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The sedimentary dynamics of active fluvial channels on the Okavango fan, Botswana

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ABSTRACT

The 1800-km^2 Okavango alluvial fan of northern Botswana represents an unusual depositional setting in which peat-forming perennial swamps (6000 km^2) occur in a region of aeolian and semi-arid sedimentation within an incipient graben of the East African Rift. A channel system distributes water and sediment on the fan surface but cannot contain seasonal flood water, which spreads laterally from the channels through permeable channel margins, sustaining the flanking swamps. All sediment introduced is deposited on the fan. A detailed study of sediment movement and associated hydrological conditions in the channels was undertaken to examine sediment dispersal. Bedload greatly exceeds suspended load (at least by a factor of four). Vegetation and peat form permeable levees which confine the channels. In the upper reaches, two-way exchange of water occurs between channel and swamp depending on the season, but on the fan itself, channels lose water to the swamp. Bedload measurements reveal that the channel system is in a state of grade disequilibrium, with interspersed depositional and erosional reaches. Deposition of most of the incoming bedload occurs on the upper portion of the fan in a meandering and anastomosed channel system, but on the midfan, deposition of bedload occurs by channel-bed aggradation, at a rate of up to 5 cm yr^{-1}. Further down slope, the channel enters a large lake where all remaining bedload is deposited. The presently observed sedimentation patterns may be due to a recent disturbance of the fluvial system, either by avulsion or neotectonics.

INTRODUCTION

The Okavango swamps, locally referred to as the Okavango Delta, are situated in northern Botswana (Fig. 1) on the fringes of the semi-arid Kalahari 'Desert' of central southern Africa. Although possessing a 'bird's-foot' distributary system, the Okavango is in fact a large (18 000 km^2) alluvial fan (UNDP, 1977). It represents the terminus of a fluvial system which drains the tropical, central highlands of Angola. Some 95% of the annual inflow ($10{\cdot}5 \times 10^9$ m^3) is lost by evapo-transpiration (Dincer *et al.*, 1981) and all of the introduced sediment is deposited on the fan surface. This deposition has resulted in the accumulation of about 300 m of sediment (Hutchins *et al.*, 1976). The age of initiation of the fan is unknown.

The fan owes its origin to a southwesterly extension of the East African Rift system which has given rise to a large graben structure transecting the course of the Okavango River (du Toit, 1927; Scholtz, 1975) and within which sedimentation is confined. The rift is developing across the Cenozoic intracratonic Kalahari Basin (du Toit, 1933) which at present is dominated by aeolian deposits extending as far north as the equator. The fan sediment is largely derived from the reworking of these aeolian deposits. The fan is dominated by an extensive area (6000 km^2) of perennial swamp land, which includes an active peat-forming environment, despite being surrounded by semi-arid to arid climatic depositional features such as aeolian dune fields (Cooke, 1976; Mallick *et al.*, 1981; Heine, 1982; Cooke & Verstappen, 1984). These tectonic, geomorphological and sedimentary features make the Okavango fan an unusual depositional system.

The investigation reported here was conducted to examine the sedimentation dynamics of the major

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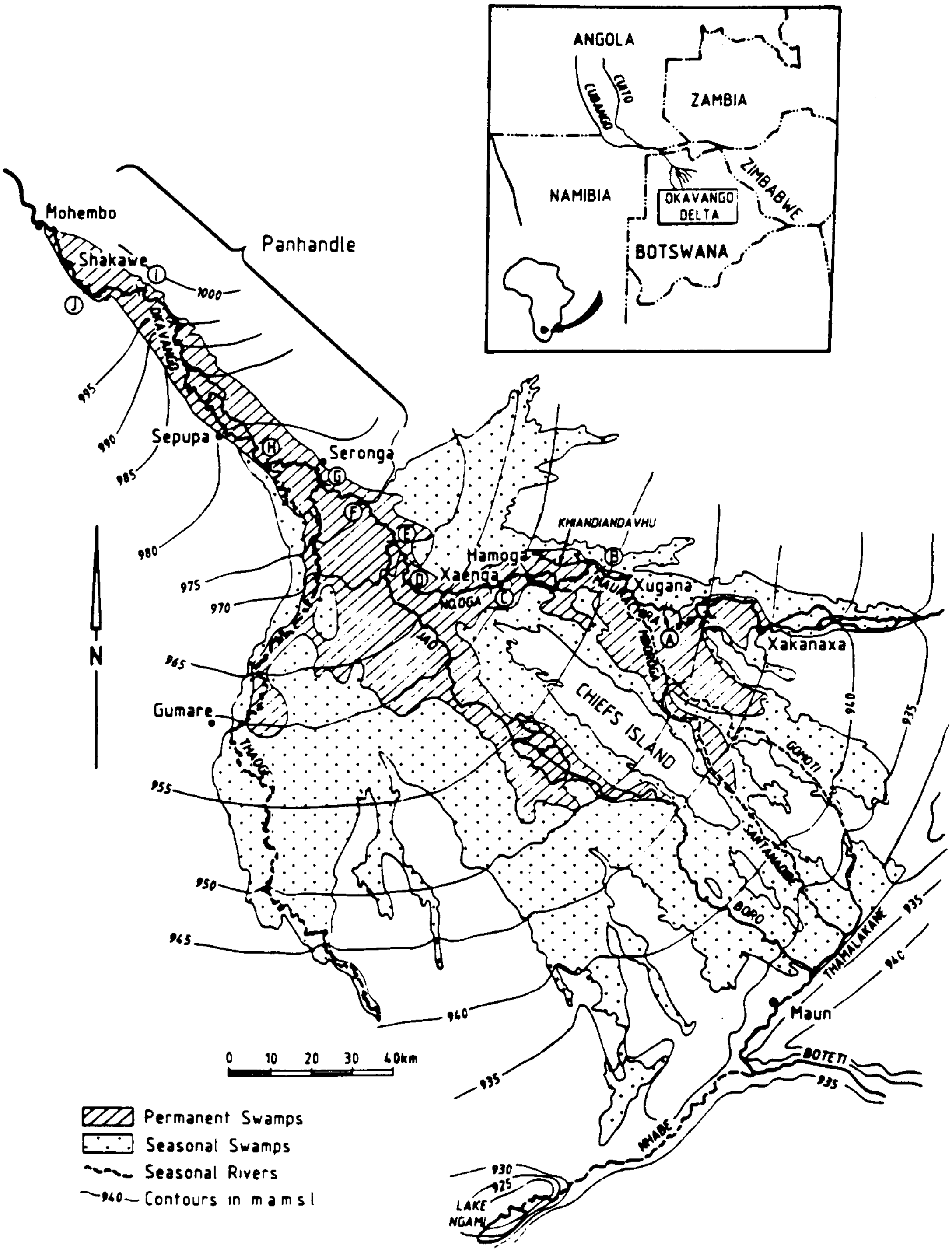

Fig. 1. Location and subregions of the Okavango Delta. Topographic contours are based on a map compiled by UNDP (1977) and are only approximate. Study sites are lettered A–J. At sites E and G, E_B and G_T are located at the head of the Jao/Boro and Thaoge distributaries respectively; E_N and G_N were located immediately upstream of these distributaries on the main channel (Nqoga).

fluvial channel system with particular emphasis on the upper, permanently flooded portion. Most of this region is covered by impenetrable swamp land and there are immense logistical difficulties in operating in this remote region. Mechanisms of deposition are not immediately apparent in this large, flat terrain. Accordingly, the approach used in this study was to measure sediment and water discharge at various points along the fluvial system to determine regions of aggradation and degradation. This knowledge, when combined with other information such as channel morphology and long-term hydrographical changes, provides insight into the fluvial processes operating on the fan.

OKAVANGO FAN CHARACTERISTICS

The Okavango Delta swamps are traditionally divided into three parts (Wilson, 1972): (i) the upper Panhandle, where swamps are confined between low shoulders of Kalahari sand, which rise about 4 m above the floodplain, and represent fault scarps (Hutchins *et al.*, 1976); (ii) the largely unconfined perennial swamps of the fan itself; and (iii) the unconfined, lower, seasonal swamps or floodplains (Fig. 1). The average gradient across the delta is about 1:3500 (0·00029) (Wilson & Dincer, 1976). The main channel system at present is the Okavango–Nqoga–Maunachira system (Fig. 1) which succeeded the Okavango–Thaoge system which dominated water distribution in the last century (Wilson, 1972; Shaw, 1984).

Systematic hydrological monitoring in the delta has been undertaken for several decades and hydrological studies have also formed a major part of two UN-funded projects in the delta. As a result of this and other ongoing studies by the Department of Water Affairs of Botswana, the hydrology of the delta is well known and a predictive hydrological model has been established (Dincer *et al.*, 1987). Summer rainfall (December–February) in central Angola is captured by the Okavango River, where the water discharge peaks in about April (Fig. 2a). The flood wave reaches the lower end of the Delta in about July (Fig. 2b) (Wilson, 1972; Wilson & Dincer, 1976). The channel system cannot contain the seasonal flood water which therefore spreads laterally through the surrounding swamps, discharging over a wide area to form the seasonal swamps or floodplain of the lower delta. This water is gradually lost by evapo-transpiration and groundwater seepage during the succeeding months, but some 6000 km^2 remain permanently inundated.

A significant feature of the *permanent* swamps is the seasonal variation in water level. At Shakawe, near the top of the Panhandle (Fig. 1), the water level has a seasonal variation of 1·5 m or more, but this decreases to only 15 cm in the region where the Jao/Boro separates from the Nqoga (Fig. 1) (Wilson & Dincer, 1976), decreasing further to about 6 cm at Xaenga Island (Fig. 1) after which fluctuations remain small. On the floodplain, seasonal water-level fluctuations are of the order of 2 m.

Much of the flow permeates through the swamps, which consist of vegetation rooted in a substrate of partly decomposed plant material with variable amounts of interstitial inorganics, normally in excess of 1 m thick (McCarthy *et al.*, 1988a, b, 1989). Typically, the substrate contains more than 50% free water and is permeable. *Cyperus papyrus*, a giant sedge, dominates the vegetation of the perennial swamp, with subordinate *Phragmites* spp. and *Miscanthus junceus*. The roots and rhizomes of these plants stabilize the substrate, particularly on the channel margins (McCarthy *et al.*, 1988a). Aerial observations indicate that the density of swamp vegetation decreases away from the channels and is much lower in

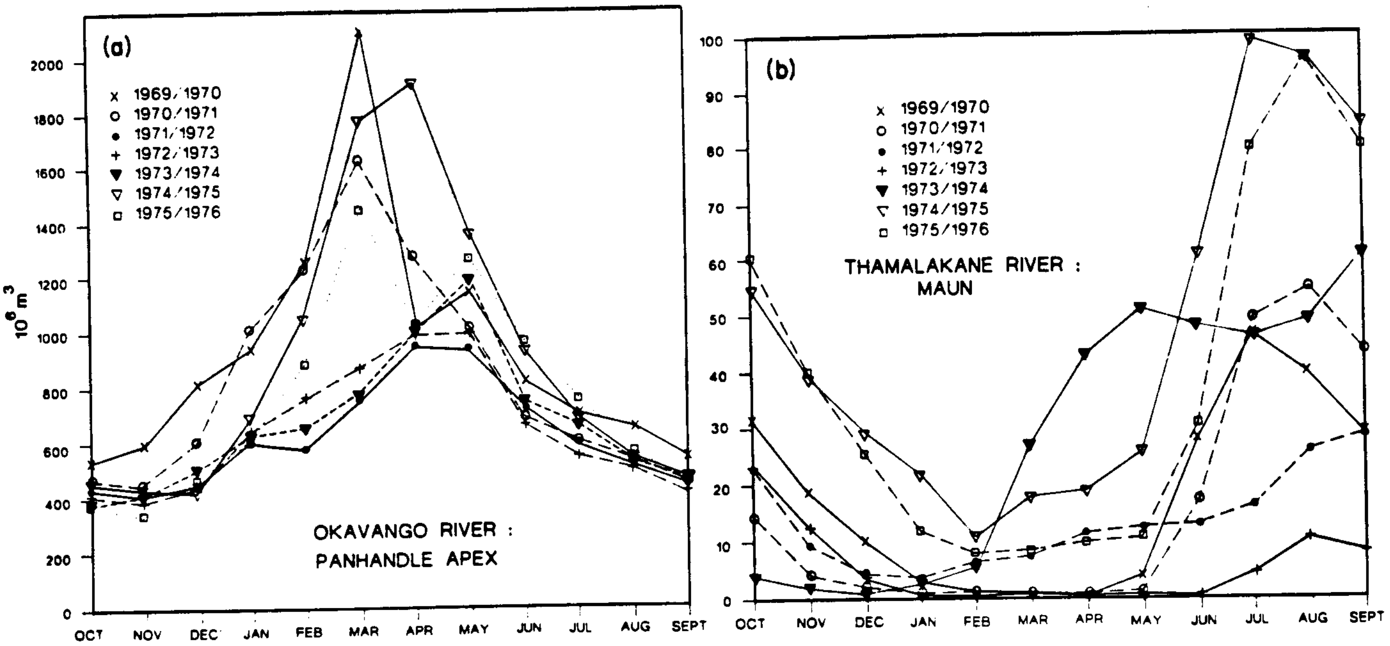

Fig. 2. Hydrographic records of the flow at (a) the apex of the Panhandle and (b) the lower end of the fan (data from UNDP, 1977).

the backswamp areas compared with the channel margins. While channel margins are well defined, they are permeable and permit both surface and subsurface water loss from the channels (McCarthy *et al.*, 1989). Particulate sediment introduced into the delta consists of: (i) bedload sand which is confined to the channels by the flanking vegetation (McCarthy *et al.*, 1988a), and (ii) small quantities of suspended load comprising clay and organic matter.

METHODS

Introduction

The survey covered a channel distance of 300 km, equivalent to a straight-line distance of 150 km, along the major waterway of the fan (Maunachira, Nqoga and Okavango channels). Ten sites were selected for detailed investigation (sites A–J in Fig. 1). In addition, the distributaries which supply the Jao/Boro and Thaoge channels were investigated (sites E_B and G_T respectively). According to available maps, the Jao/Boro and Thaoge channels are each fed by two distributaries from the Nqoga. However, at the time of our survey, each was supplied by a single channel only, the second being blocked by vegetation in both instances. Study sites were located on relatively straight sections of channel where no pronounced thalweg was present, an important factor in bedload studies (Hubbell & Stevens, 1986), and were located in order to bracket major regions of channel anastomosis. At each study site, the hydrological and sedimentological parameters given below were recorded. The major survey was undertaken during the period 28 December 1987 to 15 January 1988, at low water stage and additional sediment and water discharge measurements were made at two of the sites (H and I) in April 1989 during flood period in that area.

Hydrological measurements

Depth profile and flow velocity

The depth profiles were measured at each site using steel depth probes. Flow velocity was measured using a Watts rotating vane-type flow meter at depth intervals of 1 m and at variable distances across the channel. Flow velocity and depth measurements were contoured and spatially integrated to obtain average velocity and channel cross-sectional area. The thickness of organic-rich sediment (peat) flanking the channels was also probed for a distance of 50 m on either side of the channel. This was done by pushing a steel rod into the peat until a sand substrate was encountered.

Water surface slope

Water surface was surveyed along cut-lines over a distance of 50 m into the swamp flanking the channel (elevations measured at least every 5 m) and over a distance of 300 m along the channel, using a Kern model GKO-A level.

Sedimentological measurements

Bedload sediment

The bedload transport rate was measured using two 7·62-cm Helley–Smith bedload samplers (Johnson *et al.*, 1977) of wall thickness 5·5 mm, fitted with 0·06-mm nylon mesh bags. The samplers were held on the channel bottom for either 2·5 or 5 min, depending on flow velocity. The collected sediment was transferred to a measuring cylinder and its volume determined. Small quantities of organic debris trapped in the bags were separated prior to volume measurement. Clogging of the bag by organic material (e.g. Emmett, 1980) did not occur because of the low suspended load. The density of dry sand was measured in the laboratory to be 1·77 g cm^{-3} (standard deviation 0·03), which was used to convert measured sand volume to dry mass. Size analysis of material collected by the samplers indicated negligible loss of the fine fraction when compared with dredged samples.

Between 24 and 72 separate bedload measurements were made at each study site, depending on channel width. Measurements were taken on a uniform grid pattern, to accommodate the pulsed nature of bedload movement caused by bedform migration (Hubbell *et al.*, 1985). The sediment yields obtained in the Helley–Smith sampler showed a wide variation at a single site, emphasizing the need to make a large number of measurements. This variability has been predicted theoretically (Hubbell & Stevens, 1986) and has also been found by other workers (Carey, 1985; Carey & Hubbell, 1986; Pitlick, 1988). Emmett (1980) demonstrated that the average of a large number of samples taken with a 7·62-cm Helley–Smith sampler approximates the real sediment transfer rate. In addition, samples were dredged from the channel centre for size analysis.

Suspended load

The amount of suspended sediment is very low and attempts to quantify this by filtration were abandoned because of the long times and large water volumes needed to accumulate sufficient solid for gravimetric determination. As an alternative, turbidity was measured using a Hach model 16800 Turbidimeter. Samples were collected at various depths and precautions were taken to avoid settling of suspended particles. The results are measured in nephelometric turbidity units (NTU). Samples from different depths showed a very small range of turbidity with no systematic pattern being evident. Accordingly, results from each site were averaged.

The relationship between turbidity and suspended concentration was established in the laboratory by preparing standards of known suspended concentration and measuring their turbidity. These standards were prepared using the fine fraction extracted from a peat sample from the Dxherega area. The inorganic sediment content of this fraction was 73·2%. Notwithstanding this calibration, the conversion of NTU to suspended mass remains semi-quantitative, because the relative proportion of organic to inorganic material in the suspended load is likely to vary through the channel system and organic material is likely to have a larger effect on the turbidity per unit mass than inorganic material because of its lower density. The converted NTU results are likely to be most accurate for the upstream sites (I and J), but probably overestimate suspended concentration for the lower sites because of the probable increase in the proportion of suspended organic material downstream.

RESULTS

The results are summarized in Table 1 and are conveniently described under separate headings.

Channel morphology

Channel cross-section morphology at the 12 study sites is illustrated in Fig. 3. At all study sites, with the exception of site A, the bed consisted of sand, although locally interlayered sand and silt mixed with organic debris was encountered. The channel bed at site A was largely vegetated by submerged species which were rooted in a clay substrate. This clay is considered to represent an erosional channel surface. Helley–Smith sampling indicated that there was no significant movement of bedload at this site.

There is a general progressive decrease in channel width down the fluvial system. The cross-sectional profile of the channels at most of the sites is essentially rectangular (Fig. 3). Channel margins are vertical to overhanging, as described by McCarthy *et al.* (1988a). The areas flanking the channels are underlain by

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 width unit (kg m^{-1} s^{-1})	Total bedload discharge (kg s^{-1})	Channel gradient (%)	Turbidity (NTU)	Total suspended load (kg s^{-1})	Suspended load (kg m^{-3})
December 1987–January 1988											
J	70	2·51	129·9	0·74	175·6	0·057	4·01	0·022	7·8	1·10	0·00848
I	92	2·40	143·6	0·65	220·9	0·045	4·00	0·022	7·5	1·17	0·00815
H	60	3·22	117·9	0·61	193·3	0·013	0·76	0·017	8·7	1·12	0·00947
G_T	15	2·92	17·5	0·40	43·8	0·0085	0·13	—	9·5	—	—
G_N	55	4·19	117·6	0·51	230·6	0·0047	0·25	0·013	8·8	1·13	0·00957
F	38	4·26	100·3	0·62	161·7	0·021	0·81	0·020	8·7	0·95	0·00947
E_B	11	4·41	22·3	0·46	48·5	0·012	0·13	—	—	—	—
E_N	32	4·00	81·9	0·64	127·9	0·037	1·19	0·037	11·3	1·01	0·0123
D	26	3·85	66·0	0·66	100·0	0·038	1·00	0·045	10·3	0·74	0·0112
C	26	3·92	54·0	0·53	101·9	0·015	0·38	0·031	10·8	0·63	0·0117
B	17	3·76	30·7	0·48	63·9	0·015	0·25	0·038	1·2	0·040	0·00130
A	17	2·79	17·1	0·36	47·5	0	0	0·030	0·4	0·0074	0·000435
April 1989											
H repeat	60	4·60	168·2	0·61	275·7	0·030	1·80	—	0·5	0·091	0·00054
I repeat	88	3·36	204·1	0·69	295·8	0·040	3·52	—	0·6	0·133	0·00065

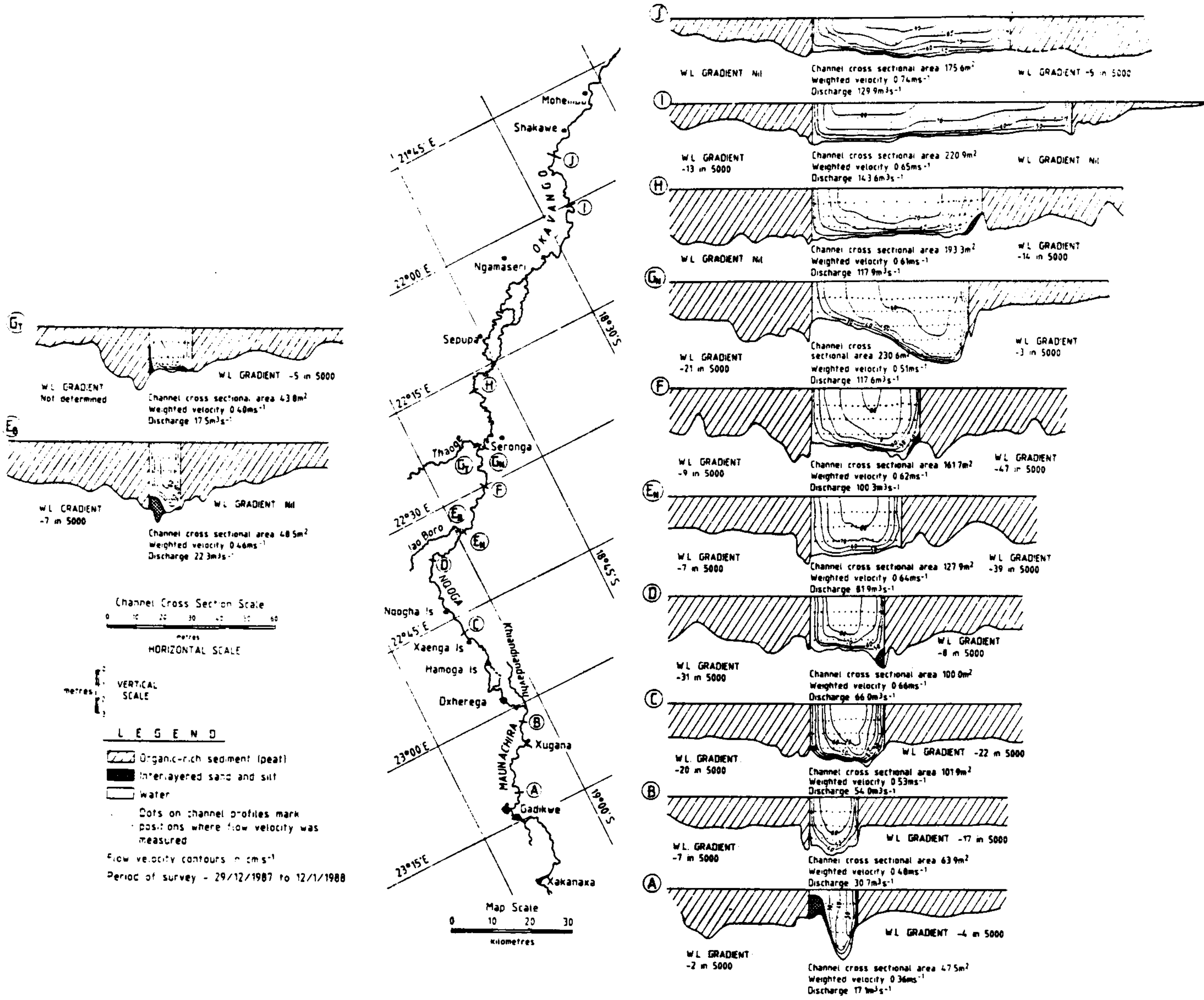

Fig. 3. Channel cross-sections at the study sites.

waterlogged, organic-rich sediment, which, for convenience, will be referred to as peat. Channel depth in the upper Panhandle is between 2 and 3 m, but rises to a maximum of around 4 m near the lower end of the Panhandle, after which the depth gradually declines.

Except for sites A and B, the channel beds appear to lie at approximately the same elevation as the base of the peat flanking the channels. The nature of the substratum underlying the channels and surrounding swamps is not known in detail, but presumably consists of older sediment similar to that described by McCarthy *et al.* (1988b).

The upper channel (around sites I and J) forms broad meanders (Fig. 4), whereas below I and extending as far as site G_N, meanders become more pronounced and ox-bow lakes are common. The channel system is anastomosed between I and H. Below site G_N is the first of the major distributary channels, the Thaoge, which supplies water to the western margin of the fan. This channel diverges from the main channel at right angles. In this reach, meanders are less well developed or largely absent. The second major distributary, the Jao/Boro, which provides water to the centre of the fan, is situated below site E_N and also diverges from the main channel at a high angle.

The channel below site D has a low sinuosity with a few rather sharp bends and some poorly developed point bars. Between sites B and C, the channel is anastomosed. A major split in the Nqoga channel occurs at Hamoga Island (Fig. 3) and the western

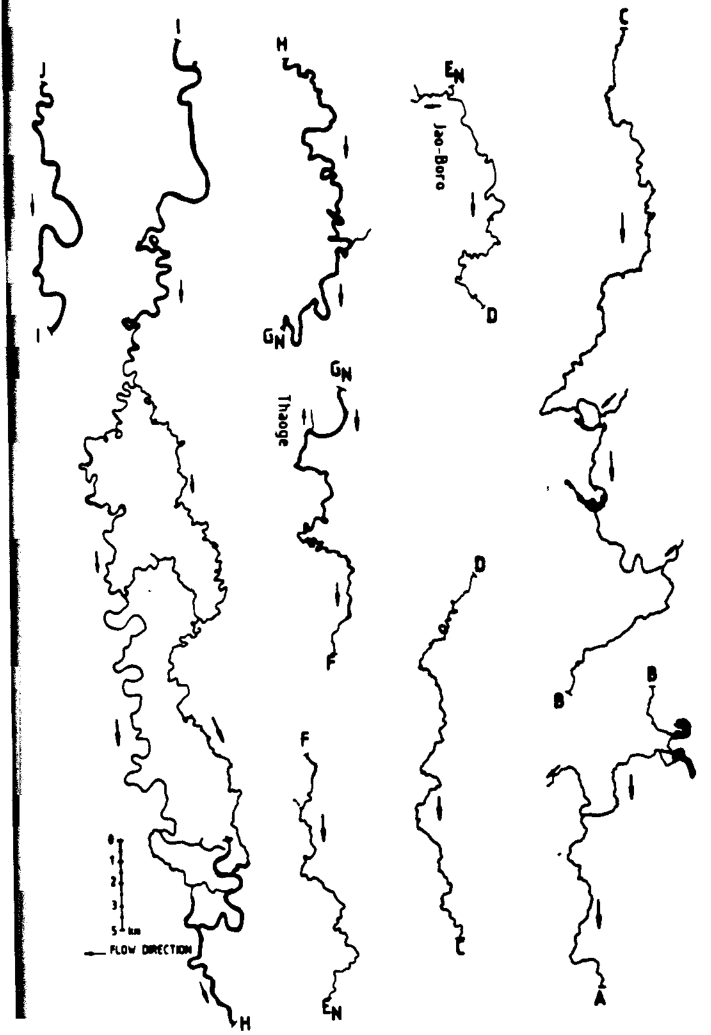

Fig. 4. Channel segments between each pair of study sites. Based on the 1:50 000 scale map series of the Government of Botswana.

branch is presently subject to frequent surface blockage by floating papyrus debris. In the past, this channel extended far to the southeast and was a major waterway (Stigand, 1923; Wilson, 1972; McCarthy *et al.*, 1986). Flow in the eastern branch dissipates through a maze of small distributary channels and swamps. The Maunachira channel rises in this region and its water is augmented from the Nqoga by way of a small channel. This combined flow enters the Dxherega *lediba*, a large lake, where the entire bedload is deposited as a large, prograding mouth bar (Fig. 5; McCarthy *et al.*, 1986). Below Dxherega *lediba*, the Maunachira is joined by a large channel, the Khiandiandavhu (Fig. 3), which rises in the swamps on the north side of the Maunachira channel. Bedload at site B is derived by erosion below the outlet at Dxherega and in the Khiandiandavhu channel.

Hydrology

Figure 6 illustrates the discharge at the apex of the Panhandle. As the catchment area is large, there are no sudden changes in discharge, but rather a steady increase to the seasonal maximum which may consist of either a single or multiple peaks, depending on the rainfall conditions in Angola. The initial survey was conducted under low water conditions (December 1987–January 1988; see Fig. 5, curve A), while the repeat measurements at site H and I were made during the flood period (April 1989).

Water discharge during the December–January survey period (Figs 7 & 8a) generally decreases downstream. The two distributaries, Thaoge and Jao/Boro, together draw off only 15 and 27% respectively of the water from the Okavango–Nqoga channel system in their immediate vicinity, emphasizing the present importance of the latter channel system. There is a slight rise in discharge between sites J and I, indicating net inflow of water into the channel. As no channel enters the Okavango between these two sites, it is inferred that at the time of the measurement inflow from the swamps was occurring. Between sites I and H, there is a large loss of water as a result of leakage from the channel to the swamps. Downstream, between sites H and F, there is no significant loss or gain from the channel system, the difference between these sites being due to outflow down the Thaoge. Between sites F and E_N there is again a large outflow to the swamps. Water balance at the Jao/Boro distributary head (between sites E_N and D) indicates a net inflow in this region, which is most likely occurring in the Jao/Boro channel, and may represent some of the water lost between sites F and E_N. As Porter & Muzila (1988) have shown, most of the discharge in the Jao/Boro and Thaoge channels is derived by lateral seepage through the swamps, with only a small proportion entering directly from the Nqoga channel. Below site D there is a net outflow between successive sites. Water is lost from the channels by slow flow through the permeable channel margins (McCarthy *et al.*, 1988a) and via small outlets such as hippopotamus trails (P. A. Smith, pers. commun.). A synoptic view of water loss from the main channel is shown in Fig. 8(a). Between sites I and G, the rate of loss is slow, but increases below site G. Repeat measurements of sites H and I during the flood season (April) indicated that discharge had increased at these sites by an average of 42% (Table 1), resulting in a significant increase in depth but little change in velocity. The average flow velocity declines

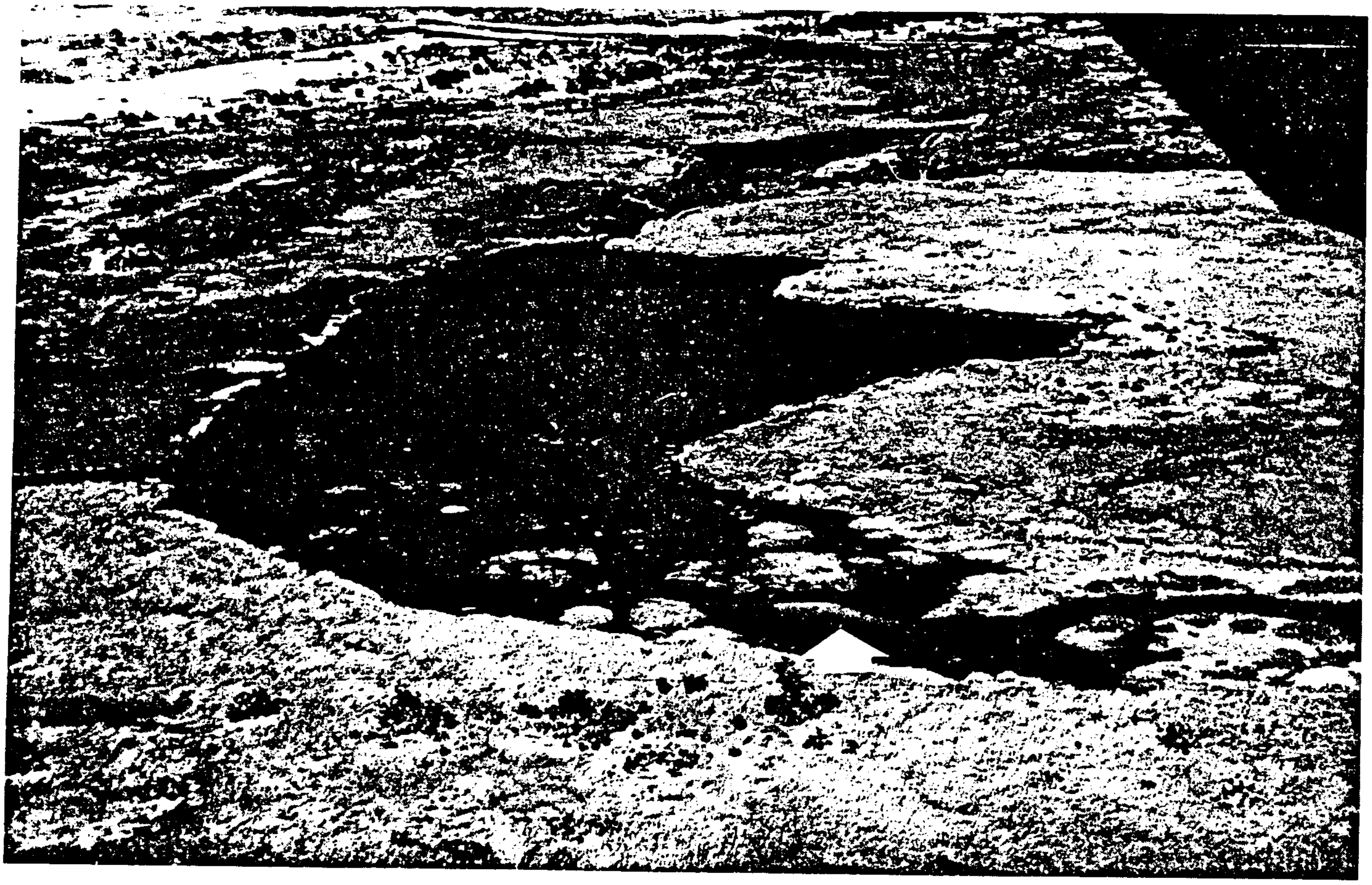

Fig. 5. A prograding mouth bar (arrowed) in the Dxherega *lediba* (lake). The major diameter of the *lediba* is in the region of 500 m.

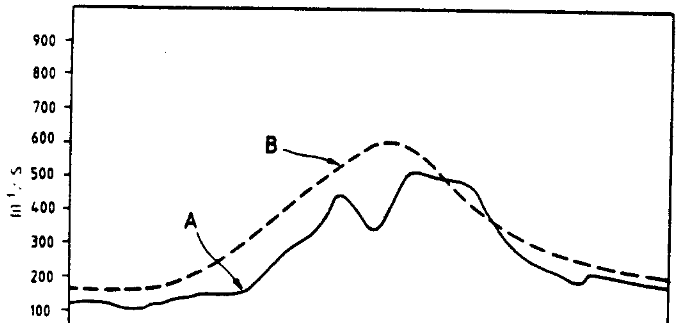

Fig. 6. Discharge of the Okavango River at the head of the Panhandle. Curve A illustrates discharge at Mohembo in the period 1987–1988 (data compiled by C. Nthobatsang, Department of Water Affairs). Curve B represents a typical discharge cycle as experienced at Shakawe (UNDP, 1977).

through sites J–G_N (Fig. 8b), but thereafter rises again to a local maximum at site D beyond which velocities show a steady fall.

Water surface gradients along the channel show little variation within the Panhandle (Fig. 8c) but steepen abruptly between sites G and D, and remain high through the remainder of the survey area. The water surface generally slopes away from the main channel into the flanking swamps (Fig. 9), the steepest being a fall of 47 cm over 50 m (site F, left bank). The channel sites H, I and J are characterized by low-gradient slopes on both banks but these lateral slopes increase downstream, reaching maximum values in the region of the Thaoge and Jao/Boro distributary heads (Fig. 10a).

Bedload movement

The size distribution of channel bed material at each of the study sites is shown in the cumulative frequency curves in Fig. 11. The sediment is moderately well-sorted sand with an average mean size of about 1·5 ϕ (0·35 mm). Median grain size varies by less than 1 ϕ.

There is an initial downstream decline in bedload discharge per unit width to site G_N followed by an increase to a local maximum at site D, after which there is a steady decline (Fig. 12a).

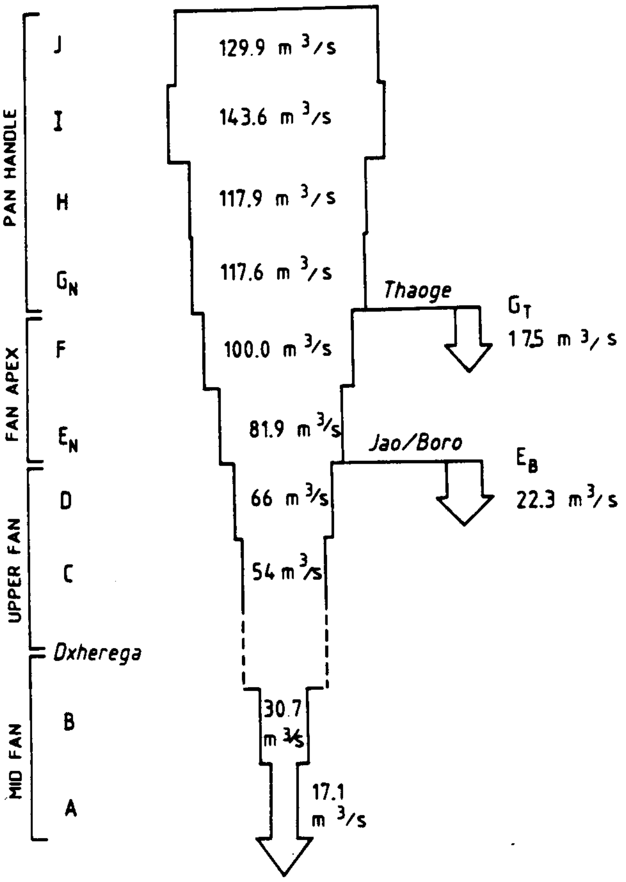

Fig. 7. Diagram illustrating the water discharge through the study area during December 1987–January 1988.

Total bedload discharge between sites J and I is essentially constant, but a massive decline occurs between sites I and H (Figs 12b & 13), implying accumulation of approximately 3 kg s^{-1} in the intervening reach. A large decrease in bedload was also evident between these two sites in the repeat determinations (Table 1) during the flood period. Below site G, sediment discharge increases, reaching a local maximum in the region of the Jao/Boro distributary head, beyond which a steady decline occurs. No bedload passes through the Dxherega *lediba* (between sites C and B) and sediment movement at B then reflects local erosion upstream of site B.

Colby (1957) has demonstrated that sediment transport is closely related to the third power of flow velocity (also see Schumm, 1977, p. 129). Data from all sites, except G$_N$ and H, define a linear relationship

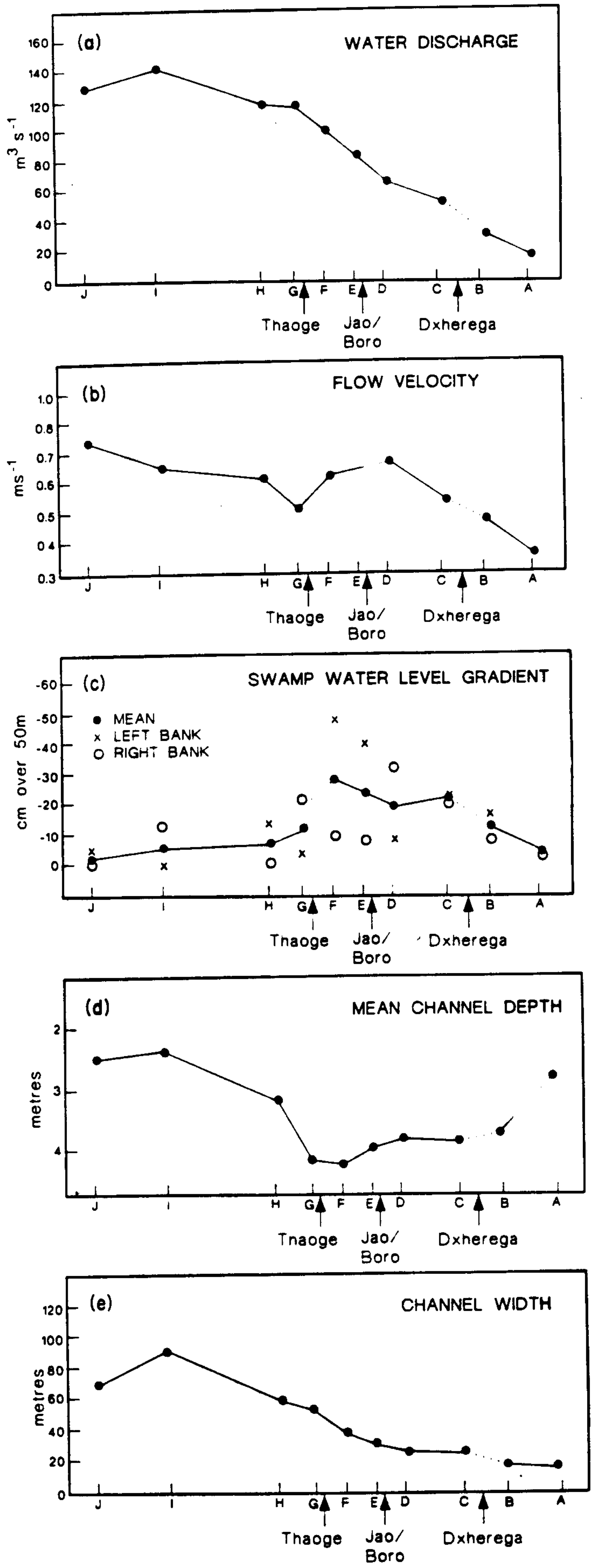

Fig. 8. Variation in (a) water discharge, (b) average flow velocity, (c) channel water surface gradient, (d) mean channel depth and (e) channel width down the main channel system. Distances between sites are scaled according to straight-line distances.

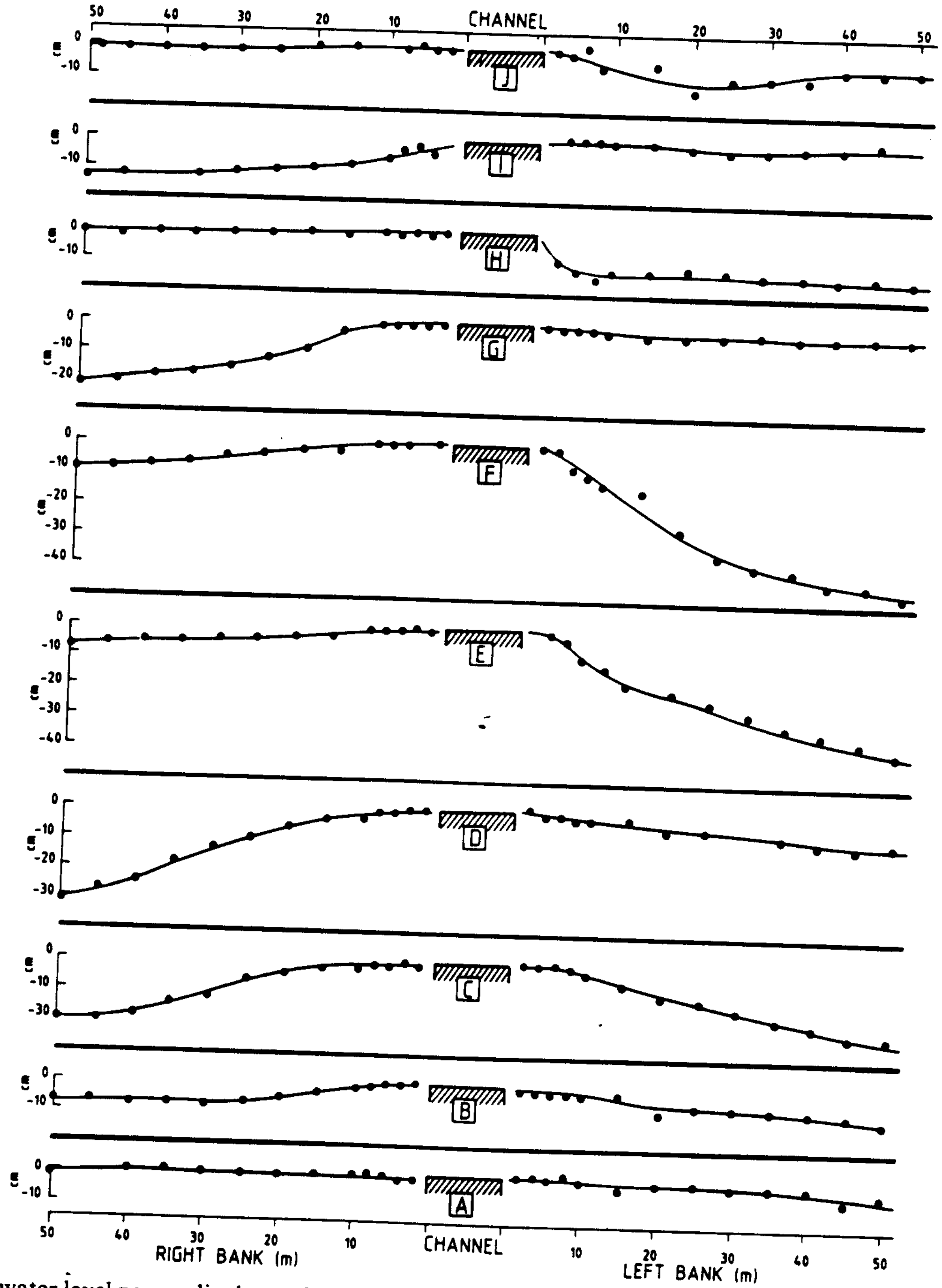

Fig. 9. Variation in water level perpendicular to the channel at each of the study sites. Channel widths are not to scale.

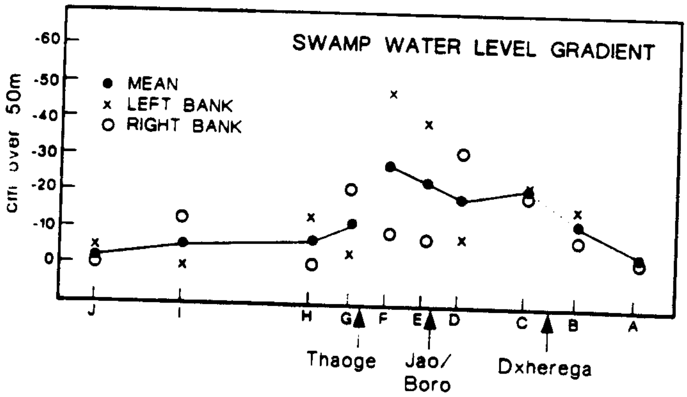

Fig. 10. Variation in water level gradient (over 50 m) into the swamps perpendicular to channels.

on a logarithmic plot of velocity against bedload discharge per unit width (Fig. 14). A least-squares fit to the data (excluding that from sites G_N and H) yielded the equation:

$$Q_b = 0{\cdot}13\, U^{3{\cdot}10}, \tag{1}$$

where Q_b is the bedload discharge per unit width (kg m^{-1} s^{-1}), and U is the flow velocity (m s^{-1}). The regression coefficient R^2 is 0·919; this decreases to 0·615 if the data from sites G_N and H are included.

The deviation of sites H and G_N may be related to the effects of depth and gradient. If these variables

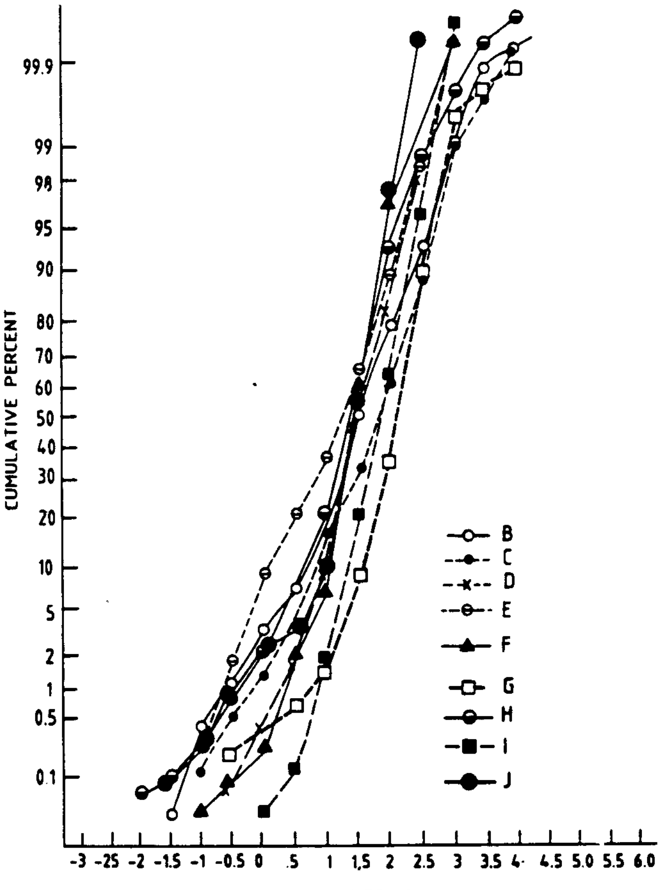

Fig. 11. Grain-size distribution of bedload from each of the study sites.

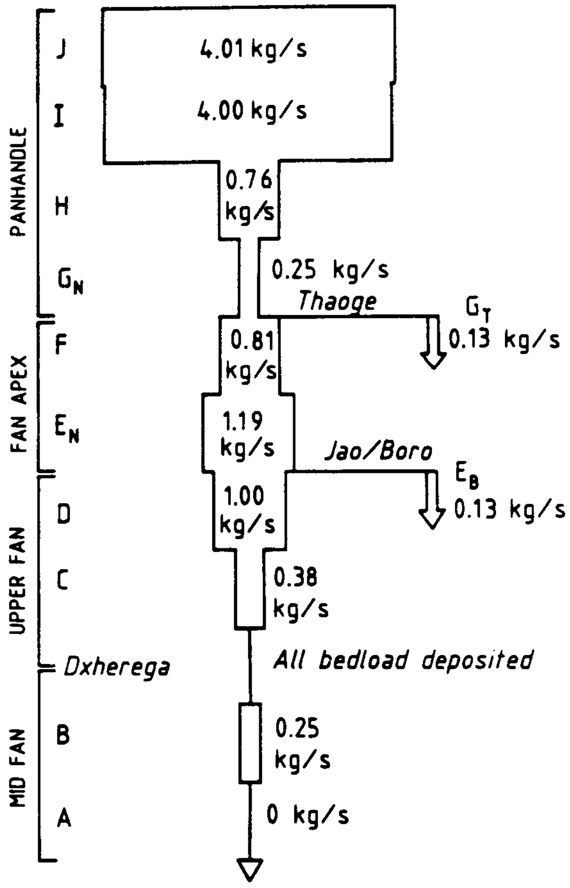

Fig. 13. Diagram illustrating bedload discharge through the study area.

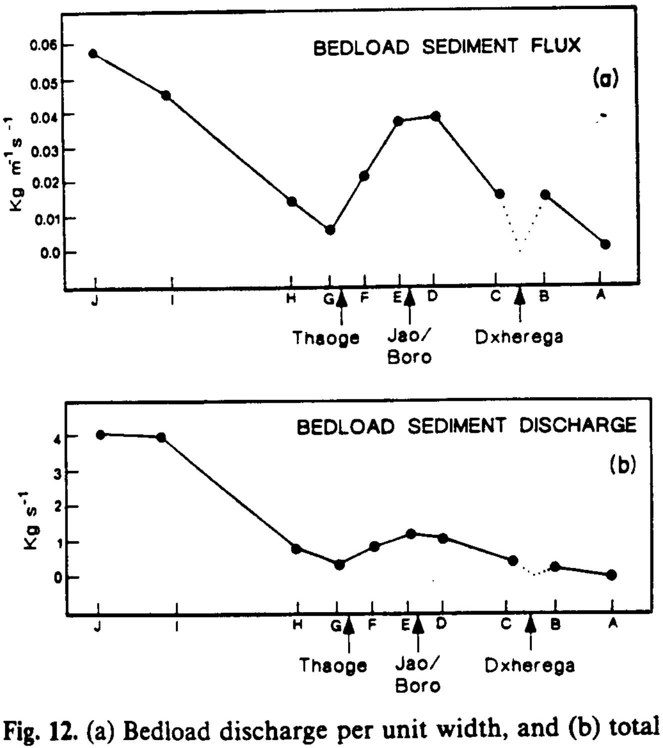

Fig. 12. (a) Bedload discharge per unit width, and (b) total bedload discharge down the main channel system.

are included in the multiple regression analysis, a best-fit line to the data (excluding sites G_T and E_B, for which gradients are not available; see Table 1) yields the following equation:

$$Q_b = 21{\cdot}2\,D^{-1{\cdot}14}\,U^{3{\cdot}47}\,G^{1{\cdot}00}, \qquad (2)$$

where D is the depth (m) and G is the gradient (%). The R^2 value for this line is 0·912.

Suspended sediment

During the major survey, turbidity showed a gradual increase downchannel (Fig. 15), until the Dxherega *lediba*, where major settling most probably occurs, as turbidities were low downstream of this lake. Suspended sediment discharge at site J (1·10 kg s^{-1}, Table 1) is less than one third of the bedload discharge (4·01 kg s^{-1}). Turbidity measurements on water samples collected during the flood season at sites H and I were *lower* than during low water, suggesting that some of the turbidity during the December–January period may be due to organic detritus carried into the

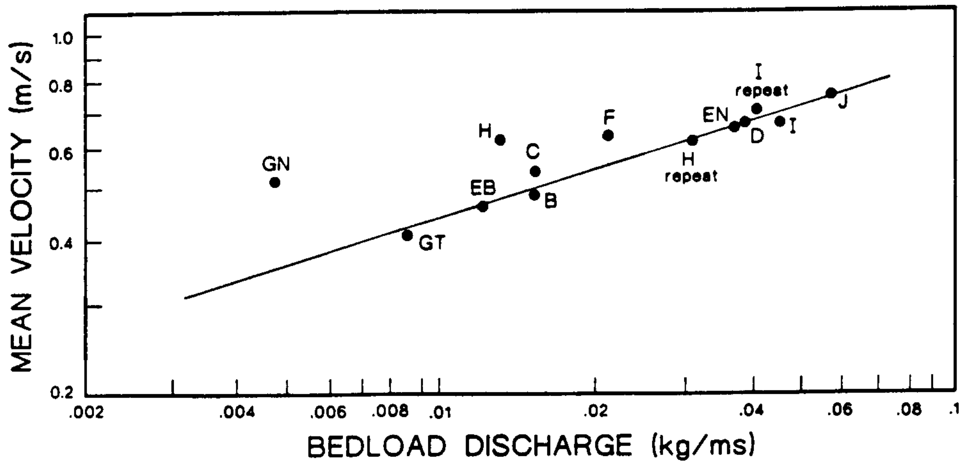

Fig. 14. Relationship between bedload discharge per unit width and mean flow velocity. The fitted line excludes sites G_N and H and repeat data.

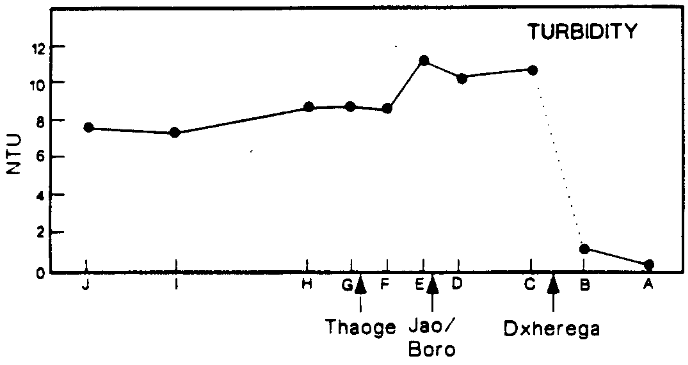

Fig. 15. Variation in average turbidity down the main channel system.

channels from the flanking swamps particularly in the Panhandle region. This is supported by the rise in turbidity downstream (Fig. 15).

DISCUSSION

Hydrology

The mechanisms whereby the seasonal floodwave passes through the system have not previously been understood, particularly as far as the middle reaches of the swamp are concerned. Specifically, the large water-level fluctuations of the Panhandle and the seasonal swamps are not reflected in the middle reaches. The key to understanding this enigma is the nature of the channel margins. McCarthy *et al.* (1988a) point out that these are permeable, consisting of peat, comprising interlocking dead roots and rhizomes with interstitial organic and inorganic detritus which supports a blanket of papyrus or miscanthus. The living plants are rooted in the waterlogged peat and only the stalks are above the water surface. Permeability of the margins increases upwards towards the free water surface and also laterally into the swamps because of the declining density of surface vegetation away from the channels. Nevertheless, water exchange between channel and swamp is slow because of the high density of stalks along the channel margins. In a sense, the peat and living vegetation adjacent to the channels form levees, but these differ from normal inorganic levees in that they are permeable to water. Water is able to flow slowly across the channel margins but dissipates more rapidly in the backswamp areas. For this reason, the steep lateral water-surface gradients (Fig. 9), which are 2–3 times greater than the downchannel gradients (Fig. 8c), can be sustained.

As the seasonal floodwave enters the Panhandle, the water spreads laterally into the adjacent swamps but is confined by the shoulders to this feature. When the floodwave has passed, water drains back into the channel. This exchange of water has the effect of extending the duration of the floodwave. At the time of the main survey, the swamp in this region was still supplying water to the channel, as indicated by the rise in discharge between sites J and I (Fig. 7). Further downstream on the fan itself (below site F), the swamps are unconfined, and the lateral water-level gradients are relatively steep. Consequently, channel overspill is completely lost to the flanking swamps. As the water level rises with the advancing flood, the flanking papyrus is flooded to a greater depth and the rate of water loss from the channel increases, because stalks offer only limited resistance to flow. This limits the seasonal range in water level in the permanent swamps.

Overspill moves away from the channels to supply lower-lying areas of the permanent swamps and, depending on the season, the seasonal floodplain. Slow rates of flow through the swamps delay the arrival of the peak flood on the seasonal floodplain, accounting for the 4-month delay between peak flood at Shakawe and peak flood on the seasonal floodplain (Fig. 2). It is perhaps significant that the Thaoge and Jao/Boro distributary channels leave the main channel in the region of steep lateral gradients. These channels leave the main channel at high angles, probably a consequence of this gradient.

Sediment movement

Total bedload discharge at site J, although somewhat below the apex of the Panhandle, approximates actual input of sediment into the Okavango system under the conditions encountered at the time of the survey. Bedload discharge through site I is virtually the same as through site J, implying a steady transfer of material. However, between sites I and H there is a dramatic decline in sediment discharge, equivalent to about 3 kg s^{-1} (Figs 12b & 13). Between sites I and G_N, representing the lower half of the Panhandle, about 94% of the incoming sediment is deposited. This channel reach is characterized by high sinuosity and also by some anastomosis (Fig. 4). Ox-bow lakes are also common in this reach. Deposition of this sediment is most likely taking place by point-bar accretion along this section of the channel system.

The Thaoge distributary, below site G_N, removes 0·13 kg s^{-1} of bedload sediment from the main channel (Fig. 13) and thus downstream of this point, the sediment discharge is only 0·12 kg s^{-1}, amounting to a mere 3% of the bedload passing through site J. Mean channel depth reaches a maximum in this reach of low bedload (Fig. 8d). From this point, however, there is a rise in sediment discharge through site F reaching a local maximum in the vicinity of sites E_N and D (Fig. 12b). This implies that erosion becomes dominant over deposition along this reach. The channel appears less sinuous (Fig. 4) and there is a rise in turbidity (Fig. 15), flow velocity (Fig. 8b), and a steepening of channel water-level gradient (Fig. 8c). The reach where these changes occur coincides with the apex of the fan.

Downstream of site E_N there is a steady decline in bedload, and throughout this reach the channel retains its low sinuosity (Fig. 4) and point bars are scarce. Vertical aggradation of the channel at a rate of at least 5 cm yr^{-1} is currently occurring in this reach (McCarthy *et al.*, 1986). Below site C is a complex region of channel anastomosis and the main channel, the Nqoga, has been substantially reduced in width by the growth of *Vossia cuspidata*, a bottom-rooted floating grass, and becomes subject to frequent blockage by plant debris. The Maunachira channel rises in this region and a cross-link seldom more than 5 m wide has developed to the Nqoga along a former hippopotamus trail (P. A. Smith, pers. commun.). The lower reaches of the Nqoga have been completely abandoned and ravaged by peat fires (Wilson, 1972; McCarthy *et al.*, 1986; Ellery *et al.*, 1989). Some of the sediment brought down the Nqoga is transferred via the cross-link channel to the Maunachira and the combined sediment from these two channels enters the Dxherega *lediba* as a large mouth bar (Fig. 5). Site B lies downstream of this lake and has no direct connection to the Nqoga channel's sediment supply. The bedload sediment discharge at site B (0·25 kg s^{-1}) must therefore be derived by erosion downstream of the Dxherega *lediba* and by erosion within the Khiandiandavhu channel, a channel system which originates in the area north of the Nqoga and Maunachira channels (Fig. 3). This sediment is largely deposited above site A as the channel bed at this site is vegetated and there is insignificant bedload transport. This implies that some local aggradation must be taking place between sites B and A. The channel at sites A and B differs from the upstream sites which are connected to an external source of sediment in that both are incised into the substratum (Fig. 3). This indicates that there is a net erosion in the channels below Dxherega, albeit slow, and a net transfer of material beyond the limits of the present survey. It is likely that this state will persist for as long as these channels remain isolated from major sediment input.

The situation described above applies to the low water period. The rate of bedload supply will, however, vary seasonally with water discharge. Although only limited measurements have been made, some indication of sediment discharge can be obtained by calculation using a typical flood cycle and Eqs (1) or (2). The results of these calculations are shown in Table 2.

At peak flood (April), bedload discharge at Shakawe, a short distance upstream of site J (Fig. 1), will rise to between 8 and 12 kg s^{-1} (based on Eqs 2 and 1 respectively), producing a seasonal pulse in sediment input. However, at the lower end of the Panhandle, the seasonal range in hydrological parameters decreases rapidly and is negligible at site E as discussed

Table 2. Typical monthly discharge at Shakawe (upstream of site J).

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
Width (m)	137	137	137	137	137	137	137	137	137	137	137	137
Average depth (m)	2·19	2·19	2·59	3·17	3·57	3·84	4·02	3·75	3·23	3·93	2·71	2·35
Average velocity (m s^{-1})	0·47	0·48	0·56	0·69	0·77	0·83	0·87	0·81	0·70	0·64	0·59	0·51
Discharge (m^3 s^{-1})	171	172	218	321	449	546	615	498	350	280	240	200
(A) Sediment discharge (t $month^{-1}$)*	4571	4722	7869	15 030	19 074	26 648	29 839	24 707	15 208	11 904	9251	5698
(B) Sediment discharge (t $month^{-1}$)*	5074	5283	7698	12 616	14 562	19 249	20 816	18 171	12 563	7606	8762	6017

Total annual sediment discharge: (A) 174 521 t, (B) 138 417 t.

*(A) Calculated using Eq. (1), (B) Calculated using Eq. (2), assuming a constant gradient of 0·022%.

above. It is therefore likely that downstream from site E, the channel carries a relatively constant amount of bedload throughout the year. Consequently, each seasonal pulse of sediment must be disposed of largely within the Panhandle. This is supported by the fact that the marked drop in bedload between sites I and H recorded during the period of low water is also evident at high water (Table 1) although is not as pronounced. The total annual bedload influx is of the order of 140 000–170 000 t (Table 2), some 95% of which is deposited in the Panhandle.

The quantity of suspended load appears to be greater during the low water stage. This may be due to flushing out of organic debris as the flood water drains back into the channel. The quantity of suspended load carried by the channels at the top of the Panhandle is much less than the bedload component, particularly during the flood period. The absence of sediment levees, in spite of the large quantity of channel overspill, is undoubtedly due to the low quantity of suspended sediment.

An important aspect of the dynamics of the channel system is the response of the flanking swamp to events occurring in the channels. The organic-rich accumulation (peat) which underlies the blanket of living vegetation and which confines the channels (Fig. 3) is volumetrically dominated by water and plant material, even when the content of inorganic material exceeds 50 dry wt% (McCarthy *et al.*, 1989). The accumulation rate of the peat is governed only by the rate of plant growth and does not depend on the availability of a fine sediment fraction from the channels which is in any event small, although, of course, such fine sediment is deposited in the peat from through-flowing water lost from the channels (McCarthy *et al.*, 1989). The plant growth rate is controlled by many variables but an important factor is water depth. A long-term rise in water level, caused, for example, by channel-bed aggradation, will promote vertical plant growth and hence aggradation of the swamp. Similarly, lateral encroachment of vegetation into channels can also occur, particularly where flow velocities are reduced such as on the inside of meander bends. The organic-rich sediment blanket therefore accretes both vertically and laterally irrespective of the quantity of fine sediment available and hence responds dynamically to processes occurring in the channels (McCarthy *et al.*, 1988a, b).

Regional synthesis

This survey has shown that bedload which is currently entering the Panhandle region of the delta is being transmitted through the upper portion of the Panhandle. More than 90% of this bedload sediment is being deposited in the lower Panhandle apparently by point-bar accretion. The lower Panhandle is also characterized by a marked decline in flow velocity. It is inferred that the quantity of sediment entering the fan will rise dramatically during the flood season. The effect this has on sediment dispersal in the Panhandle is not known, but it is probable that this sediment will be deposited in the Panhandle because the channels below the Panhandle are characterized by small, seasonal, hydraulic fluctuations. The difference in bedload discharge between sites H and I, measured during the flood period, supports this view. At the fan apex flow velocity increases and there is a rise in bedload discharge, indicating erosion. This may well be a seasonal phenomenon. On the upper fan, there is a gradual decrease in discharge and flow velocity, due to water leakage from the channel, and the bedload is deposited causing channel-bed aggradation. On the midfan, sedimentary processes are confined largely to local erosion and deposition, with a net erosional component in the channel studied. Bedload deposition appears to occur in two distinct styles: namely associated with large-scale point bars in the Panhandle and with channel-bed aggradation.

It seems that the depositional and erosional relationships described here cannot reflect a long-term condition. The erosional regime at the fan apex could not be sustained for any appreciable length of time and similarly the major depositional reach in the Panhandle could not persist indefinitely. The implication is that the fan is currently in a transient state of grade disequilibrium, with major deposition taking place in the Panhandle.

At present it is not possible to ascertain when this disequilibrium originated or even the manner in which it occurred (i.e. catastrophic or gradual). It is pertinent, however, to speculate on what may happen once the Panhandle is fully regraded. When this occurs, the large quantity of annually introduced bedload will be available for distribution on the fan and it is likely that the channels on the upper fan will radically change, taking on more of the character of the upper Panhandle channels (sites I and J), i.e. broad, shallow channels with a higher degree of sinuosity. Channels of this type are evident on the course of the now abandoned Thaoge (Fig. 1). This suggests that the Thaoge, when it was fully active, represented a stable grade condition over the fan surface. It is therefore possible that the demise of the Thaoge (late nineteenth century) was associated with the onset of the current phase of disequilibrium in the fan.

Fluvial disequilibrium in the channel system could arise from either external or internal causes. It is well established that the fan owes its origins to crustal instability (du Toit, 1927; Scholz, 1975; Hutchins *et al.*, 1976) and is confined by a series of NE-striking faults. It is therefore tempting to relate the current fluvial disequilibrium to neotectonics. It is also conceivable that the fluvial disequilibrium could be the result of an avulsion. A relatively broad, elevated meander tract may have developed along the Okavango and Thaoge channel systems during the time that the latter channel was active. An avulsion in the Panhandle region could have induced the observed disequilibrium if the new channel breached this raised tract in the region of the fan head. On the basis of presently available data, it is not possible to differentiate between these possibilities.

CONCLUSIONS

The regional survey of sediment dispersal on th Okavango fan, reported here, represents only a ver limited portion of the seasonal range, but it provide insight into the fluvial dynamics of this remarkabl system.

(1) Water from the catchment area enters a system i which the channels are confined by vegetated pea levees which are resistant to erosion.

(2) Upward growth of these permeable levees cause the channel water level to become elevated abov the surrounding swamps. Water leaks slowl through the levees, a process which is only allowe by the low suspended load which would otherwis clog the permeable peat banks.

(3) In the upper fan during periods of low flow flanking swamp water surfaces slope steeply awa from the channel, indicating enhanced flow ont the local fan surface. This is the region of wate dispersal into the Thaoge and Jao/Boro distributaries which leave the main channel at right angles, possibly sustained by this high gradient.

(4) Because of channel water loss through leakage, the water discharge in the channels decreases downstream, slowly at first in the Panhandle and more rapidly on the fan. Channel width decreases concomitantly.

(5) Bedload measured at a number of sites shows a log-linear correlation with velocity. This allows extrapolation of sediment discharges to higher flood values and predicts a seasonal variation in bedload from 1·8 to 12 kg s^{-1} with an annual discharge of 140 000–170 000 t. About 30 000 t maximum of suspended load is introduced annually.

(6) Most bedload is deposited in the Panhandle, an area characterized by meandering channels.

(7) Compared with the Panhandle, flow in the fan apex is characterized by rises in gradient, flow velocity and bedload discharge. Erosion occurs in this reach, although this may be seasonally controlled, and the eroded sediment is deposited further downstream on the upper fan. Here deposition within channels locally attains rates of sedimentation up to 5 cm yr^{-1}. Further down fan a 'cut-and-fill' process is operating in the channel system.

(8) The present channel is apparently in a phase of disequilibrium and is undergoing major readjustments in grade which may be related to the abandonment of the Thaoge in the last century.

(9) The disequilibrium may be due to causes external or internal to the fluvial system. Neotectonic fault movements on the northwestern side of the graben may have caused regrading in the Panhandle area and indeed the channel system as a whole. Alternatively an avulsion of the old Okavango/Thaoge fluvial system may have occurred in the lower portion of the Panhandle, giving rise to the modern Nqoga/Maunachira fluvial system. In the long term it seems likely that the meander belt of the Panhandle will prograde out onto the fan itself.

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