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Environmental change over two decades since dredging and excavation of the lower Boro River, Okavango Delta, Botswana

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Abstract. The Okavango Delta, southern Africa's largest wetland, is situated on the fringe of the semi-arid Kalahari Desert. It is a large alluvial fan, occupying a graben structure which is an extension of the East African Rift system. Of the 16 km^3 of water which enters the Delta each year, 96% is lost to the atmosphere by evapotranspiration, 2% to groundwater and only 2% leaves as surface flow. In order to increase surface outflow to meet human needs, the distal Boro channel–floodplain system was dredged, excavated and bunded between 1971 and 1974. The immediate impact of these measures was the destruction of in-channel flora. After 20 years, the aquatic flora has recovered in the excavated channel. However, little recovery has occurred along the channel reach which was dredged. Moreover, there has been significant encroachment of terrestrial species onto the floodplain in the region of the dredged channel. In addition, dredging created a nick point which has been migrating upstream by headward erosion since dredging ceased. The average rate of advance of the nick point has been about 500 m per year. Incision associated with nick point migration has produced a channel which is indistinguishable in form from the dredged channel and, like the dredged channel, is almost completely devoid of in-channel aquatic flora. The adverse environmental impact of dredging has therefore continued to propagate in an upstream direction, although the height of the nick point has decreased, suggesting a natural attenuation process. This is likely to result in eventual elimination of the nick point.

Key words. Botswana, Okavango Delta, Boro River, dredging, wetland, anthropogenic impact.

INTRODUCTION

The second largest river in southern Africa, the Okavango River (Hutchinson & Reiner, 1973), with its catchment in Angola, flows across the Caprivi Strip in Namibia, and enters Botswana at the town of Mohembo in the north western corner of the country (Fig. 1). This river spills out over a large area, forming a vast 'inland delta'. The Okavango Delta is actually a large alluvial fan (Stanistreet & McCarthy, 1993), and forms part of the internal drainage system known as the Kalahari Basin. The Delta itself is situated in a graben structure, which is an extension of the East African Rift Valley system (Hutchins, Hutton & Jones, 1976), the graben occurring between the Gomare fault in the north, and the Kunyere and Thamalakane faults in the south (Fig. 2). The Kunyere Fault has a scarp height of about 2 m and can be seen clearly from the air as it acts as a barrier to water flow, and separates the seasonal swamp habitat from the dryland savanna habitats to the south east.

In the upper reaches of the Delta the Okavango River is confined in a narrow depression known as the Panhandle (Fig. 2). The mean annual inflow to the Okavango Delta is 11×10^9 m^3, which is augmented by 5×10^9 m^3 of rain. Peak flows in the Panhandle occur late in the wet season (March–April; Wilson & Dincer, 1976). Downstream of the town Seronga, the river disperses into three major distributary channel systems, the Thaoge River in the west (presently inactive), the Jao-Boro River in the centre, and the Nqoga River in the north east.

Of the water entering the Okavango Delta, approximately 96% is lost to the atmosphere by evapotranspiration, 2% flows out of the system as surface flow, and a further 2% is lost to groundwater (Wilson & Dincer, 1976). The annual floodwaters take approximately 4–5 months to reach the southern end of the Delta, with peak flows in Maun usually in June or July. The maximum extent of flooding of the Delta therefore takes place in the dry season and at this critical time of the year, the seasonal swamps are an important refugium for game and cattle. The seasonal swamps are therefore crucial to the maintenance of large wildlife populations in northern Botswana.

The only river to flow out of the Okavango Delta is the Boteti River (Fig. 1), which in exceptional years flows into the south western part of Ntwetwe Pan which, in turn, forms part of the Makgadikgadi Pans complex (the terminal receiver of water in the internal Kalahari Drainage System). However, the Boteti River is not perennial, and its lower reaches have been recorded as dry for periods of up to 8 years. At present the Boro River is the main supplier of water to Maun as well as to the Boteti River.

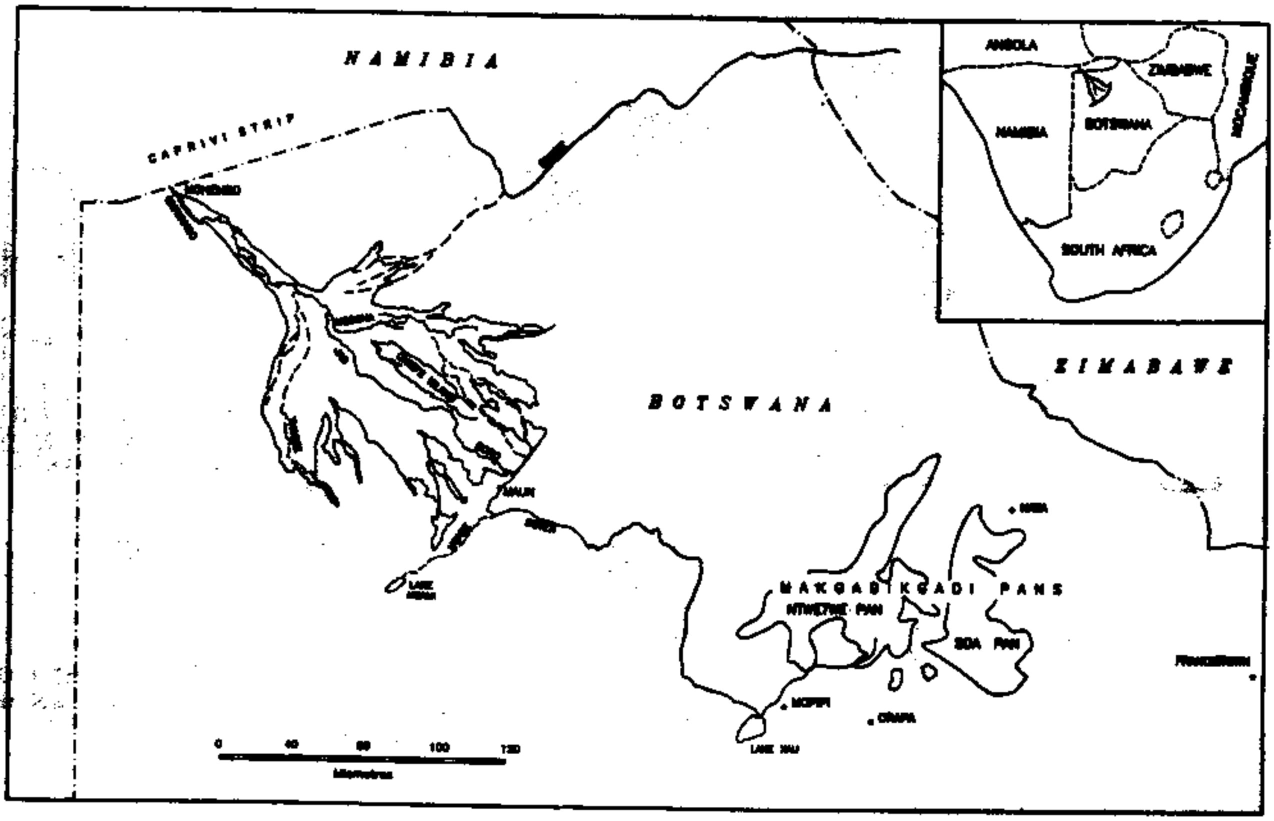

FIG. 1. The Okavango Delta and Makgadikgadi Pans system in north western Botswana.

Dredging was carried out along the lower Boro River during the period 1971–74 with a view to increasing outflow from the Delta to supply the newly commissioned Orapa Diamond Mine, in a scheme known as the Lower Boro Flow Improvement Program (Standish-White, 1972, Reiner & van Rijn, 1973). This involved the conversion of a floodplain into a canalized river. Bunds were also erected to reduce the extent of lateral flooding. Subsequently, adequate groundwater resources were located, and the mine is no longer dependant on surface water from the Boteti River. Nevertheless, Debswana Diamond Company, the operating company of the Orapa Mine, commissioned a number of scientific investigations to assess the environmental impact of the dredging (Reavell, Lee & White, 1973; Reavell & Lee, 1974) including a number which were published in the open literature (Dye, 1975; Dye, Lee & Reavell, 1976; Lubke, Raynham & Reavell, 1981; Reavell, 1982; Lubke, Reavell & Dye, 1984). These studies were carried out shortly after dredging had been completed, during February 1973, February and December 1974 and July 1979. The present study was also commissioned by Debswana, but has a broader emphasis, examining not only the biological processes but also the physical environment.

There are three main differences between the present study and those done in the past:

1. The interval since dredging is far greater (2 decades) than in past studies.
2. The emphasis in past studies was to document post-dredging recovery and plant succession, rather than examine the nature and rate of change.
3. Changes in the physical environment were documented in past studies, but no attempt was made to predict possible future changes on the basis of a mechanistic understanding of the altered physical environment produced by dredging.

In contrast to past studies the present study, therefore, provides a longer term perspective of the nature of change, and aims to provide mechanistic understanding that should enable some degree of prediction.

THE STUDY AREA

The study area is along the Boro River between the Thamalakane and Kunyere faults, north east of Maun (Fig. 3). At present the area is used mainly for livestock production, primarily cattle, donkeys and goats. There is some floodplain (melapo) farming, a form of subsistence agriculture practised by the local residents, in which crops are planted at the water's edge as the floodwaters recede. This sustains growth until the onset of the rainy season.

The study area includes the sections that were dredged, excavated and bunded. By way of comparison, a site upstream of the area impacted by dredging or excavation was investigated. This site was close to a village downstream

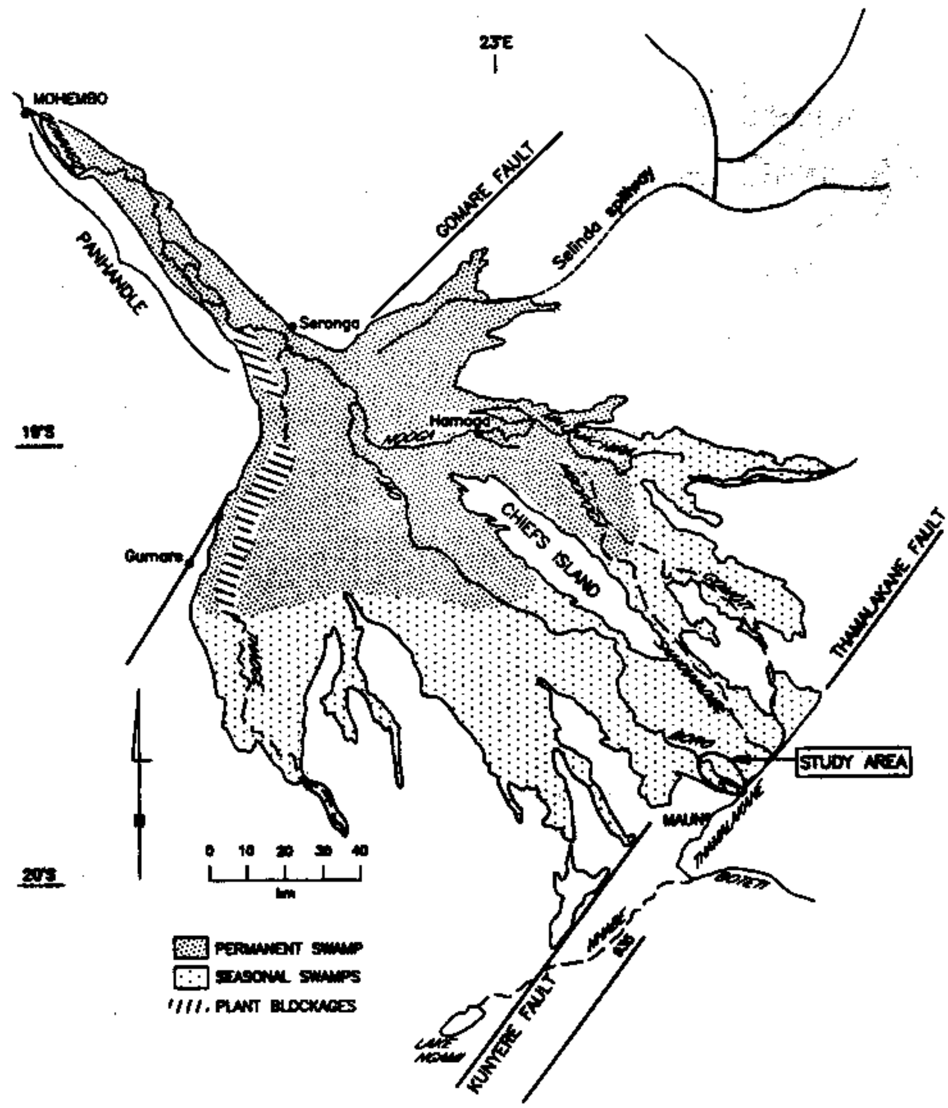

FIG. 2. A map of the Okavango Delta showing the major distributary river systems and the location of the study area, which is shown in detail in Fig. 3.

of the 'Buffalo fence' (a fence separating cattle to the south from wildlife to the north), and was therefore probably subject to similar grazing pressure as the impacted areas.

THE NATURE OF THE INITIAL IMPACTS

Dredging commenced at the junction of the Thamalakane and Boro Rivers in June 1971 (Fig. 3). It ceased in December 1974, by which time it had deepened the Boro River by approximately 3.5 m for a distance of 4.5 km (Lubke *et al.*, 1984). Dredging also involved the construction of new channels in some areas, in order to straighten the river course and thereby increase the gradient. Spoil generated by dredging was spread as a wet slurry along the banks and was also used locally to fill the original channel where diversions had been made (Fig. 4).

From December 1972 a mechanical shovel excavator was used upstream of the dredged section to deepen the bed by approximately 1 m. Spoil was spread in the immediate vicinity of the channel by bulldozer. By June 1973 when floodwaters reached the lower Boro, excavation had progressed a further 13 km upstream of the dredged section (Fig. 3). In addition to dredging and excavation, forty-four low earth bunds were constructed adjacent to the immediate floodplain of the Boro River, to prevent inundation of floodplain areas.

METHODS

The present study was undertaken in November 1993 and July and December 1994. The same methods and study sites (Fig. 3) that were used in previous studies (Dye, 1975; Dye *et al.*, 1976; Lubke *et al.*, 1981; Reavell, 1982; Lubke *et al.*, 1984) were used in this study. Channel cross-sectional profiles and down-channel gradients were surveyed using a level and staff. Vegetation was recorded along the transects

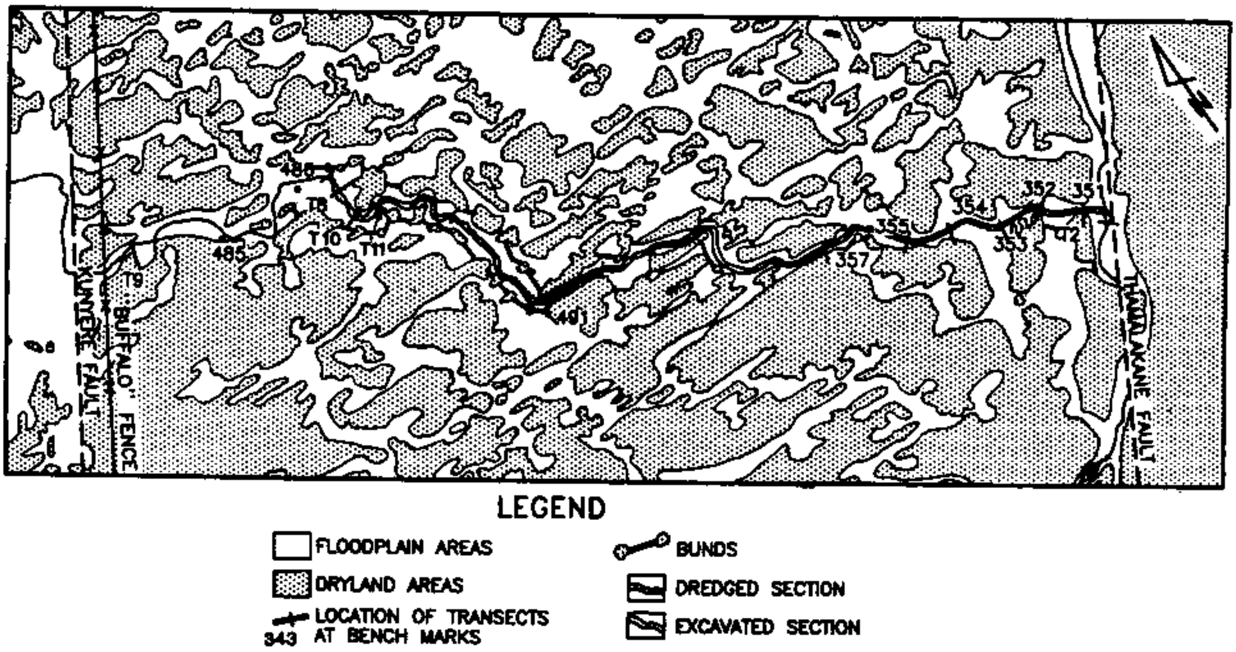

FIG. 3. The study area showing the major fault lines, the extent of dredging and excavation, the location of bunds constructed to reduce water loss to the floodplains in the region of the flow improvement works, and the location of transects.

FIG. 4. An aerial view of the dredging operation taken from a position just downstream of BM357 (Fig. 3), looking downstream. The dredge can be seen in the foreground, and the dredged section can be seen behind. The dredging operation included straightening the channel, and creating bunds beside the channel in order to confine flow to the in-channel area. The Thamalakane River can be seen in the background. Photo courtesy of *Optima*.

in contiguous 1 × 1 m quadrats within the channel as well as on the banks, with cover estimated on a scale of 1–5, representing cover intervals of <2%, 3–5%, 6–20%, 21–45% and 46–100%, respectively. Because woody species are generally larger than herbaceous species, the number and basal cover of woody species was recorded in larger quadrats than used for herbaceous species. Thus, in addition to recording woody species present in the 1 m × 1 m quadrats in which herbaceous species were measured (for purposes of comparison with previous studies), contiguous 5 × 5 m quadrats were used for woody species. The widths of various vegetation zones adjacent to the channel were estimated, and these were compared with previous studies in order to provide a basis for assessing the nature and extent of change since dredging.

Flow velocity profiles were measured using a Watts current meter, with measurements made at selected depth intervals, and at selected intervals across the channel, depending on channel width and depth. Isovels were interpolated, and a weighted mean velocity was calculated for each cross-section. Locally, plane table mapping was done, with spot heights measured using a level and staff, relative to a local datum.

In addition to these cross-sectional profiles and vegetation studies, a longitudinal profile of the water surface was surveyed for a distance of approximately 6 km, starting from about 1 km upstream of the area impacted by excavation by the excavator, and proceeding downstream.

RESULTS

THE PHYSICAL ENVIRONMENT

Immediate changes to the physical environment brought about by dredging and excavation

Cross-sections of unimpacted sites
A portion of the Boro channel was surveyed prior to dredging (Fig. 5a,b,c) by surveyors engaged by the company which undertook the dredging (R. Oelofse[1] pers. comm.), and a site upstream of the impacted sites was visited in the present study, for which results are also presented (Fig. 5d). Cross-sectional profiles show a broad, shallow channel. Gradients on the banks were between 1:20 (maximum) and 1:200 (minimum). Flow was spread over a wide zone so that movement of sediment was minimal.

Cross-sections of channels impacted by dredging
Flow was dramatically confined to an extremely narrow region of the former floodplain by dredging (Fig. 6a). In cases where the channel was deepened, spoil was spread over a wide area on one or both banks. However, in situations where the channel was straightened in order to shorten the channel length, spoil was placed as bunds on either side of the new channel, presumably to prevent lateral flow along the former thalweg, particularly during periods of unusually high flow (Fig. 6b). Both the cross-sections in Fig. 6 were compiled from the survey data acquired immediately after dredging. Maximum gradients across the floodplain were increased in many cases to between 1:10 and 1:1 in the dredged areas, which represents an increase of between 1 and 2 orders of magnitude compared to undredged sections.

Cross-sections of channels impacted by the excavator
Excavation by mechanical excavator was evidently not as deep as by dredging, and neither were gradients created by excavation as steep as those created by dredging (R. Oelofse, pers. comm.). Unfortunately the excavated reach was not surveyed after excavation, and it is only possible to present here a cross-sectional profile altered by 20 years of natural landscaping (Fig. 7). Although marginal bunds are evident, the general form of the channel is similar to unimpacted sites, i.e. broad and shallow.

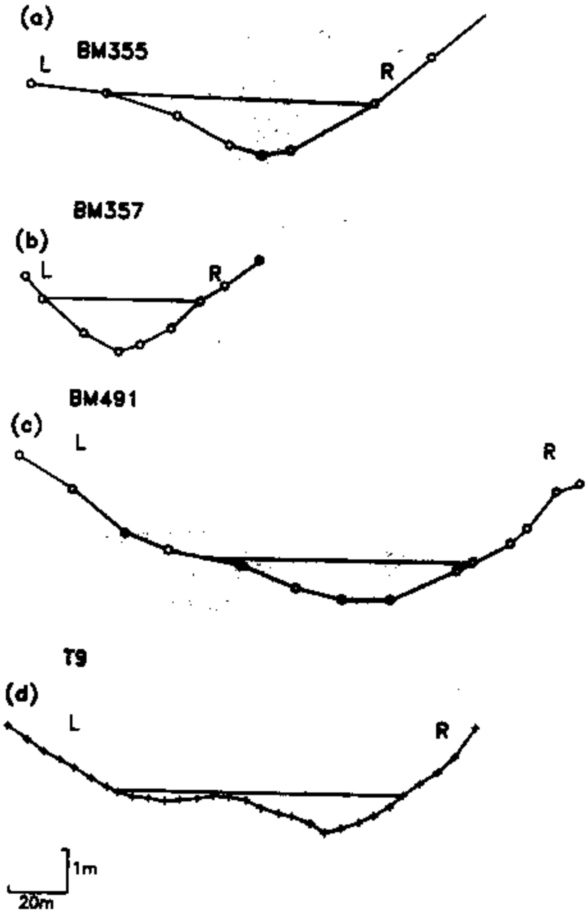

FIG. 5. Floodplain cross-sections prior to dredging (a–c) and upstream of the area impacted by dredging or excavation (d). Left and right banks are depicted looking downstream.

Comparison of natural, dredged and excavated channel morphometries
An indication of channel cross-sectional morphometry is provided in the relationship between the cross-sectional area and the wetted perimeter. The lower the wetted perimeter per unit of cross-sectional area, the more concentrated the flow within a confined channel. The impact of dredging on cross-sectional morphometry is illustrated by comparison of the relationships between the wetted perimeters and cross-sectional areas of dredged and undredged sections (Fig. 8a, b). The cross-sectional areas are far greater per unit of wetted perimeter in the dredged than the undredged sections.

Downstream gradients on the water surface
The survey of the downstream gradient on the water surface along the channel done in 1973 (Fig. 9) was completed

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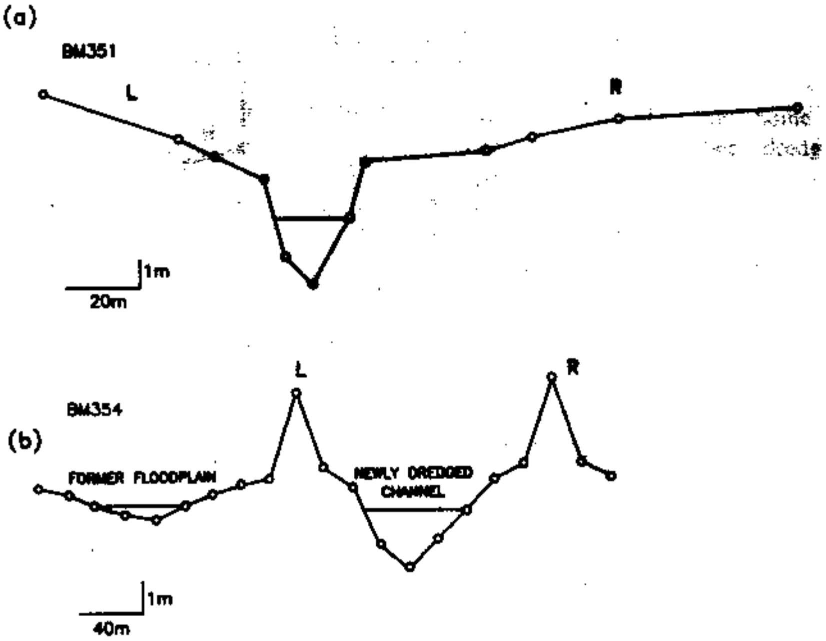

FIG. 6. Channel cross-sections along the dredged section shortly after dredging was completed.

FIG. 7. A cross-section of the excavated channel in the region of BM486, July 1994.

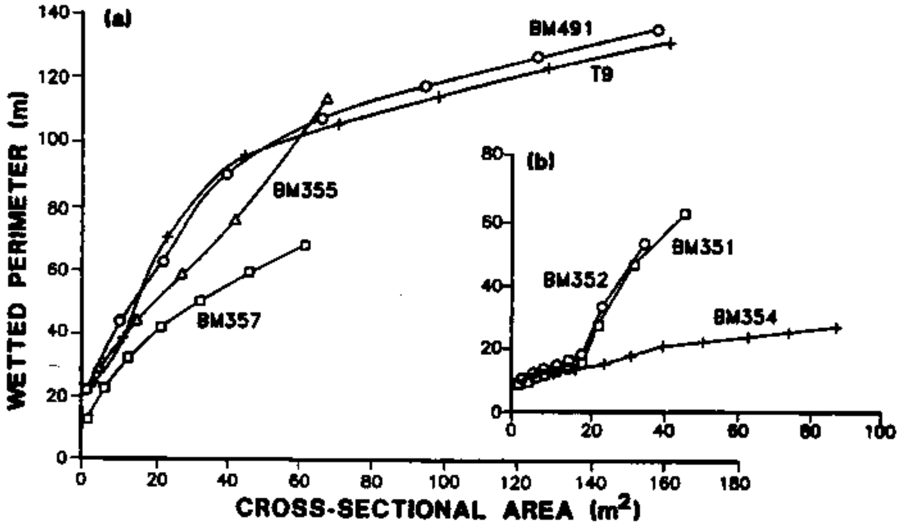

FIG. 8. The relationships between the wetted perimeter and the channel cross-sectional area of unimpacted (a) and impacted (b) channels. Each curve represents a different channel profile.

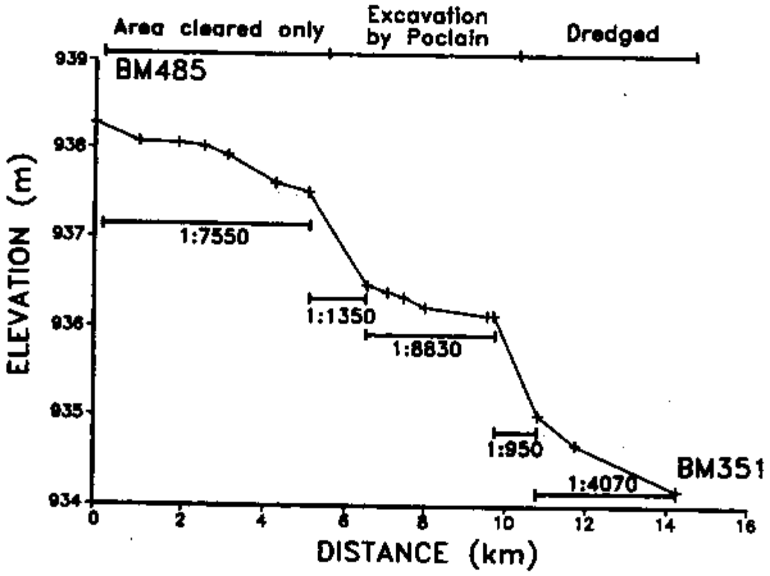

FIG. 9. Longitudinal section of the Boro River on 26 June 1973 showing the gradient on the water surface downstream of BM485. Excavation had not been completed at this stage, but the channel bed had been cleared of vegetation to enable easy access by the excavator. Excavation was subsequently extended upstream to a point between BM485 and BM486.

while excavation was still taking place. For this reason there is a 'dredged section', an 'excavated section' and a 'cleared section' (where channel vegetation had been cleared to enable easy access by the excavator). Subsequent excavation proceeded upstream and was terminated upstream of BM485. Dredging steepened the downstream gradient on the water surface, primarily as a result of straightening the watercourse. Upstream of the area impacted by either dredging or excavation, the gradient on the water surface was in the region of 1:7550 at the time of the initial survey. The gradient on the water surface in the excavated reach (1:8830) was similar to that upstream of the excavated reach (surprisingly, it was a little higher than the unimpacted site; probably due to natural variability in the gradients on the land surface). The similarity of the gradient above and below the upper limit of excavation suggests that excavation was aimed primarily at clearing and deepening the channel, rather than straightening it. Along the dredged section the downstream gradient on the water surface was approximately twice that of the unimpacted section (1:4070), due to shortening the channel length.

At the upper limits of the dredged as well as the excavated sections, the gradients on the water surface were markedly steeper, in the region of 1:1000 (1:950 and 1:1350, respectively). This is the result of the lowering of the channel bed by each of these activities. The nick points (breaks in slope) created by each of these activities would occur somewhere along each of these sections. At the time, upstream propagation of the nick point by the process of headward erosion was evidently not foreseen.

Changes in the physical environment since dredging

Lateral erosion of the dredged channel banks and alteration to the cross-sectional

Channel cross-sectional profiles measured immediately after dredging and excavation are presented together with the results from the present study (Fig. 10a,b,c). It is clear from the results that the steep banks created by dredging are eroding laterally, causing some widening of the channel and a reduction of the gradients across the floodplain. Lateral erosion of the banks is surprisingly small, however, particularly in view of the steepness of the gradient created by dredging (1:1). It can be expected that lateral erosion of the banks will continue to reduce the slope of the banks to being closer to what it was prior to dredging, but clearly this is a gradual process, and will become increasingly slow as gradients are reduced. The heights of lateral bunds have also been reduced (Fig. 10c).

The channel bed has generally changed shape to being more rounded, and possibly to being slightly elevated, compared to what it was immediately after dredging, particularly in the lower regions of the dredged section (Fig. 10a). This suggests that some deposition of sediment is occurring in this area. In the middle reaches of the dredged section, the elevation of the channel bed is similar to what it was immediately after dredging (Fig. 10b), suggesting that there has been no net erosion or deposition. In the upper reaches of the dredged section the channel bed is deeper than was the case immediately after dredging, suggesting that the channel bed has eroded. The eroded areas have a similar shape to that immediately after dredging (Fig. 10c), suggesting that erosion takes place uniformly across the dredged width.

Current velocity, channel morphometry and discharge

The mean current velocity is extremely low upstream of the dredged and excavated sections where the channel morphology is intact. At the time of measuring flow (July 1993), the cross-sectional area at T9 was 71.5 m^2, and the mean current velocity was 0.008 $m.s^{-1}$ (Table 1). In the dredged section, average velocities were an order of

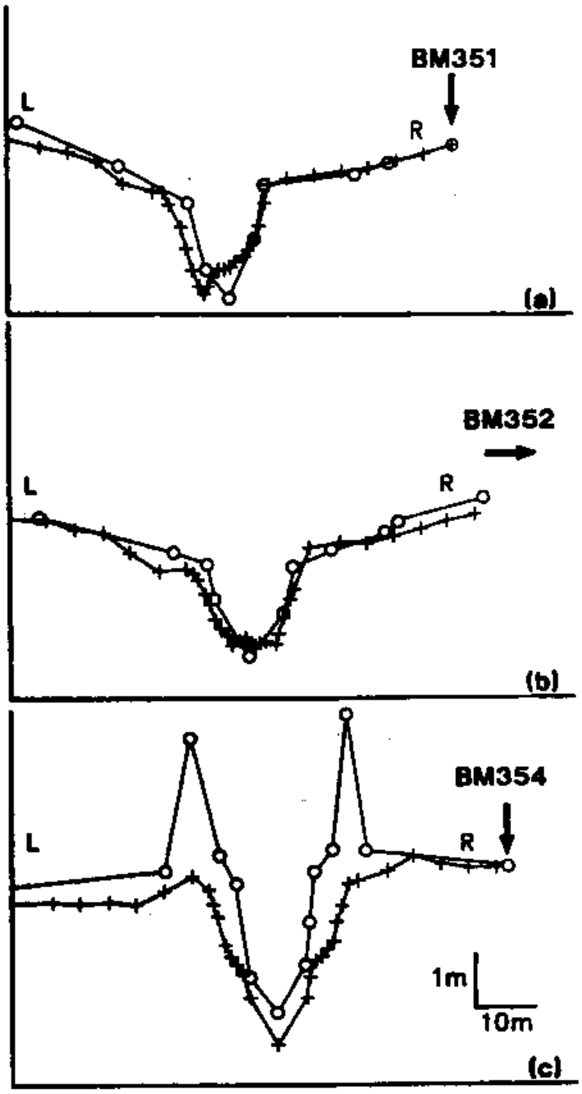

FIG. 10. Comparison of channel cross-sectional profiles in 1973 (circles) and 1993 (plus signs) for the dredged section.

TABLE 1. A summary of channel cross-sectional morphology, and flow characteristics downstream of the buffalo fence as far as the Thamalakane River. Stations are listed in sequence from the upper end of the study area to the lower end. T9 and T10 are upstream of the nick point, station T11 is immediately below the nick point, and remaining stations are further downstream. For the actual localities, refer to Fig. 3. Measurements made in December, 1994.

Station	Maximum velocity (m/s)	Average velocity (m/s)	Cross-sectional area (m^2)	Discharge (M^3/s)
T9	0.01	0.008	71.5	0.6
T10	0.3	0.052	10.82	0.56
T11	0.75	0.24	2.29	0.56
T8	0.4	0.22	2.42	0.52
BM491	0.3	0.18	3.07	0.55
BM357	0.3	0.11	4.31	0.48
BM354	0.2	0.10	6.87	0.7
BM351	0.11	0.035	10.47	0.36

magnitude higher (Table 1; BM357 & BM354), although they decreased again at the end of the dredged section (BM351), where the Boro water backs up against the slowly flowing Thamalakane River. Some sites which had been excavated but had not been dredged also showed high velocities (Table 1; T8 & T11), while others showed a low velocity (e.g. T10).

Alteration to the excavated channel morphometry

Examination of channel reaches which had been excavated but not dredged indicated a distinct dichotomy in character. Some of the profiles showed a gently sloping form similar to unimpacted channels (e.g. T10, Fig. 7). In contrast, others had undergone radical change, taking on the appearance of dredged channels (e.g. BM491, Fig. 11), with the characteristic central depression in which flow is confined.

Reconnaissance along the channel revealed that the transition between these two channel forms occurred over a short reach about 150 m in length, near BM486. A contour map of this reach is shown in Fig. 12, and cross-channel profiles across the reach in Fig. 13. Water surface gradient was measured for a distance of 1 km both up- and downstream of this locality (Fig. 14). In the upstream reach, gradient is in the region of 1:7500, while downstream, the gradient is 1:5700. Over a short distance, where the change in channel character occurs, gradient steepens to about 1:300.

The steepest reach has the form of an erosional nick point. The substrate in this reach consists of cohesive, sandy clay, and is resistant to erosion. Immediately upstream of the nick point, flow velocity is about 0.04 m.s^{-1} (Table 2), while downstream, flow velocity increases to about 0.3 m.s^{-1}. Within the nick point, flow velocity attains 0.6 m.s^{-1}.

Both excavated and unexcavated channels upstream of the nick-point are characterized by low flow velocities (<0.06 m.s^{-1}), have a broad zone of inundation (Fig. 13), and are heavily vegetated by aquatic macrophytes. Downstream of the nick point, both excavated and dredged channels have a very similar character. Flow velocities are higher (>0.1 m.s^{-1}), channels are more confined, and the channel bed is largely unvegetated or only sparsely vegetated, consisting of sandy clay or sand.

The fact that the distinction between dredged and excavated channels has largely disappeared below the nick point indicates that the nick point was created by dredging, and has migrated upstream, thereby homogenizing the cross-channel profile. The distance of movement is 10.5 km, which has taken approximately 20 years, indicating an average upstream migration of 500 m.a^{-1}. The smaller nick point created by excavation has evidently been completely attenuated without adverse impact.

Detailed examination of the contour map of the nick point (Fig. 12) indicates that the rate of migration of the nick point is unlikely to be uniform. Upstream of the nick point the channel forms a deep pool, the bed of which is at a lower elevation than the bed in the nick point region. Therefore, as the bed of the channel in the nick point is lowered by erosion, the pool will drain and a new nick point will form, probably upstream of the limit of the

FIG. 11. Cross-sectional profile of BM491 in 1993; the channel was excavated but not dredged. The channel form prior to excavation is shown in Fig. 5c.

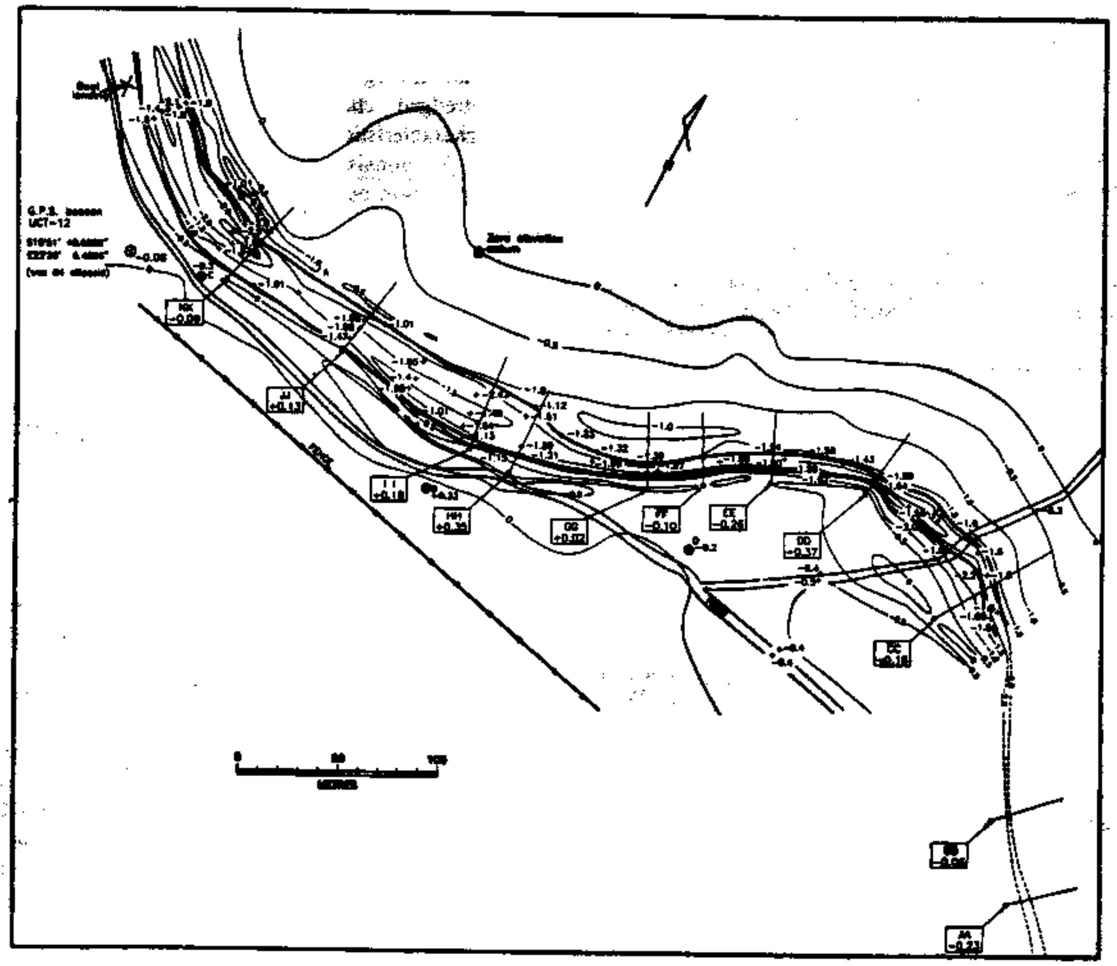

FIG. 12. Map of the region of the nick point, July 1994.

contour map. In effect, the nick point will jump across the pool. No doubt this has happened repeatedly during advance of the nick point, and hence the calculated rate of advance is simply a long-term average, which includes such periods of rapid advance.

II VEGETATION

Zonation of species prior to dredging

The vegetation prior to dredging exhibited a distinct zonation depending on the depth and duration of flooding (Fig. 15b), a zonation still prevalent upstream of the impacted channel. Typically, the areas flooded for the longest period are inhabited by submerged species such as *Limnophila ceratophylloides*, *Ottelia ulvifolia* and *Rotala myriophylloides*. In shallower water, where flooding is less prolonged, plants with leaves and flowers that float at the water surface dominate. These include *Nymphoides indica*, *Potamogeton thunbergii* and *Weisneria schweinfurthii*. The zone with submerged and floating-leaved plants has been referred to as the submerged and floating zone (Lubke *et al.*, 1984). As the duration of flooding decreases, emergent species dominate what has been referred to as the lower floodplain zone. Species typical of this zone include *Cyperus articulatus*, *Eliocharis acutangular*, *E. dulcis*, *Leersia*

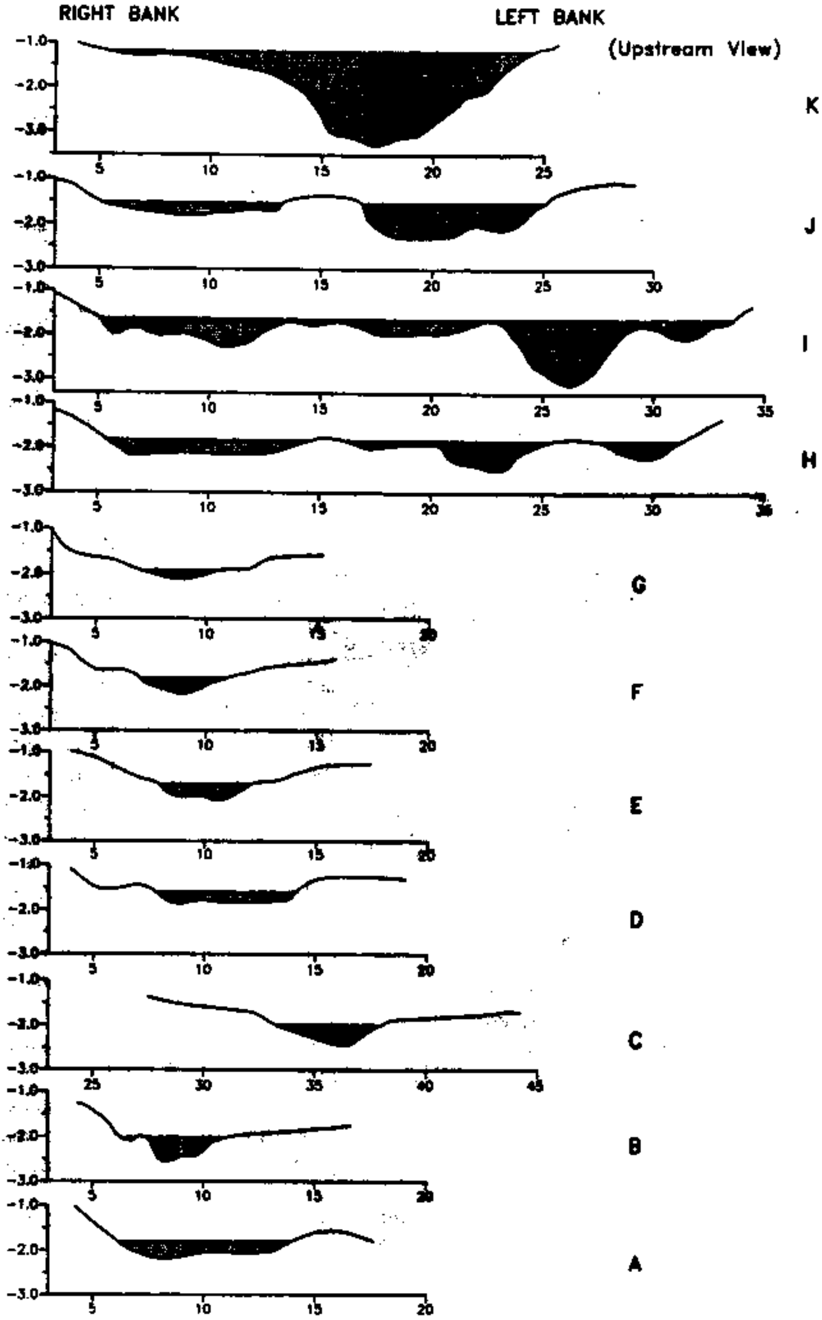

FIG. 13. Cross-sectional profiles in the region of the nick point. Refer to Fig. 12 for the location of each profile.

hexandra, *Oryza longistaminata*, *Sacciolepis typhura* and *Schoenoplectus corymbosus*. The mid-floodplain zone, flooded less frequently than the lower floodplain zone, has species such as *Cyperus denudatus*, *Eragrostis lappula*, *Imperata cylindrica*, and *Panicum repens*. Based on data from these early studies, as well as from the present study, the upper floodplain zone, which floods infrequently, is dominated by *Cynodon dactylon*. The presence of woody species which are intolerant of flooding, indicates a terrestrial habitat. This zone is referred to as a riverine woodland.

Immediate changes brought about by dredging

Results for a single transect at a site impacted by dredging (BM352) are presented in Fig. 16 for transects done in February 1973, February 1974 and December 1974 (Dye, 1975). The cross-sectional topography reveals a shallow floodplain with a deeply incised, dredged section (Fig. 16a).

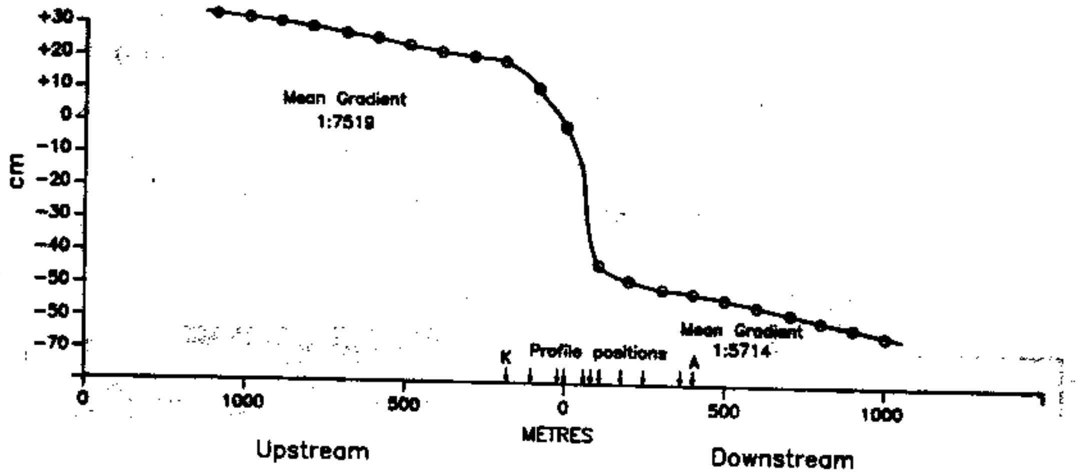

FIG. 14. Downchannel gradient on the water surface in the region of the nick point.

TABLE 2. The combined widths (left bank + right bank) of different vegetation zones at sites not impacted by dredging. The zones are as follows: S + FL, submergent and floating leaved zone; LF, lower floodplain zone; MF, middle floodplain zone; UF, upper floodplain zone.

Site	Date	S + FL	LF	MF	UF
BM357	Feb 1973	25	33	>15	
BM491	Feb 1973	19	88	>20	
T9	Nov 1993	11	95	23	>18

Immediately following dredging the in-channel flora was completely eliminated, and just a few ruderal species occur in the region of the former floodplain (Fig. 16b). During the period after this, there appears to have been establishment of a relatively diverse floodplain flora, but the channel bed remained unvegetated (Fig. 16c, d).

Changes in vegetation distribution since dredging

Dredged sites

The transect at BM352 was resurveyed in 1993 (Fig. 16e). The widths of the floodplain communities have declined substantially over the study period, as indicated by the increase in the area colonized by *Cynodon dactylon* and by the reduction in the area colonized by *Panicum repens* (compare Fig. 16c–e). Furthermore, many of the other floodplain species have been completely eliminated, and there has been encroachment of terrestrial vegetation in the region of the former floodplain communities, indicated most notably by the presence of the woody plants *Acacia tortilis* and *Combretum imberbe* in the present study. This may be due to lowering of the water table in the region of the dredged section or to a natural reduction in the extent of lateral flooding as a consequence of prolonged, below normal rainfall. The in-channel vegetation in the most distal sites showed signs of recovery in the most recent survey, with the establishment of *Potamogeton thunbergii*.

Vegetation in the excavated section downstream of the nick point

BM491 was upstream of the dredged section at the time dredging was halted, and it occurs currently downstream of the nick point. The channel at this site is incised (Fig. 11), and the zonation of vegetation indicates desiccation of the floodplain, with floodplain species confined to a very narrow region of the former floodplain, and the semi-terrestrial species *Cynodon dactylon* relatively widespread. Other terrestrial species such as *Acacia tortilis, Combretum imberbe, Pechuel-loeschea leubnitziae, Sida cordifolia* and *Urochloa mossambicensis* occur within the former floodplain, illustrating the extent of desiccation. Furthermore, many of the other floodplain species have completely disappeared.

Vegetation in the excavated reach upstream of the nick point

No detailed vegetation studies have been made of the vegetation in the excavated reach upstream of the nick point. However, observations suggest that the vegetation has recovered to being similar to what it was prior to excavation, and that there has been no observable, long-term effect. The channel bed is vegetated, small (0.5 m) bunds occur on either side of the channel (Fig. 7), and the remainder of the floodplain has a grass cover, primarily *Digitaria debilis, Eragrostis inamoena, E. lappula* and *Panicum repens* on the lower floodplain zone, and *Cynodon dactylon* on the upper floodplain zone.

Vegetation distribution upstream of the impacted section

The present zonation of species upstream of the dredged and excavated sections (Fig. 17) is similar to the zonation prior to dredging (described by Lubke *et al.*, 1984; Fig. 15b). It was not possible to distinguish the submerged and floating zone at site T9, although a number of submerged and floating-leaved plants were present, including *Nesaea crassicaulis, Nymphaea caerulea, Ottelia ulvifolia, Potamogeton thunbergii* and *Rotala myriophylloides*. Emergent species typical of the lower floodplain zone include *Cyperus articulatus, Eliocharis dulcis, Leersia hexandra,*

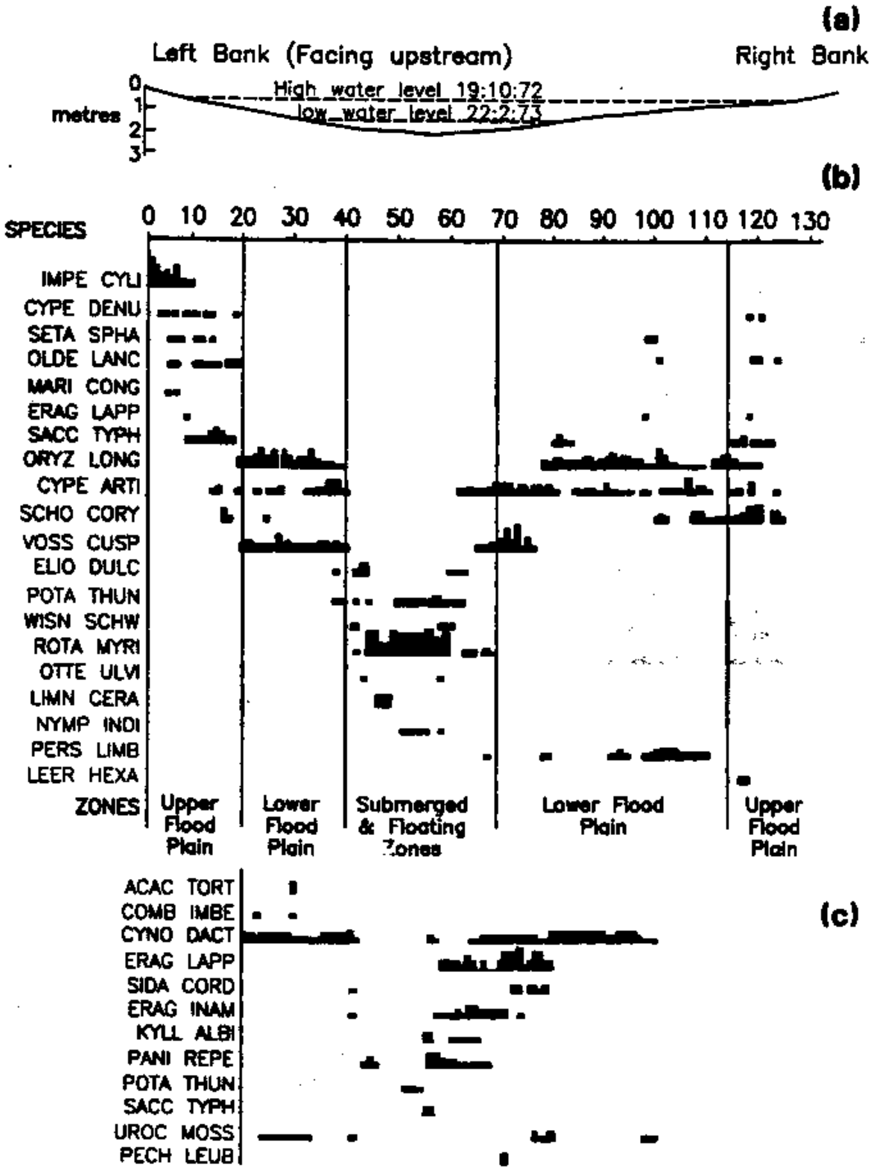

FIG. 15. Cross-sectional profile at BM491 showing (a) topography prior to excavation and (b) showing the distribution of species in relation to topography prior to dredging (Lubke *et al.*, 1984), which reflects the depth and duration of flooding. The topography was resurveyed in 1993 (Fig. 7), and the distribution of species (c) was determined at the same time. See Appendix I for species names.

Sacchiolepis typhura, *Schoenoplectus corymbosus* and *Vossia cuspidata*. Species typical of the middle and upper floodplain zones include *Cynodon dactylon*, *Eragrostis inamoena* and *Panicum repens*. Woody plants are absent from the floodplain.

DISCUSSION

Comparison of results of the present study with previous studies

Based on all the data from all the past studies by Reavell & Lee (1974), Dye (1975) and Lubke *et al.* (1984), as well as the present study, it was possible to calculate the widths of each of the zones in the unimpacted sites (Table 3). The width of each zone varied depending on the cross-sectional morphometry of the floodplain; the shallower and wider the floodplain, the wider each of the zones.

The widths of vegetation zones for sites impacted by dredging, and calculated for each of the studies mentioned above, are provided in Table 4. The results show the following:

(i) the virtual elimination of an in-channel flora (submerged and floating leaved zones) which represents the complete loss of these habitats from the impacted area;

(ii) the dramatic reduction in the width of all of the floodplain zones to metres rather than tens of metres; and

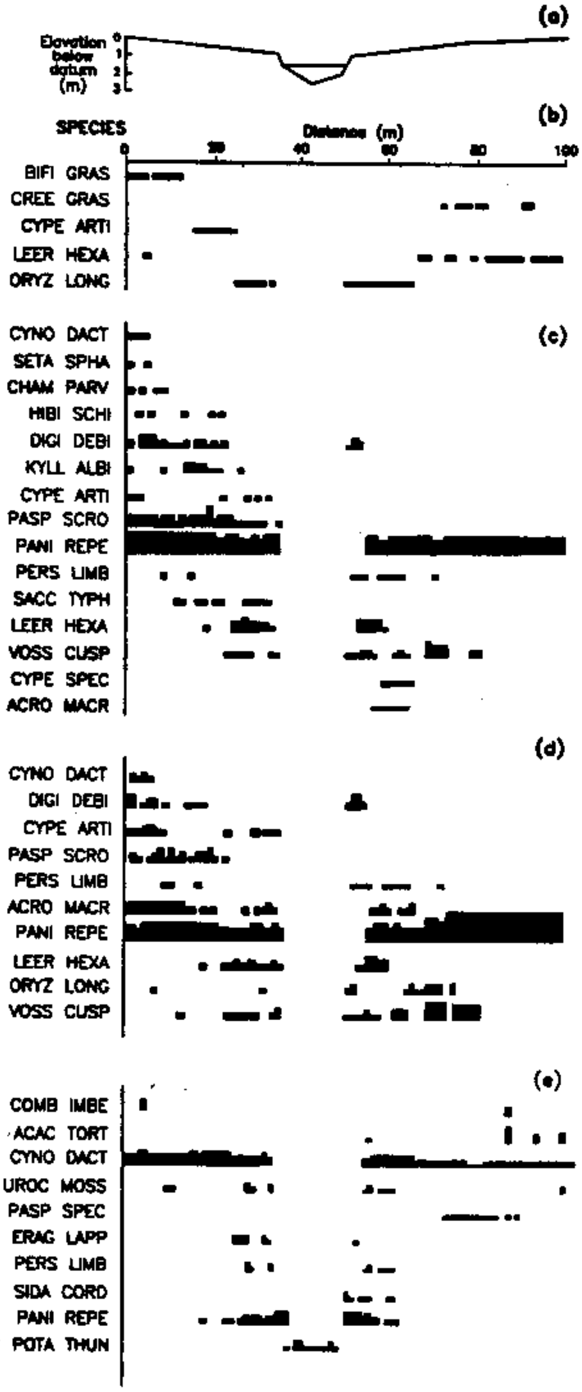

FIG. 16. Channel cross-sectional profile (a) and vegetation distribution for site BM352, February 1973 (b, Reavell & Lee, 1974), February 1974 (c, Dye, 1975), December 1974 (d, Dye, 1975) and November 1993 (e, this study). Left and right banks are depicted looking downstream.

(iii) the encroachment of the former floodplains by terrestrial communities, as indicated by the dominance of the former floodplains by *Cynodon dactylon* and the occurrence of woody plants intolerant of flooding.

(i) Virtual elimination of the in-channel flora
While this was recognized to have taken place by Lubke *et al.* (1984), it appears that there has been some rehabilitation of the in-channel areas since their study, particularly in the lower regions of the impacted area (Table 3). This may be due to the length of time since dredging, but it seems likely that headward erosion in the middle and upper reaches of the impacted area is contributing to further decline of these habitats, while deposition and stabilization is taking place in the lower reaches of the study area. The data on current velocities (Table 1) suggest that rehabilitation of in-channel areas may take place once current velocities become less than 0.10 $\mathrm{m.s^{-1}}$, ideally probably less than 0.05 $\mathrm{m.s^{-1}}$.

(ii) Reduction in the width of former floodplain communities
Once again this was anticipated in previous studies, but the extent of reduction of the upper middle and lower floodplain zones does not seem to have been expected. This is illustrated by direct quotation: '... it is seen that about four years is necessary for the vegetation to return to the same state as it was before dredging and excavating. The only difference in vegetation being the shift of the upper flood plain vegetation closer to the river because of increased elevation of the river banks after the spoil was deposited' (Dye *et al.*, 1976: 14).

(iii) Encroachment of the floodplain by terrestrial species
No woody species were recorded as being present in any of the previous studies. In the present study however, woody species were widespread. This suggests that the former floodplain habitats have been converted to terrestrial habitats, a feature not anticipated on a large scale in previous studies.

An interesting feature of the abundance of woody plants is the general upstream decrease in the extent of encroachment by woody species. This appears to reflect the gradual reduction in the flooding of the areas adjacent to the channel as a result of headward erosion in the upper reaches of the study area, and as indicated by the increased colonization of in-channel areas as one moves downstream. This, together with the survey of the down-channel gradient of the water surface provides the basis for a conceptual model of processes that have taken place, or are taking place at present.

The effects of dredging on flood plain deterioration

There have been significant vegetation changes in the region of the former floodplain and in-channel communities since dredging. Some studies have focused on re-vegetation of the spoil heaps, others on rehabilitation of the floodplain. Re-vegetation of spoil heaps seems to have taken place rapidly (Reavell *et al.*, 1973; Reavell & Lee, 1974; Dye, 1975 and Dye *et al.*, 1976). Studies of rehabilitation of the floodplain predicted recovery of the floodplain vegetation in 'tens to hundreds of years' (Lubke *et al.*, 1981), and subsequently their estimate was reduced to between 'ten and thirty years' (Lubke *et al.*, 1984). The present study shows that very little natural recovery of the floodplain has taken place in two decades and, moreover, has shown

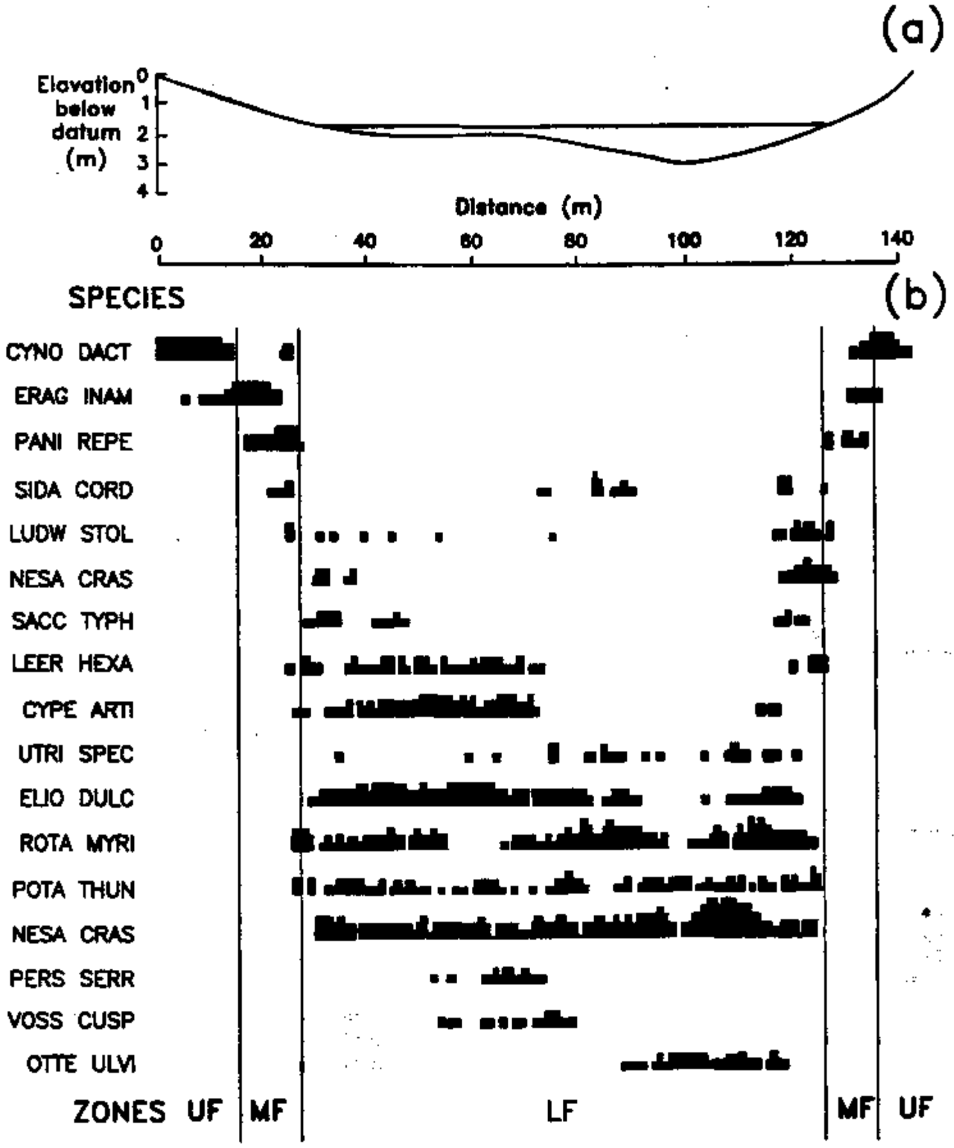

FIG. 17. Cross-sectional profile of Transect 9 (T9) showing the topography as well as the distribution of plant species. November, 1993 (this study). See Appendix 1 for species names.

that processes are taking place which are increasing the magnitude of the environmental impact of the initial dredging.

The results of this study are summarized in Fig. 18. Dredging canalized the lower reaches of the Boro River, steepened channel gradient and modified channel morphology. Excavation did not alter gradient, but removed channel vegetation. After a lapse of 20 years since dredging, several consequences are evident. In the upper reaches of the excavated section, channel vegetation has recovered. In the dredged section, vegetation recovery has been minimal. Moreover, the nick point created by dredging has migrated upstream for a distance of 10.5 km. Vegetation recovery in the reach downstream of the nick point has been minimal, and the excavated channel is indistinguishable in form from the reach which was subjected to dredging. The impact created by dredging is thus migrating upstream as the nick point advances.

The channel characteristics measured during the December 1994 survey provide some insight into the causes of channel deterioration incurred by advance of the nick point. Headward erosion of the nick point creates a narrow channel (Fig. 13), which concentrates flow and steepens the gradient (Fig. 14). The effects of this process can be analysed using Manning's equation which relates flow velocity, slope and hydraulic radius of the channel. Above the nick point, hydraulic radius is about 0.4 m, slope is 0.00013 $m.m^{-1}$, and flow is about 0.04 $m.s^{-1}$. Downstream of the nick point, hydraulic radius is about 0.2 m, slope is 0.0002 and velocity is about 0.3 $m.s^{-1}$. Mannings equation relates these variables:

TABLE 3. The combined widths (left bank + right bank) of different vegetation zones at sites impacted by dredging, and the distance from the channel of terrestrial vegetation (TV). The floodplain zones are as follows: S+FL, submergent and floating leaved zone; LF, lower floodplain zone; MF, middle floodplain zone; UF, upper floodplain zone.

Site	Date	S+FL	LF	MF	UF	TV	
						Left	Right
BM351	Feb 1973	A	[illegible]				>90
	Feb 1974	A	34	48		>48	90
	Dec 1974	A	12			>48	
	Nov 1993	14	A	40	>98	47	>105
BM352	Feb 1973	1	65				>57
	Feb 1974	A	18	>62		>55	>35
	Dec 1974	A	18	>62		>55	>36
	Nov 1993	10	A	13	19	26	21
BM354	Feb 1973	A	>34				>75
	Feb 1974	A	A	>56		>35	>56
	Dec 1974	A	A	>68		>36	>55
	Nov 1993	6	6	2	12	13	13
BM355	Feb 1973	A	>30			>56	
	Feb 1974	A	45	>25		>38	
	Dec 1974	9	>21			>38	
	Nov 1993	11	5	6	29	21	28

TABLE 4. Characteristics of the channel in the area of the nick-point.

Profile	Channel area (m^2)	Channel width (m)	Mean depth (m)	Flow velocity† (m/s)	Water surface* gradient (m/100 m)
K	15.73	19.0	0.83	0.024	0.11
J	6.28	16.6	0.38	0.059	0.11
I	10.38	28.4	0.37	0.036	0.34
H	6.01	23.8	0.25	0.062	0.60
G	0.63	3.3	0.19	0.59	0.22
F	0.77	3.7	0.21	0.48	0.15
E	1.03	4.2	0.25	0.36	0.10
D	1.36	6.3	0.22	0.27	0.05
C	1.01	3.7	0.27	0.35	0.02
B	1.09	3.8	0.29	0.36	0.02
A	1.58	7.4	0.21	0.23	0.02

* Gradients obtained by constructing tangents to water surface profile in fig. 5.
† Calculated assuming a discharge of 0.37 m^3/a at all profiles except A, B and C, which were measured.

$$V=\frac{R^{2/3}S^{1/2}}{n}$$

where V is velocity, R is hydraulic radius, S is slope and n is bed roughness. Upstream of the nick point,

$$0.04=\frac{0.4^{2/3}\times 0.00013^{1/2}}{n}$$

Hence n = 0.15.
Downstream of the nick point,

$$0.3=\frac{0.2^{2/3}\times 0.0002^{1/2}}{n}$$

Hence n = 0.016.

Across the nick point, slope increases by about 30%. The effect of this is more than offset by a decrease in hydraulic radius, which is halved. Hence the numerator in Manning's equation decreases across the nick point. The increase in velocity by an order of magnitude is therefore primarily

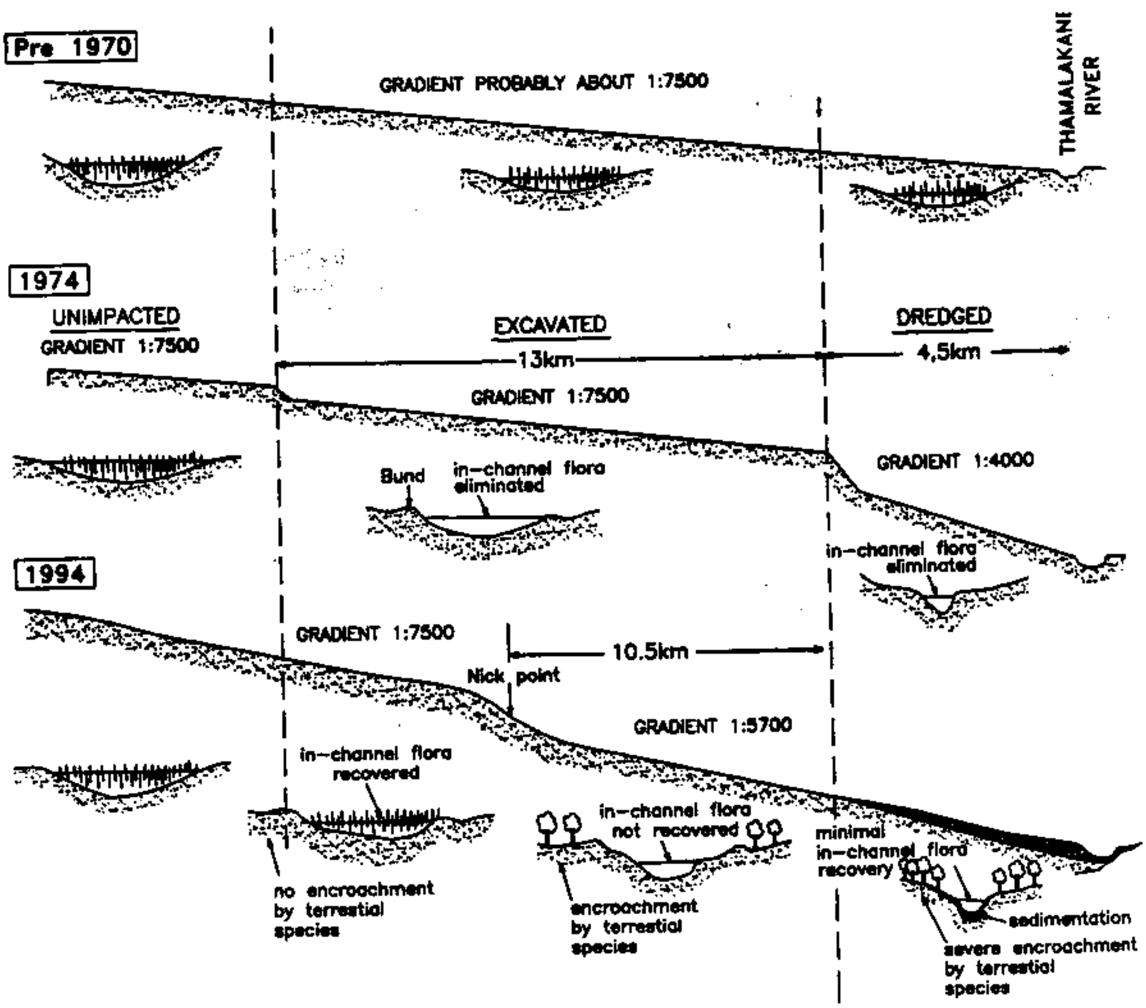

FIG. 18. Diagrammatic illustration of the effects of dredging and excavation on the lower Boro River. Dredging was carried out along the 4.5 km of the channel. This radically altered channel cross-section and steepened the channel gradient. A further 13 km of channel was excavated. Channel form was only slightly changed, mainly by the construction of bunds. Both dredging and excavation destroyed in-channel flora. By 1994, several changes had taken place. The nick point created by dredging had migrated some 10.5 km upstream, producing a channel form indistinguishable from that produced by dredging itself. The in-channel vegetation in this reach, and in the dredged reach, has not recovered. There is also significant encroachment of woody vegetation onto the old flood plain. Upstream of the nick point, in the excavated reach, in-channel vegetation has completely recovered.

due to a change in bed roughness, from 0.15 upstream of the nick point to 0.016 downstream. The high value of bed roughness upstream of the nick point is caused by the presence of in-channel vegetation. The elimination of this vegetation as the nick point advances reduces the roughness, increasing flow velocity. The high flow velocity in the downstream channel evidently inhibits recolonization by aquatic plants. In effect, advance of the nick point sets in motion a negative feedback: flow velocity is high because there are no aquatic plants, but these are unable to re-establish because flow velocity is too high.

The rôle of factors other than dredging in floodplain deterioration

It has been argued that deterioration of the floodplain vegetation is due to the presence of cattle in the area (Reavell, 1982). However, dredging is partly responsible for increased utilization of the former floodplain areas by cattle. This is based on the present field survey, and can also be explained on theoretical grounds. The vegetation in the unimpacted site visited in the present study (Fig. 17) exhibits the same zonation of vegetation growth forms as was evident in the unimpacted sites in previous studies (cf. Lubke *et al.*, 1984). Differences between the zonation would be expected if cattle were responsible for degradation of the floodplain areas, particularly as there has been an increase in livestock in the area during the last two decades. Moreover, impacted and unimpacted areas would have shown similar encroachment by woody species if cattle were responsible.

A consideration of the determinants of forage quality illustrates the reason for the low impact that cattle have on the floodplain vegetation. Forage quality is related inversely to the carbon to nutrient ratio of plant tissue. It therefore represents the outcome of the balance between environmental factors that affect both carbon assimilation and nutrient assimilation. Soils throughout the Okavango region are extremely infertile, and may be assumed to be similar in floodplain areas as well as in the surrounding dryland areas. Similarly, water in the Okavango Delta has very low nutrient concentrations. In contrast, carbon assimilation is promoted primarily by water availability. For a given soil fertility (low in soils throughout the Okavango Delta), therefore, forage quality will decline as water availability increases. Floodplain and swamp vegetation is well known to be of extremely low value for animal production, and is avoided by stock except during the most extreme conditions. The desiccation of the former floodplain vegetation as a result of dredging would have improved the quality of forage, and thus made these areas far more suitable for animal production. This is a benefit of dredging for the local population.

The contribution of livestock to the decline of in-channel species appears to be small. Vegetation upstream of the nick point has recovered, in spite of both excavation and grazing pressure. Moreover, downstream of the dredged section, the Thamalakane river supports an abundant in-channel flora, in spite of intense grazing pressure.

It is suggested that because of the alterations in the physical environment as a result primarily of dredging, the former floodplains can be expected to change to a terrestrial habitat. The channel is a reasonably permanent feature, as indicated by the extremely slow rates of bank recession, and it is unlikely that the former floodplains will ever be restored to either their original shape or extent.

FUTURE DEVELOPMENTS

The extent to which the nick point will continue to propagate upstream is uncertain, and continued monitoring is desirable. The nick point initiated by dredging has become attenuated, and is currently represented by a change in the elevation of the river bed of approximately 1.5–2 m. Originally the dredged channel was in the region of 3.5 m deep. Thus, a 50% attenuation has been achieved over the course of a 10.5 km advance. Complete elimination may be achieved over the course of a further 10 km advance or probably less, because of reduced flow velocities and accumulation of eroded sediment. The rate of headward erosion is likely to slow down as the elevation of the nick point is reduced. The estimate of the rate of headward erosion in this study is based on the location of two points over a period of 20 years. This is far from ideal, and is a long-term figure. The rate of migration is probably non-uniform, and will depend on upstream channel morphology. A source of possible concern is that the nick point may cross the Kunyere fault, which is represented by a 2 m scarp. This could result in a major influx of water into the lower Boro channel, with unpredictable results. However, steps could easily be taken to prevent this, should it prove necessary.

The results of this study indicate that high flow velocity in the reach below the nick point retards recolonization of the channel by aquatic flora. It may be possible to speed up rehabilitation of the impacted area by erecting control structures which reduce flow velocity and by recreating the original channel in the dredged section.

CONCLUSIONS

Dredging of the lower reaches of the Boro River in the Okavango Delta has largely eliminated the submerged and floating-leaved plant communities, has substantially reduced the width of former floodplain communities, and has resulted in the encroachment of these communities by terrestrial vegetation. Further unexpected impacts have resulted from headward erosion initiated from the upper limit of dredging, downstream of which the gradient of the channel was steepened by channel straightening. Headward erosion is having a similar effect on the in-channel vegetation and floodplain communities as dredging itself, extending the environmental impact of initial dredging. The average rate of advance of the nick point has been about 500 m per year, but is probably highly variable. The nick point has advanced 10.5 km since dredging ceased, during which time it has halved in height. It is likely that the nick point will ultimately become completely attenuated, but it is not possible to estimate the ultimate distance to which it will migrate. The dredged channel is showing some natural recovery in the lower reaches, but the present study suggests that recovery is being inhibited by the increased flow velocities in the channel which are caused by nick point migration.

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APPENDIX 1. Key to species abbreviations used in Figs 15–17

ACRO MACR	*Acroceras macrum* Stapf.
ACAC TORT	*Acacia tortilis* (Forssk.) Hayne
BIFI ARAS	*Poaceae* 1
CYPE ARTI	*Cyperus articulatus* L.
CYNP DACT	*Cynodon dactylon* (L.) Pers.
CYPE DENU	*Cyperus denudatus* L.f.
CREE GRAS	*Poaceae* 2.
CHAM PARV	*Chamaecrista parva* (Steyaert) Lock
COMB IMBE	*Combretum imberbe* Wawra
CYPE SPEC	*Cyperus* sp.
DIGI DEBI	*Digitaria debilis* (Desf.) Willd.
ELIO DULC	*Eliocharis dulcis* (Burm.f.) Hensch.
ERAG INAM	*Eragrostis inamoena* K. Schum
ERAG LAPPI	*Eragrostis lappula* Nees
HIBI SCHI	*Hibiscus schinzii* Guerke
IMPE CYLI	*Imperata cylindrica* (L.) Raeuschel
KYLL ALBI	*Kyllinga albiceps* (Ridley) Rendle
LIMN CERA	*Limnophila ceratophylloides* (Hiern) Skan
LEER HEXA	*Leersia hexandra* Swartz
LUDW STOL	*Ludwigia stolonifera* (Guill. & Perr.) Raven
MARI CONG	*Mariscus congestus* (Vahl) C.B. Cl.
NESA CRAS	*Nesaea crassicaulis* (Guill. & Perr.) Koehne
NYMP INDI	*Nymphoides indica* (L.) Kuntze
OLDE LANC	*Oldenlandia lancifolia* (Schumach.) DC
ORYZ LONG	*Oryza longistaminata* A. Chev. & Roehr.
OTTE ULVI	*Ottelia ulvifolia* (Planch.) Walp.
PERS LIMB	*Persicaria limbata* (Meisn.) Hara
PECH LEUB	*Pechuel-loeschea leubnitziae* (Kuntze) O. Hoffm.
PASP SCRO	*Paspalum scrobiculatum* L.
PANI REPE	*Panicum repens* L.
PERS SERR	*Persicaria serrulata* (Lag.) Well & Moq
PASP SPEC	*Paspalum* sp.
POTA THUN	*Potamogeton thunbergii* Cham. & Schlechtd.
ROTA MYRI	*Rotala myriophylloides* Welw. ex Hiern
SIDA CORD	*Sida cordifolia* L.
SCHO CORY	*Schoenoplectus corymbosus* (Roth. ex Roem. & Schult.) J Raynal
SETA SPHA	*Setaria sphacelata* (Schumach.) Moss
SACC TYPH	*Sacchiolepis typhura* (Stapf) Stapf
UROC MOSA	*Urochloa mosambicensis* (Nack.) Dandy
UTRI SPEC	*Utricularia* sp.
VOSS CUSP	*Vossia cuspidata* (Roxb.) Griff.
WISN SCHW	*Wisneria schweinfurthii* Hook f.