Biological Conservation 70 (1994) 159–168
© 1994 Elsevier Science Limited
Printed in Great Britain. All rights reserved
0006-3207/94/$07.00

PRINCIPLES FOR THE SUSTAINABLE UTILIZATION OF THE OKAVANGO DELTA ECOSYSTEM, BOTSWANA

W. N. Ellery* & T. S. McCarthy

Geology Department, University of the Witwatersrand, Private Bag X3, PO WITS, 2050, Republic of South Africa

(Received 6 September 1993; revised version received 12 January 1994; accepted 26 January 1994)

Abstract

A broad understanding of the structure and functioning of the Okavango Delta ecosystem has provided a basis for evaluating the kinds of perturbations that are likely to affect the ecosystem as a whole. Sediment introduced into the system results in constant changes in the distribution of water on the fan surface. This promotes the occurrence of a variety of habitats in different stages of wetting and drying, and accounts for the overall habitat diversity in the system. It also promotes regeneration of saline soils that are locally toxic to vegetation on islands in the Okavango Delta. Water abstraction from the lower reaches of the fan by activities such as dredging may be rendered useless by changes in the distribution of water on the fan over relatively short time spans. However, water abstraction in itself is not necessarily a problem. Ideally it should be done from the apex of the fan, provided it is small relative to the total inflow (1–2%), and does not disrupt sediment supply to the system from source areas, such as by the construction of a weir or dam. An additional impact of the construction of an impoundment in the catchment would be an increase in the total dissolved solid concentration of inflowing water. The system is adapted to low total dissolved solid concentrations and, by affecting the nature of plant communities at the apex of the fan, the system as a whole could be affected.

The dominance of transpiration over evaporation in this wetland ecosystem results in the accumulation of dissolved substances, notably silica and calcium and magnesium carbonate below surface, where they are biologically not deleterious. Sustained removal of vegetation may result in salinization of surface water, and would have a large impact on the ecosystem. Additional impacts that could alter the structure and functioning of the ecosystem include eutrophication that may result from agricultural development in the catchment, which may profoundly affect the nature of vegetation communities in the upper reaches of the fan, and thus the patterns of sediment and water dispersal. We do not regard the present utilization of areas around the periphery of the Delta as a direct threat to the ecosystem itself.

Keywords: Okavango Delta, ecosystem processes, sustainable utilization.

INTRODUCTION

The visit by David Livingstone to Lake Ngami on the southern fringe of the Okavango Delta in southern Africa in 1849 (Livingstone, 1857) drew the attention of the world to the region, and several famous travellers visited the area in the decade after his arrival. These explorations revealed a vast swampland set in the semi-arid Kalahari Desert. Its remoteness, the threats posed by wild animals, and the frequent occurrence of disease amongst these early travellers, including malaria and sleeping sickness caused by the tsetse fly *Glossina morsitans*, reduced the area to the status of a geographical curiosity during the early colonial period.

However, the presence of large quantities of water in this semi-arid environment provided a continual challenge to colonial developers. This has been stimulated from two main sources. The livelihoods of the local people have been disrupted by natural changes in the distribution of water in the Delta, prompting government agencies to attempt to restore flow (Wilson, 1973). In addition, suggestions were made to exploit the water resources of the Okavango Delta on a large scale for national and international benefit. Amongst these water development schemes, the proposals of Schwartz (1919) and Wellington (1948) were the most destructive, including the diversion of water into the Makgadikgadi Pans to form a large inland lake. The remoteness of the area from markets and the presence of tsetse fly prevented any large-scale effort to utilize the water. In the early post-colonial era, two major investigations were carried out by the United Nations into possible utilization of the water, the first between 1960 and 1965, the second in the early- to mid-1970s (UNDP, 1977). The latter was motivated in part by the discovery of diamonds in the region. Dredging of the lower channels of the Delta was carried out at this time and proposals for more extensive manipulations were formulated (Earnest, 1976).

The discovery of local groundwater resources for the town of Maun, situated on the fringe of the Delta, and for the diamond mining complex of Orapa, reduced the urgency of water manipulation in the Delta. Rapid

---

*Present address: Department of Geographical and Environmental Sciences, University of Natal, King George V Avenue, Durban 4001, South Africa.

population growth in and around Maun prompted the Botswana Government in the mid-1980s to commission the Australian firm SMEC to investigate possibilities for increasing outflow from the Delta (SMEC, 1987). As a result, recommendations were made to undertake further dredging in the Delta. However, Greenpeace (1991) produced a highly critical evaluation of the proposals, and following an independent evaluation by the World Conservation Union (IUCN, 1992) these proposals were shelved.

The situation as far as the Botswana Government is concerned is currently at a stalemate. Maun continues to suffer water shortages and local water needs continue to grow. To compound matters, the Namibian Government has formulated plans to abstract water from the Okavango River a short distance upstr the Okavango Delta to supply its Eastern N Water Carrier (van der Heiden, 1992). The plai remove 90 million m³ of water annually, which sents less than 1% of the mean annual inflow. Pr on the water resources of the Okavango Del clearly mounting.

The Earth Summit of June 1992 in Rio de J brought into sharp focus the divergent standpoi the developed and developing nations regardir utilization of wetland and other important ecosy many of which occur in the developing countrie developed nations view these as a global he which must be conserved at all costs. In contras developing nations see them as resources which n

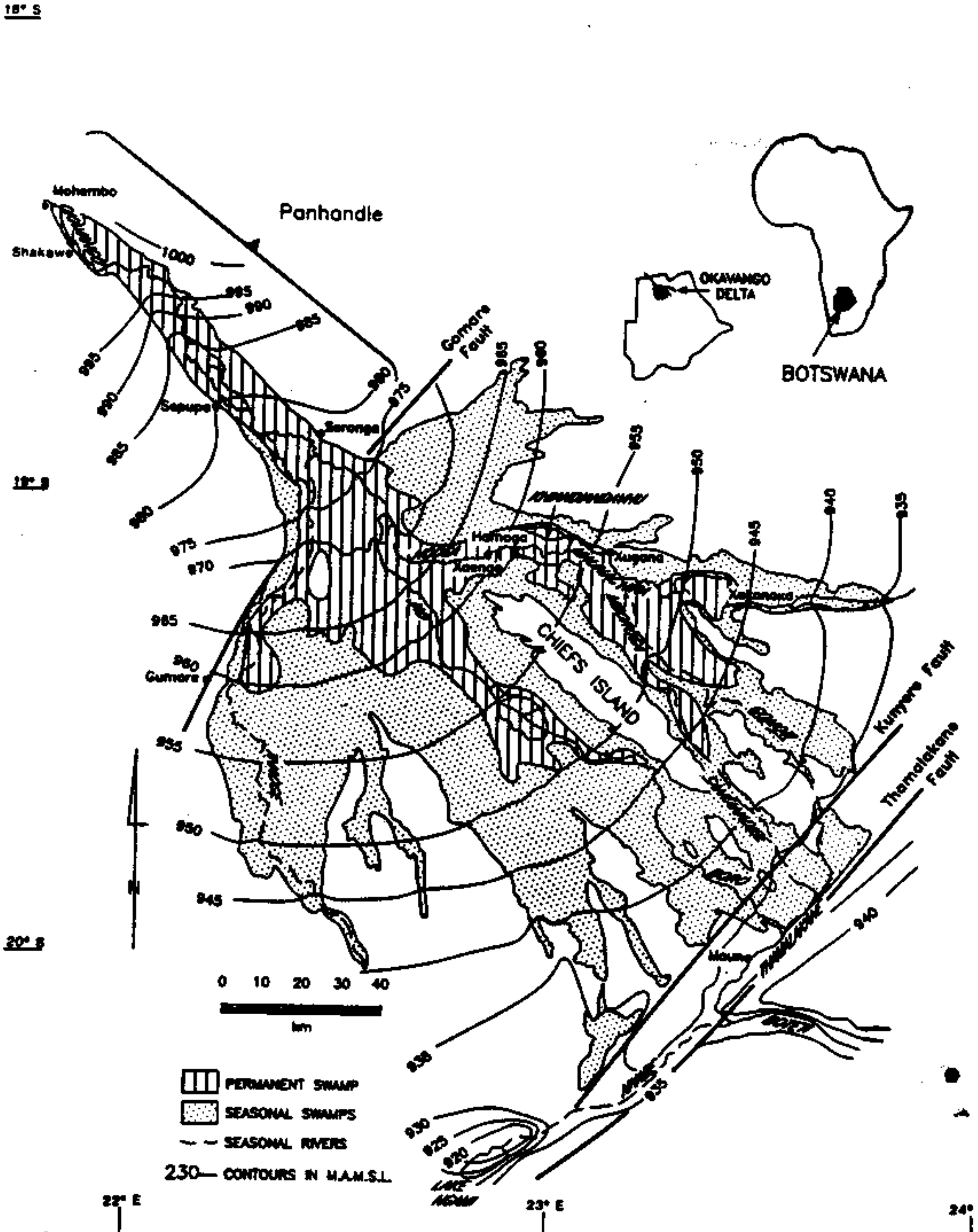

Fig. 1. Map of the Okavango Delta.

be harnessed in order to free their people from the spiral of poverty (Pearce, 1992). These are relatively new developments and reflect the changed stance of the developed world in the post-colonial era, and particularly the changed perceptions of the global ecosystem. In the not too distant past, colonial governments spearheaded ambitious so-called 'development projects' in the colonies, with wetland 'reclamation' a highly favoured practice. The history of development and utilization of the Okavango Delta in many ways epitomizes this evolution of attitudes to wetlands.

The important message of the Rio Declaration was one of sustainable development of resources. On the basis of eight years of interdisciplinary research in the Okavango Delta, we believe that sustainable development is an attainable goal, and that there need not be conflict between the development needs of the region and conservation of this unique ecosystem. It is essential, however, that water abstraction schemes take cognisance of the functioning of the ecosystem, so that its integrity is not disrupted. In this article we outline the important environmental criteria which we believe need to be considered in formulating development proposals for the region.

REGIONAL SETTING

The Okavango Delta (Fig. 1) is situated on the fringes of the Kalahari Desert where the Okavango River discharges into a collapsed section of the earth's crust, which is an extension of the East African Rift Valley System. The region is seismically active; the largest recorded earthquake was in 1952 and of magnitude 6·7 (McCarthy *et al.*, 1993*a*). Sediments deposited by the Okavango River have created a large alluvial fan upon which the Okavango Delta wetlands have developed.

Central southern Africa, including the Okavango region, was at one time a vast sandy desert (Thomas & Shaw, 1991) which extended northwards from the Cape Province in the Republic of South Africa to the Congo Republic in central Africa. The soils derived from these aeolian deposits are sandy and inherently infertile. Most of the catchment of the Okavango River in central Angola is underlain by these wind-blown sands, although a small area in the north-west is underlain by granitic rocks. This simple geology of the catchment has two important consequences. First, very little clay and silt are available, so suspended load in the Okavango River is very low and is primarily kaolinite, which has a low exchange capacity. The total sediment load is dominated by bed-load which consists of eroded aeolian sand (McCarthy *et al.*, 1991*a*). Second, the dissolved solid load of the Okavango River where it enters the Delta is very low, primarily because of the lack of rock weathering in the catchment.

The low rainfall and infertile sandy soils are the most important environmental variables that affect the vegetation of the region around the Delta. The regional vegetation forms part of the semi-arid southern African vegetation zone (White, 1983), and is dominated by a tree savanna in the north and east, which includes extensive cover by *Colophospermum mopane*, and by a tree and shrub savanna to the south and west, from which *C. mopane* is absent (Weare & Yalala, 1971). The Okavango Delta itself is a swamp ecosystem dominated by emergent grasses and sedges in the permanent swamps, and by hydromorphic grasslands in the seasonal swamps (Smith, 1976).

The Okavango Delta

The Okavango Delta is traditionally divided into four regions (Fig. 1): the panhandle, the upper permanent swamps, the lower seasonal swamps and a number of large sandveld tongues and islands. The Okavango River enters the Delta at Mohembo at the apex of the panhandle, and the water is conveyed into the Delta itself by a system of channels. These differ in character in different regions of the Delta (McCarthy *et al.*, 1991*a*, 1992). In the panhandle they are broad (*c*. 70–90 m) and meandering, with some anastomosis. On the upper fan in the upper permanent swamps, channels are sinuous but not meandering. Both types, here termed primary meandering channels (i.e. the Okavango River in the panhandle) and primary sinuous channels (i.e. the Nqoga River), contain water and sediment derived from the catchment. In the lower reaches of the permanent swamps, water is transferred from these primary channels to a system of secondary channels (e.g. Jao-Boro River, Maunachira River) by flow through densely vegetated swamp which flanks the channels. These secondary channels do not carry sediment derived from source areas, but in their upper reaches they transport bed-load sediment derived by local erosion. Further downstream these channel beds are generally vegetated, and there is very little sediment transfer (Ellery *et al.*, 1990). In the seasonal swamps channels are poorly defined, and consist of shallow sinuous depressions which receive the earliest flood waters.

The channels become progressively narrower downstream and their discharge declines (McCarthy *et al.*, 1991*a*). The reason for this is that water leaks from the channels continuously through the flanking vegetation fringe (McCarthy *et al.*, 1988), carrying with it suspended load. Bed-load sediment is confined to the channels themselves, and in the meandering channels it accumulates by point bar formation, whereas in the sinuous channels it accumulates by bed aggradation. Water level in the channels is generally elevated relative to the surrounding swamps, and they serve as arterial systems to the permanent and seasonal swamps (McCarthy *et al.*, 1992).

The variation in topographic relief over the Delta is minimal and the total fall from Mohembo at the apex of the panhandle to Maun at the toe of the Delta, a distance of approximately 250 km, is about 65 m. On the alluvial fan itself, the terrain is gently undulating with a local relief of approximately 2 m. The high ground in the permanent and seasonal swamps forms islands which vary in size from individual anthills to several square kilometres. There are a number of very

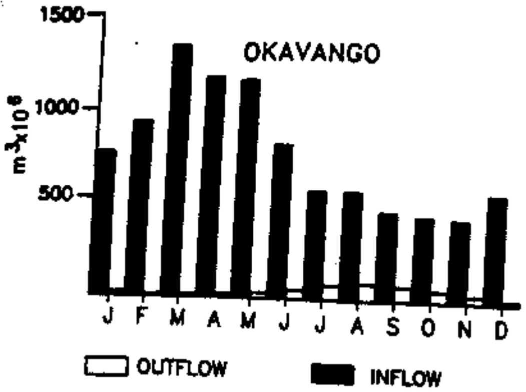

Fig. 2. Monthly discharge at the inlet and outlet of the Okavango Delta.

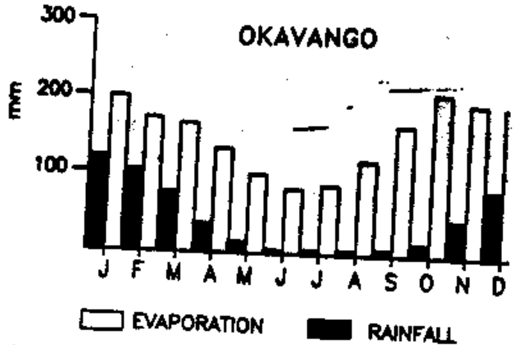

Fig. 3. Monthly rainfall and evaporation in the Ok Delta (Sutcliffe & Parks, 1989).

large islands within the Delta that are probably of tectonic origin, most notably Chiefs Island (Fig. 1). The smaller islands appear to arise in one of a number of ways: some are due to termite activity, others to topographic features associated with old channel systems (scroll bars, point bars and topographically inverted channel beds) and, lastly, due to the subsurface precipitation of carbonate and silica which induces swelling (McCarthy & Metcalfe, 1990; McCarthy *et al.*, 1991*b*, 1993*b*).

Certain areas of the permanent swamps are characterized by lakes which may be several square kilometres in extent. These represent ancient oxbow systems (McCarthy *et al.*, 1993*c*).

Hydrology and climate

Rainfall in the catchment as well as in the region of the Okavango Delta itself occurs in summer, mainly from December to February, and peak discharge in the Okavango River at Mohembo occurs late in the wet season or immediately thereafter, usually in February to March. Peak discharge is *c.* 1600 cumecs. The total annual discharge is approximately $10{\cdot}6 \times 10^9$ m^3 (Wilson & Dincer, 1976), but varied from $7{\cdot}4 \times 10^9$ m^3 to $15{\cdot}8 \times 10^9$ m^3 during the period 1950–1976 (UNDP, 1977). The flood stage rises gradually and short-lived catastrophic floods are exceptionally rare. The water discharges into the Delta and water levels in the panhandle rise. Channels are unable to confine water (McCarthy *et al.*, 1988) which therefore flows into the surrounding swamps. The shoulders of the panhandle confine lateral flooding to a narrow zone and consequently the seasonal water level fluctuations in the panhandle can be as much as 2 m. At the bottom end of the panhandle, lateral confinement ceases and seasonal floodwater which leaks from the channels spreads laterally across the fan (McCarthy *et al.*, 1988). Water level fluctuations in the permanent swamps are therefore generally less than 15 cm.

The floodwater continues to spread out onto the floodplain forming the seasonal swamps, ultimately arriving at the distal end of the fan in the Thamalakane River some four months after peak flood at the apex of the panhandle (Fig. 2). There is consequently maximum extent of floodwater in August, during the winter drought period. This is ecologically impc for wildlife in the Kalahari, which concentrate ar the Okavango at this time.

Only 2% of the total surface water leaves the vango via the Boteti River as surface outflow, a further 2% leaves as groundwater flow (Dincer e 1982). The remainder is lost to the atmosphere dı evapotranspiration. Potential annual evapotrans tion has been calculated as 1860 mm, while an rainfall is 500 mm (Wilson & Dincer, 1976). Evap tion exceeds rainfall during all months of the (Sutcliffe & Parkes, 1989; Fig. 3).

Climatic variations

The Okavango region has been subject to m climatic oscillations in the past. Extensive lin dunefields have developed west and south of the De indicating periods of extreme aridity with rainfall bel 150 mm year^{-1} (Thomas & Shaw, 1991). In contrast, shorelines occur around Lake Ngami and the Mab Depression, indicating the former existence of an ext sive lake system in the distal region of the Delta. Sh (1985) has estimated that some of the large lakes in cated by these shorelines could only be sustained if t rainfall was 200% that of the present. The geomorph logical record therefore indicates rainfall fluctuatio from less than 150 to over 1000 mm year^{-1}.

Thomas and Shaw (1991) have synthesized the Qua ternary climatic record for the region. Between 50 0 and 20 000 BP, generally humid conditions appear t have prevailed, interspersed with a dry period aroun 25 000 BP which dried lakes in the southern Okavang region. Between 20 000 and 18 000 BP (the last glaci maximum), conditions appear to have been dry, wit some aeolian activity. Rainfall appears to have in creased in the period 17 000 to 12 000 BP, followed b generally drier conditions. Minor humid episode occurred from 6000 to 5000 BP, 4000 to 3600 BP, and 2500 to 2000 BP. During the last-mentioned phase rainfall was sufficient to create lakes in the region of the southern Okavango.

Vegetation of the Okavango Delta

The vegetation of the Okavango Delta has been described in general terms by Smith (1976) and local descriptions have been compiled by Tinley (1973), Heemstra (1976), Ellery (1987), Ellery *et al.* (1990) and Ellery *et al.* (1991). Nomenclature follows Arnold and de Wet (1993). The beds of primary channels are generally not vegetated, although *Vossia cuspidata* may occur along protected banks. Vast areas flanking the primary channels in the upper regions of the Delta are dominated by the giant sedge *Cyperus papyrus*, which reaches a height of up to 4 m, and forms virtually monospecific stands. The fern *Thelypteris interrupta* may occur in association with papyrus. This community gives way laterally as well as distally to a community dominated by *Miscanthus junceus*. This community has a number of other associated species, including a number of sedges, grasses and climbers. Locally, *Phragmites australis* may dominate. The backswamp areas are a mosaic of open water areas with submerged species including *Najas pectinata*, *Webbsteria confervoides*, *Rotala myriophylloides*, *Nesaea crassicaulis*, *Ottelia muricata* and *O. ulvifolia*; of shallower areas with floating leaved species dominated by *Brasenia schreberi*, *Nymphaea caerulea*, *N. lotus*, and *Nymphoides indica*; and of even shallower areas with short emergent species, notably *Pycreus nitidus* and a number of other sedges and grasses.

The floodplains of the seasonal swamps exhibit a marked zonation of vegetation reflecting the extent and duration of flooding. Areas flooded for the longest periods may have submerged or floating leaved species similar to those occurring in the permanent swamps. These give way to a sedgeland dominated by *Cyperus articulatus* and *Scirpus corymbosus*. Areas flooded for shorter periods are typically dominated by *Eragrostis inamoena*, *Panicum repens* or *Sorghastrum freesii*, followed by a zone dominated by *Imperata cylindrica*.

Small islands in the delta are typically surrounded by a grassland or sedgeland grading into a wooded fringe of *Ficus verruculosa* and *Syzygium cordatum*, which are both tolerant of flooding. On higher ground a tall broadleaved evergreen riparian woodland occurs, including *Ficus natalensis*, *F. sycamorus*, *Diospyros mespiliformis*, *Phoenix reclinata* and *Garcinia livingstonei*. Further towards the interior regions of islands, a zone dominated by deciduous species occurs, including *Berchemia discolor*, *Acacia nigrescens* and *Croton megalobotrys*. *Hyphaeane ventricosa* forms dense stands around the interior regions of islands, where a short *Sporobolus spicatus* grassland occurs.

The large islands and sandveld tongues are covered with *Acacia erioloba* thornveld, or by woodland typically dominated by *Lonchocarpus capassa*, *L. nelsii*, or *C. mopane*.

Fauna

The swamp habitats are home to hippopotami *Hippopotamus amphibius* and to Nile crocodiles *Crocodylus niloticus*. The sitatunga *Tragalephus speckii* and the red lechwe *Kobus leche* are antelope that are restricted to swamp and floodplain habitats respectively. A wide diversity of bird species occurs within the Okavango Delta, including a number of extremely uncommon, rare and endangered species.

The Okavango Delta also forms an important refugium for a rich fauna from outside the Delta during the dry winter season, when flooding of the Delta itself is at its maximum.

PRESENT ECOSYSTEM STRUCTURE AND FUNCTIONING

Ecosystem dynamics

Accounts of historical changes in water distribution in the Okavango region (Fig. 4) have been compiled by Shaw (1983, 1984). Following Livingstone's visit in 1849, Lake Ngami was described by several travellers as a large lake with a length of at least 80–110 km; Chapman, 1868; Andersson, 1857), and an average depth of about 2·2 m. At the time of these visits, the lake appears to have been fed by the Thaoge River, which was described by Andersson (1857) as '40 yards wide and always deeper than 5 feet' (37 and 1·5 m respectively). By the mid 1880s this river had stopped flowing into the lake (Shaw, 1984).

The most useful information on changes in water distribution in the Okavango Delta is summarized by Wilson (1973). It appears that the failure of the Thaoge River was co-incidental with increased flow of the Nqoga, Mboroga and Santantadibe Rivers (Stigand, 1923). During the early part of this century, the Mboroga and Santantadibe Rivers flowed into the Thamalakane River, and were the major suppliers of water to Maun up until the 1930s. In the 1920s, the lower reaches of the Nqoga River started failing, and this was accompanied by an increase in flow along the Maunachira River further to the north. Capture of flow by the Maunachira did not altogether cut off flow to the Mboroga River as there is considerable flow into the Mboroga from the Maunachira along its lower reaches. In the mid 1950s the Jao-Boro River system began to receive increased flow, and currently it is the main supplier of water to the Thamalakane River system, and therefore to Maun (Wilson, 1973). Figure 4 shows that the changes described above represent radical changes in water distribution, and that the time scales involved are relatively short.

The failure of the Thaoge and Nqoga Rivers has been well documented (Brind, 1955; Wilson, 1973; McCarthy *et al.*, 1986*a*, 1992). The process starts with constriction of the channel by *Vossia cuspidata* at its distal end followed by the development of *Cyperus papyrus* blockages and by encroachment of papyrus from the banks into the channels, leading ultimately to their complete obliteration. With the reduction in water supply peat deposits flanking the channel burn in subsurface peat fires (Ellery *et al.*, 1989). This leads to the complete destruction of swamp habitat, and the area reverts to dry land. Nutrients previously locked up in the peat deposits are released to the environment, giving rise to productive habitat which supports large concentrations of game animals (Ellery

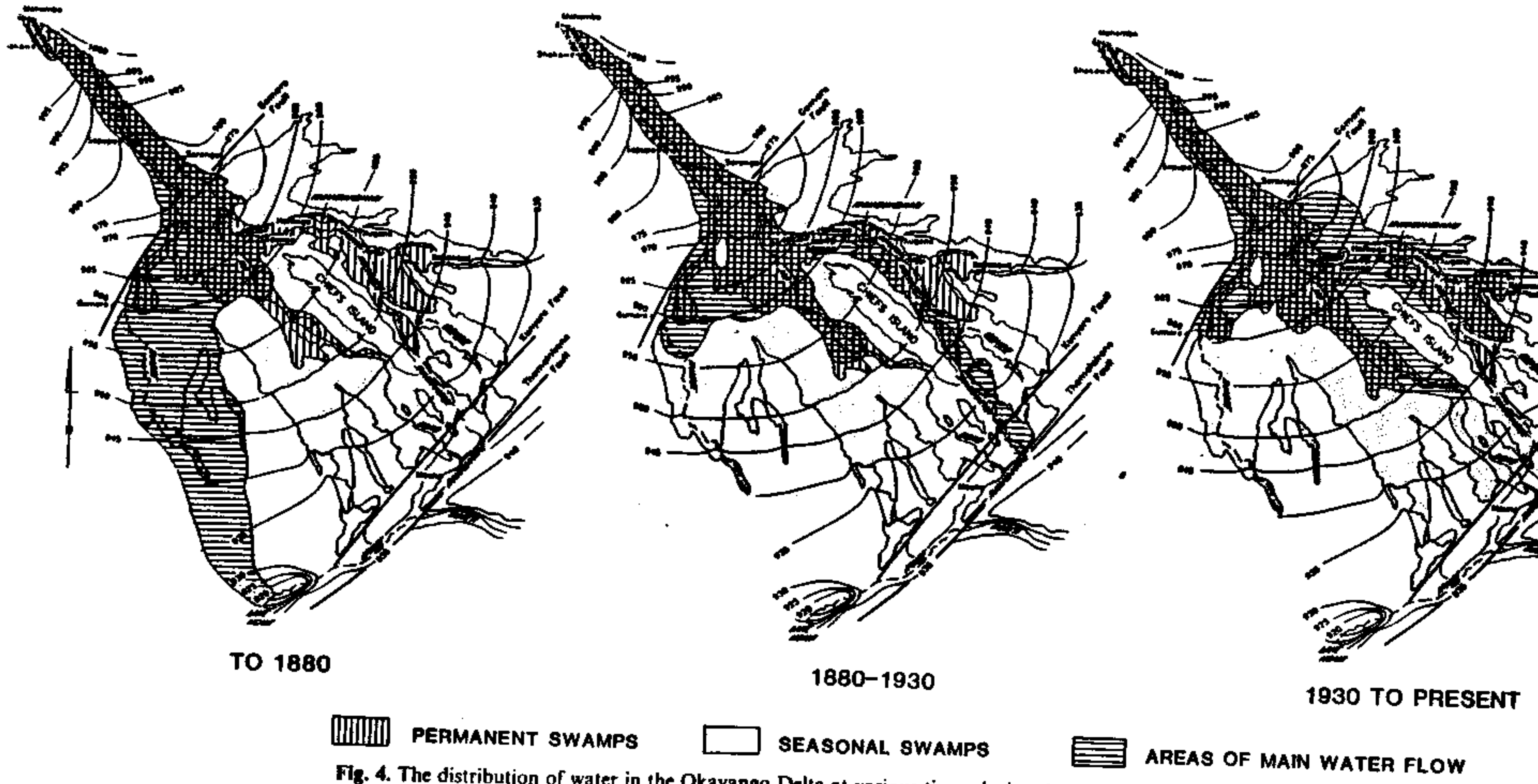

Fig. 4. The distribution of water in the Okavango Delta at various times during the 19th and 20th centuries.

et al., 1989). This entire sequence propagates upstream over decades.

The development of papyrus debris blockages, and the encroachment of papyrus into the channel, are symptoms of channel deterioration (Ellery *et al.*, 1993*a*, 1994). However, channel failure is caused by one or a combination of sedimentation and tectonic activity. The accumulation of bed-load sediment in primary, sinuous channels causes rapid aggradation (up to 5 cm year^{-1}). This leads to elevation of the channel above the surrounding terrain. The increase in hydraulic gradients away from an aggrading channel results in increased water loss, and ultimately to channel failure. Alternatively, it appears that neotectonic activity may be important (McCarthy *et al.*, 1993*a*). Because of low topographic gradients on the Delta surface, relatively small earth movements are capable of inducing large-scale changes in the distribution of water.

These changes in water distribution cause profound changes in habitat within the Delta. When a distributary channel is active, it is flanked by papyrus swamp which is essentially monospecific. This grades laterally into backswamp communities comprising a mosaic of open water with submerged communities, shallow areas with floating leaved species, short and tall emergent communities (Ellery *et al.*, 1991). Successional processes in these backswamp areas suggest that the climax community is dominated by *Miscanthus junceus*, with a minor contribution of the swamp fig *Ficus verruculosa* growing on well developed peat deposits (Ellery, 1987). Peat acts as a nutrient sink (McCarthy *et al.*, 1989). Following channel failure, and the resulting peat fires, there is rapid conversion to terrestrial habitat or seasonal swamp.

Water chemistry

The waters of the Okavango Delta can be classified as hyperoligotrophic (Wetzel, 1983), with extremely low concentrations of total nitrogen and phosphorus (Ellery *et al.*, 1991). The concentration of total dissolved solids in water entering the Delta is also very low, but increases towards the distal reaches of the Delta (Table 1) from 30 mg litre^{-1} at Seronga to 95 mg litre^{-1} in the lower Boro River (Sawula & Maartens, 1991). Increases in salinity resulting from transpirational losses in the permanent swamps are offset by fixation of some metals in the peat (McCarthy *et al.*, 1989).

Table 1. Concentrations of dissolved solids in water entering the Delta in the Panhandle, and of water in the lower Boro River (from Hutton & Dincer, 1976)

	Concentration in the upper panhandle (ppm)	Concentration in the lower Boro River (ppm)
Silica	16·0	35·0
Calcium	5·0	9·0
Magnesium	0·6	2·0
Sodium	2·0	6·5
Potassium	1·4	4·3
Chlorine	<1	<1
Sulphate	<1	<1

In spite of high evapotranspirational losses, the occurrence of saline surface water in the Okavango Delta is rare. The reason for this is the dominance of transpiration over evaporation. A significant proportion of the water loss in the permanent swamps occurs from trees around islands (McCarthy *et al.*, 1991*b*, 1993*b*; Ellery *et al.*, 1993*b*). One of the consequences of these processes is to fix a high proportion of the dissolved solids in insoluble forms (carbonate and silica) in the soil. Potassium is fixed in insoluble forms as silicate minerals (McCarthy *et al.*, 1991*b*), but the sodium remains soluble as a bicarbonate, and reaches concentrations in the soil and at the soil surface that are biologically toxic (McCarthy *et al.*, 1986*b*, 1991*b*; Ellery *et al.*, 1993*b*). Transpirational processes confine the build-up of the sodium to the interiors of islands, and its impact on the system as a whole is therefore very small. In the seasonal swamps, aquatic vegetation produces widespread precipitation of silica below the soil surface, while trees growing on islands cause localized calcium and magnesium carbonate precipitation, and the local concentration of sodium in the groundwater beneath the interior regions of islands (McCarthy & Ellery, 1994).

The changing distribution of surface water described in the previous section periodically removes water from island systems, and during these periods the accumulated salts are flushed from the system by rainwater (McCarthy *et al.*, 1991*b*). The system is therefore renewed by change and the sustained accumulation of salts in surface water does not take place.

It appears that the species that form dominant components of the swamp system are adapted to tolerate extremely low levels of dissolved substances. They exhibit clonal growth, and appear to recycle nutrients very efficiently.

IMPLICATIONS FOR WATER ABSTRACTION AND CONSERVATION

Studies of hydrology, sedimentation and biological processes have provided a broad understanding of the present structure and functioning of the ecosystem as a whole and afford a useful framework to evaluate its overall sensitivity to impacts, and to identify factors that are particularly sensitive to perturbation. From this framework criteria can be identified that need to be taken into account in developing the region, both for conservation as well as for human needs. We recognize that any perturbations will have some effect, but here focus on ones that may affect the system as a whole.

Water abstraction

The Okavango River provides one of the few sources of permanent water in the region, and has been viewed as a possible source of water for development purposes. In view of the large amounts available, abstraction of water may not necessarily be deleterious. Water abstraction should be seen in the context of climatic variations in the region, where rainfall has varied almost by an order of magnitude over the last few tens of thousands of years. The system has persisted despite these fluctuations, although its character may have been very different from what it is today. Furthermore, the system needs to be viewed in the context of short-term (decades) climatic variation which has resulted in inflows varying by a factor of two in the period 1950–1976. The system appears to respond to these fluctuations by changing the area of permanent and seasonal flooding. In this context we believe that the removal of a small percentage of the total inflow (1–2%) is likely to have a negligible effect on the system as a whole.

However, we add a number of caveats, particularly in the manner in which water is abstracted. There are lessons to be learned from past approaches. In the early 1970s a decision was taken to dredge and straighten the lower outflow channels. The effects of this were documented less than a decade after dredging (Lubke *et al.*, 1984). Impacts were local, but were primarily associated with decreased stability of the channel bed and the loss of the in-channel flora. Furthermore, the floodplains dried out and were converted to an essentially terrestrial habitat. The character of successional processes that were expected was described by these authors, who considered that it had not nearly reached completion. A further impact on local inhabitants was the loss of subsistence farmland on the floodplain.

A potentially serious problem associated with dredging at the lower end of the Delta is the dynamic nature of water distribution over relatively short periods. A canal system could be rendered useless due to changing flow patterns in the upper reaches of the Delta. In such an event the temptation to extend the length of the dredged canal would increase, and the associated impacts would therefore escalate, possibly to catastrophic proportions.

In contrast to the removal of water from the distal reaches of the Delta, abstraction from the top of the Delta would be equivalent to slightly reducing the size of the flood. The system is subject to floods of varying magnitude and it appears that such an approach would have minimal impact, provided that abstraction was small relative to the total inflow (1–2%). However, the method of abstraction is of critical importance if such an approach were to be used. Our studies have shown that the inflow of sediment to the Delta is critical to its functioning. The erection of weirs or dams in the upstream catchment would impound the sediment and this would have a major and immediate impact on the entire ecosystem. Channels would incise and the regular changes in water distribution brought about by this sedimentation would cease. This would lead to long-term stagnation of the ecosystem, with vegetation succession in backswamp areas leading to a decrease in overall habitat diversity. Furthermore, there would be long-term localized accumulation of toxic salts in the lower swamps, and the system would become moribund. Ultimately, the combination of these processes could lead to sterility of the ecosystem.

A further potentially serious consequence of construction of dams in the catchment would b increase in the salinity of inflowing water. Becaus the low relief in the lower catchment, any dam w have a large surface area to volume ratio and, bec of the high evaporative demand, this would lead t increase in salinity. It appears that papyrus is par larly sensitive to salinity increases (Smith, 1976) the disruption of the present distribution of this c munity in particular would have a detrimental effec the system as a whole. Papyrus is important as it c fines sedimentation to in-channel areas and contrib to the dynamic nature of the ecosystem. It simult ously allows water to leak from the upper chan and thereby sustains a large area of permanent seasonal swamp.

The most suitable method of water abstraction fr the upper reaches of the panhandle or further upstre in the catchment would be via a pump system. Idea the pumping volume should be in phase with the fl cycle, or else should be increased at times of high flo

The most suitable location for storage dams is in lower reaches of the Delta, where the impact of sa ization would be local, and where plant communi are adapted to higher salinities.

Activities designed to restore flow locally

A number of efforts have been made to restore fl locally along channel reaches that have failed. Th have taken place both along the Thaoge River as w as along the lower Nqoga River (Potten, 1976). Th have invariably incurred large investments of mon and resources, and without exception have failed achieve the desired effects. The abandonment of t Thaoge as well as the lower Nqoga River has been a companied by the encroachment of *Vossia cuspida* and the development of papyrus blockages, but it is misconception that these are the cause (Ellery *et al.*, press). The removal of these superficial obstructions therefore not likely to restore flow along the form watercourses, and it appears to be a futile exercise attempt any such activity.

AGRICULTURAL IMPACTS

Nutrient pollution

The catchment of the Okavango Delta offers potenti for commercial agricultural development as has alrea taken place in eastern Caprivi, Namibia. Rainfall sufficiently high, and temperatures are suitable for cro production, but extensive application of artificial ferti izer would be required. Leaching of this fertilizer int the river systems would lead to eutrophication, an may profoundly affect the structure and functioning the ecosystem. Plants in the Okavango exhibit clon growth, and appear well adapted to low nutrient level In particular, if the integrity of areas dominated b papyrus were compromised, sedimentation pattern and water distribution patterns may be altered, wit potentially large impacts.

Cattle

Cattle make use of floodplain grasslands in the lower seasonal swamps during the dry winter months when grazing in the surrounding grazing lands is in poor condition. However, these grasslands are of low forage quality, and the impact of cattle in these areas is low. Their present concentration around the Delta ecosystem is therefore not considered to be a major threat to the ecosystem itself, although competition with wild ungulate species would be a problem if cattle were allowed to move into the Delta proper. Furthermore, if cattle were allowed further into the Delta itself and these areas were subjected to sustained heavy utilization, salinization of surface water would occur if the grass cover was substantially reduced for long periods.

Due to low topographic relief in the area, in combination with low rainfall, soil erosion resulting from overgrazing is not serious, but wind erosion is a potential problem, as illustrated by large dust storms that occur in the area during the late winter months.

Siting of conservation areas

The water dispersal patterns of the Okavango Delta are constantly changing due to events in the upper fan area. It is important to conserve the area in which this switching process is functioning, because it is one of the essential components of the dynamics of the ecosystem as a whole. It is also important when setting aside areas for conservation that the full range of possible dispersal patterns be taken into account. If this is not done, a situation may arise where water disperses into an area that has not been set aside for conservation, and some wetland habitats could be entirely lost from the conservation area.

The current state of planning and conservation in and around the Okavango Delta has been described by van der Heiden (1992). Approximately 75% of the Delta is included in the Moremi Game Reserve and two adjacent wildlife management areas, which have been set aside for controlled hunting, tourism, commercial utilization or a combination of two or more of these activities. Moremi Game Reserve itself has been divided into a wilderness zone which has been set aside for preservation of ecosystem processes, and a tourism development zone which will be the focus of tourist activities. The boundary between these protected areas and communal planning areas is a buffalo fence which separates livestock from wildlife by running around the southern, western and northern periphery of the Delta (van der Heiden, 1992). The panhandle falls within a communal planning area which emphasizes economic development by improving existing land use practices rather than introducing new developments. It is possible that the panhandle may be set aside as a conservation area within this communal planning zone, where utilization of resources would be regulated.

ACKNOWLEDGEMENTS

The Office of the President, Botswana, is gratefully acknowledged for granting permission to work in the Okavango Delta. The University of the Witwatersrand and the Jim and Gladys Taylor Trust have supported the work financially, and Mr P. A. Smith has taken an active interest throughout. Comments by the editor and anonymous referees have been valuable.

REFERENCES

Andersson, C. J. (1857). *Lake Ngami*. Reprinted by C. Struik, Cape Town, 1967.

Arnold, T. H. & de Wet, B. C. (1993). Plants of southern Africa: names and distribution. *Mem. Bot. Surv. S. Afr.*, No. 62.

Brind, W. G. (1955). The Okavango Delta. Report on the 1951–1953 field surveys. Resident Commissioner, Mafeking (unpublished report).

Chapman, J. C. (1868). *Travels in the interior of Africa. 1849–1863*. Reprinted by A. A. Balkema, Cape Town, 1971.

Dincer, T., Hutton, L. G. & Kupee, B. B. J. (1982). *Study using stable isotopes of flow distribution, surface–groundwater relations and evapotranspiration in the Okavango Swamp, Botswana*. International Atomic Energy Agency, Proc. Ser. STI/PUB/493, pp. 3–26.

Earnest, H. M. (1976). Manipulation of the Okavango Delta for increased outflow: its impact and constraints. In *Symposium on the Okavango Delta and its future utilization*. Botswana Society, Gaborone, pp. 337–45.

Ellery, K. (1987). The composition and dynamics of wetland plant communities of the Maunachia River system, Okavango Delta, Botswana. MSc thesis, University of the Witwatersrand, Johannesburg.

Ellery, K., Ellery, W. N., Rogers, K. H. & Walker, B. H. (1991). Water depth and biotic insulation: major determinants of back-swamp plant community composition. *Wetl. Ecol. Manage.*, **1**, 149–62.

Ellery, W. N., Ellery, K., McCarthy, T. S., Cairncross, B. & Oelofse, R. (1989). A peat fire in the Okavango Delta, Botswana, and its importance as an ecosystem process. *Afr. J. Ecol.*, **27**, 7–21.

Ellery, W. N., Ellery, K., Rogers, K. H., McCarthy, T. S. & Walker B. H. (1990). Vegetation of channels of the northeastern Okavango Delta, Botswana. *Afr. J. Ecol.*, **28**, 276–90.

Ellery, W. N., Ellery, K., Rogers, K. H., McCarthy, T. S. & Walker, B. H. (1993*a*). Vegetation, hydrology and sedimentation processes as determinants of channel form and dynamics in the northeastern Okavango Delta, Botswana. *Afr. J. Ecol.*, **31**, 10–25.

Ellery, W. N., Ellery, K. & McCarthy, T. S. (1993*b*). Plant distribution in islands of the Okavango Delta, Botswana: determinants and feedback interactions. *Afr. J. Ecol.*, **31**, 118–34.

Ellery, W. N., Ellery, K., Rogers, K. H. & McCarthy, T. S. (in press). The role of *Cyperus papyrus* in channel blockage and abandonment in the northeastern Okavango Delta. *Afr. J. Ecol.*

Greenpeace, (1991). *Okavango — delta or desert? A question of water*. Greenpeace International, Amsterdam.

Heemstra, H. (1976). The vegetation of the seasonal swamps. *UNDP BOT/71/506 Tech. Note*, No. 28. Maun.

Hutton, L. G. & Dincer, T. (1976). Chemistry and stable isotope composition of Okavango Delta waters. UNDP BOT/71/506 Tech. Note No. 23, Maun.

IUCN (1992). *The IUCN review of the Southern Okavango Integrated Water Development Project. Final Report*. Gabarone.

Livingstone, D. (1857). *Missionary travels and researches in South Africa*. John Murray, London.

Lubke, R. A., Reavell, P. E. & Dye, P. J. (1984). Effects of dredging on the macrophytic vegetation of the Boro River, Okavango Delta, Botswana. *Biol. Conserv.*, **30**, 211–36.

McCarthy, T. S. & Ellery, W. N. (1994). The effect of vegetation on soil and groundwater chemistry and hydrology of islands in the seasonal swamps of the Okavango fan, Botswana. *J. Hydrol.*, **154**, 169–93.

McCarthy, T. S. & Metcalfe, J. (1990). Chemical sedimentation in the semi-arid environment of the Okavango Delta, Botswana. *Chem. Geol.*, **89**, 157–78.

McCarthy, T. S., Ellery, W. N., Rogers, K. H., Cairncross, B. & Ellery, K. (1986*a*). The roles of sedimentation and plant growth in changing flow patterns in the Okavango Delta, Botswana. *S. Afr. J. Sci.*, **82**, 579–84.

McCarthy, T. S., McIver, J. R. & Cairncross, B. (1986*b*). Carbonate accumulation on islands in the Okavango Delta. *S. Afr. J. Sci.*, **82**, 588–91.

McCarthy, T. S., Rogers, K. H., Stanistreet, I. G., Ellery, W. N., Cairncross, B., Ellery, K. & Grobicki, T. S. A. (1988). Features of channel margins in the Okavango Delta. *Palaeoecol. Afr.*, **19**, 3–14.

McCarthy, T. S., McIver, J. R., Cairncross, B., Ellery, W. N. & Ellery, K. (1989). The inorganic chemistry of peat from the Maunachira channel-swamp system, Okavango delta, Botswana. *Geochim. Cosmochim. Acta*, **53**, 1077–89.

McCarthy, T. S., Stanistreet, I. G. & Cairncross, B. (1991*a*). The sedimentary dynamics of active fluvial channels on the Okavango fan, Botswana. *Sedimentology*, **38**, 471–87.

McCarthy, T. S., McIver, J. R. & Verhagen, B. Th. (1991*b*). Groundwater evolution, chemical sedimentation and carbonate brine formation on an island in the Okavango Delta swamp, Botswana. *Appl. Geochem.*, **6**, 577–95.

McCarthy, T. S., Ellery, W. N. & Staniskeet, I. G. (1992). Avulsion mechanisms on the Okavango fan, Botswana: the control of a fluvial system by vegetation. *Sedimentology*, **39**, 779–95.

McCarthy, T. S., Green, R. W. & Franey, N. J. (1993*a*). The influence of neo-tectonics on water dispersal in the northeastern regions of the Okavango Swamps, Botswana. *J. Afr. Earth Sci.*, **17**, 23–32.

McCarthy, T. S., Ellery W. N. & Ellery K. (1993*b*). Vegetation induced subsurface precipitation of carbonate as an aggradational process in the permanent swamps of the Okavango (Delta) fan, Botswana. *Chem. Geol.*, **107**, 111–31.

McCarthy, T. S., Ellery, W. N. & Stanistreet, I. G. (1993*c*). Lakes of the north eastern region of the Okavango swamps, Botswana. *Z. Geomorph. N. F.*, **37**, 273–94.

Pearce, F. (1992). No Southern comfort at Rio? *New Scient.*, **134**, 38–41.

Potten, D. H. (1976). Aspects of the recent history of Ngamiland. *Bots. Notes Rec.*, **8**, 63–86.

Sawula, G. & Martens, E. (1991). Major ion chemistry of the lower Boro River, Okavango Delta, Botswana. *Freshw. Biol.*, **26**, 481–93.

Schwartz, E. H. L. (1919). *The Kalahari or thirstland tion*. Maskew Miller, Cape Town.

Shaw, P. (1983). Fluctuations in the level of ~~Lake~~ Ng historical evidence. *Bots. Notes Rec.*, **15**, 79–84.

Shaw, P. (1984). An historical note on the outflow Okavango Delta system. *Bots. Notes & Rec.*, **16**, 12

Shaw, P. (1985). Late Quarternary land forms and e mental change in northwest Botswana: the evid Lake Ngami and the Mababe Depression. *Trans. I Geogr., N.S.*, **10**, 333–46.

SMEC (1987). Southern Okavango Integrated Water opment Project. Phase 1. Final Report, Departn Water Affairs, Gabarone, Botswana.

Smith, P. A. (1976). An outline of the vegetation of th vango drainage system. In *Symposium on the Ok Delta and its future utilization*. Botswana Gaborone, pp. 93–112.

Stigand, A. G. (1923). Ngamiland. *Geogr. J.*, **62**, 401–1

Sutcliffe, J. V. & Parkes, Y. P. (1989). Comparative balances of selected African wetlands. *Hydrol. Sci.* 49–62.

Thomas, D. S. G. & Shaw, P. A. (1991). *The Kalaha ronment*. Cambridge University Press, Cambridge.

Tinley, K. L. (1973). *An ecological reconnaissance Moremi Wildlife Reserve, northern Okavango s Botswana*, 2nd end. Okavango Wildlife Society, Joh burg.

UNDP (1977). Investigation of the Okavango Delt primary source of water for Botswana. FAO DP/BOT/71/506. report to the Department of Affairs, Gabarone.

van der Heiden, L. J. (1992). The Okavango Delta: c state of planning and conservation. In *Wetlands Co tion Conference for Southern Africa. Proceedings Southern African Development Coordination Conf Gabarone, June 1991*, ed. T. Matiza & H. N. Cha IUCN, Gland.

Weare, P. & Yalala, Y. (1971). Provisional vegetation n Botswana. *Bots. Notes Rec.*, **3**, 131–47.

Wellington, J. H. (1948). The food-producing possibili the Okovango Delta. *S. Afr. Sci.*, **11**, 65–7.

Wetzel, R. G. (1983). *Limnology*. 2nd edn. W. B. Sa Co., Philadelphia.

White, F. (1983). *The vegetation of Africa*. UNESCO, P.

Wilson, B. H. (1973). Some natural and man-made ch in the channels of the Okavango Delta. *Bots. Notes R* 132–53.

Wilson, B. H. & Dincer, T. (1976). An introduction t hydrology and hydrography of the Okavango Del *Symposium on the Okavango Delta and its future utili* Botswana Society, Gaborone. pp. 33–48.