For info and comment

Aspects of Swamp Hydrology in the Okavango

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Introduction

In the north-west of Botswana lie the swamps of the Okavango Delta. A vast area of wetlands, varying seasonally from 6 000 km² to 10 000 km², it supports a great variety of flora and fauna in a unique environment embedded within the semi-arid sandy tracts of the Kalahari. In addition to the wetlands, the delta of the Okavango, around 25 000 km² in area, encompasses extensive savannah woodlands which support predators and prey such as lion, leopard, cheetah, and many species of antelope; as well as the large herbivores - elephants, giraffe and hippopotamus; while the swamps themselves are the habitat of many fishes, crocodiles, and otter, and are a haven for birdlife.

The delta was formed by an uplift of land between parallel geological faults, causing the river waters to spread out behind the uplift and to deposit their load of sediment. There is clear evidence that the Boteti River, which drains south below the delta, was in former times a much larger river and fed the Makgadikgadi Pans, which were a vast lake.

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Until quite recently, the Okavango Delta remained a virtually untouched wilderness. This was due in part to its remoteness, but more due to its environment in which tropical diseases are endemic. Malaria and bilharzia were real menaces, but the main protector of the swamps was the tsetse fly. The blight of the tsetse fly discouraged settlement within the confines of the delta and effectively limited human intrusion into the swamps.

Within the past twenty years great changes have occurred. The tsetse fly has been almost eradicated by a government programme which has focussed on chemical spraying techniques. Similar methods have made inroads against the malaria-bearing mosquitoes. Bilharzia, or schistosomiasis remains prevalent, but can be avoided by prudent bathing and by precautions against skin contact with swamp waters.

Some measure of restraint on access to the delta has been maintained fortuitously through the erection of a veterinary cordon fence on the western and southern fringes of the delta; fortuitous because the primary purpose of the fence is to restrict the spread of foot and mouth disease by separating the wild herds of buffalo in the delta from the domesticated herds of cattle which are the keystone of the rural economy. But it also constitutes a control on access, and restricts activities such as hunting and herding.

National importance of Okavango water   Although most of Botswana's population live elsewhere, far from the Okavango, the delta assumes disproportionate importance in the national economy. In a nation critically short of water resources - even in normal times - the Okavango represents Botswana's most abundant source of water, and almost the only natural source of perennial surface water in the country. (The other perennial surface water resource is the Linyanti/Chobe River, which forms the far north-eastern border).

More importantly, at least for the present, is the burgeoning international tourist trade, which is primarily interested in the Okavango Delta because of its reputation as a great wilderness area and because of the wild animal populations it supports. For those who can afford it the Okavango is now readily accessible and is no longer hazardous - though to visit there is still an adventure.

Taking into account that most beef cattle in Ngamiland rely heavily on the Okavango River or the overflows from the delta as a reliable supply of water, and that in better times the diamond mine at Orapa depended on water from the Boteti, one can appreciate the role that the Okavango has already played in the dominant troika of the national economy: beef, diamonds, and tourists.

Potential future conflicts in water development

That role in the national economy is set to increase in the future. Thereby potential conflicts are likely to arise; and at a policy level there will be conflict between the notion that the use of the water in such a parched land is too valuable to allow the resource to go untapped, and the notion that the environment, the fauna, and the traditional ways of life are too precious to disrupt. In brief, the conflict between the development and the conservationist ethic.

There will be conflicts between competing uses of water. This will involve not only competing users of water, but will also and importantly involve landholders who will perceive a threat to their traditional use of the land because of development, and tourist operators who will perceive a threat to their income because of increasing regulation and control of water.

In the Okavango these conflicts have been mercifully postponed, at least to some degree, but the time is fast approaching when they must be addressed. From similar experiences in other countries we may be sure of two things. Obviously, it will be impossible to please everyone. Secondly, it will be very difficult to preserve a balance between the opposing ethics of development and conservation. Generally, one will prevail. In a nation like Botswana struggling to pursue its independence, it is especially difficult to refute development goals.

It is in this context that the water resources of the delta are coming to be analyzed, and more attention is being given to the complex hydrology of this unique area.

Early Studies

Several scientific expeditions to Ngamiland and the Okavango region took place prior to independence in 1966. Foremost among these were those lead by du Toit (in 1925), Jeffares (in 1937), and Brind (in 1951-53). Some measurements of river levels commenced at Mohembo (the Okavango River) in 1929, and at Maun (the Thamalakane) as early as 1921; but these were discontinued, and for various reasons it is difficult to properly correlate these early records with modern measurements. Systematic collection of field hydrology data commenced only after independence, initiated under the auspices of United Nations Development Programme projects in collaboration with the Botswana Department of Water Affairs. DWA has continued to maintain an extensive network of observation stations within the delta, so that now up to 20 years of useful continuous data are available from some key locations.

Notable contributions to the published body of material on the water resources of the Okavango include those by Wilson(1973), and Dincer, Child & Khupe (1987). Dincer developed a multi-cell water balance model of the main throughflow system of the delta (Okavango-Ngokha-Boro- Thamalakane). More recently, in a series of papers McCarthy and co-workers have addressed aspects of sediment deposition and salinity within the delta. Other important analysis can be found in government departmental reports, some of which were prepared by consultants.

Problems of Prediction

Sources of the Okavango The Okavango River rises in the central highlands of Angola, and is fed by two main tributaries: the Cubango and the Cuito. The catchment area to the north of Botswana is 150 000 km^2, so that the average annual runoff of 10 000 million cubic metres represents a mean runoff depth of only 67 mm per annum. However, because the southern part of this great area is mainly Kalahari sands and has much lower rainfall, almost all of the river flow originates from the northern sectors, as much as 750 km remote from the Botswana border. As a result the rise and fall of the river is regular and seasonal, commencing to rise at Mohembo usually in November and peaking at the end of the rainy season in March or April. Given an adequate raingauge network in Angola, it could also be fairly predictable; but communications and political problems have thus far not enabled such predictions to be made.

As it happens the implications of this shortcoming are not serious. The sparse population along the Panhandle (the north-western corner of the delta) is not threatened by flooding, and has a reliable source of water. At the southern or distal end of the delta flooding can affect livelihoods, and droughts can produce water shortages, but some degree of prediction is possible because of the great delay which is imposed upon the transmission of the seasonal flood wave through the delta. In a normal year, the Thamalakane River which drains the distal end of the delta peaks at Maun in August, over four months after the peak inflow to the delta.

This is attributable to the huge storage which exists in the delta - like a vast reservoir, although a reservoir which is dispersed over the 25 000 km². It is continually being depleted by evaporation (and transpiration), but at its maximum in a normal year the delta holds an estimated 10 000 million cubic metres of water (equivalent to one years inflow). Its water surface area is then around 10 000 km². Most supports an abundant growth of aquatic vegetation (papyrus, phragmites, reeds, bullrushes, water grasses, etc.), but evaporation combined with transpiration can still proceed at a rate comparable to (i.e. of the same order as) evaporation from an open body of water.

Local precipitation Given the magnitude of storage effects mentioned above, and the corollary that flow at any point within the delta will be affected not only by the current year's inflow but also by the residual storage from the preceding year or years, channel flow at any one location in the delta can vary in different years which have the same inflow. The flow can also vary for the additional reason that seasonal rainfall over the delta influences the discharge. The influence of rainfall is reduced because maximum extent of water storage within the delta is out of phase with seasonal rainfall. Nevertheless, local rainfall can be an important factor in years when rainfall is well above average, and years of high delta outflow in 1956 and 1974 were associated primarily with high local rainfall. Local rainfall here is construed as general rainfall over the Okavango Delta, as distinct from rainfall in the Angolan highlands which produces the river inflow to the delta.

This much is known about the factors influencing the flows through the channels and swamps, and so much could be forecast in the sense that mathematical techniques exist which could enable prediction given adequate input data.

Hydrological instability   The most intriguing aspect of delta hydrology, however, is its instability. In addition to the factors above, the flow at any one location is also affected by the dynamics of the delta. Deltas throughout the world are dynamic systems because they are zones of very active sediment deposition. This implies aggradation of channels, reduced longitudinal gradients, and ultimately channel relocation. One can readily imagine that with an appropriately extended time interval for time-lapse photography, the main channels of the Okavango would be seen to perpetually wander across the face of the delta, flickering from one course to another in response to the imperatives of the natural processes responsible for genesis of the delta itself.

In addition to the usual instability natural to any deltaic system, other factors contribute to instability of the Okavango hydrology. These factors include earthquakes, cycles of vegetation growth, animal activity and human intervention.

The role of earthquakes In 1952 a period of unusual seismic activity occurred in the Okavango region. This may have coincided with a change in flow regime of the Thamalakane River as reported by Hutchinson & Midgeley (1973), and others. The evidence in that instance is not entirely clear, as data prior to 1952 is quite limited and alternative explanations are possible. Irrespective of whether that was or was not the case, seismic activity must be responsible for shifts in flow regimes in some instances. The origins of the delta itself, after all, are due to the agency of earthquake activity. The frequency of such seismically active periods is much too low, however, to account for the frequency with which significant shifts in flow regimes occur within the delta. Logically the great majority of changes must occur due to other causes.

Vegetation dynamics Chief amongst these is the role of vegetation, particularly aquatic vegetation, and the response of vegetation to the abundance or scarcity of water. In the perennial swamps, as shall be explained later, aquatic vegetation can play a stabilizing role; but under more variable conditions of water supply which exist in the seasonal swamps and lower delta the growth and decline of vegetation can help to determine the paths which water will take. Each species of aquatic flora has its optimum conditions for growth with regard to depth and duration of flooding. In relatively dry years some species may prosper while others decline. A particular species may prosper in one location (where depths approach optimum), while simultaneously declining in another location (where depths are reduced below optimum). In this way lower water levels in a distributary channel during dry years may lead to a proliferation of aquatic growth, leading to a vegetation blockage; while in a potential parallel channel usually blocked by profuse growth in more normal years, drier conditions may cause the vegetation to die off. When the next good flood comes, the preferred route may change to the drier channel where the hydraulic resistance to flow is much reduced.

To understand the plausibility of this scenario the extremely flat gradients within the delta must be appreciated. The average fall line between Mohembo and Maun is about 1:4 000. Longitudinal gradients along meandering channels can be much less. The importance of vegetation in determining hydraulic resistance - and thereby water levels and direction of flow - is evident too in the records available from any hydrometric station in the seasonal swamps. Here, discharge ratings (the relationship between channel flows and channel depths) vary from season to season, and even within a season. This variation is directly attributable to vegetation growth, which responds to good and poor seasons or, within a single flood season, to the improved supply of water as the season progresses.

The mechanisms affecting flow paths described above are believed to be the primary reason for the common observation by those familiar with the seasonal swamps that the route which flood waters take as they penetrate the flood plains will vary from year to year. More water may be found in one location this year, while at another location there may be less. The dynamics of vegetation growth mean that the distribution and extent of flooding in a particular locality is never entirely predictable.

Activities of man and beast Other factors which can affect flow distribution within the delta are human and animal activity. The paths which hippopotamus make through the swamp vegetation are clearly visible from the air, and these have sometimes been suggested as factors in the redirection of flows. The fact that the decline of the Thaoge last century coincided with the arrival of Europeans and the introduction of modern weapons for hunting has also been noted, although this may well have been mere coincidence. In recent times the opening of navigation channels within the perennial swamps has certainly had some impact on flow distribution. The role that channels play in the distribution of water within the deltaic swamps has probably been underestimated. More will be said of this later.

Examples of instability The best documented and most dramatic shift in regime within the delta in recent history is that of the Thaoge. This channel system, which until 1850 conveyed sufficiently large volumes of water to render Lake Ngami a large body of perennial water, has since been in decline and has apparently not reached Lake Ngami at all this century. Currently, it only occasionally progresses beyond Gumare, some 340 river km short of the lake. Very interesting accounts of the decline of the Thaoge and the fate of Lake Ngami were presented by Wilson(1973), and Shaw(1985).

Further to the east, the Gomoti has suffered a similar dramatic decline in a similar time span. The Gomoti was remarked as a major channel system early this century by Stigand. Today, in relatively arid tracts of the delta south of Chengwa Lediba, the well-incised former channel of the Gomoti remains quite dry. The source of water for the modern Gomoti appears to have suffered a significant shift. At the southern extremity of the Mboroga channel in the locality of Txaba the relict channel of the Gomoti to the east no longer functions adequately and is substantially blocked by vegetation (see Fig.2). The Guekha channel system now feeds the Gomoti by collecting overflows from the east bank of the Mboroga further north. The poorly defined channel of the Guekha presumably signifies its recent emergence as an important flow route for floodwaters. In time it may develop the characteristics of a major channel.

In the same general region of the delta, the Santantadibe channel, which was formerly a reliable (i.e. perennial) though insubstantial supplier of water to the Thamalakane, has just within this current decade entirely stopped flowing in its lowest reaches. Indications are that it is unlikely to resume.

Irregular discharge records on the upper Xudum channel at Thapagadi (site of the pontoon) indicate a proportional increase in flow in recent years in relation to flows in the Boro channel. Other examples are known where particular localities within the seasonal swamps have received flows for the first time in many years on occasions when the flood inflow to the delta has been unexceptional or even below normal, illustrating the point about instability of the delta hydrology.

The Role of Channels

Channels radiate in all directions through the Okavango Swamps. While some small channels may be kept open by men or hippopotamus for navigation most channels are a natural manifestation of the swamps. They vary from small channels less than two metres wide to the main Ngokha channel up to 75 metres wide, while depths are generally from two to five metres.

The cross-sectional shapes of the channels are distinctively different from those of normal river channels. The depth is relatively uniform across the section, with aquatic vegetation forming near-vertical side walls. These side walls are not discrete boundaries of flow. Rather, a sharp lateral velocity profile develops because of the strong hydraulic resistance to flow of water within the vegetation at the sides. As a result of these factors, the velocity profiles within the open channel section are remarkably near uniform, both laterally and with depth. This too is quite different from normal river channels, in which significant velocity gradients occur.

The role of channels in conveying flow through the perennial and seasonal swamps has remained a matter of interpretation, even for those with intimate knowledge of the region. Because the cross-section available for flow in the channels is such a minute fraction of the total cross-section of the swamp floodplains, the role of channels has been considered by some to be secondary, or even minor, in the movement of water towards the distal end of the delta.

Measurements of flow velocities by means of fluorescent tracers in the vegetated floodplain of the Panhandle at Mohembo indicated that typical velocities there were around 0.02 cm/sec (UNDP/FAO,

1977) and it was estimated that during peak floods 5% to 10% of total flow could conceivably be conveyed down the floodplain outside the main channel. If these velocities are at all applicable further down the delta where the floodplains are much less confined, then swamp floodplain flow would be a very substantial component of the total flow down the delta.

Observations of the authors during repeated visits during 1986 and 1987 suggest, however, that such velocities are rare within the seasonal swamps. In one series of measurements in the seasonal swamps between the Xudum and Kiri distributary systems, a special pygmy current meter capable of measuring velocities down to 0.025 m/s was used. At lower velocities, detached floating or submerged vegetation could be observed to estimate water velocity.

As an example, at one location where water was passing between two islands 325 m apart, measurements indicated that velocities were negligible across 65% of the span. An estimated 35% of total flow was being conveyed in a central channel just 7 m wide by 0.9 m deep, where velocities were up to 0.4 m/s. Our extensive observations imply that this is reasonably typical, at least in the seasonal swamps. Indeed, in many less confined places during the 1986 flood peak water in the seasonal swamps was effectively not flowing, but remained as a simple backwater with water levels merely responding to the passage of the flood wave down or adjacent to channels, not too far distant. The importance of the role of channels in conveying flood flows through the swamps may not, therefore, have been fully appreciated.

The Okavango is too vast and complex to be easily classified, defined and dismissed, however. Indisputably there are locations where flow through the floodplains is significant and important. There is no continuous channel system, for example, feeding the

Matsibe distributary system. The Matsibe, which traverses the eastern edge of the Sandveldt Tongue, is fed by flood spill through the Jao Flats swamps. Discontinuous channels in the Flats may contribute, but ultimately the entire Matsibe flow must at some stage(s) pass through the swamp floodplain unassisted by channel flow.

To investigate the hydrological role of channels in the perennial swamps and the interaction between channels and adjacent floodplains, two series of field discharge measurements were undertaken. The first series of measurements focussed on the accession of flow to the upper Boro or Jao distributary system from the main Ngokha (or Nqogha) system, and was conducted during 1986 and 1987. The second series of measurements was conducted during 1987 and 1988 in the Thaoge distributary system north of Gumare.

Unfortunately, it was not possible to measure flow velocities in the swamp floodplains proper because it is exceedingly difficult to penetrate the papyrus without the aid of channels and the dense rhizome mat which grows at the surface prevents the employment of conventional measurement techniques. Rates of flow through the swamps had to be inferred from measurements at accessible locations.

Ngokha/Boro In the first series of measurements ten locations were selected in the Ngokha and upper Boro (or Jao) channels and in secondary channels entering the Boro from the perennial swamps. The locations are shown in Fig. 3. Site 1 was selected well upstream of the channel which links the Ngokha and Boro, and was thought to be far enough upstream to be above the beginning of accession of flow to the Boro. Sites 2, 3 and 4 were located progressively downstream in the Ngokha. Site 3 is at Duba where DWA operate an hydrometric station for regular measurement of water levels (and occasional measurement of discharge), while site 4 was located a short distance below the link channel to the Boro. Site 5 was in the link channel, site 6 was in the main secondary channel entering the upper Boro from the swamps, and site 9 was in another secondary channel entering near Jediba. Sites 7,8 and 10 were in the upper Boro, with site 8 at another hydrometric station operated by DWA at Kwihum.

Five sets of measurements were made between June 1986 and June 1987, encompassing one complete hydrological year. In 1986 the peak discharge at Mohembo in the upper Panhandle occurred in mid-April, and peak discharge at Thapagadi on the Xudum below Xo Flats was at the beginning of June. Very similar timing occurred during 1987, from which it may be inferred that peak discharge at site 1 would have occurred in early May. In both years the Okavango flood entering Botswana at Mohembo was below average (well below average in 1987).

The results of field measurements are presented in Table 1.

Of particular interest is the fact that discharges remain relatively constant at some main channel sites (sites 3, 4, 8), which is true also at a site on the Ngokha further downstream at Gaenga (which is operated as an hydrometric station by DWA). Water level records at Duba (site 3) and Gaenga also display remarkably little variation in water levels. The conclusion to be drawn from these observations is that these channels have a very definite conveyance capacity, and the Ngokha channel is flowing at full capacity virtually all the time. The capacity of the Ngokha channel decreases in the downstream direction, from approximately 90 m^3/s at site 3 (Duba), 75 m^3/s at site 4, and approximately 50 m^3/s at

Table 1: NQOGHA/BORO FIELD MEASUREMENTS OF DISCHARGE

Units m^3/s

SITE[1]	SET[2]				
	I	II	III	IV	V
1	160.2	116.0	116.3	127.4	146.0
2	127.3	113.7	108.0	122.7	126.7
3	88.9	90.3	93.3	96.8	91.6
4	79.0	76.5	73.4	75.8	78.7
5	-1.3	+11.1	+15.7	+17.2	+7.7
6	49.6	23.5	10.3	13.4	33.1
7	42.2	38.6	33.1	36.2	42.6
8	26.1	25.2	26.3	28.2	27.3
9	38.0	21.9	7.8	10.0	28.5
10	61.1	46.5	33.0	35.1	52.1

NOTES:

1. Refer to Fig. 3 for site locations
2. Set I: 1-3 June 1986
   Set II: 11-13 August 1986
   Set III: 11-13 October 1986
   Set IV: 25-26 February 1987
   Set V: 17-19 June 1987
3. The Nqogha-Boro link channel may flow in either direction. Positive here means flow from the Nqogha to Boro.

Gaenga. This is consistent with observations of decreasing width (and depth) of the Ngokha in the downstream direction, although significantly from the point of view of sediment transport the water velocity remains fairly steady down the channel.

Discharges (and presumably water levels) vary at sites 1 and 2 because there the channel is being surcharged by the annual flood wave from the Okavango during measurements I and IV; though at other times there is relatively constant discharge suggesting channel capacities of approximately 115 m^3/s and 110 m^3/s, at sites 1 and 2 respectively. Because the channel capacity decreases in the downstream direction, lateral spill to the surrounding papyrus swamps occurs along a considerable length of the main channel during the seasonal flood and one could anticipate that in years of normal or above-average Okavango inflows, the surcharging of the Ngokha channel would extend further into the delta than during these observations.

The Ngokha channel carries considerable quantities of sediment, principally bedload, and is an aggrading system. The channel fringes support very dense growths of papyrus and other aquatic vegetation because their location affords them more light and energy than is available within the swamps (Thompson et.al., 1979), and perhaps a better supply of nutrients. These favourable conditions for growth mean that the vegetation in the perennial swamps lends stability to the channel margins, which may be further enhanced by the entrapment of finer sediment to create low stable banks. Aerial photographs show that the course of the Okavango and Ngokha channels in the Panhandle and upper delta has altered surprisingly little during the past three decades and more. Surcharge from the channel spills through and over these permeable banks into surrounding swamps, which are floodplains that are perennially flooded because of the very low longitudinal gradients in the delta.

Comparing the April 1986 peak of approximately 700 m^3/s at Mohembo in the upper Panhandle with the measured discharge of 160 m^3 /s at site 1 on June 3 1986, and notwithstanding that the latter was measured perhaps a month after the peak at site 1, it is evident that a very considerable proportion of the flow during the seasonal inflow flood passes into the delta from the Panhandle by traversing through the swamps. Although much of this must be diverted into the Thaoge, Selinda spillway and Matsibe distributaries further up, or passes down the swamp floodplains on the other side of the Ngokha, some is collected by the upper reaches of the Boro.

The discharges at sites 6 and 9 are the most variable of those measured. These are flows from the swamp adjacent to the Ngokha contributing to the upper Boro (or Jao). The flows at these sites are particularly high during June measurements (sets I and V). The fact that their combined flow during June and August 1986 exceeds the decrease in flow between sites 1 and 3 on the Ngokha is especially significant. In June 1986, for example, 87.6 m^3/s was entering the Boro through sites 6 and 9; but only 71.3 m^3/s was being lost (on both sides of the Ngokha) between sites 1 and 3. Flow delay through the swamps due to storage effects should be taken into account, so that the measured flows at sites 6 and 9 do correspond to an earlier and higher stage of the seasonal hydrographs than the coincident measured flows at sites 1 and 2. The arithmetic nevertheless suggests that some of the inflow to the upper Boro measured at sites 6 and 9 originates from reaches of the Okavango/ Ngokha upstream of site 1.

Water which spills over the right bank between sites 1 and 3 collects in the lagoons (or madiba) which are shown in Fig. 3. As their levels rise, they discharge through the swamps and minor channels towards the upper Boro.

During the seasonal inflow flood most of the flow is passing through the swamps. Because levels in the swamps adjust more slowly due to greater hydraulic resistance, after the peak in June the link channel between the Ngokha and Boro flows from the swamps around the upper Boro to the Ngokha. As swamp storage is gradually released in subsequent months and water levels there fall, flow in the link channel re-asserts itself towards the upper Boro. During late winter and spring when the Panhandle flows are much lower, the water levels in the Ngokha channel are elevated above those in the surrounding swamps. Most of the flow is retained within the Ngokha, although some lateral spill occurs through the permeable banks because of the diminishing channel capacity in the downstream direction.

One final aspect that requires comment is that discharge at site 7 is consistently greater than discharge at site 8, although the latter is downstream of the former. Field reconnaissance revealed that there is a free interchange of flow between the channel and the swamp floodplains in this vicinity. Presumably because of much lower sediment transport rates, the channel does not have the same integrity as the aggrading Ngokha channel, and is actually immersed within the swamps. As previously noted, discharge at site 8 (Kwihum) varies little; but, unlike those stations on the Ngokha where both discharges and water levels vary little, at Kwihum the DWA records show that water levels can vary appreciably. The explanation must be that the water level in the channel at Kwihum can go up and down with the water level in the papyrus swamp. A channel capacity of around 25 m^3/s is maintained because the section is deep and narrow. Therefore, little change in cross-sectional area occurs, and the longitudinal water surface slope presumably also changes little. When upstream discharge at sites 6 and 7 increases, most of the excess is diverted through the surrounding swamp floodplain.

Thaoge distributary A second series of discharge measurements in the perennial swamps was commenced in 1987 to evaluate the distribution (and dispersion) of flow in the Thaoge distributary system. Twelve sites were selected for measurements, as shown in Fig. 4. One complete set of measurements is presented in Table 2.

There are two feeder channels from the Okavango (or Ngokha) to the Thaoge system. The first, which shall be referred to as feeder channel #1, has a typical reverse entry channel junction; that is, the feeder departs from the main channel in a backward flow direction on the outside of a meander in the main channel. This seems to be a natural configuration in the swamps to minimise transfer of sediment and/or floating papyrus which would in time otherwise block the channel entrance. Although feeder channel #1 is blocked by vegetation about 400 m from the junction, an open collector channel (collecting lateral spill from the main channel) commences not far to the south-west of this blockage and remains open down to the latitude of the Ikoga Lagoon. The channel is blocked both upstream and downstream of the overflow or outflow channel from the lagoon. Comparison of 1969 and 1983 aerial photography shows that the blockages are still developing. Helicopter reconnaissance revealed that much of the remainder of the channel is still open, although it is blocked for a short distance at the downstream end where it connects with feeder channel #2 to form the main Thaoge.

Feeder channel #2 occurs a further 36km downriver on the Ngokha, below Seronga. This channel is open and fully navigable.

Table 2: FIELD MEASUREMENTS OF DISCHARGE IN THAOGE DISTRIBUTARY

Units: m^3/s

SITE	DATE	DISCHARGE
1	21 Jun 1987	5.3
2	21 Jun 1987	23.6
3	23 Jun 1987	4.7
4	22 Jun 1987	9.4
5	21 Jun 1987	25.9
6	1 Jul 1987	13.5
7	24 Jun 1987	5.6+
8	1 Jul 1987	10.7
9	1 Jul 1987	2.8
10	24 Jun 1987	6.4
11	1 Jul 1987	10.5
12	1 Jul 1987	12.2

NOTE: 1. The cross-section at station 7 (Thaoge-Xhamu link) extends some distance, at least 2.5 m, under the papyrus mat on the right bank, so full discharge at this site could not be measured.

It is also a reverse entry channel junction.

Site 1 was located in the link channel to feeder channel #2 not far below the junction, site 3 was located in feeder channel #1 just downstream of Ikoga Lagoon, and site 2 was in feeder channel #2 at Crescent Island. Measurements show that the manner of flow accession to the Thaoge distributary system is similar to that previously described for the Boro distributary system. Most flow in the upper Thaoge derives not from the link channels, but from the accumulation of lateral spill from the Ngokha percolating through the papyrus swamps. The large increase in flow in a short distance between sites 1 and 2 reveals that significant flow enters from a relict channel system, probably a former channel of the Ngokha, which intercepts feeder channel #2 below site 1. Although blocked on the surface this old channel must still function partially.

Discharge measurements in the Thaoge on both sides of the Guma Lagoon outflow channel (sites 4 and 5) reveal a considerable increase in flow due to outflow from Guma Lagoon. There is also some spill from Guma through the papyrus on the southern fringe of the lagoon which accumulates in a small channel passing through papyrus and reed swamps which penetrates as far as Qaaxhwa Lagoon. Guma Lagoon therefore seems to play an important role in intercepting swamp flow and then distributing it southwards.

A significant proportion of the flow at Crescent Island (site 2) spills from the channel before reaching the level of Guma Lagoon, and a significant portion of the flow immediately below Guma Lagoon (site 5) spills from the channel above Xhamu Lagoon.

The discharge measured in the channel from the Thaoge into Xhamu Lagoon (site 7) is underestimated because the channel extended under the papyrus rhizome mat on the right bank for some distance. The effective width of the channel was thus significantly greater than the surface width of 6 m. A channel which has been opened to the east of Xhamu Lagoon for safari operations (site 10) was conveying 6.4 m^3/s from the Thaoge to a parallel flow system known as the Khayalalahatshe. The channel into Qaaxhwa from the Thaoge has also been opened by tourist operators, and the average velocity in excess of 0.5 m/s at site 8 is much greater than natural channel velocities, indicating a good lateral gradient from the old Thaoge channel.

There is a connecting channel between Qaaxhwa and Weboro Lagoons which is navigable and has a strong flow (site 11). The channel connecting between Weboro Lagoon and the old Thaoge is very large and similar to that leading from Guma Lagoon. Although the channel is unsuitable for discharge measurement, the outflow from Weboro is probably also high.

The Thaoge between Xhamu and Weboro Lagoons is totally blocked. In effect, the Thaoge now passes down the cut channel and through Qaaxhwa and Weboro lagoons. Below Weboro, the Thaoge attains its maximum dimensions with widths estimated up to 40 m. In recent history this channel must have conveyed a considerable flow, but today the current is very sluggish (site 12). It appears that water is banked up behind the main blockage, which is encountered 6-7 km downstream of Weboro. Satellite imagery indicates a major efflux of water from the Thaoge system as lateral spill in this region. That which is not lost as evaporation in intervening swamps ultimately collects in the headwaters of the Karongana and Potae to the south-east.

The main blockage to flow currently extends for approximately 80 km between Weboro and Gumare. Below Xusinqua the blockage becomes gradually drier. At the extremity of flow the channel is filled with a marshy peat accumulated from the detritus of vegetation produced by seasonal wetting and drying. The thick peat at the termination of the blockage acts like a plug and provides the ultimate obstacle to flow. Further downstream, the channel cross-section partially opens up again after the organic detritus is permanently dry and subject to wind erosion.

Water Balance of Madiba

Madiba (singular is lediba) are attractive stretches of open water which occur irregularly throughout the swamps. They are also termed lagoons. Wilson(1973) considered them cut-off river meanders, and while this could be the origin of some, their shapes are too various for this to be generally true. McCarthy et.al.(1986) have described how recent peat fires have caused subsidence of over one metre in the lower Ngokha area (now dry). This provides an alternative hypothesis for the origin of madiba, and one which could explain their many varied shapes. It is necessary to conceive the ephemeral nature of swamp flows in a geological time-frame, with a cycle of drying, burning, and re-flooding to attain the current lediba condition. If the theory is correct, bed deposits should contain significant amounts of ash.

Depth soundings made in Guma and Qaaxhwa Lagoons in June 1987 indicated mean depths of around 3.2 m in both madiba. This is less than the typical depth of active major channels (4.0-5.5 m). From aerial photography the surface area of Guma Lagoon was measured as 1.354 km^2, so the volume contained at the time of the soundings was around $4.3\text{x}10^6$ m^3. This coincided nearly with peak water levels in Guma during 1987, and represents just over 1% of the estimated throughflow of Guma Lagoon that year. Put another way, the average retention time of water in Guma Lagoon appears to be about three to four days. Net evaporation depth in 1987 is estimated as 1700 mm (2050 mm evaporation, less 350 mm precipitation). Thus a volume loss of approximately $2.3x10^6$ m^3 was due to evaporation, which is 0.6% of estimated annual throughflow.

The volume of water stored in the madiba is therefore a very small fraction of annual throughflow. Their main hydrological role is to collect flow from the swamp floodplains and redirect it.

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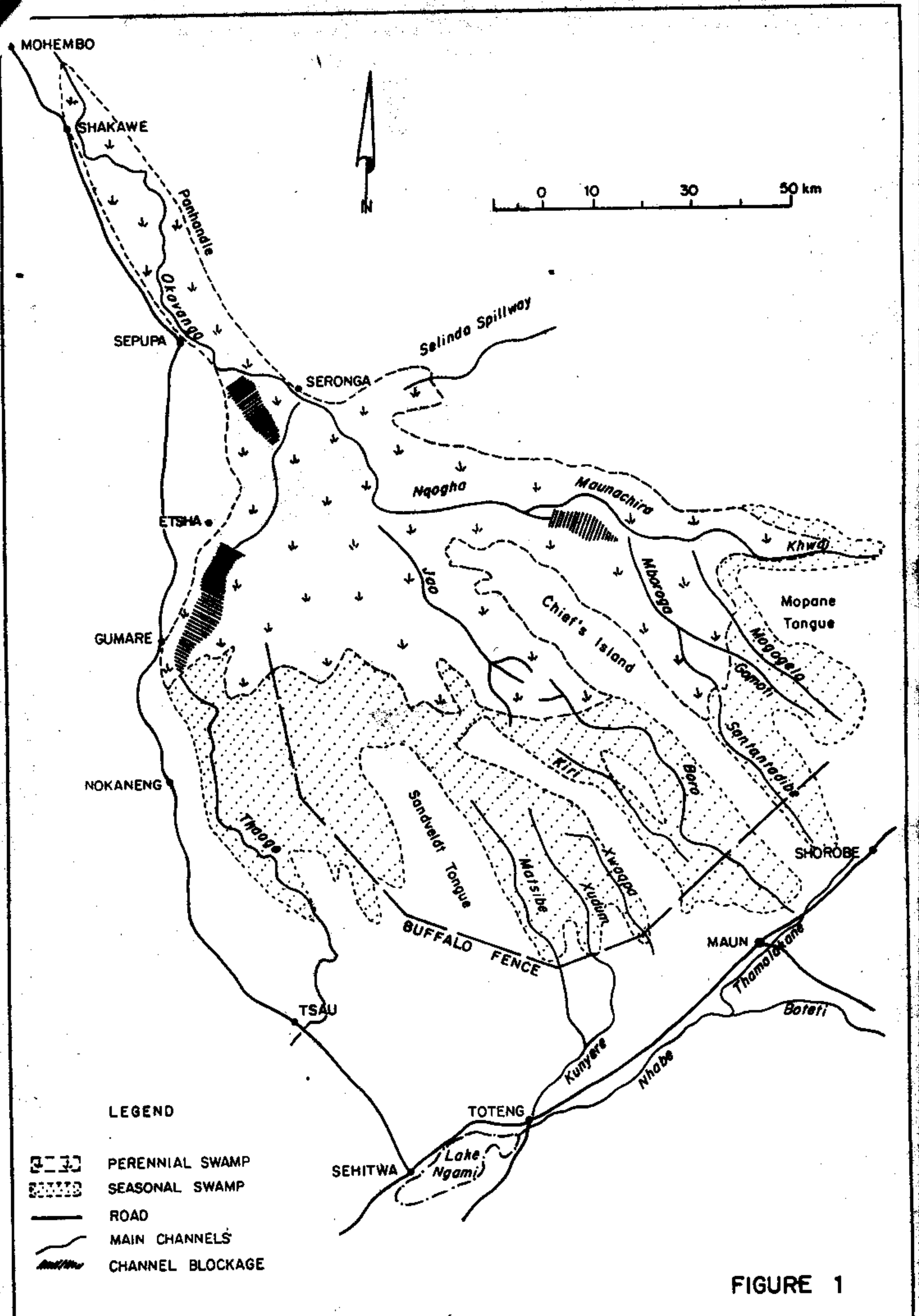
MOHEMBO
SHAKAWE
Panhandle
Okavango
SEPUPA
SERONGA
Selinda Spillway
ETSHA
GUMARE
NOKANENG
Nqogha
Maunachira
Khwai
Jao
Chief's Island
Mboroga
Mopane Tongue
Mogogelo
Gomoti
Santantadibe
Boro
Kiri
Thaoge
Sandveldt Tongue
Matsibe
Xwaapa
Xudum
BUFFALO FENCE
SHOROBE
MAUN
Thamalakane
Boteti
TSAU
Kunyere
Nhabe
TOTENG
SEHITWA
Lake Ngami
N
0
10
30
50 km
LEGEND
PERENNIAL SWAMP
SEASONAL SWAMP
ROAD
MAIN CHANNELS
CHANNEL BLOCKAGE

FIGURE 1

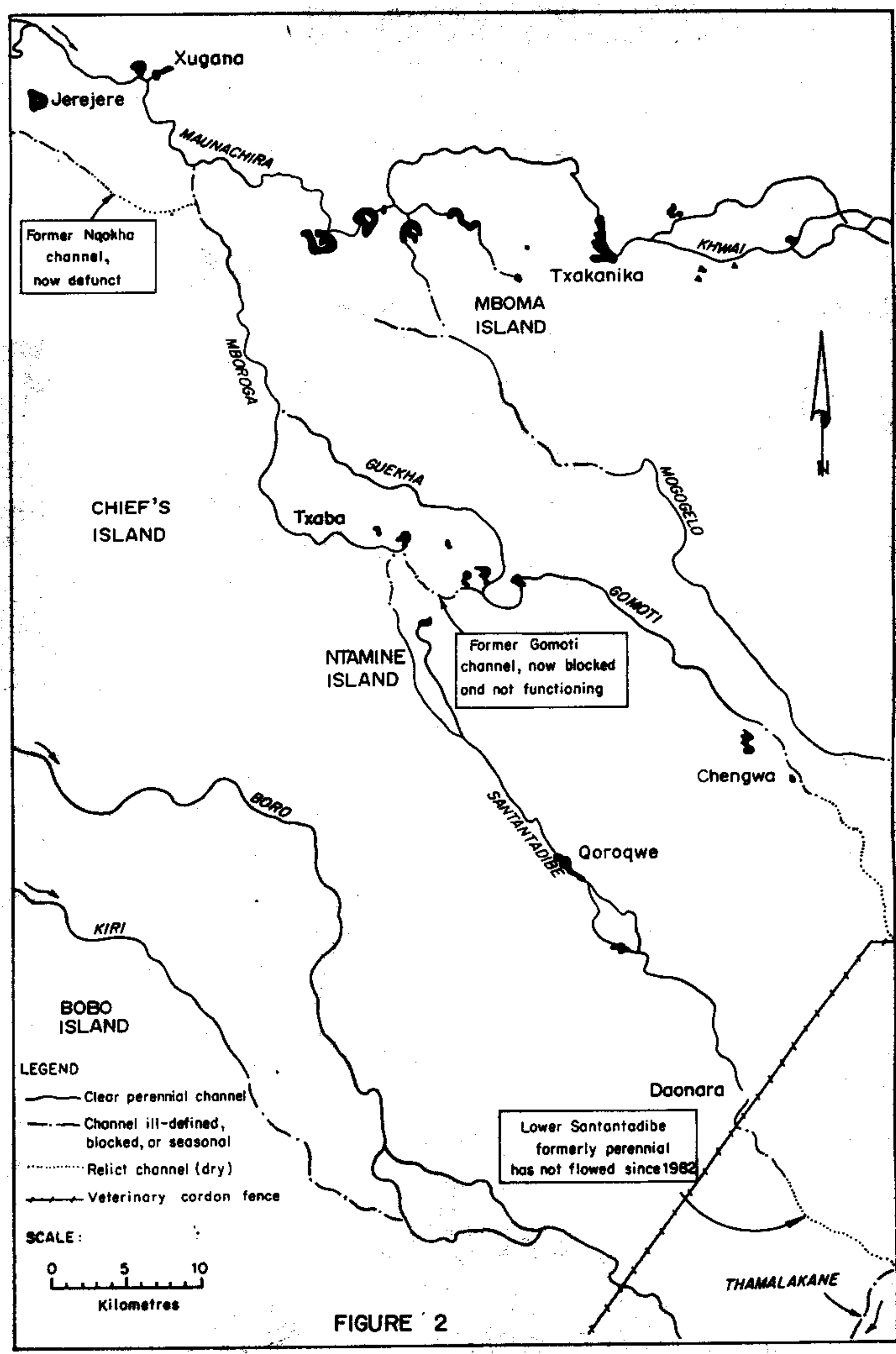
Xugana
Jerejere
MAUNACHIRA
Former Nqokha channel, now defunct
KHWAI
Txakanika
MBOMA ISLAND
MBOROGA
GUEKHA
MOGOGELO
CHIEF'S ISLAND
Txaba
GOMOTI
NTAMINE ISLAND
Former Gomoti channel, now blocked and not functioning
Chengwa
BORO
SANTANTADIBE
Qoroqwe
KIRI
BOBO ISLAND
LEGEND
Clear perennial channel
Channel ill-defined, blocked, or seasonal
Relict channel (dry)
Veterinary cordon fence
SCALE:
0
5
10
Kilometres
Daonara
Lower Santantadibe formerly perennial has not flowed since 1982
THAMALAKANE
N

FIGURE 2

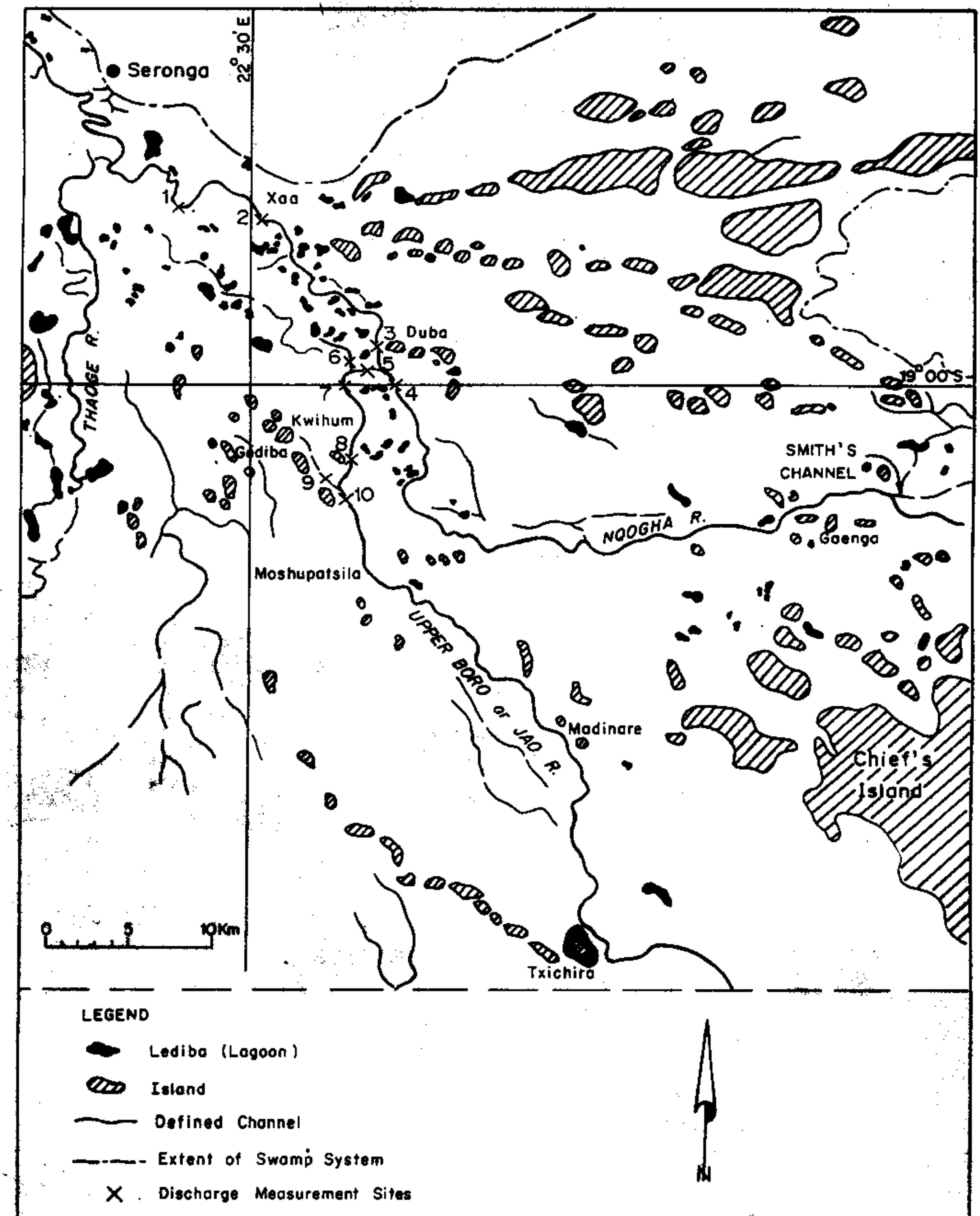
Seronga
22°30'E
Xaa
1
2
3 Duba
6
5
7
4
19°00'S
THAOGE R.
Kwihum
Gadiba
8
9
10
SMITH'S CHANNEL
NQOGHA R.
Gaenga
Moshupatsila
UPPER BORO or JAO R.
Modinare
Chief's Island
Txichira
0 5 10Km
LEGEND
Lediba (Lagoon)
Island
Defined Channel
Extent of Swamp System
Discharge Measurement Sites
N

FIGURE 3

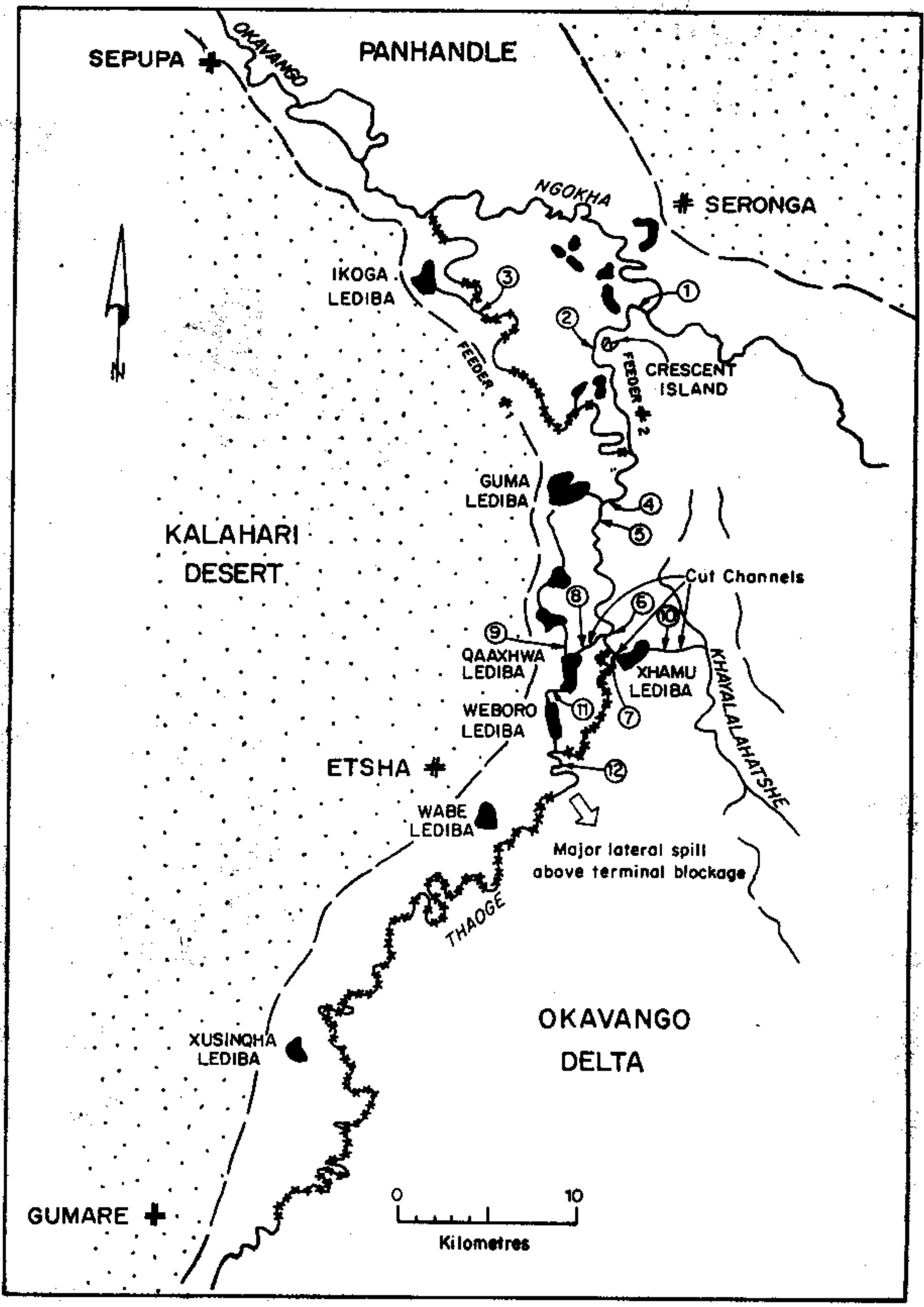
SEPUPA
OKAVANGO
PANHANDLE
NGOKHA
SERONGA
IKOGA LEDIBA
FEEDER #1
FEEDER #2
CRESCENT ISLAND
GUMA LEDIBA
KALAHARI DESERT
Cut Channels
QAAXHWA LEDIBA
XHAMU LEDIBA
KHIAYALALAHATSHE
WEBORO LEDIBA
ETSHA
WABE LEDIBA
Major lateral spill above terminal blockage
THAOGE
OKAVANGO DELTA
XUSINQHA LEDIBA
GUMARE
0
10
Kilometres
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
⑪
⑫
N
LEGEND
Approximate extent of flood plain
Vegetation blockage
② Discharge measurement site

FIGURE 4