blockage developed further upstream (blockage 2; Fig. 9). Subsequent

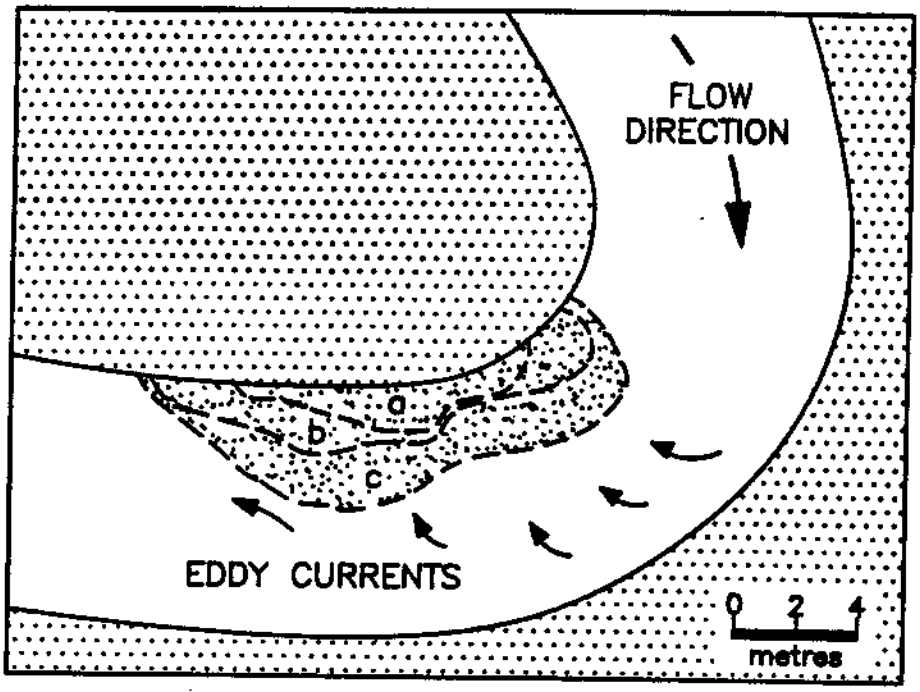


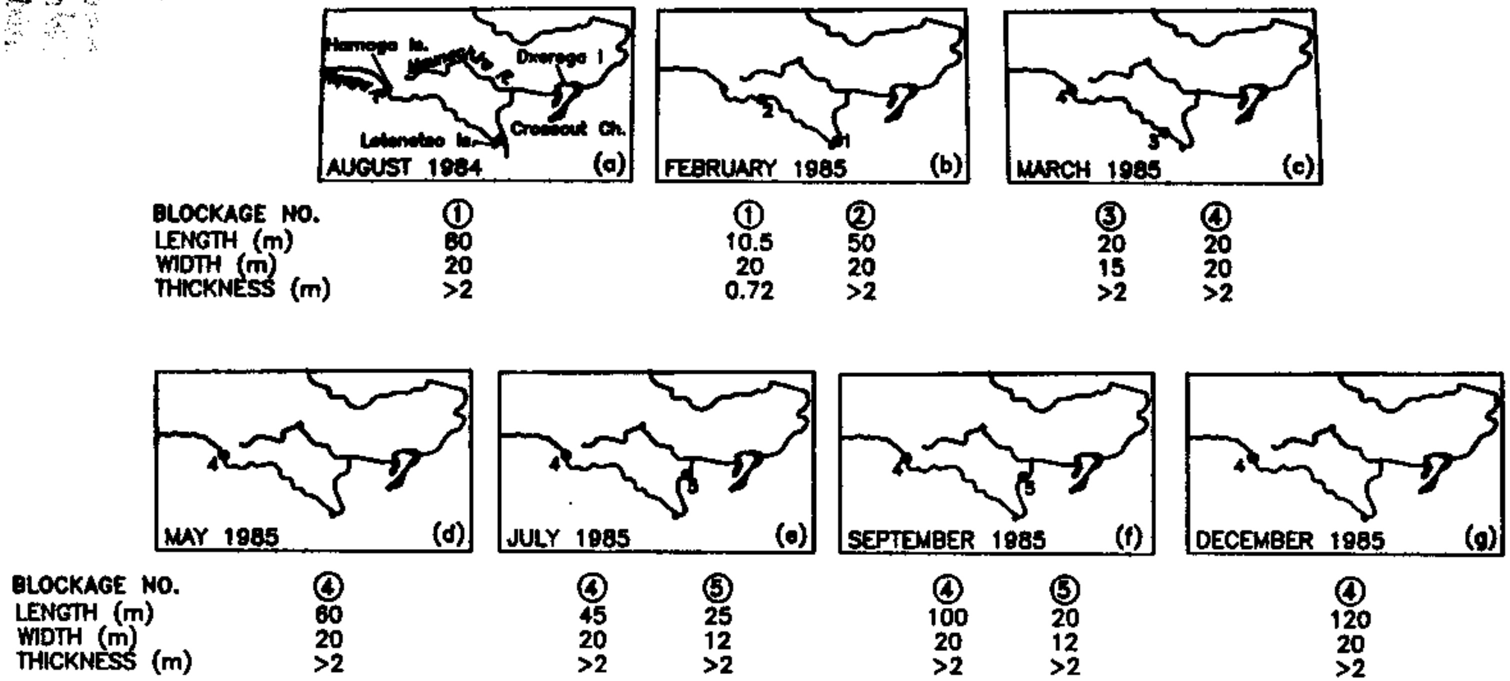
Fig. 8. The development of a marginal debris accumulation along the convex bank of a channel in February (a), March (b) and May (c). The entire accumulation had disappeared by July.

to the formation of this (first) blockage little or no material was added to its upstream end (Table 3), due to debris being trapped by the blockage which had formed upstream. The second blockage in this comparison formed in the Nqoga channel immediately downstream of Hamoga Island (blockage 3, Fig. 9), and for a long period had material continuously added to its upstream end.

The first blockage declined in length from 80 to 10·5 m over a period of six months, and declined in thickness from >2 to 0·72 m over the same period, illustrating the importance of debris removal from the downstream end as well as from underneath the blockage. In the case of the second blockage, it varied in length from 20 to 120 m depending on the interactions between the removal of material from the downstream end and the addition of material to the upstream end.

Colonization of blockages by plants was considered an important aspect of their stability. The most important species that colonize these blockages are rhizomatous and their growth would increase blockage stability. The blockage that formed and subsequently had little debris added to its upper end was the most suitable one to compare rates of colonization by different plant species. Papyrus and *Phragmites australis* colonized relatively slowly over the study period, while *Vossia cuspidata* rapidly colonized the blockage and appeared to be most important in enhancing stability (Table 4).

In contrast to colonization, which would increase the stability of blockages, decomposition of dead debris would have the opposite effect. Decomposition of papyrus, which makes up by far the greatest volume of blockages, was slow (25% over 26 weeks; Fig. 10), but it would appear that qualitative changes, such as the breakdown of structural components and softening of tissue induced by microbial activity, was more important in determining the stability of blockages than the proportional loss of mass. The plant tissue removed from the bags after



BLOCKAGE NO.	①	①	②	③	④
LENGTH (m)	80	10.5	50	20	20
WIDTH (m)	20	20	20	15	20
THICKNESS (m)	>2	0.72	>2	>2	>2

BLOCKAGE NO.	④	④	⑤	④	⑤	④
LENGTH (m)	60	45	25	100	20	120
WIDTH (m)	20	20	12	20	12	20
THICKNESS (m)	>2	>2	>2	>2	>2	>2

Fig. 9. The positions of debris blockages and the approximate dimensions of blockages in the study area over the period of the study.

Table 3. Blockage dimensions of two contrasting blockages in the study area. Blockage I formed at the same time as another blockage further upstream and therefore had no material added to its upstream end, whereas blockage II had no blockages further upstream and its size was determined by the addition and removal of material to its upstream and from its downstream side respectively

Blockage no.	I		II				
Date	Aug	Feb	Mar	May	July	Sept	Dec
Length (m)	80	10·5	20	60	45	100	120
Thickness (m)	>2	0·72	>2	>2	>2	>2	>2

Table 4. Rhizome density (no. m^{-2}) of *Cyperus papyrus*, *Phragmites australis* and *Vossia cuspidata* on Blockage 1 (cf. Table 3; Fig. 8) in August 1984 and February 1985

Date	August 1984	February 1985
C. papyrus	0·25	4·33
P. australis	0·05	2·58
V. cuspidata	0·10	11·00

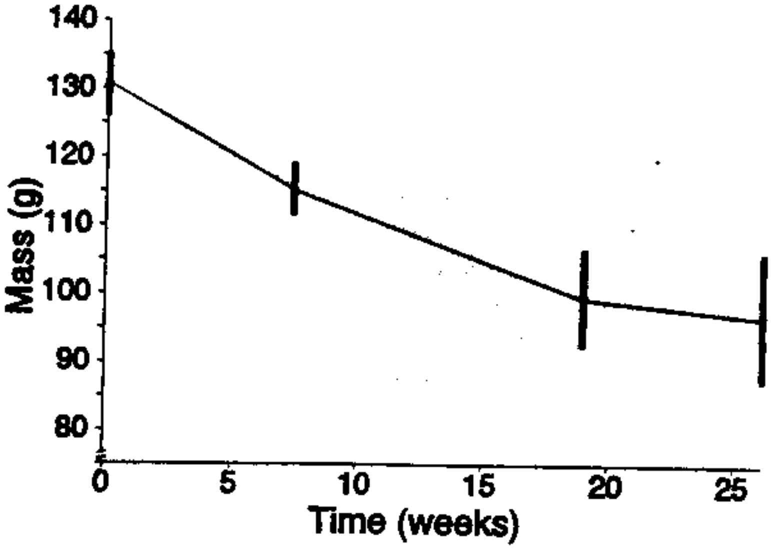


Fig. 10. Decomposition of papyrus debris over a period of 26 weeks as indicated by the loss of mass (g). Vertical bars indicate standard deviations.

26 weeks was flaccid and would not provide any substantial strength to blockages in the areas in which they occur, where flow rates are frequently in excess of 0·6 m.s^{-1}. The loss of buoyancy associated with decomposition would cause debris to be easily removed from underneath the blockage by the current.

The dynamic behaviour of blockages in the study area is illustrated by changes in their distribution over the study period (Fig. 9). There is little evidence that they develop progressively upstream as has been described in the case of the Thaoge and lower Nqoga Rivers, this probably due to the current velocities prevalent in the channels in the study area. Their ultimate fate is to be

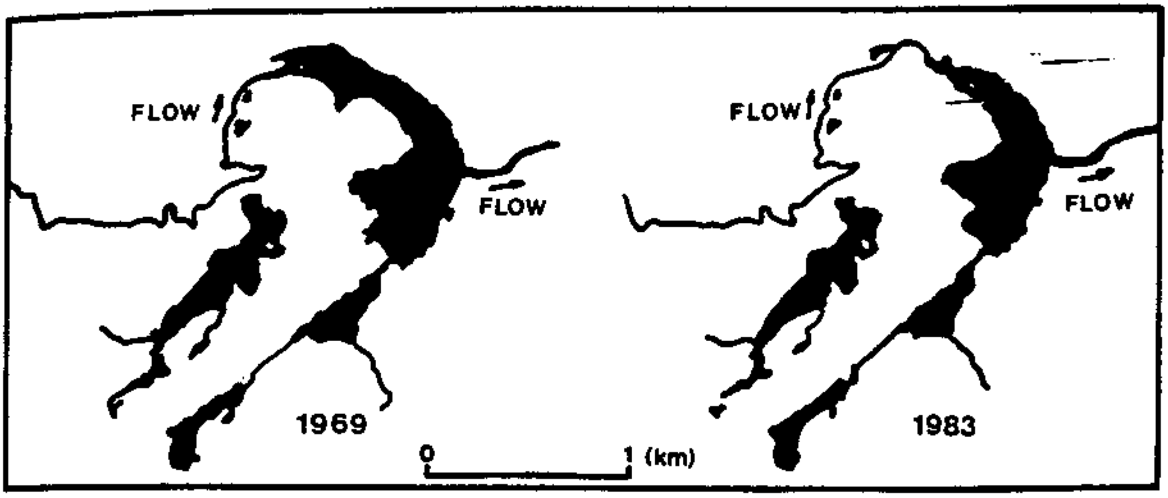


Fig. 11. Dxerega Lake mapped from vertical aerial photographs taken in 1969 and 1983. The extensive shrinkage in the area of the inlet is due largely to encroachment by *Cyperus papyrus* and *Vossia cuspidata.*

deposited in Dxerega Lake which is experiencing rapid closure, in large measure due to the deposition of debris in its mouth (Fig. 11). As there is no detectable flow in this lake, the debris deposited there is rapidly colonized by plants, the most prominent being large floating rafts of *Vossia cuspidata.*

It seems clear that blockages are dynamic entities and that there are a variety of factors that influence their dynamics. Over the time span of the study there was no evidence of the gradual upstream development of blockages within a channel system that is clearly at an advanced stage of decline. Observations in the study period for almost a decade corroborate this suggestions. Nonetheless, it is conceivable that once a blockage developed permanently in a channel, in a situation where the addition of debris exceeded its rate of removal, there may be a gradual upstream expansion of the blockage as has been described elsewhere in the literature, such as the Thaoge and Nqoga blockages. It seems, however, that under the prevailing flow regime in the study area this is unlikely.

Discussion

The growth and vigour of papyrus in the channel fringe

Papyrus vigour in the channel fringe, including the height of adult culms, rhizome density per unit channel margin length, and biomass production per rhizome and per unit channel margin length, tends to decrease downstream in the study area. This suggests that vigour is related to the proximity of sites to the apex of the Delta.

Channels close to the apex of the Delta, and therefore closer to source areas, have greater nutrient supply than those in the distal reaches of the Delta. Upstream of Dxerega Lake, water clarity tends to be lower due to the presence of some suspended load, largely kaolinite, but downstream of this, water is clearer (Ellery *et al.*, 1990; McCarthy *et al.*, 1991). Dxerega Lake appears to be an effective trap for nutrients adsorbed to clays that are carried in suspension in channels that connect directly to the Okavango River (such as the Okavango–Nqoga–Maunachura River system as far downstream as Dxerega Lake). In contrast, channels that receive water as overspill from this 'primary river system' (McCarthy *et al.*, 1991) are relatively depleted in nutrients due to the filtering effect of vegetation communities flanking these channels. This pattern is clearly evident in remotely sensed satellite images which have been processed to enhance vegetation standing crop (McCarthy *et al.*, 1993c).

Despite having a high growth rate in channels closest to source areas, the rate of encroachment by papyrus from the bank into the channel is limited by current velocity. The mechanism by which current velocity appears to reduce encroachment is by removing rhizomes, together with their attached culms, from the channel fringe. A consequence of this is that channels that are predicted to be most susceptible to blockage by papyrus are least prone to encroachment. However, the generation of large quantities of debris from the margins of these channels renders them prone to blockage by floating rafts of debris, these being initiated as marginal debris accumulations.

Debris blockages

A short-term study such as this makes it difficult to be conclusive about the role of debris blockages in channel blockage and abandonment. However, data collected in this study suggest two features of debris blockages that are important. Firstly, they are relatively transient features of channels in the study area. Secondly, where they do occur, their effect on flow is not of major consequence.

Two features of the environment in the study area support these suggestions. Firstly, hydrological conditions in channels in the study area are remarkably uniform, and they are not prone to episodic events such as particularly high discharges (in the event of flooding in the catchment). Primary channels tend to be raised relative to the surrounding swamps (McCarthy *et al.*, 1992) and, in the event of flooding in the catchment, overspill from these channels upstream of the present study area increases and dissipates this potential catastrophic event over an extremely large area of permanent swamp. Hydrological conditions in channels in the study area are therefore remarkably uniform from year to year.

Secondly, channels are an essential component of water delivery in the Delta and arise as a result of the need to disperse water that arrives at the apex of the fan. This has been recognized previously and has been described in detail elsewhere (McCarthy *et al.*, 1991). The relationship between channel cross-sectional area and discharge (Fig. 12) illustrates the suggestion that channel dimensions evolve to accommodate water flow. With this in mind, it is inconceivable that blockages are a major factor on their own in channel blockage and abandonment.

The generation of debris from the channel fringe however, appears to be essential in the dispersal of propagules in the study area, particularly for papyrus and probably for *Vossia cuspidata*. The establishment of *V. cuspidata* (initially) and of papyrus in the mouths of lakes in the study area has been described in detail elsewhere (Wilson, 1973; McCarthy *et al.*, 1991; Ellery *et al.*, 1993; McCarthy, Ellery & Stanistreet, 1993a), having led to the closure of a number of lakes along the Crosscut Channel. The presently observed closure of Dxerega Lake is also the result of encroachment by *V. cuspidata* and papyrus.

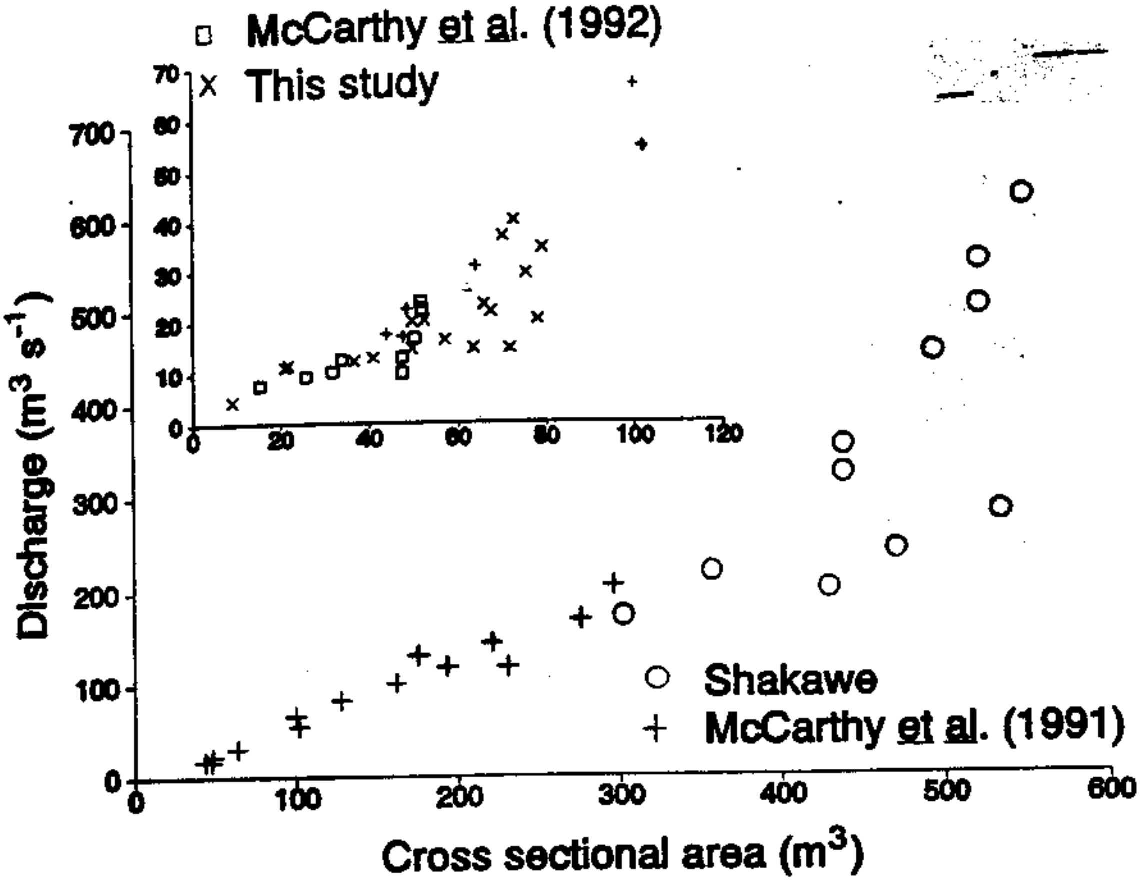


Fig. 12. The relationship between discharge and channel cross-sectional area in channels in the Okavango Delta including the present study area.

The dispersal of papyrus along the channels themselves by the generation of debris from the channel margins has also been recognized by Smith (1976), who reports never having seen papyrus establish from seed anywhere in the Delta. Where debris is added to the convex banks of channels to form marginal debris accumulations, propagules are able to establish locally. This would account for the observed distribution of *V. cuspidata* on convex and straight banks of channels upstream of Dxerega Lake (Ellery *et al.*, 1990), and of papyrus on the convex banks and along straight channel sections downstream of Dxerega Lake (McCarthy *et al.*, 1988; Ellery *et al.*, 1990).

The general pattern of channel closure

Observations in the study area over the past 10 years, particularly events on the lower Nqoga River and the Crosscut Channel, have provided a useful record of events that seem to take place during channel abandonment. Undoubtedly, events that have taken place in this area have been accelerated by the creation of the man-made channel at Hamoga Island. However, it is likely that a similar diversion of water from the Nqoga River into the Maunachira River would have taken place naturally by headward erosion of the Maunachira River itself (cf. McCarthy *et al.*, 1986, 1991).

Since the first observations in the study area were made in 1984, there has been gradual encroachment of the lower Nqoga and Crosscut Channels by *Vossia cuspidata*. At the time of a preliminary survey of channels in the study

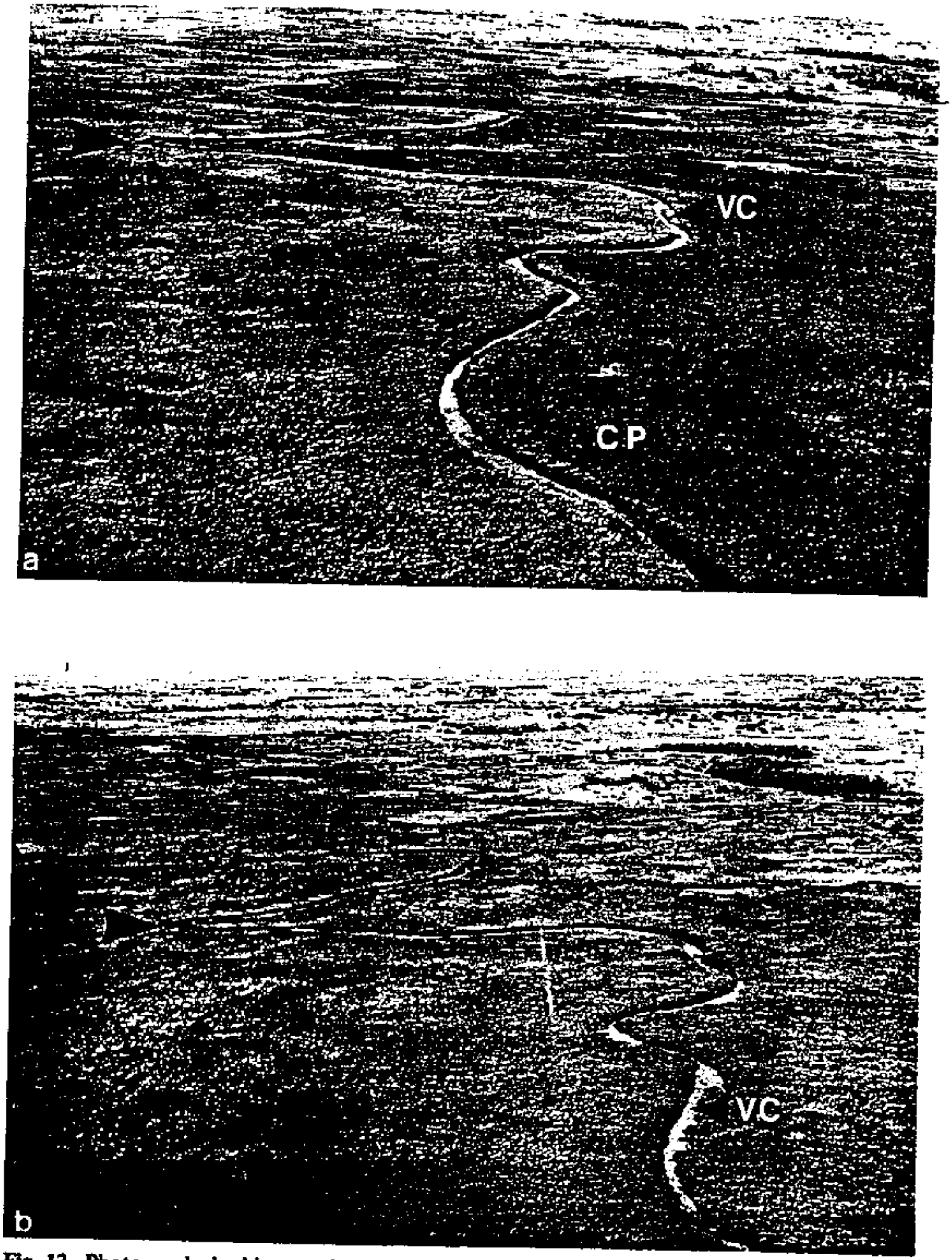


Fig. 13. Photographs looking south-east along the lower Nqoga channel in 1986 (a) and 1993 (b), giving some impression of the processes that take place during channel decline prior to final abandonment. Small patches of *Vossia cuspidata* (Vc) can be seen in the earlier view. These had been overgrown by papyrus (Cp) and virtually the entire channel had been colonized by *V. cuspidata* at the time of the second photograph. The arrow in the photographs corresponds to the bend in the channel indicated in Fig. 6.

area in 1984 (Ellerty *et al.*, 1990), the Nqoga channel downstream of Hamoga Island was approximately 15–20 m wide (Fig. 13a). *Vossia cuspidata* was the only species rooted in the channel bed. It was confined to a narrow fringe on the convex side of channel bends and occurred as a sparse fringe along straight channel sections. At that time a single papyrus blockage was encountered along the Lower Nqoga River (this study). Numerous visits to the study area since then have seen increasing occurrence of *V. cuspidata* (Fig. 13b), which had reduced the width of active flow to 2–3 metres at present. In some areas the channel is not visible at all.

This encroachment has been accompanied by an increase in the number of papyrus blockages along this stretch of channel. *Vossia cuspidata* acts as an effective debris trap and provides support for debris blockages. These, therefore, tend to become more permanent features. Furthermore, the presence of *V. cuspidata* along the edges of channels provides physical support for papyrus encroaching from the channel margin. It also reduces current velocities sufficiently to prevent removal of rhizomes and culms from the channel fringe. During the final phases of channel decline, it would appear that *V. cuspidata* is completely excluded by papyrus, which completely overgrows the former channel. This sequence of events is typical of channel decline as described previously (Brind, 1955; Wilson, 1973), and illustrates the importance of a longer-term record than was possible in the present study. However, the present study suggests that this sequence of events is a symptom and not the cause of channel decline and abandonment.

An alternative model

A longer-term record than has been achieved in this study exists in hydrographic data from Hamoga Island (Fig. 14a). Over the period of measurement from 1977 to 1990 the water level at Hamoga Island has risen approximately 0·5 m, whereas the mean current velocity has declined from nearly 0·7 to less than 0·4 $\mathrm{m.s^{-1}}$ from 1977 to 1984 (Fig. 14b). This combination of processes has been attributed to sedimentation and concomitant aggradation of the bed of the Nqoga Channel (McCarthy *et al.*, 1986; McCarthy *et al.*, 1992). Aggradation of the channel bed and the concomitant rise in the water level in the channel is accompanied by aggradation of the vegetated peat banks in the channel margins (McCarthy *et al.*, 1986). The formation of vegetation levees is due to a combination of processes. Firstly, plant growth closest to the channel is greater than further away due to increased nutrient supply, and peat formation is greatest in this region. Secondly, peat formation takes place only below the level of permanent flooding and a rise in the water level would enable peat to accumulate to a new elevation. Thirdly, papyrus is capable of growth as a floating raft of vegetation and a rise in the water level would cause the root zone to rise.

This combination of processes results in an increase in the gradient of the water surface at right angles to the channel axis. Gradients away from channels in the study area have been measured, sometimes being in the region of 1:250 (McCarthy *et al.*, 1992). This is an order of magnitude greater than the average gradient along the length of the Delta (1:3600; Wilson & Dincer, 1976). As a channel aggrades, increasing quantities of water would be lost from the channel and current velocities in the channel decline. The present study has shown that the decline in current velocity of the channel would be accompanied by an increase in the rate of encroachment of papyrus from the channel margin into the channel.

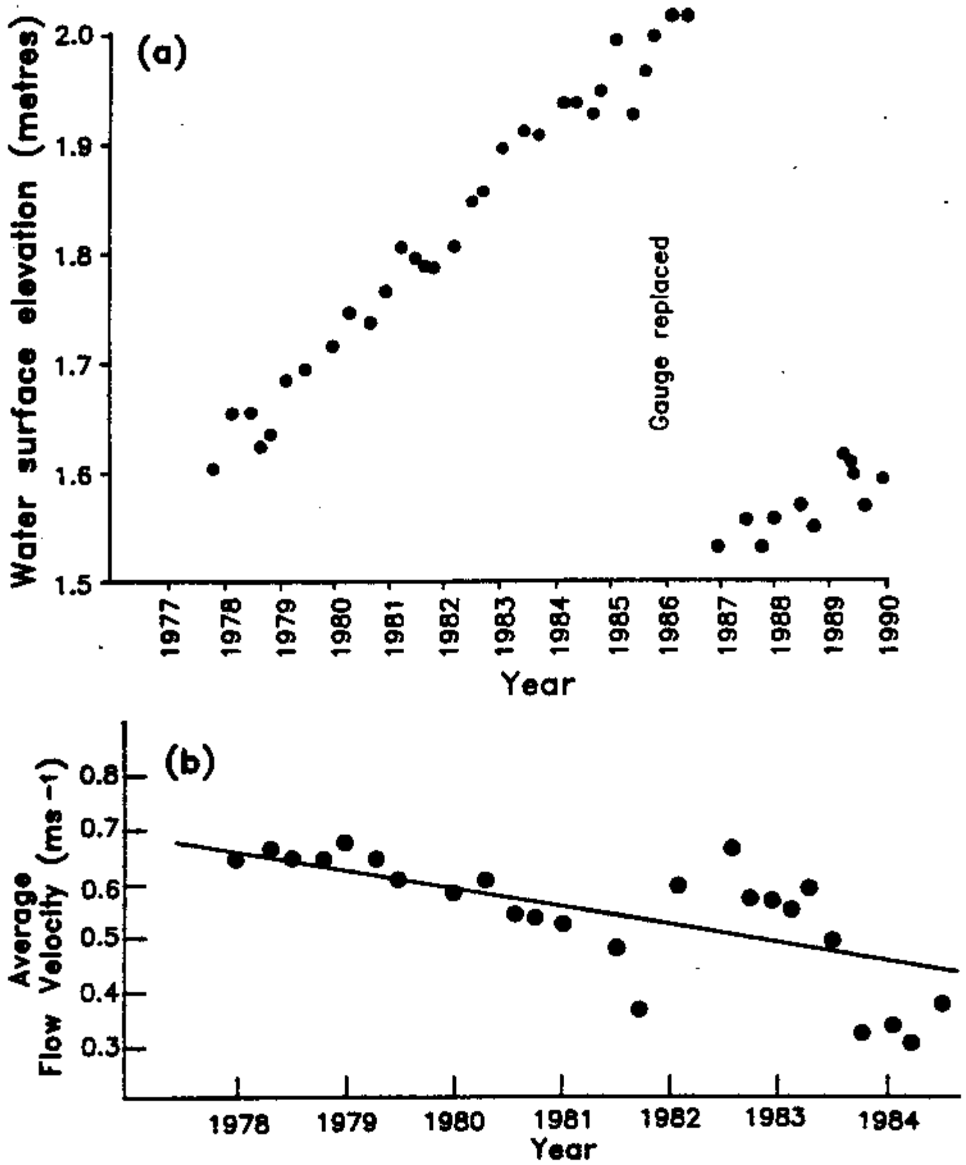


Fig. 14. Water elevation (a) and average current velocity (b) over a period of many years at Hamoga Island. Data supplied by the Department of Water Affairs, Gaborone, Botswana.

Conclusions

The present study suggests that neither plant growth from the channel banks into the channels, nor the development of papyrus debris blockages are the primary cause of channel blockage and abandonment in the Okavango Delta. Rather it suggests that the development of these, preceded by encroachment of the channel by *Vossia cuspidata*, is a symptom of channel decline. An alternative model, in which interactions between vegetation growth and sedimentation are considered to cause channel aggradation and decline, is more plausible. Recent studies (McCarthy, Green & Franey, 1993b) suggest that tectonic activity may be more important than previously recognized. The Okavango Delta is situated in a region that is seismically active, and neo-tectonic activity may cause small changes in elevation on either side of conjugate fault sets that trend southwest–northeast and southeast–northwest (McCarthy, Green & Franey, 1993b). If neo-tectonic activity is important, then predictive models of patterns of channel change are unlikely to materialize and medium to long-term planning for management purposes becomes difficult, particularly for activities related to conservation as well as for water abstraction.

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