

Vegetation, hydrology and sedimentation processes as determinants of channel form and dynamics in the northeastern Okavango Delta, Botswana

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Summary

The relationships between vegetation, hydrology, and the landscape-forming processes of erosion and deposition are examined in channels of the northeastern Okavango Delta, Botswana. Channel development appears to be due to the confinement of rapid water movement by vegetation processes and peat formation in backswamp areas. The channels have sandy beds and densely vegetated banks composed of erosion-resistant peat deposits between 1.5 m and 4 m thick. Sediment introduced into the delta is transported as bed-load, is unable to escape from the peat-lined channels and is therefore deposited along the channel floor. Channels that receive their water supply directly from source areas are therefore dominated by depositional processes. In contrast, channels that receive their water supply as overspill from these aggrading source channels do not receive bed-load sediments from source areas, and their beds tend to be erosional. Channel switching is therefore suggested to be due to a combination of erosional and depositional processes, rather than simply the result of depositional processes as has previously been suggested. A conceptual model of channel development and change within the northeastern Okavango Delta is presented.

Key words: channel, dynamics, Okavango Delta, swamp vegetation

Résumé

On étudie les relations entre la végétation, l'hydrologie et les processus de formation du paysage par l'érosion et la redéposition dans des canaux du nord-est du delta de l'Okavango, au Botswana. La formation des canaux semble être conditionnée par la limitation imposée au mouvement rapide de l'eau par la végétation et par la formation de tourbe dans les zones marécageuses. Le lit des canaux est sableux et comprend des bancs de végétation dense composés de dépôts de tourbe d'un mètre cinquante à quatre mètres d'épaisseur, qui résistent à l'érosion. Les sédiments qui sont amenés dans le delta sont transportés sur le fond, ne peuvent franchir les canaux longés de tourbe et se déposent donc le long des canaux. Les canaux qui reçoivent leur apport d'eau directement des régions des sources sont pour cette raison dominés par les processus de déposition. Au contraire, ceux dont

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l'eau provient des excédents des premiers, ne reçoivent pas de sédiments de la région des sources et leur lit tend à s'éroder. Le déplacement des canaux semble donc devoir être attribué à une combinaison des processus d'érosion et de déposition plutôt qu'à la seule déposition comme on le croyait jusqu'alors. On présente un modèle conceptuel de développement et de transformation des canaux du nord-est du delta de l'Okavango.

Introduction

The biotic component of wetlands exerts an affect on both the hydrological regime and the landscape-forming processes of erosion and deposition. General features of the hydrological regime that are affected by vegetation processes are well documented and include confinement of water flow, flood attenuation, the maintenance of base flows and modification of water chemistry (Gosselink & Turner, 1978; Howard-Williams, 1983; Mitsch & Gosselink, 1986; Breen, Rogers & Ashton, 1988). The importance of vegetation in modifying erosional and depositional processes has not been well documented by wetland ecologists. Where work has been done it has focused on the influence of vegetation on depositional processes (Smith & Putnam, 1980; Smith & Smith, 1980). A study of channel change in the Okavango Delta (McCarthy *et al.*, 1986) similarly emphasized the effect of vegetation on depositional processes.

In the Okavango Delta in northern Botswana large-scale changes in flow direction take place over timespans of decades to centuries (Wilson, 1973; Smith, 1976; Wilson & Dincer, 1976; Shaw, 1984). These events (known as channel avulsion) involve the progressive senescence and abandonment of one channel system, with the concomitant diversion of water to inundate a new area, leading to the formation of a new channel system. Based on studies of a section of an abandoned channel, as well as of a senescing channel, McCarthy *et al.* (1986) proposed that depositional processes, modified by vegetation, were responsible for channel avulsion in the Okavango Delta.

Since the study by McCarthy *et al.* (1986) others have focused on the infilling of backswamp areas by plant growth and peat accumulation (K. Ellery *et al.*, 1990, 1991), a process leading to the confinement of rapid water movement to in-channel areas within developing channel systems. Furthermore, characteristics of developing as well as senescing channels in the northeastern Okavango Delta based on morphometric (width, depth), hydrological (current velocity, degree of confinement, seasonal and longer term water level fluctuations), landscape forming (depositional vs erosional) and vegetation (within-channel and channel margin) characteristics have been described (W. Ellery *et al.*, 1990). These studies have illustrated interactions between vegetation and landscape-forming processes during channel initiation, development and senescence, and indicate that the model of McCarthy *et al.* (1986) was oversimplified in that it emphasized events late in the life of a channel. The aim of this study was to investigate these interactions along a gradient from developing to senescing channels, in order to present a more complete model of channel development and senescence.

The study area

The Okavango Delta forms part of an internal drainage system situated in north-western Botswana. The catchment in southern Angola is composed predominantly

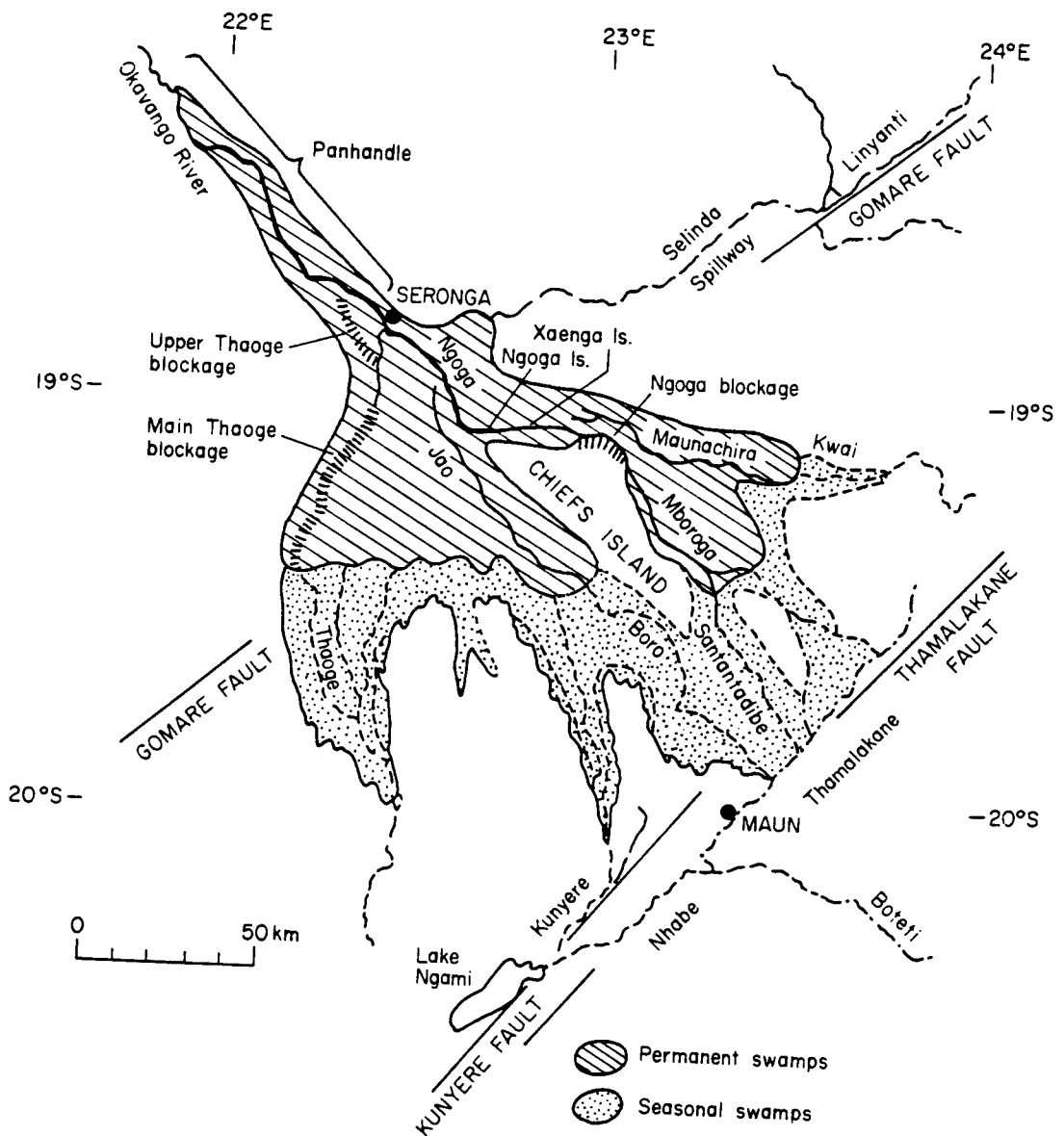


Fig. 1. Map of the Okavango Delta, Botswana, showing the major physiographic features and distributary channels.

of unconsolidated Kalahari sands of aeolian origin. These well sorted sands are brought into the Okavango Delta via the Okavango River, mainly as bed-load sediments. Suspended load is negligible. Downstream of the town Seronga the Okavango River divides into a number of distributary channels (Fig. 1). Overspill from these rivers gives rise to permanently inundated areas in the north, while seasonal inundation occurs in the south.

The five channel types recognized in a detailed study of channels in the Nqoga and Maunachira River systems (W. Ellery *et al.*, 1990) formed the basis of site selection in the present study. Distinctions between these channel types were based on differences in vegetation (rooted in the channel bed, as well as rooted in the peat deposits in areas flanking the channel), hydrology, whether or not the channels received sediments from source areas, and if so, for how long (W. Ellery, *et al.*, 1990). 'Long-term aggradational' channels had received sediments from source areas for considerably greater than 20 years, while 'short-term aggradational' channels had received sediments from source areas for less than 20 years. 'Primary filter' channels received their water supply as overspill from the aggradational

channels and, therefore, they were free of any bed-load sediment being introduced into the Delta from source areas. 'Confined outlet' and 'unconfined outlet' channels received their water supply as outflow from the primary filter channels, and also did not transport sediments introduced from source areas.

Methods

Channel development and change: aerial photographic interpretation

The nature of channel development was investigated in the lower Maunachira River, an area that appears to have been inundated relatively recently (P. A. Smith, pers. comm.), by comparing aerial photographs taken in 1937 and 1983. The scale, rate and nature of changes in flow and sediment transport, in a region of channel switching, were investigated by comparing aerial photographs of the lower Nqoga and upper Maunachira Rivers taken in 1937, 1951, 1969 and 1983. Current understanding of sedimentary patterns within the region of change (W. Ellery *et al.*, 1990) has provided insight into the temporal patterns of flow and sedimentation, and provides a useful framework for the interpretation of present cross-sectional morphologies within the study area, and hence determined site selection and interpretation of studies of active channel morphology and flow conditions.

Channel morphology and flow conditions

Channel cross-sectional morphology was determined at more than 60 sites, located in a stratified manner within the five channel types described by W. Ellery *et al.* (1990), by measuring the water depth at 2 m intervals across the channel. Peat thickness in areas flanking the channel was measured in a stratified subsample of these sites ($n = 30$) by pushing a metal pole through the peat until it could be felt to strike either the sandy substratum underlying the peat (usually the case) or any other impermeable layer. The peat in the study area has extremely low bulk density (100 kg m^{-3} ; Ellery *et al.*, 1989), and it was therefore not difficult to distinguish the presence of the substratum under the peat. Current velocity profiles were measured at each of these sites using a current meter at 2 m intervals across the channel, and at depth increments of 1 m. Current velocity of the surface waters in the areas flanking the channel was determined by measuring the rate of movement of fluorescent dye over a period of several minutes.

Evidence of channel development and change from the abandoned channel

In an attempt to integrate information from studies on active channels, a study was carried out along a section of the abandoned lower Nqoga River (Fig. 2). The former course of the Nqoga river in the area in which it is abandoned, was visible as a sinuous, sandy tract in which the original bar forms were still clearly distinguishable (McCarthy *et al.*, 1987). A dumpy level and staff were used to measure the level of the former channel bed in relation to the level of the surrounding areas. The stratigraphy of deposits within and adjacent to the former channel was recorded in a number of surveyed pits, and these were superimposed on the cross-sectional profile.

Results and discussion

Examination of active channel morphology and flow conditions

Within active channels in that study area there is an abrupt change in water depth at the channel edge between the sandy channel bed and the peat bank (Fig. 3),

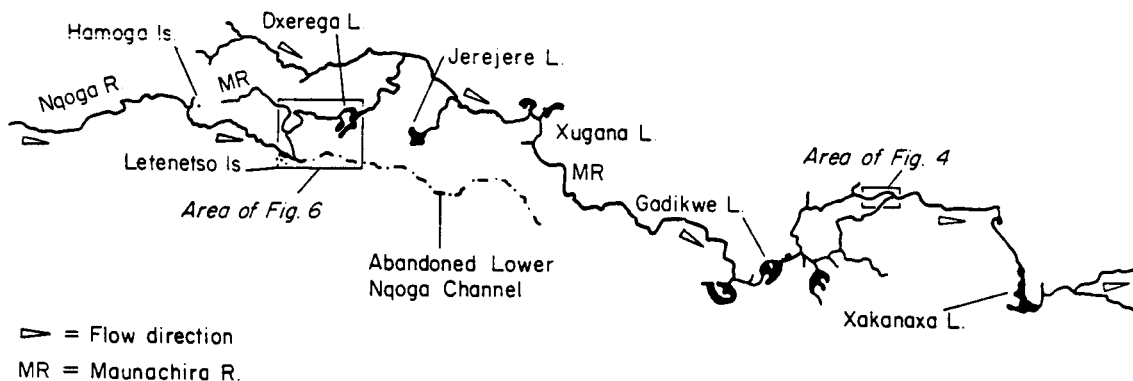


Fig. 2. Map of the study area in the perennial swamps of the northeastern Okavango Delta.

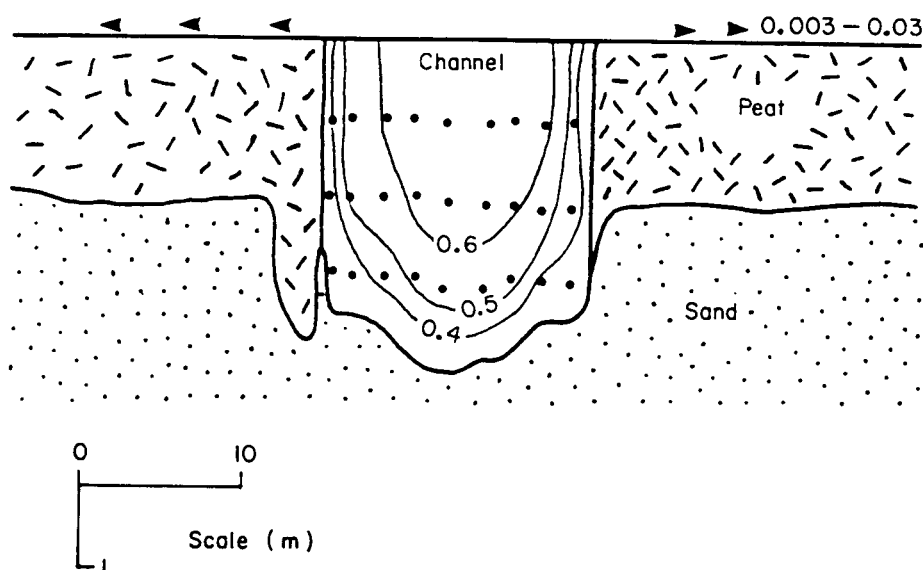


Fig. 3. Typical cross-sectional morphology and current velocity profile of a channel and channel margin in the Okavango Delta. Velocity contours are given in ms^{-1} .

which is always covered with vegetation. The current velocity of channels is highest in the middle of the channel close to the surface, and decreases with depth as well as towards the channel edges. The current velocity of surface water in the channel margin varies between less than 0.003 ms^{-1} to 0.03 ms^{-1} , which is one or two orders of magnitude lower than in many of the channels themselves. Although this can be regarded as typical, channels are variable in depth, width, current velocity and within-channel and channel margin vegetation (cf. W. Ellery *et al.*, 1990).

The evolution of channels in the northeastern Okavango Delta

Changes accompanying channel development: encroachment and erosion of the channel bed. The nature of channel change in the downstream reaches of the study area is illustrated in the comparison of 1937 and 1983 aerial photographs of the lower Maunachira River (Fig. 4a,b). In the earlier photograph (Fig. 4a) which was taken obliquely, the developing channel (W) appears sparsely vegetated with relatively unconfined flow, probably corresponding to an unconfined outlet channel (W. Ellery *et al.*, 1990). The physical characteristics of this channel type are

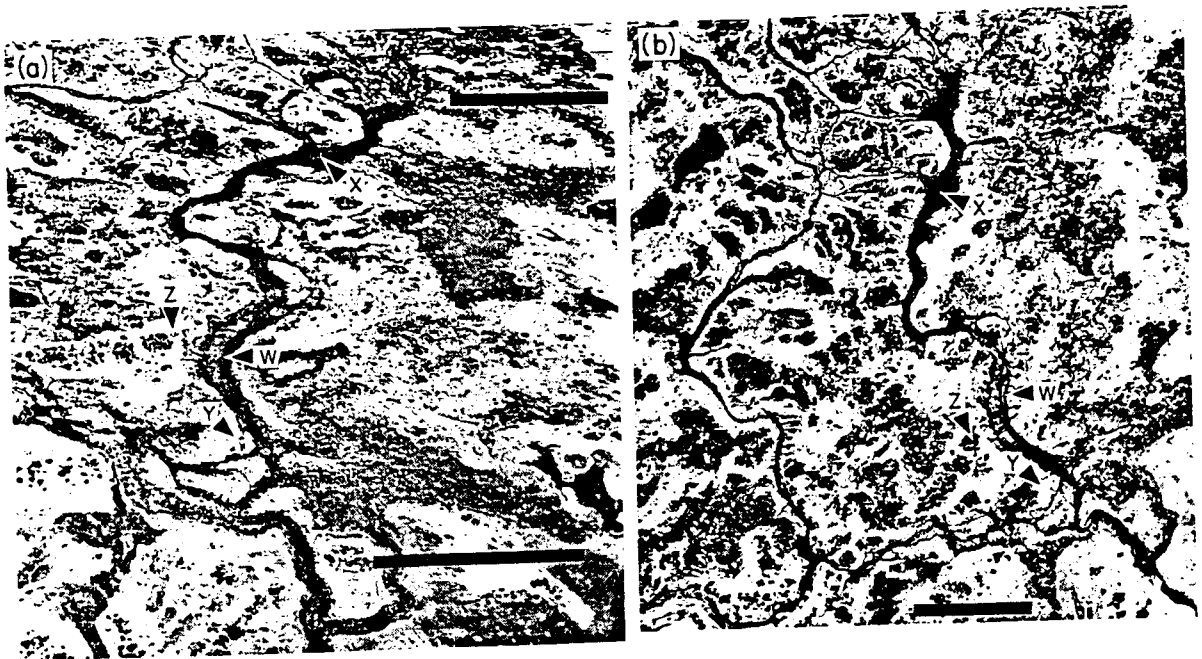


Fig. 4. Comparison of an oblique 1937 (a) and vertical 1983 (b) aerial photograph of a section of the lower Maunachira River illustrating how vegetation processes and peat formation lead to the confinement of water flow to in-channel areas. Horizontal bars indicate a distance of 0.5 km. Features indicated are the developing channel (W), areas of open water with a few emergent species (X), sites densely colonized by swamp emergents (Y) and island vegetation (Z).

Table 1. Summary of channel dimensions, flow conditions, peat thicknesses and landscape forming processes that characterize the channels and channel margins in the northeastern Okavango Delta

Channel type	Flow rate (ms ⁻¹)	Width (m)	Depth (m)	U/C*	Peat thickness (m)	Landscape process
Unconfined outlet	«0.3	25–75	1.5–3	U	1.5–2.5	Pre-erosional
Confined outlet	<0.3	10–30	1.5–3	C	1.5–2.5	Early erosional
Primary filter	<0.5	10–30	2–3	C	1.5–2.5	Erosional
Short-term aggradational	<0.7	10–25	3–4	C	2.5–3.5	Early depositional
Long-term aggradational	<0.6	10–25	3–4	C	3.0–4.5	Depositional

*U/C = Unconfined/confined flow, respectively.

indicated in Table 1. For comparison, areas labelled 'X' represent areas of open water with a low density of emergent aquatics, while those labelled 'Y' and 'Z' are sites colonized by dense stands of emergent aquatics and island vegetation, respectively.

By 1983 a section of the channel previously sparsely colonized had become colonized by dense stands of emergent vegetation (Fig. 4b). In addition to being narrower, the current velocity would probably have increased, the channel here having the characteristics of a confined outlet channel (Table 1). Vegetation processes including plant succession and peat formation, as well as the encroachment

of emergent aquatic species from the margins of the developing channel, lead to a reduction in channel width (K. Ellery *et al.*, 1990). The rate of these encroachment processes appears to be extremely slow and is modified by animal activity, particularly the repeated movement of hippo (*Hippopotamus amphibius* (L.)) along paths between resting and terrestrial feeding sites (K. Ellery *et al.*, 1990). This promotes channelized water flow within the developing swamp, thereby promoting channel development.

Outlet channels in the lower reaches of the Delta (Gadikwe to Xakanaxa madiba, Fig. 2) are of relatively recent origin (Smith, 1976), and do not receive sediments from source areas. They receive their water supply as overspill and seepage from channels further upstream, with rainfall an important contributor to the water supply (W. Ellery *et al.*, 1990). The slight increase in depth that appears to accompany encroachment, despite the peat deposits flanking the channel being of similar thickness (Fig. 5a,b; Table 1), appears to be caused by erosion of the channel bed. These channels are therefore considered to be at a pre- to early erosional stage of development, with encroachment from channel margin areas being important processes characterizing channel development.

'Primary filter' channels (W. Ellery *et al.*, 1990) between Dxerega and Gadikwe madiba (Fig. 2), are between 10 m and 25 m wide, and generally have higher energy hydrological regimes than the outlet channels, with mean current velocities up to 0.5 ms^{-1} (Table 1). This suggests a greater degree of confinement than in the outlet channels. They receive their water supply as overspill and seepage from source channels, but do not receive sediments. Water depth is between 2 m and 3 m, which is greater than in the case of the outlet channels, but the thickness of the peat deposit areas flanking the channel is similar to that of the outlet channels—between 1.5 m and 2.5 m (Fig. 5c; Table 1). This indicates that the channel is incised into the pre-channel substratum, and these channels are therefore considered to be at a more advanced erosional stage than the previous channel type.

Changes accompanying channel avulsion: Sediment deposition on the channel floor. Changes in the direction of water flow and sediment transport during a channel avulsion event are illustrated in the sequence of aerial photographs of the lower Nqoga and upper Maunachira Rivers taken in 1937, 1951, 1969 and 1983. These are presented in stylized form (Fig. 6a,b,c,d).

The Nqoga River in 1937 was connected directly to the Okavango River, and it would have received sediments from source areas, primarily as bed-load. *Cyperus papyrus* L. blockages had developed in the lower reaches of the Nqoga Channel, which must, therefore, have been senescing for prior to this (Wilson, 1973). The Maunachira River, however, received its water supply as overspill and seepage from the aggrading Nqoga River; there were no direct channel connections between the two river systems (Fig. 6a) along which sediment could move. At the point at which the present Letenetso Channel joins the Nqoga River (Fig. 6d), a small open water body ('lediba' in Setswana; plural = 'madiba') was present (A, Fig. 6a). The only outlet from the lediba was a narrow hippo path, which is only just visible in the 1937 photograph (B, Fig. 6a).

By 1951 the lower Nqoga River downstream of its present junction with the Letenetso Channel had further abandoned as indicated by the upper limit of papyrus blockages at that time (Fig. 6b). The lediba adjacent to the Nqoga River

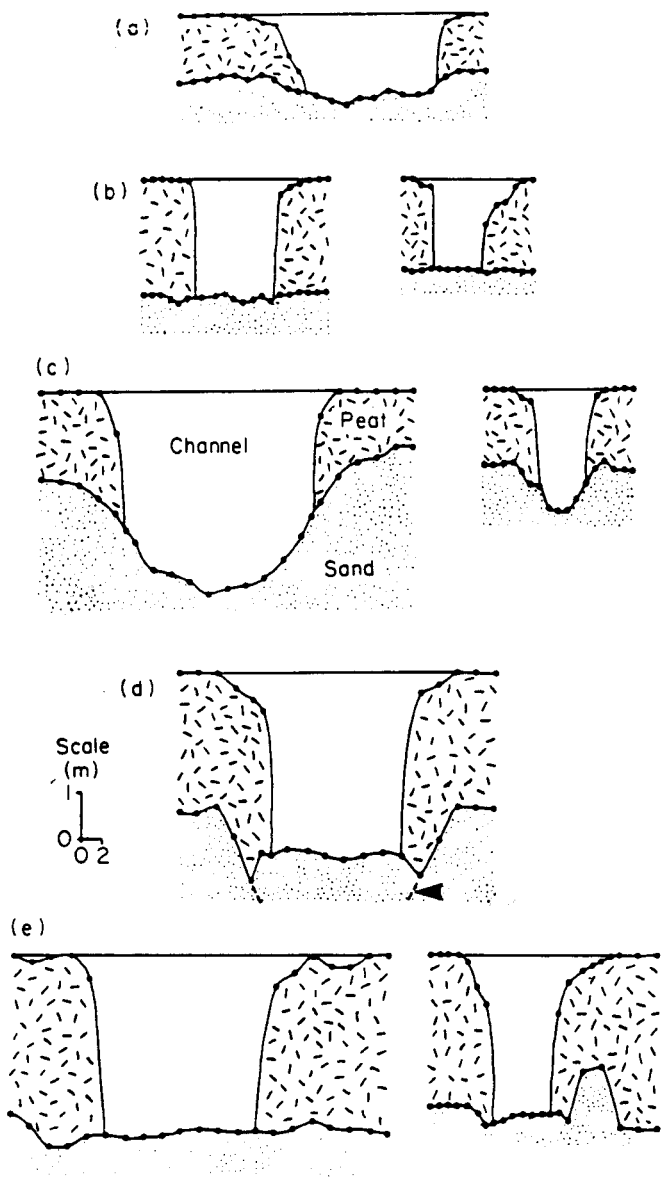


Fig. 5. Cross-sectional profiles of examples of (a) an unconfined outlet channel, (b) a confined outlet channel—both of which are at a pre- or early-erosional stage, (c) a primary filter channel which is at a more advanced erosional stage, (d) a short-term, aggradational channel which is at an early depositional stage, and (e) a long-term aggradational channel which is at an advanced stage of deposition. The broken lines (indicated by arrow in d) represent the position of the erosional surface prior to the introduction of bed-load sediments into this channel reach.

(A, Fig. 6b) had partly closed by a combination of vegetation and sedimentation processes, but it still prevented the movement of sediment into the developing Letenetso Channel and Maunachira River. In addition to these changes, the former hippo channel leading out of this lediba had been widened compared to 1937 (B, Fig. 6b), suggesting that erosion was an important feature of the formation of the Letenetso Channel.

The Nqoga River downstream of its present confluence with the Letenetso Channel was entirely abandoned by 1969 (Fig. 6c), the lediba adjacent to the Nqoga Channel had been entirely closed, and closure of Bokoro Lediba (Fig. 6c, C), which at that time acted as a trap preventing the movement of sediment from source areas into the Maunachira River, had started. With the exception of those portions remote from the developing Letenetso Channel (Fig. 6d, C*), Bokoro Lediba had become completely closed by 1983. Its closure enabled sediments from source areas to enter the Maunachira River for the first time in the present cycle of inundation. These sediments were transported as far downstream as Dxerega Lediba (Fig. 6d), which presently acts as a trap preventing the movement of

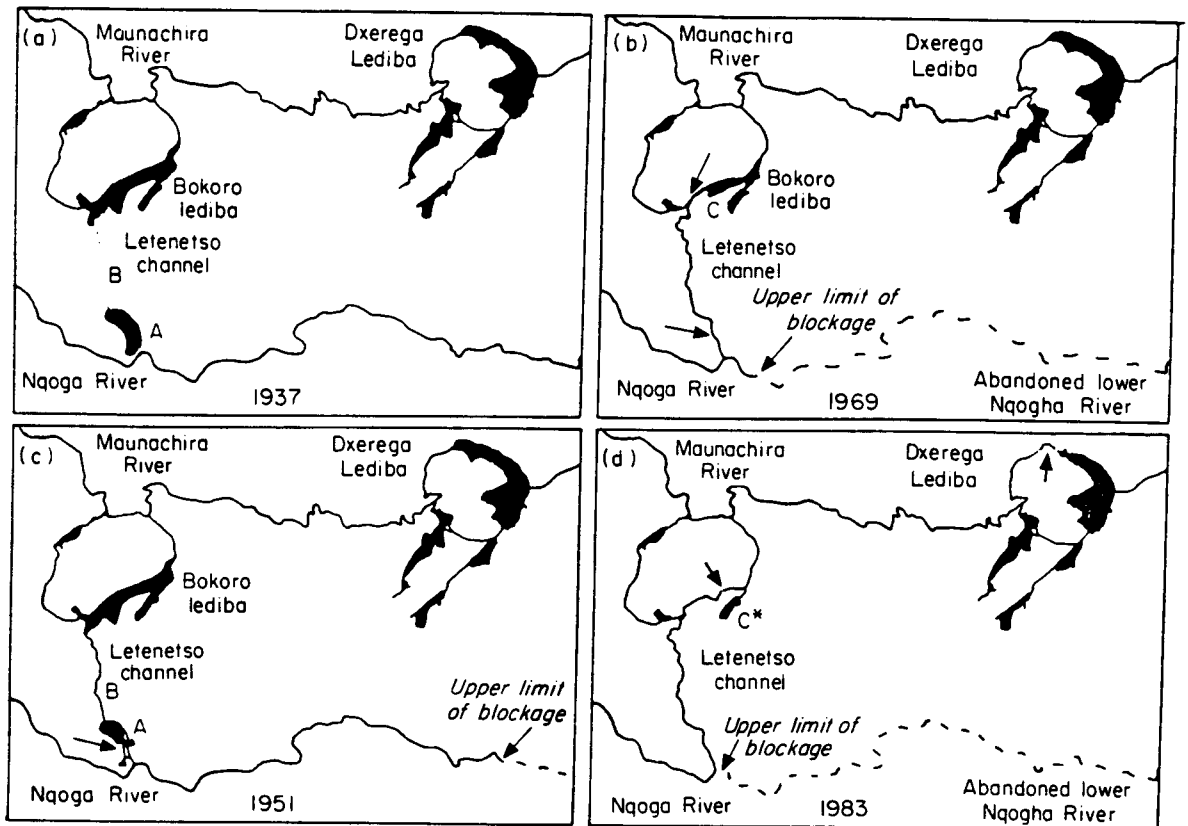


Fig. 6. Comparison of physiographic features indicated by comparison of 1937 (a), 1951 (b), 1969 (c) and 1983 (d) aerial photographs illustrating the abandonment of a section of the lower Nqoga River, the development of the Letenetso Channel linking the Nqoga and Maunachira Rivers and closure of madiba along the courses of the developing Letenetso Channel. Arrows indicate features that have changed most markedly since the previous photograph.

sediments into the Maunachira River downstream of this point, and which is presently undergoing closure.

The processes accompanying channel senescence and abandonment are reflected in the cross-sectional morphologies of various channel sections. Short-term aggradational channels upstream of Dxerega lediba, but downstream of the confluence of the Letenetso Channel with the Maunachira river (Fig. 2), are between 10 m and 25 m wide, and experience relatively high current velocities up to 0.7 ms^{-1} (Table 1). Water depth is between 3 m and 4 m, and is greater than that of the substratum sands underlying the peat deposits flanking the channel which are between 2.5 m and 3.5 m thick (Fig. 5d). The troughs in the substratum sands adjacent to the channel appear to correspond to a previous erosional surface of the channel bed (inferred 'pre-depositional' surface, Fig. 5d).

The long-term aggradational channels comprising the lower Nqoga river and Letenetso Channel (Fig. 2) have received sediments from source areas for a longer period than the short-term aggradational channels, but have similar dimensions, with a width between 10 m and 25 m, and a depth between 3 m and 4 m (Table 1). The level of the channel bed, however, is similar to that of the pre-channel substratum underlying the peat deposits flanking the channel (Fig. 5e), creating the impression that they are neither erosional nor depositional. Hydrological data have shown that the level of the channel bed in this region has risen approximately 0.6 m during the 10 year period from 1975 to 1985 (McCarthy *et al.*, 1986; W. Ellery

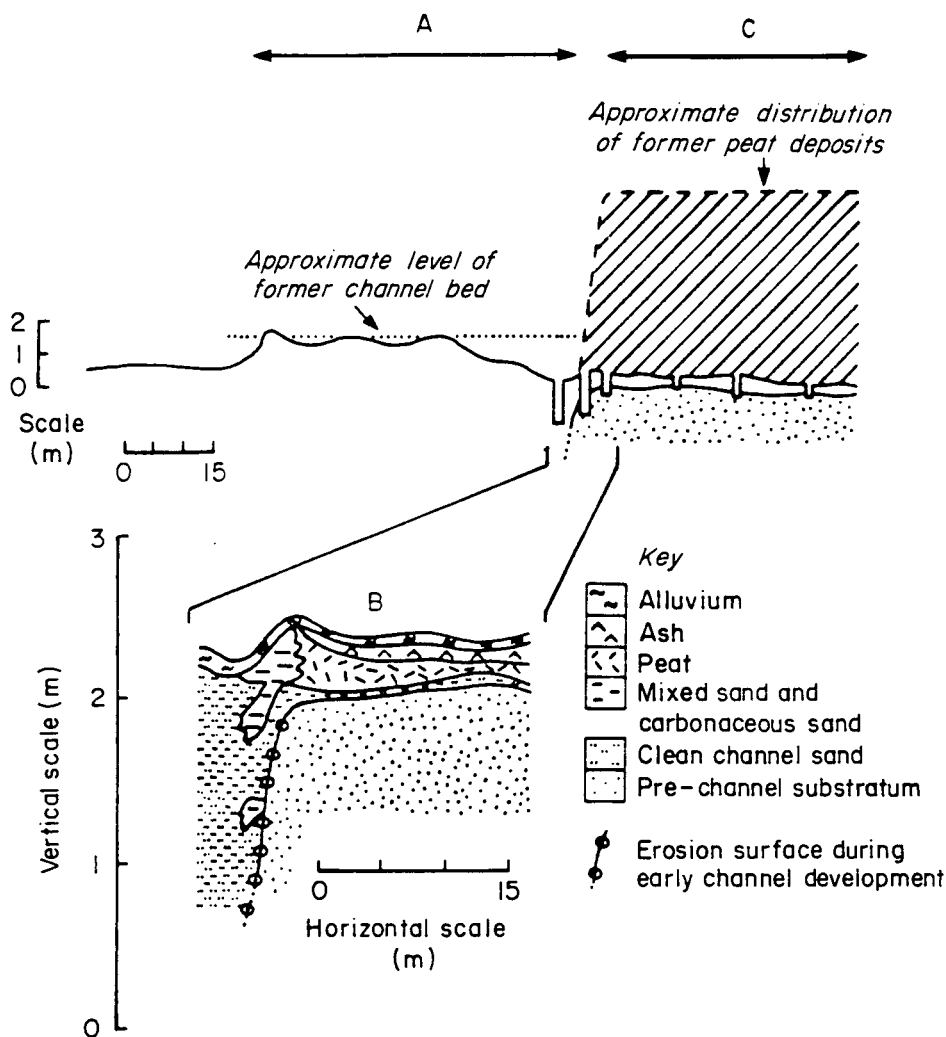


Fig. 7. Channel profile and cross-section of a region of the abandoned lower Nqoga River showing the distribution of the former channel (A), channel margin (B) and peat deposits flanking the channel (C) at the time of abandonment. The inferred distribution of pre-channel and channel sands is also illustrated.

et al., 1990), suggesting that it is depositional. Therefore, the present-day sandy channel bed appears to represent a depositional surface and *not* the surface that was present prior to the introduction of sediments from source areas along this section.

A study of the end product of channel development and senescence

In areas flanking the former channel (i.e. at the abandoned section of the Nqoga river, Fig. 2) the peat has been largely removed by subsurface peat fires which have passed through the area subsequent to abandonment (Ellery *et al.*, 1989). The ash residue of the former peat deposits overlies a thin layer of peat, which in turn overlies the sand that was present prior to the development of any channels in the area ('pre-channel substratum'; Fig. 7). The sands of the pre-channel substratum within the area of the abandoned lower Nqoga River were grey-black, and easily distinguished from the channel sands themselves which were clean and off-white. The former channel bed (Fig. 7, Region A) was raised approximately 1 m above the level of the ash-covered plain surrounding the abandoned channel (Fig. 7, Region C). Prior to abandonment the peat deposits must therefore have been considerably

thicker than 1 m in order to confine the flow of water and sediment, probably—as in the case of long-term aggradational channels—in the region of 4–5 m.

Excavation of the former channel margin (Fig. 7, Region B) revealed that the pre-channel substratum was deeply eroded in the region of the former channel. Erosion of the pre-channel substratum sands was therefore confined to within the former channel, and would have taken place in the absence of the introduction of sufficient bed-load sediments to overcome net erosion. Subsequent to the erosional phase the channel bed became depositional as indicated by the formerly eroded channel being filled with clean river sand. This was the result of the introduction of bed-load sediment from source areas into this channel. Once again the channel bed was the locus of bed-load sediment deposition, and in this case it resulted in the channel bed becoming progressively raised, ultimately to above the level of the pre-channel substratum (Fig. 7). In order for flow and sediment to have been confined to the channel during the period of aggradation of the channel bed, it must have been accompanied by peat accumulation in areas flanking the channel.

A conceptual model of the life of a channel in the Okavango Delta

An earlier model of channel change in the Okavango Delta emphasized the instability of channels subject to depositional processes (McCarthy *et al.*, 1986). This model examined the fate of sediments entering the Delta from source areas. They are transported primarily as bed-load, being rolled along the floor of channels which receive their water supply by direct connection to source areas. The presence of vegetated peat banks confines the bed-load sediments to within channel areas of the source channels, while water is lost from them as overspill and seepage. This results in a decline in the ability of the channels to carry bed-load sediment, which is deposited on the channel bed causing aggradation. These events are accompanied by aggradation of the peat banks flanking the channel, aggradation being most rapid in areas close to channels due to increased nutrient supply compared to backswamp areas. This causes the channel as a whole to become raised relative to the surrounding areas resulting in an increase in hydraulic gradients at right angles to the channel axis. Eventually hydraulic gradients away from the aggrading source channel become so great that they become subject to capture by headward erosion in a developing channel elsewhere on the Delta surface (McCarthy *et al.*, 1986).

Implicit in the above model was the suggestion that the final level of the channel bed above the surrounding substratum would be equivalent to its total aggradation, and also that the peat deposits at the time of abandonment would have been 3–4 m greater than this final level. It is suggested that by ignoring processes that take place during channel initiation and development, the model of McCarthy *et al.* (1986) provided an incomplete picture of channel change. A more complete explanation is provided in a conceptual model (Fig. 8).

An area that was previously dominated by seasonally flooded plant communities would be increasingly inundated (Fig. 8a(i); Table 2) as a result of increased water loss from an aggradational channel (Fig. 8a(iii)). Aggradation of the lower reaches of the Nqoga River, and its abandonment since the 1920s, appears to have resulted in an increase in water flow along the Maunachira River system in relatively recent times (Wilson, 1973; Smith, 1976). This view is supported by stands of dead trees which often occur in the vicinity of the lower Maunachira

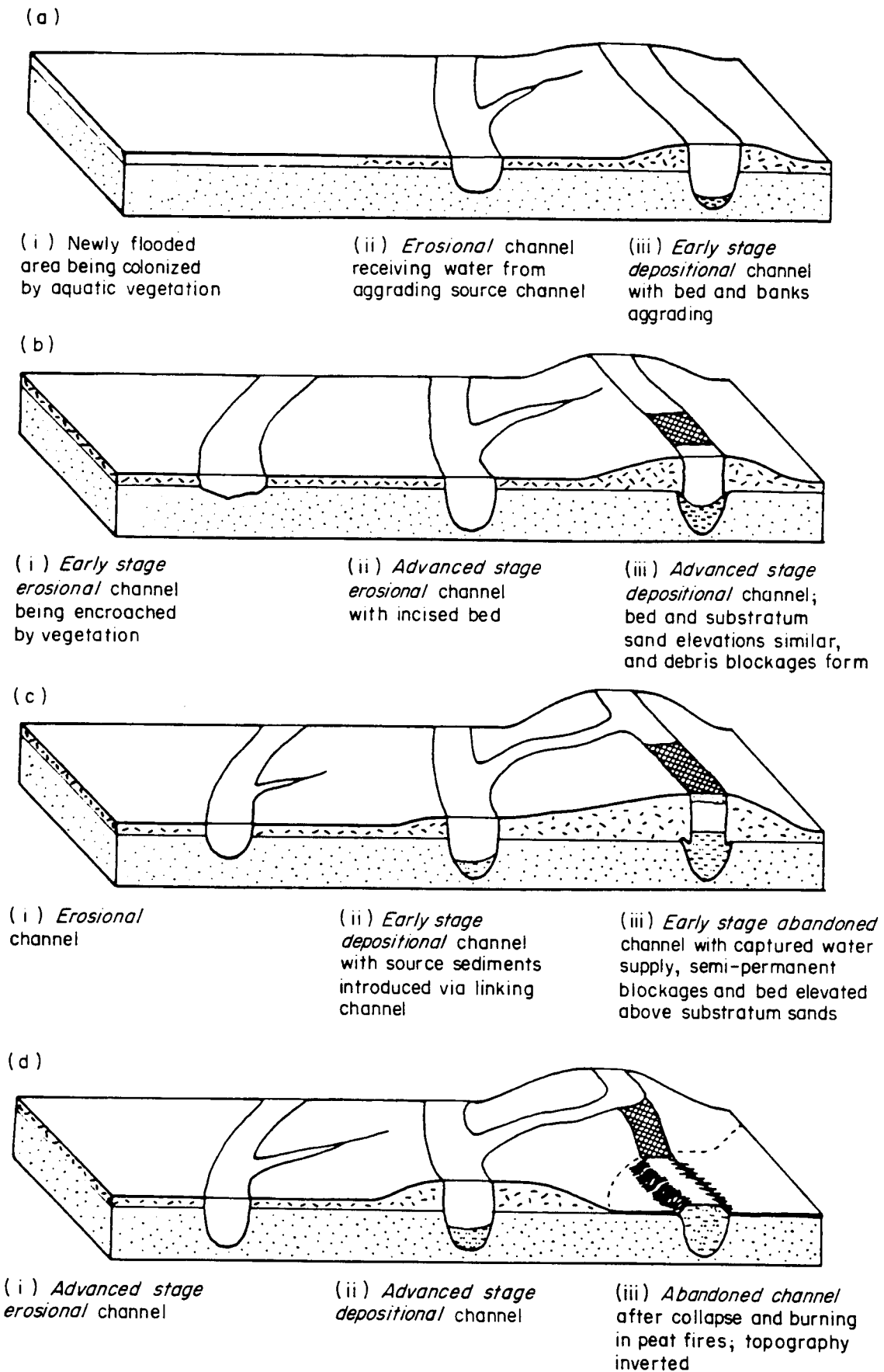


Fig. 8. A representation of the conceptual model of channel dynamics in the northeastern Okavango Delta. See text for explanation.

Table 2. Processes considered to characterize the transitions between channels in different stages of development in the northeastern Okavango Delta

Channel type	Phase of development	Transition processes
↓ ↓ (Post abandonment)		
↓	Inundation	Colonization of inundated areas by aquatics (topographically modified)
Unconfined outlet		
↓	Early channel development	Plant succession and peat formation in backswamp areas, hippo activity and encroachment of unconfined open water areas
Confined outlet		
↓	Channel development and maturity	Plant succession and peat formation in backswamp areas, hippo activity, vegetation encroachment, bed and headward erosion within channel areas
Primary filter		
↓	Channel ageing*	In-channel areas subject to headward erosion, water and sediment capture, and aggradation
Short-term aggradational		
↓	Channel senescence*	Aggradation, vegetation debris deposition and encroachment, reduced flow
Long-term aggradational		
↓	Channel abandonment*	Desiccation, peat fires, topographic inversion
(Post abandonment)		
↓ ↓		

*Process described in model of McCarthy *et al.* (1986).

River system in low-lying areas that presently are either permanently or seasonally inundated.

In the absence of wetland plant communities, flow across the flooded areas would be predominantly as sheet flow. As the area continues to flood, wetland plant communities would become established (K. Ellery *et al.*, 1990). The initial biotic response of the establishing wetland communities would appear to be determined by interactions between the hydrological regime (rate, depth and duration of flooding, and seasonal water level fluctuations), and topography (Mitsch & Gosselink, 1986; Breen *et al.*, 1988). Vegetation processes accompanying wetland development including plant succession, peat formation and vegetative

encroachment from marginal areas, would decrease the total area of open water (Fig. 8b(i)) and promote channel flow along areas offering least resistance to water movement. Field observations indicate that hippo paths in such backswamp areas naturally capture and channelize flow. Hippo movement and increased flow rate then act as positive feedback mechanisms preventing plant growth and peat accumulation, and promoting channel development.

As confinement of water to in-channel areas increases, the developing channel would become increasingly erosional (Fig. 8b(i) a(ii)). The channel bed is the locus of erosional processes during channel development and maturity (Table 2), resulting in the channel bed being topographically lower than the surrounding substratum sands. Throughout the early life of a channel the thickness of its flanking peat deposits appears to remain fairly constant, despite increased water flow by a combination of increased water loss from the aggrading source channel and the infilling of open water areas by peat formation in the backswamp areas. This increase in channelized flow is accommodated by the increase in channel cross-sectional area consequent upon erosion of its bed.

Erosion of the channel bed would be accompanied by headward erosion of the upper reaches of the developing channel (Fig. 8a(ii), b(ii)), eventually leading to the capture of both water and sediment from the ageing, aggrading source channel (Fig. 8c(i)). Hippo trails facilitate river capture and the H-configuration of the capture process (Fig. 8), which is considered characteristic by P. A. Smith (pers. comm.), appears due to changes in the most favourable hydraulic gradient as aggradation takes place. Prior to aggradation the hydraulic gradient would be in the direction of the channel axis, but as the channel and peat banks aggrade, the most favourable hydraulic gradient would shift gradually away from the channel axis until, at an advanced stage, it would be at right angles to the channel. The position and course of the channel linking the developing and senescing channels are thus determined by the presence and erosion of an existing hippo path with a direction approximating the new hydraulic gradient.

Since capture is accompanied by the introduction of bed-load sediments into the developing channel, the capturing channel soon becomes aggradational (channel ageing), initiating the cycle of change described by McCarthy *et al.* (1986).

A feature of the senescing channel (Table 2) is the formation of vegetation debris blockages within the channel, and the encroachment into the channel by vegetation growing on the channel banks (Wilson, 1973; Fig 8b(iii), c(iii)). At the time of its demise, the level of the channel bed of the declining source channel is raised above the level of the surrounding substratum sands by as little as 1 m, despite total aggradation having been considerably greater than this.

Subsequent to avulsion, the former source channel below the avulsion point experiences desiccation, and the peat deposits flanking it become susceptible to collapse and destruction in peat fires (Ellery *et al.*, 1989). This results in the virtual restoration of former topographic levels (McCarthy *et al.*, 1987; 1988), with the exception of the former channel bed which is raised above the surrounding substratum sands (Fig. 8d(ii)). The restoration of its former topography makes the area susceptible to inundation as a result of aggradational processes within a channel elsewhere on the surface of the Delta, with the initiation of the entire sequence of events once again (Table 2).

Implications for local topography

Large-scale changes in water flow distribution within the Okavango Delta have been described (Wilson, 1973; Smith, 1976; Wilson & Dincer, 1978; Shaw, 1984), and the mechanisms causing these changes in flow have been postulated (McCarthy *et al.*, 1986). The implications of these processes for the abandoned channel section have also been described (McCarthy *et al.*, 1987; 1988; Ellery *et al.*, 1989). The past emphasis has been on aggradation of the channel bed and the subsequent collapse of the peat deposits flanking the former channel. In a more regional context, a change in flow from one region to another may leave pre-erosional, early erosional and advanced erosional channels without a water supply. The topography that results from an avulsion event may therefore leave channels as features incised into the surrounding substratum sands (erosional features) or standing out as positive topographic features (depositional features). Channels may therefore contribute to island formation or to future channel courses with a subsequent phase of inundation, depending upon their stage of development at the time of their abandonment.

Conclusions

This cycle of erosion and deposition appears to have characterized the lower Nqoga River since its initiation late during the last century, and the concomitant increase in flow along the Maunachira River system since the 1920s. The study illustrates the importance of understanding the nature of interactions between hydrology, vegetation processes and landscape-forming processes in elucidating the determinants of wetland dynamics within the Okavango Delta. The emphasis in wetland studies as a whole on hydrology and biota has resulted in the neglect of sedimentary processes as determinants of wetland structure and function. The nature and fate of past and present sedimentary characteristics would appear to be an important determinant of the character and dynamics of wetland ecosystems in general and are clearly aspects that warrant further investigation.

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