WETLAND DYNAMICS AND CONSERVATION: IDENTIFYING KEY FACTORS IN THE OKAVANGO DELTA, BOTSWANA

WILLIAM N. ELLERY AND T. S. McCARTHY

Geology Department, University of the Witwatersrand, P.O. Wits 2050, South Africa

ABSTRACT

The importance of considering ecosystem processes and dynamics for planning sustainable resource use and conservation is outlined. In the Okavango Delta large scale changes in the distribution of water take place over timespans of decades to centuries. These changes are partly the result of sediment introduction into channels in the upstream areas, and partly the result of neotectonic activity. Change promotes the maintenance of a mosaic of habitats in different stages of wetting and drying, and with different inherent fertility statuses, creating a mosaic with varying suitability for wildlife utilization. It also enables regeneration of surface soils on islands of the Okavango Delta, which are prone to salinization in areas which are flooded for extended periods. The disruption of this sediment supply by construction of impoundments anywhere in the catchment would have immediate negative impacts on the ecosystem as a whole. Principles that need to be considered for water abstraction, as well as for conservation planning are outlined.

INTRODUCTION

Conservation has witnessed a noticeable shift in emphasis in recent decades, from conservation of species to habitats, and even more recently to ecosystems and landscapes. At the broader scales, the biological consequences of habitat, ecosystem, or landscape degradation and fragmentation have been considered from a biogeographical perspective, with an emphasis on species loss (Wilcox 1986; Wilcox and Murphy 1985; Wilcove *et al.* 1986). A number of authors have recognized that maintaining ecosystem processes is ultimately of greater importance than the conservation of species and habitats *per se*, because species require functioning ecosystems in which to persist (Walker 1989; Grumbine 1990; Hobbs 1993). The features of an ecosystem or landscape that are generally considered important include the physical and chemical fluxes across the landscape (Saunders *et al.* 1991). However, the importance of these processes for ecosystem dynamics over timespans of decades to centuries, and their incorporation as part of conservation planning and management, do not appear to have been considered in any detail.

In the face of ever increasing development pressure in the region of the Okavango Delta, particularly for water abstraction, the question is how best to develop the water resources of the region. There need not be a conflict between conservation and development, provided that the ultimate goal is sustainability. We believe, following on from the ideas of Smith (1976), that the key to the persistence of the Okavango Delta ecosystem as we know it, lies in renewal brought about by natural changes in the distribution of water over timespans of decades to centuries. Change not only promotes the occurrence of a mosaic of habitats in different stages of wetting and drying (biotic diversity), but it also allows regeneration of saline surface soils in an environment with an extremely high potential for salinization.

REGIONAL SETTING

Introduction

The Okavango Delta, situated in northern Botswana on the fringes of the Kalahari Desert, forms part of an internal drainage basin known as the Kalahari basin. The Delta receives its water primarily from the highlands of central Angola via two main tributaries, the Cubango and Quito Rivers. The catchment of the Okavango River is underlaid largely by aeolian deposits of a once far more extensive desert which stretched from the northern Cape Province in South Africa, to the Congo Republic in central Africa (Thomas and Shaw 1991), although a small area in the northwest is underlaid by granitic rocks. This simple geology of the catchment has two important consequences. First, the total sediment load is dominated by fine sand which is saltated along the river bed as bed-load (McCarthy *et al.* 1991). Very little clay and silt are available, so suspended load in the Okavango River is low, and consists primarily of kaolinite. Second, the concentration of dissolved substances in the Okavango River is very low because of the lack of rock weathering in the catchment.

The Okavango Delta itself is situated in a collapsed section of the Earth's crust (Figure 1), which is an extension of the East African Rift Valley system (Hutchins and Hutton 1976). The region is seismically active, and suggests that subsidence of the collapsed section of the crust is still taking place (McCarthy *et al.* 1993). The Delta is more correctly classified as an alluvial fan, and is not a "delta" in the true sense of the word (Stanistreet and McCarthy 1993).

The Okavango Delta

The Okavango River enters Botswana at Mohembo, downstream of which it is confined to a narrow, linear depression known as the "panhandle" (Figure 1). At the town of Seronga, the Okavango River is no longer confined to this linear depression and it spreads out onto the fan surface. This is the result of water loss from the source channel. A number of distributary channels arise within this region of permanent swamps, and many of these discharge water seasonally onto the lower reaches of the fan, giving rise to the seasonal swamps. Within the Delta itself, particularly in the distal reaches of the fan, large islands and sandveld tongues occur which are seldom flooded.

Channels differ in character in different regions of the Delta (McCarthy *et al.* 1991a, 1992). In the panhandle the Okavango River is broad (70-100 m) and typically meandering, although there is some anastomosis. In the upper reaches of the fan the Nqoga River tends to be sinuous, but it is not meandering (McCarthy *et al.* 1991a; Stanistreet *et al.* 1993). Both of these channels have been referred to as primary channels as they contain both water and sediment derived from the catchment (McCarthy *et al.* 1991a), but we here refer to them as primary meandering (Okavango River in the panhandle) and primary sinuous (Nqoga River in the permanent swamps) channels respectively. Water is transferred to other channels in the permanent swamps as overspill from these primary channels, by flowing through densely vegetated swamp. 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 there is very little sediment transfer, and the channel beds are generally vegetated (Ellery *et al.* 1990). In the seasonal swamps channels are poorly defined, and consist of shallow depressions which receive the earliest flood waters.

The topographic relief over the Okavango Delta is minimal, with an average gradient from the top of the panhandle to the toe of the fan of approximately 0.28 m/km^{-1} (Wilson and Dincer 1976). On the fan itself the terrain is gently undulating with a local relief of 2 to 3 m. The high ground forms islands in both the permanent and the seasonal swamps, varying in size from single termitaria to several square kilometers. Floating-leaved and emergent communities characterize many of the backswamp areas at intermediate elevation. Areas of low relief form lakes which are usually several square kilometers in extent, and which generally represent ancient oxbow systems (McCarthy *et al. in press*).

Climate and hydrology

Rainfall in the catchment as well as in the Okavango Delta itself occurs in summer, mainly from December to February. Peak discharge in the Okavango river at Mohembo occurs late in the wet season, usually in February or March. Total annual discharge is 10.6x10^9 m^3 (Wilson and Dincer 1976). The flood stage rises gradually as water discharges into the swamps in the panhandle. Due to lateral confinement in this region, water level fluctuations may be as much as 2 m. At the bottom of the panhandle lateral confinement ceases, and seasonal floodwater spreads laterally over the fan itself. Water level fluctuations in the permanent swamps are therefore small, generally in the region of 0.15 m. Floodwater continues to disperse, ultimately discharging into the seasonal swamps, and arriving at the distal end of the fan some 4 months after peak flood in the panhandle. As a result there is maximum extent of floodwater in July and August, during the midwinter drought period.

Local rainfall contributes approximately 5x10^9 m^3 to the total water budget, being in the region of 500 mm/annum (Anderson 1976). Rainfall is exceeded by potential evapotranspiration during every month of the year (Sutcliffe and Parkes 1989), with annual potential evapotranspiration having been calculated as 1,860 mm (Wilson and Dincer 1976).

Both short term as well as longer term climatic oscillations have characterized the region of the Okavango Delta. Although mean figures for discharge, rainfall and evapotranspiration have been given, there is great variation from year to year. For example, annual discharges varied from 7.4x10^9 m^3 to 15.8x10^9 m^3 over the period from 1950 to 1976 (UNDP 1977). Similarly, rainfall is spatially and temporally extremely variable (Anderson 1976). Geomorphological evidence in the region, such as the presence of ancient dunefields and of former shorelines around marginal lakes, suggests that rainfall has varied from less than 150 mm/a to over 1,000 mm/annum in the last few thousand years (Shaw 1985; Thomas and Shaw 1991). The quaternary climate record for the region has been synthesized by Thomas and Shaw (1991).

GENERAL ECOSYSTEM FUNCTIONING

The water and sediment budgets for the Okavango Delta are presented in Table 1 (after McCarthy and Metcalfe 1990). Although water entering the Okavango Delta each year has low concentrations of dissolved solids, because of the large volume of water involved, large amounts of dissolved substances are introduced into the Delta. It has been estimated that the total quantity of dissolved solids entering the Delta each year is more than twice the quantity of clastic sediments (McCarthy and Metcalfe 1990). Only a small proportion of the dissolved solids leaves the system as surface outflow (Table 1). It is difficult to determine the quantities lost as subsurface outflow. However, large quantities of dissolved substances must be accumulating within the ecosystem each year, probably in the region of twice the quantity of clastic sediments (McCarthy and Metcalfe 1990). This is the result of high rates of evapotranspiration.

The processes leading to accumulation of dissolved substances beneath islands as well as at the soil surface in the center of islands in the permanent swamps (McCarthy and Metcalfe 1990; McCarthy *et al.* 1991b, *in press*), and beneath the floodplains and islands in the seasonal swamps (McCarthy and Ellery, in press), have been described in detail. From this work it is clear that the salinization of surface and subsurface soils in the Okavango Delta is localized to island and floodplain areas, and that surface waters remain extremely fresh as they move through the system. This is due to the dominance of transpiration over evaporation in the Okavango Delta, causing subsurface precipitation of dissolved substances (McCarthy *et al.* 1991; McCarthy and Ellery, in press).

ECOSYSTEM DYNAMICS

Major distributary channels of the Okavango Delta have a history of abandonment, leading to large-scale changes in the distribution of water (Wilson 1973; Smith 1976). Based on historical accounts and on more recent observations, it is possible to describe some of these changes. The earliest written account of the Okavango Delta was by David Livingstone after visiting Lake Ngami in 1849 (Livingstone 1857). His visit was followed by a number of others, notably Charles Andersson in 1853 (Andersson 1857), James Chapman in 1853 and thereafter (Chapman 1886), and Thomas Baines (1864). Lake Ngami was described by these visitors as an extensive body of shallow water, and appears to have been supplied at the time with water from the Thaoge River (Figure 2a). Andersson (1857) traveled upstream along the Thaoge River from Lake Ngami, covering a distance of approximately 80 kilometers. He described the river as 40 yards wide, and always deeper than 5 feet.

During the latter part of the last century, the upper reaches of the Thaoge River became subject to blockage by rafts of papyrus debris in two distinct areas (Figure 1), the upper and main Thaoge Blockages (Stigand 1923; Brind 1955; Wilson 1973). These were associated with the failure of the Thaoge River, which ceased to flow into Lake Ngami from about 1880. The decline of the Thaoge River appears to have been accompanied by an increase in flow along the Nqoga, Mboroga, and Santantadibe Rivers (Figure 2b). During the late 1920's the lower reaches of the Nqoga River started failing, once again associated with the development of papyrus blockages (Wilson 1973), and this was accompanied by an increase in flow along the more northerly Maunachira River, as well as along the Jao-Boro River system (Figure 2c; Wilson 1973; Smith 1976). The failure of these river systems has been well documented (Stigand 1923; Brind 1955; Wilson 1973; McCarthy *et al.* 1986a, 1992; Ellery *et al.* 1993, *in press*). The first visible signs are constriction of the channel by *Vossia cuspidata*, followed by the development of papyrus blockages and by the encroachment of papyrus from the banks into the channels themselves. These processes lead to obliteration of the channel, but are not the primary cause of change.

CAUSES OF CHANGE

There appear to be two important processes - sedimentation and neotectonics - that contribute to channel failure, and it is difficult to assess the relative contribution of each. First, the introduction of bed-load sediment into the Okavango Delta, and its confinement to in-channel areas by vegetated peat deposits flanking the channels, causes channel aggradation. Sediment in the meandering channels of the panhandle is deposited as point bars, leading to slow rates of aggradation (McCarthy *et al.* 1991). However, the deposition of sediments along the channel beds of primary sinuous channels may lead to channel aggradation rates in excess of 5 cm/a (McCarthy *et al.* 1986, 1992). This causes aggradation of several meters over the life of a channel, leading to increases in hydraulic gradients away from these channels far in excess of downstream gradients along the channel axis (McCarthy *et al.* 1986, 1992; Ellery *et al.* 1993). Furthermore, water lost in this way from an aggrading channel carries no sediment, initiating headward erosion in lines of weakness leading away from an aggrading primary channel, such as along a hippo path (Ellery *et al.* 1993).

Although the role of neotectonics as a possible cause of channel change has been alluded to in the past (Hutchins *et al.* 1976; Wilson and Dincer 1976; Smith 1976), evidence for the role of neotectonics in promoting channel change has recently been described in some detail (McCarthy *et al.* 1993). The region of the Okavango Delta is seismically active, and is associated with active rifting. It has given rise to conjugate faults tending southwest to northeast, and northwest to southeast (McCarthy *et al.* 1993). Tectonic activity and the formation of these conjugate faults is characteristic of rifting, which may cause changes in surface elevations over relatively short timespans, and may thus contribute to changes in the distribution of water in the Okavango Delta.

CONSEQUENCES OF CHANGE

Changes in the distribution of water are associated with profound changes in habitat within the Okavango Delta. At the time a channel system is active, the channel itself is flanked by virtually monospecific stands of the giant sedge *Cyperus papyrus* (Ellery *et al.* 1990). This community grades laterally to backswamp communities, whose distribution is dependent on water depth and on time since flooding (Ellery 1987; Ellery *et al.* 1991). These communities include open water areas with submerged vegetation, shallower areas with floating-leaved vegetation, and even shallower areas with short or tall emergent communities (Ellery 1987). Successional processes in these backswamp areas suggest that these communities are dominated ultimately by an emergent grass, *Miscanthus junceus*, which occurs in association with other grasses, sedges, and the swamp fig *Ficus verruculosa* (Ellery 1987).

The peat deposits associated with plant succession in backswamp areas act as a nutrient trap (Moore and Bellamy 1974; McCarthy et al 1989). Subsequent to abandonment, the peat deposits flanking a former channel system are susceptible to burning in subsurface peat fires (Ellery *et al.* 1989), which lead to the conversion of former swampland to terrestrial habitat, or to seasonal swamps. These peat fires release nutrients formerly locked up in the peat deposits, giving rise to soils with much higher nutrient status than the surrounding environment. These habitats are productive, and appear to support large concentrations of game as well as bird species in an environment that otherwise has a low carrying capacity (Ellery *et al.* 1989).

IMPLICATIONS FOR ECOSYSTEM FUNCTIONING

The ever changing distribution of water in the Okavango Delta ecosystem is important for two reasons. First, it appears to create a mosaic of habitats in different stages of wetting and drying. In the absence of change, the Okavango Delta would generally support low habitat diversity. The typical habitats that might be expected in a swamp of this kind are typically unfavorable for herbivores (Thompson and Hamilton 1983). For this reason, in the absence of changes in water distribution, the Okavango would typically support low concentrations of herbivores. Second, change enables regeneration of island soils. Surface salinization of soils by sodium carbonate and sodium bicarbonate (trona; McCarthy *et al.* 1986b) in the Okavango Delta is associated with the occurrence of the hardy grass *Sporobolus spicatus*, and even the complete absence of vegetation (Ellery *et al. in press*). The drying out of an area due to channel switching allows regeneration of these soils by leaching of these waste products into the subsurface, and possibly into the deep groundwater, so that when an area in which these islands occur is reflooded, these soils will not be toxic to terrestrial vegetation (McCarthy *et al.* 1993; Ellery *et al.*, *in press*).

IMPLICATIONS FOR CONSERVATION

Maintaining the natural dynamics

Change is brought about by a combination of sedimentation and tectonic activity. It is clearly not possible to manipulate the latter element of change, but changes in the quantity and nature of sediments introduced into the Okavango Delta each year could arise in several ways. We will focus first on clastic sediments. The construction of any impoundments (dams or weirs) in the catchment, particularly on the Okavango River itself, would have immediate and possibly catastrophic consequences. In contrast, the removal of relatively small quantities of water from upstream areas in the Okavango Delta is not considered to be a major threat to the ecosystem in itself, particularly in the context of climatic change that has taken place in the recent and not-so-recent past. However, the removal of the sediment supply that contributes to change in the distribution of water over timespans of decades to centuries could lead to a reduction in habitat diversity, and also to extensive soil salinization, and possibly to the salinization of surface water in the long-term.

Construction of an impoundment in the catchment would also affect the quality of inflowing water, and thus affect the character of dissolved sediments. The giant sedge *C. papyrus* appears to be sensitive to changes in water quality, and any impact on its distribution within the ecosystem would probably affect patterns of sedimentation. It is the only species in the Okavango capable of matching channel bed aggradation rates in excess of 5 cm/a (Ellery 1988), and plays an important role in the overall patterns of clastic sediment deposition in channels. As such its role in facilitating change should not be underestimated.

The most suitable means of water abstraction in the catchment or upper reaches of the Okavango Delta is therefore by pumping. Ideally pumping should be in phase with the flood cycle, or should peak during periods of high flows.

In the past, there has been dredging in the lower regions of the Delta, and proposals to increase outflow from the Okavango Delta have tended to focus on dredging and canalizing existing channels in these areas (Earnest 1976; SMEC 1987). A potentially serious problem associated with water development schemes 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 if patterns in the upper reaches change. In such an event, the temptation to extend the length of the dredged section would increase, possibly with catastrophic impacts. However, the most suitable location for storage dams is in the lower reaches of the Delta, where the impact of salinization would be local, and where plant communities are better adapted to higher salinities.

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 (Figure 3), because it is an essential component of the dynamics of the ecosystem as a whole. It is also important that a 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 wetland habitats could be lost from the conservation area entirely.

CONCLUSIONS

A broad understanding of the structure and functioning of the Okavango Delta ecosystem has provided a useful basis for evaluating the kinds of perturbations that are likely to affect the ecosystem as a whole. Dissolved sediments are precipitated out of solution below surface in the permanent and seasonal swamps, with the exception of sodium carbonate and bicarbonate, which precipitate out at the soil surface of islands. Clastic sediment introduced into the system results in constant changes in the distribution of water on the fan surface. This promotes the occurrence of a mosaic 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 permanent and seasonal swamps. 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, and provided it does not disrupt sediment supply to the system from source areas. 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.

Proposals made here for water abstraction have a minor impact on the most important ecosystem processes, particularly the movement of bed-load sediment into the primary channels. This is important in promoting diversity and renewal through change, and must contribute to the present structure and functioning of the Okavango Delta ecosystem as we know it today.

ACKNOWLEDGMENTS

The Office of the President, Botswana, is 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. Mr. P. A. Smith has taken an active interest throughout, Karen Ellery commented on a draft of the manuscript. Logistical support has been provided by David Hartley of Xugana Lodge, and by Paul and Penny Rawson of Xaxaba. The staff of these camps are also acknowledged.

REFERENCES CITED

Andersson, C. J. 1857. Lake Ngami. Harper Bros., New York. Reprinted by C. Struik, Cape Town, South Africa, 1967. 503 pp.

Anderson, R.F.J. 1976. Weather of the Okavango Delta. Pages 29-31 *in* Botswana Society, Symposium on the Okavango Delta and its future utilization. Gaborone, Botswana.

Baines, T. 1864. Explorations in south-west Africa. Longman, Green, and Co., London, UK.

Brind, W. G. 1955. The Okavango Delta: report on the 1951-1953 field surveys. Unpublished report to the Resident Commissioner, Mafeking. 41 pp.

Chapman, J. C. 1868. Travels in the interior of Africa, 1849-1863. Reprinted by A. A. Balkema, Cape Town, South Africa, 1971.

Dincer, T., L. G. Hutton, and B.B.J. Kupee. 1981. Study, using stable isotopes of flow distribution, surface-ground water relations and evapotranspiration in the Okavango Swamp, Botswana. Pages 3-26 *in* International Atomic Energy Agency, Vienna, Proc. Ser. SII/AUB/493.

Earnest, H. M. 1976. Manipulation of the Okavango Delta for increased outflow: its impact and constraints. Pages 337-345 *in* Botswana Society, Symposium on the Okavango Delta and its future utilization. Gaborone, Botswana.

Ellery, K. 1987. The composition and dynamics of wetland plant communities of the Maunachira River system, Okavango Delta, Botswana. Unpublished M.S. Thesis. University of the Witwatersrand, Johannesburg, South Africa.

Ellery, K., W. N. Ellery, K. H. Rogers, and B. H. Walker. 1991. Water depth and biotic insulation: major determinants of back-swamp plant community composition. Wetlands Ecology and Management 1: 149-162.

Ellery, W. N., K. Ellery, T. S. McCarthy, B. Cairncross, and R. Oelofse. 1989. A peat fire in the Okavango Delta, Botswana, and its importance as an ecosystem process. African Journal of Ecology 27: 7-21.

Ellery, W. N., K. Ellery, K. H. Rogers, T. S. McCarthy, and B. H. Walker. 1990. Vegetation of channels of the northeastern Okavango Delta, Botswana. African Journal of Ecology 28: 276-290.

Ellery, W. N., K. Ellery, K. H. Rogers, T. S. McCarthy, and B. H. Walker. 1993. Vegetation, hydrology and sedimentation processes as determinants of channel form and dynamics in the northeastern Okavango Delta, Botswana.

African Journal of Ecology 31: 10-25.

Ellery, W. N., K. Ellery, K. H. Rogers, T. S. McCarthy, and B. H. Walker. *In press*. The role of *Cyperus papyrus* in channel blockage and abandonment in the northeastern Okavango Delta. African Journal of Ecology.

Ellery, W. N., K. Ellery, and T. S. McCarthy. 1993c. Plant distribution in islands of the Okavango Delta, Botswana: determinants and feedback interactions. African Journal of Ecology 31: 118-134.

Grumbine, E. 1990. Protecting diversity through the greater ecosystem concept. Natural Areas Journal 10: 114-128.

Hobbs, R. J. 1993. Effects of landscape fragmentation on ecosystem processes in the western Australian wheatbelt. Biological Conservation 64: 193-201.

Hutchins, D. G., S.M.R. Hutton, and C. R. Jones. 1976. The geology of the Okavango Delta. Pages 13-20 *in* Botswana Society, Symposium on the Okavango Delta and its future utilization. Gaborone, Botswana.

Livingstone, D. 1857. Missionary travels and researches in South Africa. John Murray, London, UK.

McCarthy, T. S., W. N. Ellery, K. H. Rogers, B. Cairncross, and K. Ellery. 1986a. The roles of sedimentation and plant growth in changing flow patterns in the Okavango Delta, Botswana. South African Journal of Science 82: 579-584.

McCarthy, T. S., J. R. McIver, and B. Cairncross. 1986b. Carbonate accumulation on islands in the Okavango Delta. South African Journal of Science 82: 588-591.

McCarthy, T. S.., J. R. McIver, B. Cairncross, W. N. Ellery and K. Ellery. 1989. The inorganic chemistry of peat from the Maunachira channel-swamp system, Okavango delta, Botswana. Geochimica et Cosmochimica Acta 53: 1077-1089.

McCarthy, T. S. and J. Metcalfe. 1990. Chemical sedimentation in the semi-arid environment of the Okavango Delta, Botswana. Chemical Geology 89: 157-178.

McCarthy, T. S., I. G. Stanistreet, and B. Cairncross. 1991a. The sedimentary dynamics of active fluvial channels on the Okavango fan, Botswana. Sedimentology 38: 471-487.

McCarthy, T. S., J. R. McIver, and B. Th. Verhagen. 1991b. Groundwater evolution, chemical sedimentation and carbonate brine formation on an island in the Okavango Delta swamp, Botswana. Appl. Geochemistry 6: 577-595.

McCarthy, T. S., W. N. Ellery, and I. G. Stanistreet. 1992. Avulsion mechanisms on the Okavango fan, Botswana: the control of a fluvial system by vegetation. Sedimentology 39: 779-795.

McCarthy, T. S. and W. N. Ellery. ~~In press~~. The effect of vegetation on soil and groundwater chemistry and hydrology of islands in the seasonal swamps of the Okavango fan, Botswana. Journal of Hydrology.

McCarthy, T. S., R. W. Green, and N. J. Franey. 1993a. The influence of neo-tectonics on water dispersal in the northeastern regions of the Okavango Swamps, Botswana. Journal of African Earth Sciences 17: 23-32.

McCarthy, T. S., W. N. Ellery, and K. Ellery. 1993b. Vegetation induced subsurface precipitation of carbonate as an aggradational process in the permanent swamps of the Okavango (Delta) fan, Botswana. Chemical Geology 107: 111-131.

McCarthy, T. S., W. N. Ellery, and I. G. Stanistreet. 1993c. Lakes of the north eastern region of the Okavango swamps, Botswana. Zeitschrift Geomorphologie 37: 273-294.

Moore, P. D. and D. J. Bellamy. 1974. Peatlands. Paul Elek, London, UK. 220 pp.

Saunders, D. A., R. J. Hobbs, and C. R. Margules. 1991. Biological consequences of ecosystem fragmentation: a review. Conservation Biology 5: 18-32.

Shaw, P. 1985. Late Quarternary land forms and environmental change in northwest Botswana: the evidence of Lake Ngami and the Mababe Depression. Transactions of the Institute of British Geographers N. S. 10: 333-346.

Snowy Mountains Engineering Corporation (SMEC). 1987. Southern Okavango Integrated Water Development Project. Phase 1: final report.

Smith, P. A. 1976. An outline of the vegetation of the Okavango drainage system. Pages 93-112 *in* Botswana Society, Symposium on the Okavango Delta and its future utilization. Gaborone, Botswana.

Stanistreet, I. G. and T. S. McCarthy. 1993. The Okavango Delta and the classification of subaerial fan systems. Pages 115-133 *in* C. R. Fielding, ed., Current research in fluvial sedimentology. Sedimentary Geology 85.

Stanistreet, I. G., B. Cairncross, and T. S. McCarthy. 1993. Low sinuosity and meandering rivers in the Okavango Fan: channel confinement by vegetated levees without fine sediment. Pages 135-156 *in* C. R. Fielding, ed., Current research in fluvial sedimentology. Sedimentary Geology 85.

Stigand, A. G. 1923. Ngamiland. Geographical Journal. 62: 401-419.

Sutcliffe, J. V. and Y. P. Parks. 1989. Comparative water balances of selected African wetlands. Hydrological Science Journal 34: 49-62.

Thomas, D.S.G and P. A. Shaw. 1991. The Kalahari environment. Cambridge University Press, Cambridge, UK.

Thompson, K. and A. C. Hamilton. 1983. Peatlands and swamps of the African continent. Pages 331-373 *in* A.J.P. Gore, ed., Ecosystems of the world. Vol. 4B, Mires: swamp, bog, fen and moor. Elsevier Scientific, Amsterdam, The Netherlands.

United Nations Development Programme (UNDP). 1977. Investigation of the Okavango Delta as a primary source of water for Botswana. UN/FAO DP/BOT/71/506, Gaborone, Botswana.

Walker, B. H. 1989. Diversity and stability in ecosystem conservation. Pages 121-130 *in* D. Western and M. C. Pearl, eds., Conservation for the twenty-first century. Oxford University Press, Oxford, UK.

Wilcove, D. S., C. H. McLellan, and A. P. Dobson. 1986. Habitat fragmentation in the temperate zone. Pages 237-256 *in* M. E. Soule and B. A. Wilcox, eds., Conservation biology: an evolutionary and ecological perspective. Sinauer, Sunderland, Massachusetts, USA.

Wilcox, B. A. 1986. Insular ecology and conservation. Pages 95-117 *in* M. E. Soule and B. A. Wilcox, eds., Conservation biology: an evolutionary and ecological perspective. Sinauer, Sunderland, Massachusetts, USA.

Wilcox, B. A. and D. D. Murphy. 1985. Conservation strategy: the effects of fragmentation on extinction. American Naturalist 125: 879-887.

Wilson, B. H. 1973. Some natural and man-made changes in the channels of the Okavango Delta. Botswana Notes and Records 5: 132-153.

Wilson, B. H. and T. Dincer. 1976. An introduction to the hydrology and hydrography of the Okavango Delta. Pages 33-48 *in* Botswana Society, Symposium on the Okavango Delta and its future utilization. Gaborone, Botswana.

Table 1. Annual water, chemical, and sediment budgets for the Okavango Delta.

Source	Input	Surface outflow	Subsurface outflow
Rainfall[1]	$5x10^9$ m^3		
Okavango River[1]	$11x10^9$ m^3	$0.3x10^9$ m^3	$0.3x10^9$ m^3
Bed-load[2]	170,000 t	nil	nil
Suspended load[2]	30,000 t	nil	nil
Dissolved solids[3]	457,390 t	29,832 t	?

[1] Dincer *et al.* 1981

[2] McCarthy *et al.* 1991a

[3] McCarthy and Metcalfe 1990

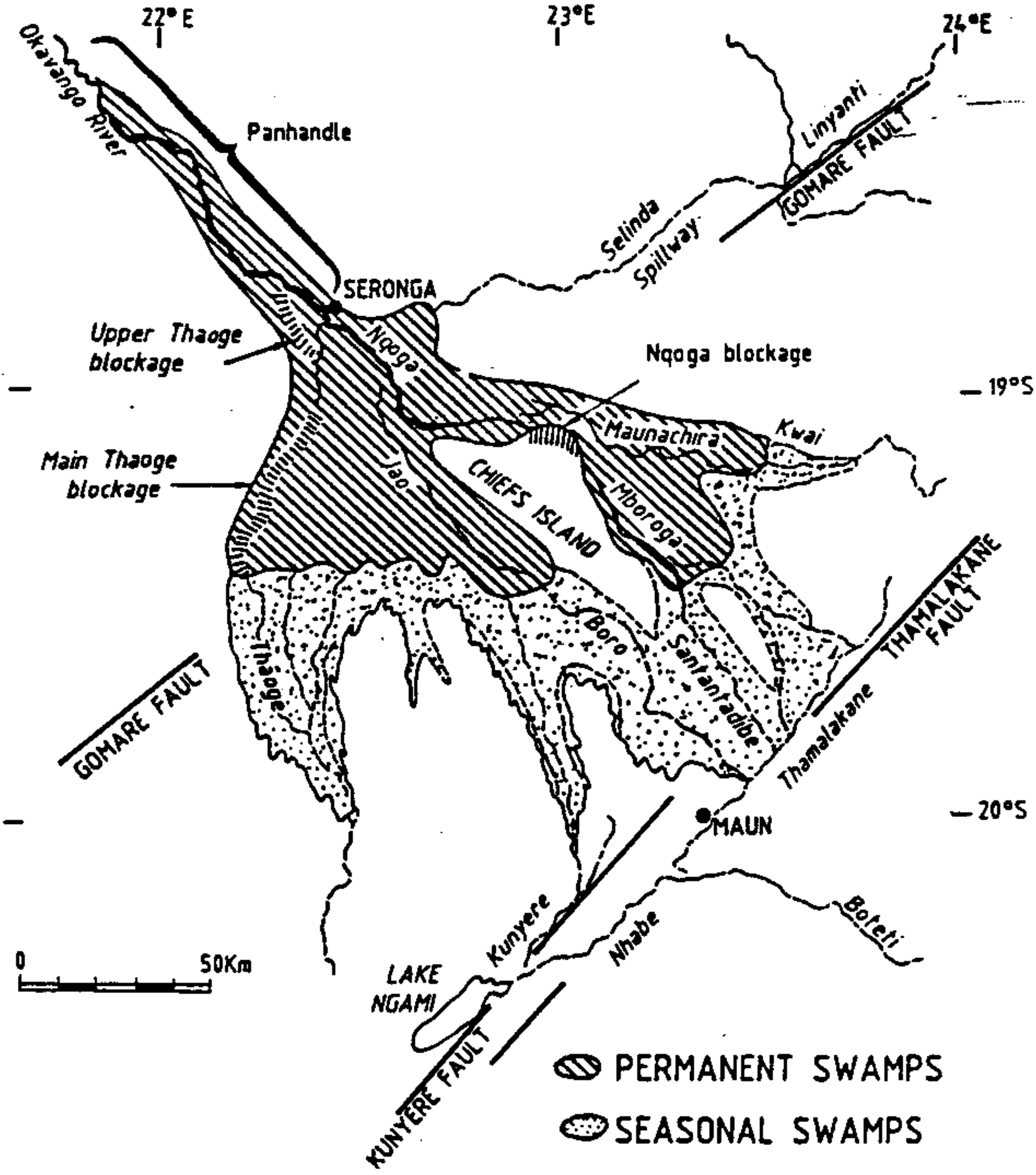
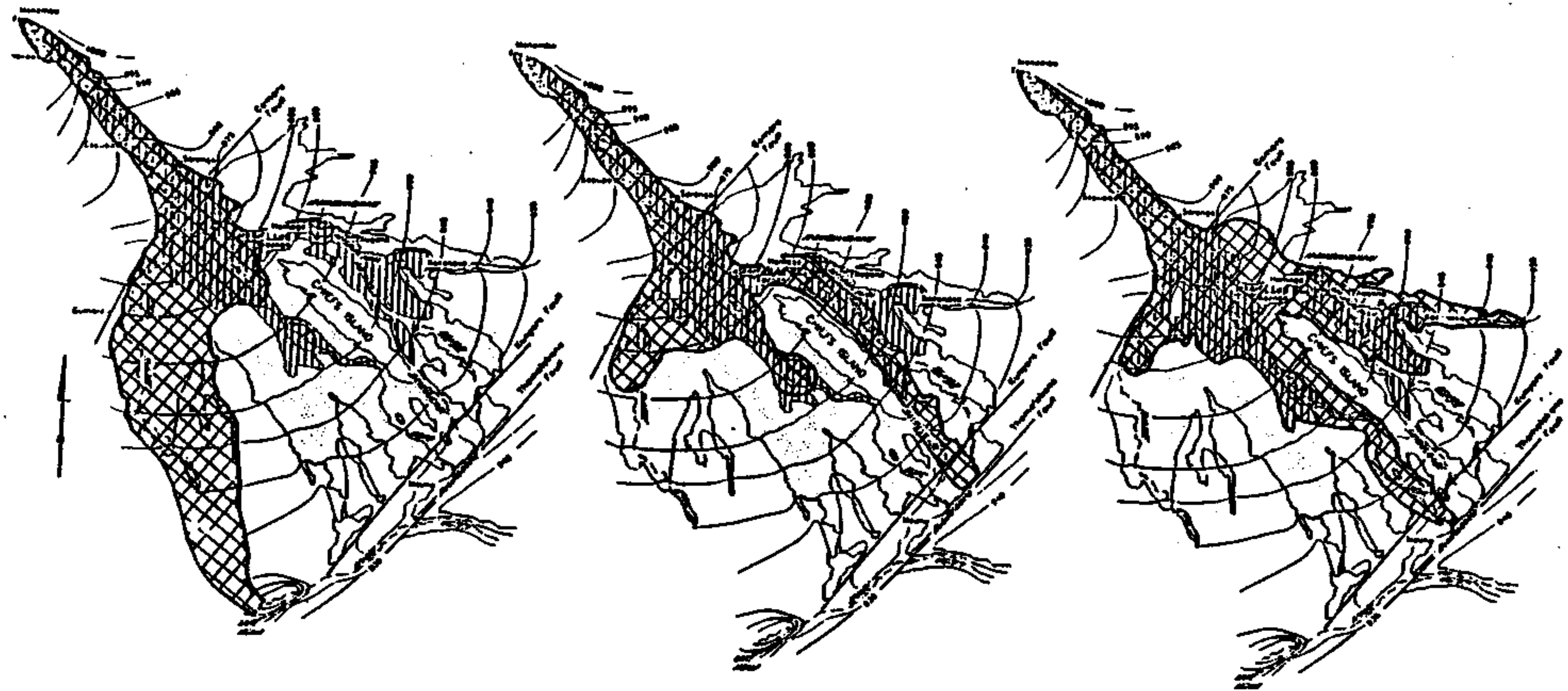


Figure 1. Map of the Okavango Delta.



To 1880

1880 - 1930

1930 to present

Figure 2. The distribution of water in the Okavango Delta at various times during the 19th and 20th centuries. Vertical lines and stippled areas indicate the present distribution of permanent swamp and seasonal swamp respectively; cross hatching indicates the approximate areas of main flow in the periods shown.

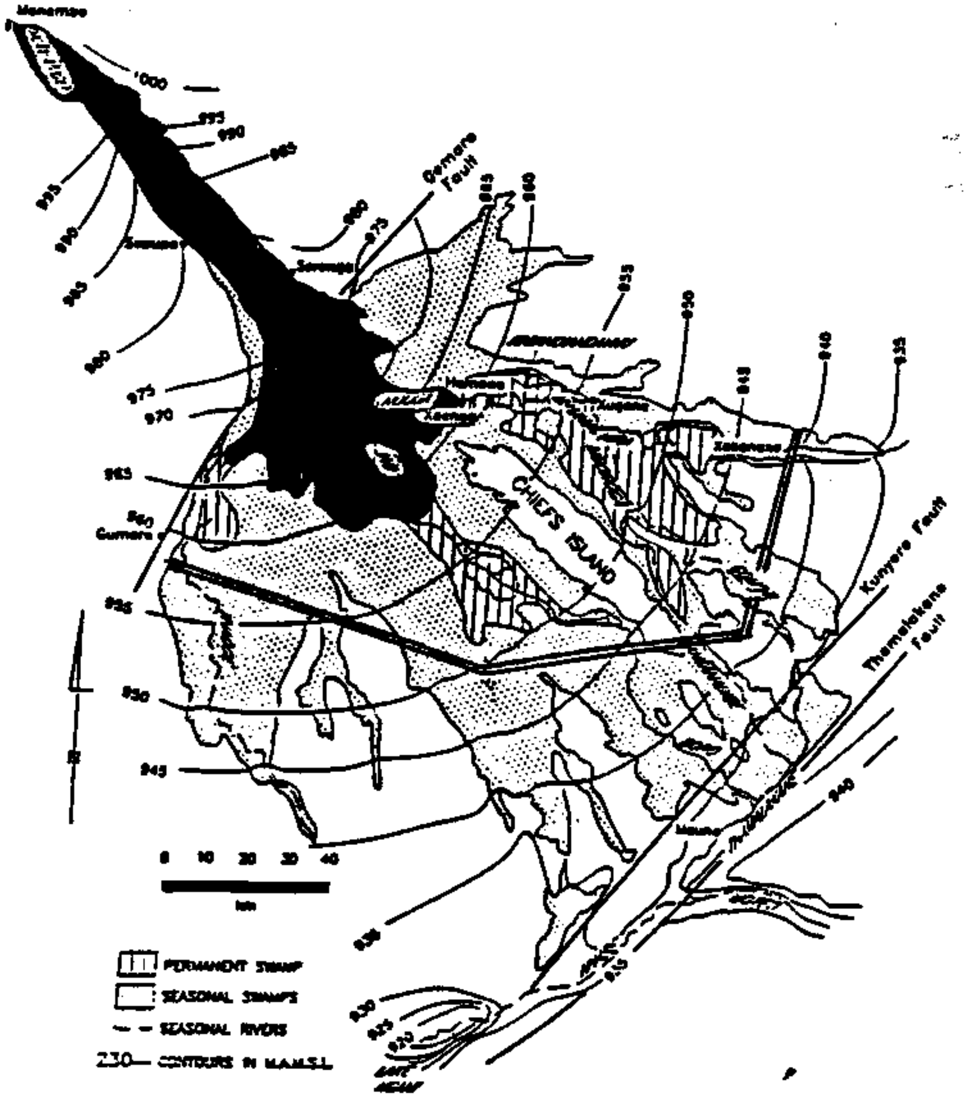


Figure 3. The area of the Okavango Delta in which the processes that contribute to channel switching are taking place (solid), and an example of the inclusion of a range of areas over which flooding may occur in the future (double solid line).