CHANNEL BLOCKAGE AND ABANDONMENT IN THE NORTH-EASTERN OKAVANGO DELTA: THE ROLE OF *CYPERUS PAPYRUS*

William Nolan Ellery

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DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

W. Ellery

Fifth day of February, 1988.

ABSTRACT

The progressive upstream encroachment of river courses by *Cyperus papyrus* L. has accompanied the abandonment of two major distributary channels within the Okavango Delta, Botswana, in historic time. The aim of this study has been to evaluate the importance of this species in contributing to channel avulsion, and to determine the mechanisms by which it does so.

The study area was located along the lower Nqoga river which appears to be in the process of blockage, and along the Maunachira river system which has experienced an increase in flow over the last fifty years. The channels within these river systems were classified into four major Groups according to their floristic and hydrological characteristics, as well as the patterns of sediment movement inferred from water clarity (suspended load), and from evidence of a combination of water levels over a period of several years and the depth of the channel bed in relation to the pre-channel surface (bed-load).

Various aspects pertaining to the growth and encroachment of *C. papyrus*, a major channel fringing species in three of the four channel types delimited in the classification, were examined. Attributes of the growth characteristics relating to vigour, namely, height, number of rhizomes per unit channel length and biomass production indicated a downstream decrease in vigour which was attributed to downstream decreases in both current velocity and nutrient availability.

Despite exhibiting vigorous growth at the study site on the channel type which historically appears to be most prone to blockage and

abandonment, encroachment of this species into the channel was shown to be minimal (-2,0 to 6,5cm.a^{-1}). This encroachment was limited by a high current velocity ($\bar{x}$ = 0,3m s^{-1}), which forced rhizomes to move backwards towards the bank, and also caused an increase in the loss of rhizomes from the channel margin. The removal of papyrus rhizomes in this way resulted in the production of large amounts of debris, and contributed to the formation of debris blockages.

Papyrus comprised greater than 95% of the total debris measured within the Nqoga channel. It appeared to aggregate into rafts by being deposited against the bank on the convex side of channel bends with a well developed eddy current. The continuous input of debris to one such bank resulted in a gradual increase in its size. It was dislodged on a single occasion as a large raft which was sufficiently large to block the channel further downstream.

During the period of the study debris blockages formed along the lower Nqoga river and Crosscut channel, and vegetative colonisation by *C. papyrus*, *Phragmites australis* (Cav.) Steud. and *Vossia cuspidata* (Roxb.) Griff. increased their initial stability. The waterlogging of plant tissue associated with initial decay however, in association with the high current velocity in the lower Nqoga river and Crosscut channel, led to the eventual break-up of the blockages, or portions of them. Decomposition of papyrus debris however, was shown to be slow (25% decomposition over a period of 25 weeks), and breakdown of the plant material was thus incomplete. The debris removed from the blockages by the current was deposited in the mouth of Dxerega lediba, resulting in a 27% reduction of the surface area of the portion in which the debris was deposited over the period 1969 - 1983.

In addition to the short lifespan of debris blockages, they did not appear to reduce channel cross-sectional area substantially under the present flow regime due to erosion of the sandy channel bed beneath the blockage. Based on this evidence it was suggested that debris blockages were not capable of substantially reducing flow.

On the basis of inferred patterns of sediment deposition a conceptual model combining aspects of vegetation growth and sediment deposition was proposed to account for the blockage and abandonment of channels in the north-eastern Okavango Delta.

Sediments introduced as bed-load from source areas are confined to those channels which arise by direct connection to the Okavango river. The Nqoga river is presently the major offtake. The apparent gradual rise in its water level at Hamoga island is considered due to the deposition of bed-load sediments along the channel floor. Aggradation of the channel bed appears to be accompanied by aggradation of the vegetated peat banks. Over time the channel becomes progressively raised relative to the surrounding areas. This results in an increase in the hydraulic gradient at right angles to the channel axis, and more and more water is lost to the surrounding swamp. Water lost as overspill in this manner carries no bed-load, and a new channel forms by headwater erosion. Current velocity in the old channel declines, and it becomes susceptible to temporary blockage by rafts of debris. Encroachment by *V. cuspidata* becomes an important feature of the declining channel. A further decline in the current velocity of the old channel results in papyrus blockages becoming more permanent, and encroachment from the banks into the channels also takes place.

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CHAPTER 1

INTRODUCTION

1.1 Introduction to the study

The Okavango Delta, situated in north-western Botswana, forms part of the large, semi-arid, internal drainage basin known as the Kalahari Basin. The Delta receives its waters primarily from the highlands of central Angola via two main tributaries, the Cubango and Quito rivers. These join to form the Okavango river which flows southwards across the Caprivi Strip of Namibia, and enters Botswana at Mohembo. Downstream of this it is confined in a narrow linear depression in the region known as the "panhandle" (Fig. 1.1). At the town Seronga the river system disperses into a deltaic shaped basin as it enters several distributary channels. These are insufficient to carry the seasonal floodwaters of the Okavango river, and there is overspill of a permanent nature in the upper portion of the Delta and of a seasonal nature in the lower portion (Fig. 1.1).

Major distributary channels of the Okavango Delta have a history of blockage and abandonment leading to large-scale changes in the distribution of water (Wilson, 1973). These changes have important implications for the nature and long-term success of any development schemes for the region (UNDP, 1977), which, to varying degrees, involve the use of water. The significance of channel blockage and abandonment as an ecosystem process has been recognised, most notably by Smith, P.A. (1976) who concluded that "an understanding of

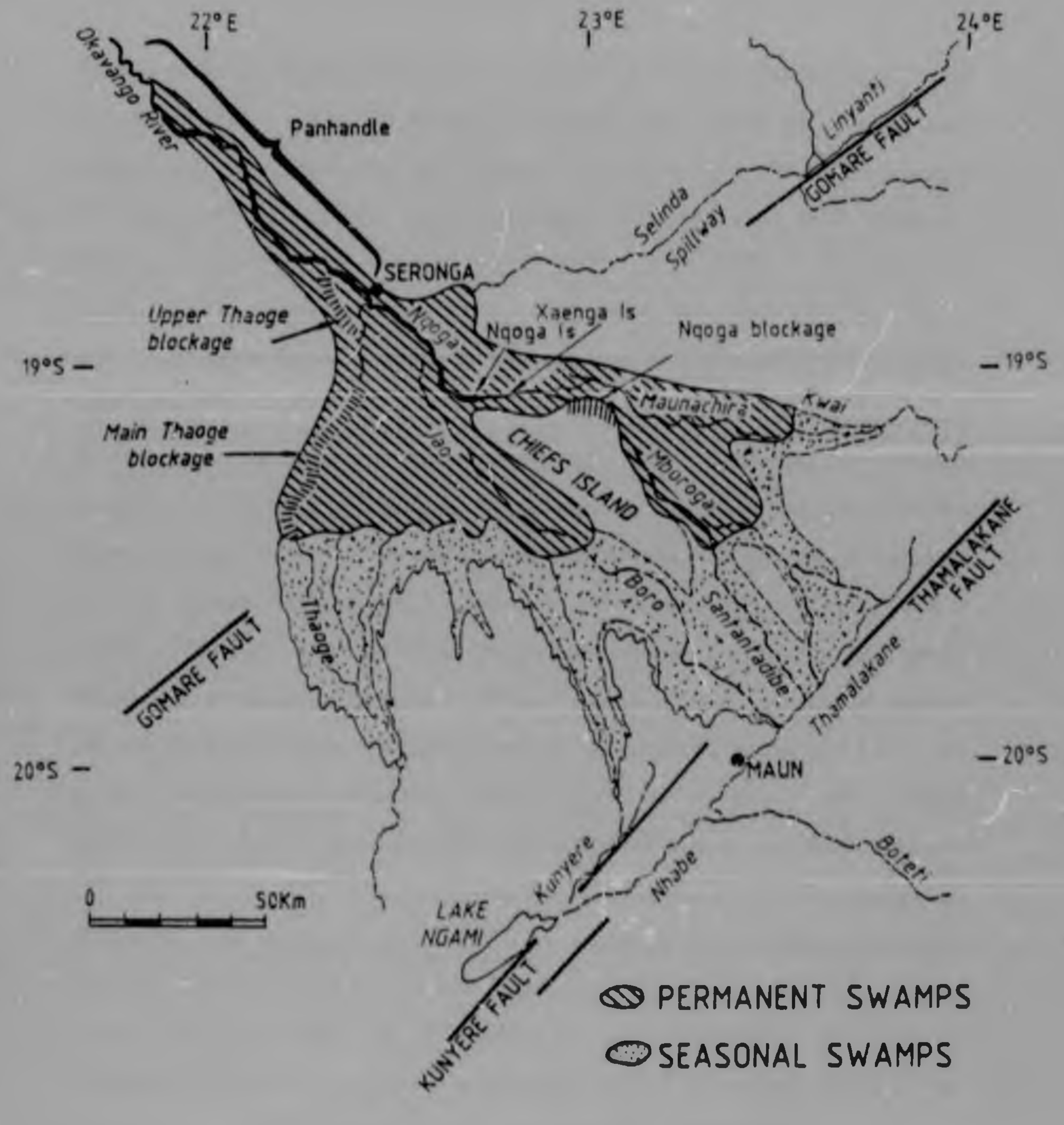

FIGURE 1.1 Map of the Okavango Delta, Botswana

most of the changes occurring in the Delta today lies within the investigation of the causes of channel blockages".

Based on historical accounts and observations in the area of the Delta several causes of channel blockage and abandonment have been suggested, of which the most widely accepted are climatic change (Tinley, 1973), seismic activity (Pike, 1970; Wilson, 1973; Scholz, 1975), vegetation growth (Stigand, 1923; Pole Evans, 1948; Brind, 1955; Grove, 1969; Wilson, 1973), and sedimentation (Smith, P.A., 1976; Wilson & Dincer, 1976). The subject has however not been investigated scientifically. The aim of the present study has been to evaluate the contribution of one of these factors, vegetation growth, to channel blockage and abandonment, with an emphasis on *Cyperus papyrus* L. which dominates the fringes of the upper reaches of the major distributary channels (Wilson, 1973; Smith, P.A., 1976). Papyrus is considered to promote channel blockage and abandonment in two ways (Wilson, 1973). Firstly, the extension growth of its rhizomes into channels results in channel constriction. If papyrus extension growth was unrestricted, it would ultimately lead to the blockage of channels. The question arises as to which factors (if any) limit the extension growth of this species into channels. Secondly, the removal of *C. papyrus* culms and rhizomes from the channel margins by the current, and the aggregation of this debris into large floating rafts leads to the formation of 'debris blockages' (Wilson, 1973). Are these debris blockages capable of reducing flows sufficiently to cause channel abandonment?

The most recent example of a large-scale change in flow has been attributed to the progressive blockage by *C. papyrus* debris, and the subsequent abandonment, of the lower reaches of the Nqoga river

(Wilson, 1973). This is known as the Nqoga Blockage (Fig. 1.1) and has been accompanied by an increase in flow along the more northerly Maunachira river system (Smith, P.A., pers. comm.). This process has been facilitated largely by the natural formation of the Crosscut Channel (Fig. 1.2) which is therefore of relatively recent origin (1940's to present). The presently active portion of the lower Nqoga river downstream of Hamoga Island, as well as the Crosscut Channel, are showing signs that they are becoming increasingly moribund (Wilson, 1973; Smith, P.A., 1976).

An understanding of processes which are taking place along the active portion of the Nqoga river, the ageing lower Nqoga river and Crosscut Channel, and the recently inundated Maunachira river system, was considered to be crucial in the investigation of the causes of channel blockage and abandonment, and has been the reason for the location of the present study site. This forms part of a broader ecological study; the other component being an investigation of the consequences of the increased inundation of the Maunachira river system as a result of the abandonment and desiccation in the region of the Nqoga blockage (Ellery, K., 1987)

1.2 Objectives of the study

- To describe the channels of the active portion of the lower Nqoga river and of the entire Maunachira river system in terms of their vegetation, dimensions, cross-sectional morphology and attributes of the hydrological regime including current velocity and seasonal and longer-term (years) water level fluctuation.

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[1] P.A. Smith, c/o Department of Water Affairs, Maun, Botswana.

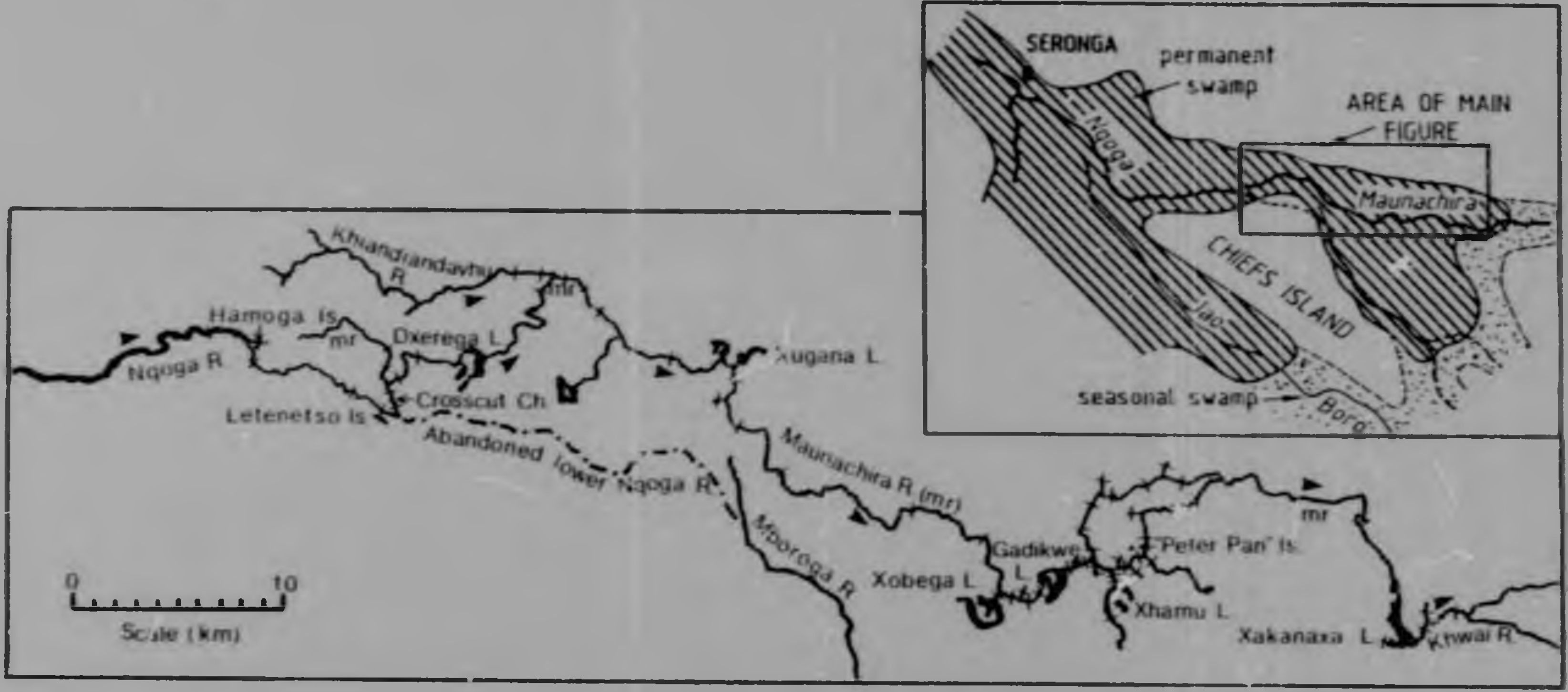


FIGURE 1.2 Map of the study area showing the positions of the transects included in the classification of channel vegetation. Arrows indicate flow direction

FIGURE 1.2 Map of the study area showing the positions of the transects included in the classification of channel vegetation. Arrows indicate flow direction

- To determine rates of, and factors influencing, encroachment of *Cyperus papyrus* into channels from the channel margins.

- To determine the contribution of *C. papyrus* within the channel margins to the production of debris which accumulates in channels as debris blockages.

- To determine factors resulting in the initiation of *C. papyrus* debris blockages, their colonisation by plants, their decomposition and ultimate fate, and thereby evaluate their importance as a factor contributing to channel abandonment.

1.3 Literature review

The hydrological regime is the most important abiotic determinant influencing the establishment and development of wetland ecosystems (Gosselink & Turner, 1978; Mitsch & Gosselink, 1986). The attributes of the hydrological regime which interact with basin physiography to regulate the biotic response of wetland ecosystems are the depth, timing, and duration of flooding, as well as the duration of the exposed period (Cole, 1973; Furness & Breen, 1980; Menges & Waller, 1983). In contrast, the biotic component of wetlands exerts a strong reciprocal effect on the hydrological regime. As plants increasingly fill the available space in wetland ecosystems, the frictional drag to water flow increases and velocities decline, and ultimately, water may be forced into narrower channels which experience an increase in current velocity (Breen et al., in prep.).

The present study has aimed at investigating the reciprocal interactions between the hydrological regime in channels, and the distribution, growth and demography of *Cyperus papyrus* within the channel margins.

1.3.1 The distribution of C. papyrus in African swamps

The natural distribution of *Cyperus papyrus*, the most characteristic and widely distributed swamp plant of eastern and central tropical Africa, appears to be limited by temperature; even within the tropics it is restricted to warmer areas at altitudes below 2000m (Beadle, 1981). Within particular wetlands however, the distribution of *C. papyrus* appears to be restricted to water with a low electrical conductivity. It has not been recorded in water with an electrical conductivity greater than 800umhos.cm^{-1} (Gaudet, 1982), and within the Okavango Delta occurs only in water with an electrical conductivity between 45 and 65umhos.cm^{-1} (Smith, P.A., 1976). In addition to temperature and electrical conductivity, the distribution of *C. papyrus* in particular wetlands appears to be limited to those in which the amplitude of the seasonal flood cycle is small. The most extensive papyrus swamps are therefore associated with large, shallow basins, in which the response time to seasonal flooding is slow (Thompson et al., 1979). The scarcity of *C. papyrus* west of Lake Chad has been attributed to the large seasonal changes in the volume of flow of these rivers and the fluctuations in water depth which accompany this (Thompson, 1976a,b). The reduction of papyrus swamps in Egypt and the northern Sudan in recent times is considered due to the increasing amplitude of the lower Nile river which has accompanied agricultural activity (Thompson, 1985). The distribution of papyrus in the Okavango Delta is similarly restricted to areas in which the seasonal fluctuation in water level is small (Smith, P.A., 1976).

1.3.2 The growth characteristics of C. papyrus

Cyperus papyrus is the largest sedge and one of the largest entirely herbaceous plants (Thompson, 1976b). It forms extensive, virtually monospecific stands in which it contributes greater than 95% of its community phytomass (Thompson, 1976b). Having a clonal growth habit, it propagates by the renewal of ramets which are composed of roots plus a section of rhizome which support the emergent culm and the photosynthetic umbel (Thompson et al., 1979). Papyrus produces between 4 and 8 ramets per annum, and culms generally attain a height of between 3 and 4m (Thompson, 1976b).

Papyrus swamps are considered to have the highest primary productivity of any natural plant community (Westlake, 1975; Thompson, 1976a,b). This has been attributed to the ability of this species to recycle carbon and mineral nutrients from old to new portions of the plant (Gaudet, 1975, 1976; Thompson, 1976a,b; Howard-Williams & Gaudet, 1985). The productivity of papyrus appears to be affected by a combination of water nutrient status (Thompson et al., 1979), as well as the redox potential of the substratum (Jones & Muthuri, 1985).

1.3.3 Features of the growth characteristics of C. papyrus which enable the modification of hydrological conditions

Cyperus papyrus is capable of growth rooted in the substratum which is generally composed of an interwoven mass of rhizomes, roots, peat, and inorganic sediments filtered from through-flowing waters. At the edges of lakes and rivers it extends beyond the substratum, in which case it floats (Wilson, 1973; Smith, P.A., 1976; Thompson, 1985). The extension growth of this species within the floating fringe enables encroachment, and leads to a reduction in the area of open water in many African lakes (Thompson, 1985) as well as a reduction of the width of channels in the Okavango Delta (Wilson, 1973).

In addition, papyrus shoots are not produced sufficiently close together on the rhizomes to be in contact with one another. This species therefore, can be considered to have a guerilla growth form, and thus has the potential to invade new areas rapidly (Hutchings & Bradbury, 1986). The other common channel fringe plant species which occurs within the margins of channels in the permanently inundated regions of the Okavango Delta is *Miscanthus junceum* (Stapf) Stapf (Smith, P.A., 1976), which has a phalanx growth form, and is therefore not capable of invading new areas rapidly (Hutchings & Bradbury, 1986).

Coupled with its ability to grow either floating or rooted, and its guerilla growth form, the robustness of *C. papyrus* rhizomes enables its encroachment into channels and lakes from the margins. The rate and extent of encroachment of papyrus into lakes from the lake-edges appears to be inversely related to winds and water currents, as these remove individual rhizomes or even large pieces of the mat which then form floating islands (Thompson, 1985). The encroachment of papyrus from the banks into channels of the Okavango Delta similarly appears to be inversely related to current velocities (Wilson, 1973). The present study has aimed at quantitatively estimating the relationships between rates of extension growth, rates of encroachment, the removal of rhizomes from the channel margins, and current velocities.

Despite the robustness of papyrus, culms, and in many cases the rhizomes together with their attached culms, are removed from the margins of channels in the Okavango Delta (Wilson, 1973). These float downstream, become entangled to form floating rafts, and eventually become lodged in the channels as they become progressively narrower downstream (Wilson, 1973). The progressive upstream development of debris blockages of this nature in channels in the process of abandonment has been considered to be evidence that they cause channel avulsion (Brind, 1955).

1.3.4 The blockage of river courses by C. papyrus

The role of *C. papyrus* in the blockage of river courses has been recorded for many African river and swamp systems. Rafts of papyrus have been described blocking the Lualaba (upper Zaire) river (Camus, 1957); rivers in the Upemba swamps (Thompson & Hamilton, 1983) as well as the Upper Nile swamps (Rzoska, 1974; Denny, 1984), and rivers in the region of Lake Chad (Iltis & Lemoalle, 1983), and Lakes Kioga and Victoria (Thompson, 1976b). The possible role of papyrus debris blockages in the evolution of major distributaries of the Okavango Delta has been speculated on, most notably by Brind (1955) and Wilson (1973). The consequences of these debris blockages for the hydrological regime have however, never been investigated in detail.

1.4 The study area

1.4.1 Location and general description of the Okavango Delta

The Okavango Delta is situated between latitudes 18°30'S and 20°30'S and longitudes 22°E and 24°E, at an altitude of approximately 950m. Within the Delta, the extent and duration of inundation has formed the basis for the distinction between perennial swamps, seasonally inundated areas, floodplains, islands and mainland edges (Smith, P.A., 1976). Within the perennial swamps, hydrological conditions are relatively stable, and give rise to vast expanses of monospecific stands. Extensive beds of *Cyperus papyrus* occur in the upper reaches, whereas *Miscanthus junceum* is dominant further downstream. The hydrological regime of the seasonally inundated areas is less stable, and a variety of plant communities occur (Smith, P.A., 1976). Islands differ in size from approximately ten square metres to many square kilometres, and are dominated by woodlands which may vary from being relatively dense to open. Many of the islands originate as termitaria which are common throughout the Delta. Evaporite deposits occur on the margins of a large number of islands (McCarthy et al., 1986a), these being indicated by the presence of *Sporobolus spicatus* (Vahl) Kunth and *Juncellus laevigatus* (L.) C.B. Cl. Floodplains and mainland edges are mainly grasslands in which species distributions are dependant on their tolerance to flooding (Smith, P.A., 1976; Lubke et al., 1984). Open water bodies or 'madiba' (singular, lediba) and channels are mostly dominated by submerged plant species such as *Najas pectinata* (Parl.) Magnus and *Rotala myriophylloides* Welw. ex Hiern respectively. Shallower areas are colonised by floating-leaved and emergent species. The water-lilies, *Nymphaea spp.*; the water chestnut, *Trapa natans* L.; *Brasenia schreberi* J.F. Gmel. and *Nymphoides indica* (L.) Kuntze are common floating-leaved species, while *Phragmites australis* (Cav.) Steud. and *Typha capensis* (Rohrb.) N.E Br. are common emergents (Smith, P.A., 1976).

1.4.2 Geology

Throughout the middle Kalahari region, including the catchment of the Okavango river in central Angola, Kalahari sand is ubiquitous (Cooke, 1976), although scattered outcrops of rocks of older origin do occur (Hutchins et al., 1976). The sand is largely of aeolian origin and is medium to fine grained (Hutchins et al., 1976). The slope and topography of the delta itself however, suggest that it has been built up entirely of water-borne sediments, except near the margin north-east of Maun (Fig. 1.1), where submerged, wind-blown dunes are evident (Wilson & Dincer, 1976).

The confinement of the Delta in a rift valley was first recognised by Du Toit (1926) who suggested that the north-east trending linear zones containing the Okavango swamps represented a "sagging of the earths crust over an area 100 miles (160km) broad and with a length of at least 300 miles (480km)". Evidence from photogeological surveys, satellite imagery, geophysical surveys and microseismic investigations have all supported the existence of two major north-east trending fault sets which define the graben in which the Okavango Delta is largely situated (Hutchins et al., 1976). The more northerly fault is the Gomare fault, while the Kunyere and Thamalakane faults define the southern limit of the Delta (Fig. 1.1).

They have a Holocene downthrow which probably exceeds 200m, and they are the sites of continuing seismic activity (Scholz, 1975). In addition to the main north-east trending fault sets, a north-west trending graben confines the Okavango river in the region known as the "panhandle" (Fig. 1.1).

1.4.3 Climate

The climate of the region is dominated in summer by the equatorial air masses associated with the inter-tropical convergence zone (ITCZ), and in the winter by the subtropical high pressure belt which has its axis on the Tropic of Capricorn at this time of the year (Andersson, 1976). The weather experienced at the Maun weather station is considered fairly representative of the Delta as a whole (Wilson & Dincer, 1976). Mean monthly temperatures for the eleven year period 1975 to 1985 (Table 1.1) show November to be the hottest month with a mean daily temperature of 26,6°C (mean maximum = 33,7°C; mean minimum = 19,7°C) and June and July the coolest months with a mean daily temperature of 16,2°C (mean maxima of 25,3 and 25,2°C and mean minima of 7,0 and 7,1°C respectively). The mean annual rainfall is 415mm for the same period, although the area is characterised by extreme variability spatially and temporally. The minimum annual figure recorded at Maun over the same period was 209mm for the rainy season of 1981/1982, while the maximum was 734mm for 1977/1878. Rainfall occurs during the summer months with January and February having the highest mean values of 85,1mm and 93,8mm respectively - there being virtually no rainfall from May until September (Table 1.1).

TABLE 1.1 Mean climatic data for the Maun weather station covering the period 1975 - 1985

Month	Mean maximum temperature (°c)	Mean minumum temperature (°c)	Mean temperature (°c)	Rainfall (mm)
January	32,4	19,2	25,8	85,1
February	30,5	19,2	24,9	93,8
March	31,2	18,4	24,9	58,3
April	30,5	14,8	22,8	13,3
May	28,0	9,4	19,2	4,8
June	25,4	7,0	16,2	1,2
July	25,3	7,1	16,2	0,0
August	28,7	10,0	19,4	0,1
September	32,8	15,1	24,0	4,2
October	33,2	18,6	24,1	22,0
November	33,7	19,7	26,6	53,4
December	33,0	19,1	26,1	78,8

1.4.4 Hydrology

The water balance of the Okavango Delta is characterised by an extremely small outflow relative to the inflow. The annual input from the catchment in Angola has been estimated to be in the region of $11,4 \times 10^9 m^3$, while the annual input from rainfall is approximately $5 \times 10^9 m^3$, giving a total annual input of $16,4 \times 10^9 m^3$ (Wilson & Dincer, 1976). The outflow from the Boteti is less than 2% of the inflow, being $0,3 \times 10^9 m^3 . a^{-1}$. Preliminary investigations suggest that the loss to groundwater is a maximum $0,3 \times 10^9 m^3 . a^{-1}$ (Wilson & Dincer, 1976). The remainder is lost as evapotranspiration. It has been estimated that the mean area of the swamp is 10 000km^2, in which case evapotranspirative loss would be 85% of Penman open water evaporation calculated for the weather station at Maun (Wilson & Dincer, 1976).

Preliminary survey work indicates that the Delta has a typical conical form with an extremely shallow gradient averaging 1 in 3 600 from its apex to its distal end (Wilson & Dincer, 1976). The annual flood within the Delta is largely out of phase with the local rainfall; the flood maximum at Mohembo occurs in March at the end of the rainy season, and only reaches its peak in Maun, at the foot of the Delta, in August (Wilson & Dincer, 1976). At the southern end, outflow from the majority of the distributaries unite in the Thamalakane and Kunyere rivers which flow into the Boteti river and Lake Ngami respectively (Fig. 1.1).

1.4.5 An historical overview of channel changes within the Okavango Delta

Within historic time the distribution of flow in the Delta has undergone some major changes. At the time of the "discovery" of Lake

Ngami by Livingstone, Murray and Oswell in 1849 the Thaoge river flowing down the western side of the Delta (Fig. 1.1) appears to have been the major offtake of the Okavango river, and the lakes principle source of water (Schapera, 1971). During this period the Thaoge river was up to 40m wide, deep and fast flowing in the flood season (Andersson, 1857). By 1884 the Thaoge river had stopped flowing into Lake Ngami (Stigand, 1923). Surveys of the Thaoge river carried out in the 1950's reveal that it was blocked completely by *C. papyrus* in two areas (Brind, 1955). The upper Thaoge blockage occupied the uppermost 40km of the river course, downstream of which the main Thaoge blockage was encountered, which occupied a total of 160 river kilometres (Brind, 1955; Fig. 1.1). The latter blockage had developed progressively upstream and was accompanied by an increase in flow along the more northerly Nqoga - Santantadibe river system, which during the early part of this century was the major offtake of the Okavango river (Wilson, 1973). Stigand (1923) quoted the haMbukushu people telling him that the Nqoga river was formed during the reign of Letsholatebe I (c.1840 - 1874), prior to which it was a 'melapo' or shallow swamp channel. Through the activity of hippopotami (*Hippopotamus aquaticus L.*), a path was trampled through the papyrus beds eastwards from the Thaoge river. This became enlarged to form the Nqoga river which was between 3,5 and 6,0m deep and 40m wide at the time of Stigand's visit to the area.

Since the 1920's the lower reaches of the Ngoga river have been subjected to the progressive upstream development of vegetation blockages, and the channel itself has become increasingly desiccated (Wilson, 1973). Today the lower portion of the channel is completely abandoned, and comprises a dry, sinuous, sandy tract, which is surrounded by a flat, featureless plain (McCarthy et al., in press a). The blockage and abandonment of the lower Nqoga channel has been accompanied by an increase in the flow along the Crosscut channel, which based on aerial photography taken since 1937, appears to have changed from a hippopotamus path into a fast flowing channel. As a consequence of the abandonment of the lower Nqoga river, the Maunachira river has experienced an increase in flow (Wilson, 1973; Smith, pers. comm.)

1.4.6 A description of the active lower Nqoga and Maunachira river systems

The Nqoga river is presently the major offtake of the Okavango river, being its direct extension. Due to the progressive loss of water from this river by overspill and seepage, the dimensions of this channel decrease downstream. The channel width at Mohembo is 100m, while at Letenetso island the Nqoga river is just 13m wide (Wilson & Dincer, 1976). The water within this river is turbid due to the presence of suspended material which is introduced from source areas.

The Maunachira river is linked to the Nqoga river by the Crosscut channel (Fig. 1.2). Only a small proportion of the water entering the Maunachira river system however, does so via this channel. The remainder enters by overspill and seepage from the Nqoga river. The plant communities flanking the Nqoga river remove much of the suspended material from water leaving the Nqoga river by overspill (Smith, P.A., 1976) and the Maunachira river is therefore extremely clear. The presence of several lediba along this river may also contribute to increased water clarity.

The lower reaches of the active Nqoga river, the Crosscut channel and the Maunachira river system as far downstream as Xakanaxa lediba are included in the study area. Both rivers are perennial and are characterised by small seasonal water-level fluctuations (0,1 - 0,3m).

CHAPTER 2

METHODS

2.1 Classification and description of channels

Channels within the study area have experienced recent changes in their flow patterns. The lower Nqoga river and Crosscut channel (Fig. 1.2) appear to be in the process of blockage and abandonment (Wilson, 1973), while the Maunachira rive[illegible]s experienced an increase in flow (Smith, P.A., pers. comm[illegible]is part of the study was aimed at describing the biotic and abiotic features which distinguish the major channels types [illegible]hin the study area, and was done within the framework of a hierarchical classification technique.

2.1.1 Physical characteristics and vegetation of channels in the study area

Stands were located to cover a wide range of channel sizes and flow conditions using 1:50 000 aerial photographs in conjunction with a two month preliminary survey of the study area. Transects three metres wide were placed across the channel at each of 59 sample sites (Fig. 1.2). An estimate of cover-abundance of plant species was made using a cover-abundance scale (Table 2.1) similar to that outlined by Meuller-Dombois & Ellenberg (1974).

Since the distribution of aquatic plants in rivers may be related to aspects of channel morphology and flow conditions (Wetzel, 1983), channel width, the channel cross-sectional profile and mean surface

TABLE 2.1 The scale and associated percentage cover interval used in the estimation of cover-abundance of plant species in channels in the study area. The figures that were used in the data analysis are the approximate midpoints of the percentage cover intervals

Scale value	Percentage cover interval	Corresponding percentage cover value (used in data analysis)
1	0 - 2	1
2	3 - 5	4
3	6 - 10	8
4	11 - 25	18
5	26 - 50	38
6	51 - 100	75

mid-channel flow rate were measured. Within a stratified subsample (16) of the total number of stands, detailed measurements of flow conditions were made in which flow rate was measured using an Ogawa Seiki flow meter at 20% and 80% of the total channel depth (British Standards Institution, 1964) at 2,0m intervals across the channel. Depth to the substratum sands was also measured in the peat covered areas flanking the channel, this representing the level of the area before inundation.

2.1.2 Data analysis

2.1.2.1 TWINSPAN classification

TWINSPAN (Two Way INdicator SPecies ANalysis), a polythetic divisive classification technique devised by Hill (1979), was used to classify the channels in the study area. The algorithm is based on reciprocal averaging and is considered to be appropriate in the clustering of ecological data (Gauch, 1981). Polythetic techniques base divisions between sampling units on species assemblages, and the divisive approach uses the entire set of sampling units and species, and hierarchically divides them into groups of increasing similarity (Gauch, 1982). Major groupings are provided with diagnostic or indicator species, as well as preferential species, which are those that occur in a minimum of 20% of the samples, and are at least twice as likely to occur on one side of a group as the other. The results are displayed in a dendrogram in which the relationships within and between groups are exhibited as clearly as possible.

The normal TWINSPAN program (cf. Hill, 1979) was run using the percentage cover value which represents the midpoint of each of the percentage cover intervals (Table 2.1). For each stand the data for the vegetation within and fringing channels were combined, and any species occurring in a single stand only, were deleted from the analysis as recommended by Gauch (1982).

Analyses of these results indicated that *C. papyrus* is a major component of the channel fringe of the lower Nqoga river and Crosscut channel, both of which appear to be in the process of blockage and abandonment (Wilson, 1973; Smith, P.A., 1976). Papyrus is less predominant along the Maunachira river, which appears to have a relatively stable planform geometry (Wilson, 1973). These results formed the basis of an evaluation of the importance of this species in channel blockage and abandonment, both by extension growth from the bank into the channel, as well as by the production of debris which leads to the formation of vegetation debris blockages.

2.2 The growth characteristics of C. papyrus within the channel margins

Wilson (1973) proposed that the rate and extent of encroachment of *C. papyrus* from the banks into the channels was limited by current velocity. This hypothesis was investigated by determining its growth characteristics and demography within the channel margin in relation to its rate of encroachment into channels, and the mean current velocity within the channel margin. The channel margin is defined as the zone at the edge of the channel in which plants are not supported by a solid substratum. This is distinguished from the bank in which plants are physically supported by peat deposits.

The approach adopted was to select one study site within each of the channel types identified in the TWINSPAN cluster analysis in which the banks were dominated by *C. papyrus*. Plots were thus located on concave, straight and convex channel banks at 3 localities (study sites) within the study area (Fig. 2.1), namely (1) the lower Nqoga

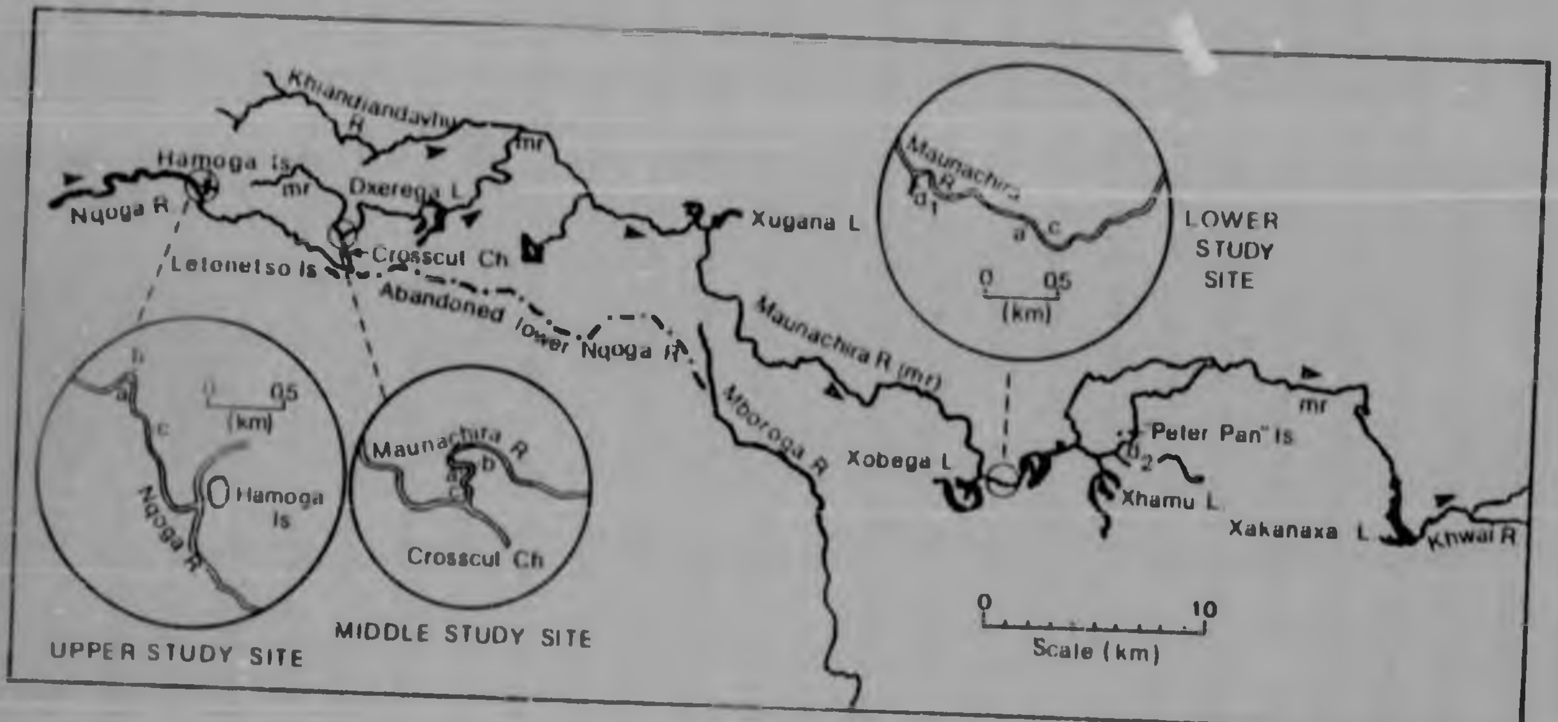


FIGURE 2.1 The locality of plots in which the growth and demographic studies of *C. papyrus* within convex (a), concave (b), and straight (c) channel margins were measured. The lucality of plots in the margin of channels with extremely low current velocities (d) is also indicated

river upstream of Hamoga island (upper study site), (2) the upper Maunachira river downstream of its confluence with the Crosscut channel (middle study site), and (3) the middle Maunachira river (lower study site). Since papyrus was absent from all the concave banks of the middle Maunachira river, only the convex and straight banks were examined in this site. Two additional plots were placed on banks of small distributary channels in this area, along channels in which the flow rate was too slow to measure (less than $0{,}03 m.s^{-1}$). This arrangement of plots ensured that a wide range of current velocities was covered - both within and between sites. Plots were also placed on the concave, straight and convex banks of the Nqoga river downstream of Hamoga island, as well as on the Crosscut channel. These had to be abandoned however due to inaccessibility caused by the development of debris blockages on their upstream and downstream sides during the study period.

Each plot was set up by placing markers at intervals along the bank. The plots varied in length from 15m to 40m and included a minimum of 25 individual rhizomes within the channel margin. At six intervals over the period of a year, the number of rhizomes within the channel margin was counted, and each newly produced culm on each rhizome was tagged and its height measured. The rate of culm production was thus recorded. The production of biomass was estimated by determining an allometric relationship between culm height from immediately above the rhizome, and the biomass of the ramet as a whole (rhizome + basal leaves + culm + umbel) for randomly collected ramets in the study area. The linear regression of logarithmically transformed data for both culm height and ramet biomass (Fig. 2.2) was significant (F = 311,0, which is significant at a probability level of 0,99), and was used to estimate biomass production per rhizome. The summation of all the biomass production values per rhizome in each plot gave an estimate of the total biomass production

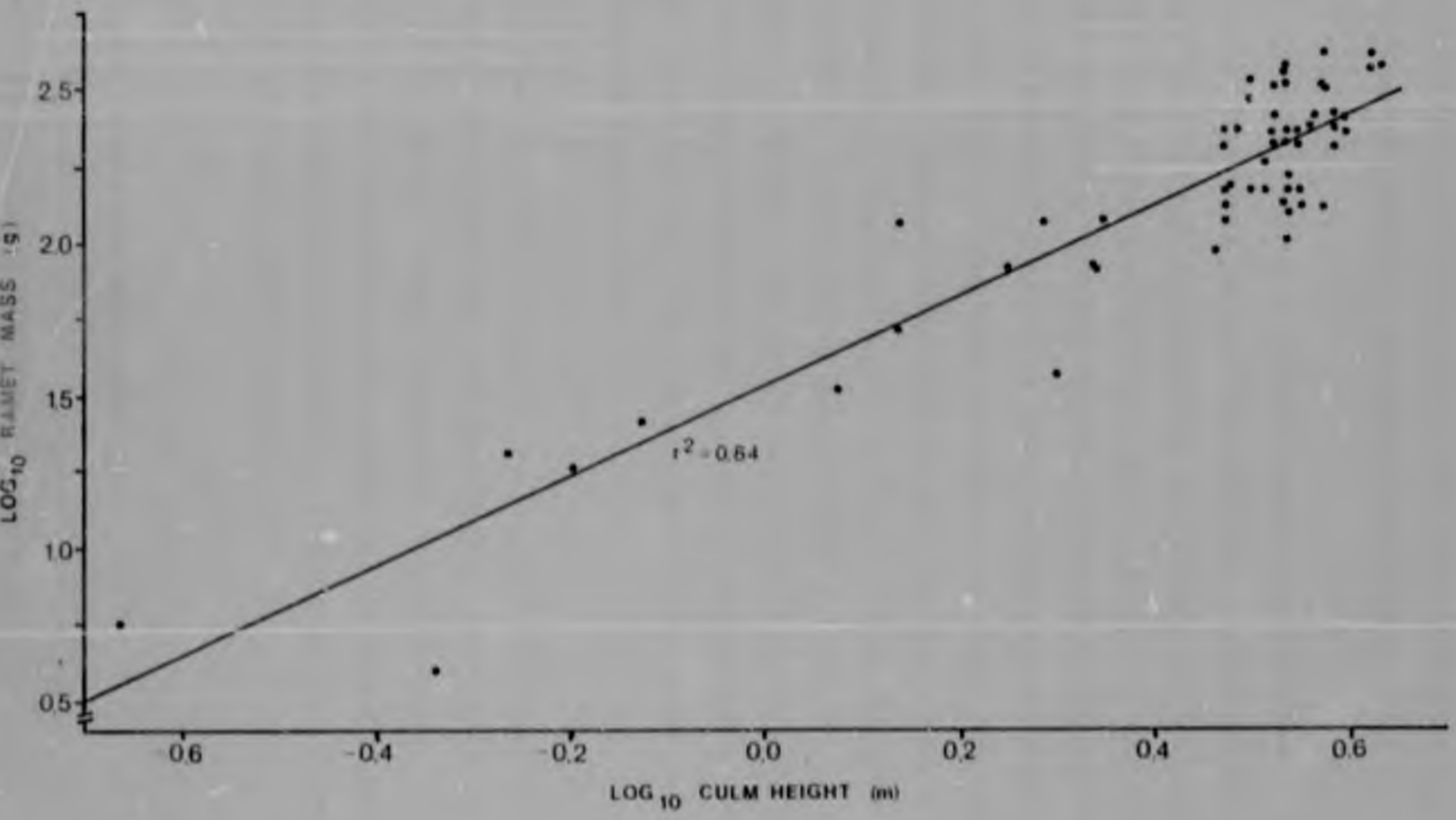


FIGURE 2.2 The linear relationship between $\log_{10}$ transformations of both culm height (m) and ramet biomass (g) for *C. papyrus* within the north-eastern Okavango Delta

in the margin of each plot, and this was converted to per unit channel margin length so that comparisons could be made.

The individual marking of rhizomes enabled the determination of the loss and recruitment of rhizomes within the channel margin. Each value was converted to a percentage of the total number of rhizomes encountered within each plot over the study period. The value by which recruitment exceeded loss was considered to indicate the extent to which the number of rhizomes per unit channel margin length was increasing. Conversely, the amount by which loss exceeded recruitment indicated the extent to which the current was removing rhizomes from the channel margin at a greater rate than they could be replaced, thereby causing rhizome numbers per unit channel margin length to decrease. The extent of increase or decrease in rhizome numbers within the channel margin over the study period was considered to reflect the ability of papyrus or the current to modify channel planform geometry.

The extension growth of each of the tagged rhizomes was measured, and its rate of encroachment was determined by measuring the distance out of the furthest ramet from markers within the bank. Current velocity was measured at 4 intervals along the length of the plot, at a depth of 1,0m, and at 75% of the distance out from the bank of the rhizome which extended furthest.

2.3 The formation of debris blockages

2.3.1 The production of *C. papyrus* debris

The production of *C. papyrus* debris was estimated in each of the plots in which its growth, demography and encroachment into channels were measured (Section 2.2). Debris production was estimated as the product of the biomass production per unit channel margin length, and the proportional loss of rhizomes from the channel margin.

The proportional contribution of papyrus to total debris flow, and the amount of debris flowing within the lower Nqoga river and the Crosscut channel, where debris blockages were common, was estimated by setting up nets across the entire channel at these two localities. Debris was trapped for periods of between one and six hours, depending on the amount. Total debris flows were measured by mass, and divided by the time over which the net was in position. The contribution of each species was estimated visually as a percentage of the total.

2.3.2 The aggregation of debris into rafts

Debris removed from the channel margin by the current generally comprises individual culms and their attached umbels, as these generally become detached from the rhizome. Frequently however, entire rhizomes with their attached culms and umbels are removed from the channel margin. This component of the study has aimed at documenting the mechanisms involved in the aggregation of individual pieces of debris into rafts. Based on observations in the field, it was proposed that individual pieces of debris become caught in eddy currents on the convex sides of channels. They are deposited against the bank and aggregate into rafts. These rafts appear to be dislodged and to float downstream as a single unit, having the potential to cause a blockage as the channels become progressively narrower downstream. To evaluate this hypothesis, the pattern of accumulation and release of one such debris bank was determined by mapping its size and shape over the period of a year. Only one such debris bank was recorded as it was the only one which remained accessible throughout the study period.

2.4 The effect of debris blockages on channel morphology

The ability of debris blockages to reduce flow is considered to be due to a reduction in channel cross-sectional area. The effect of a debris blockage on channel morphology was determined at 4m intervals in a transect down the length (20m) of a debris blockage. The thickness of the blockage was estimated, and the depth to the channel bed was measured. The depth to the channel bed at 4m intervals to a further distance of 20m downstream of the blockage was measured for comparison. It would have been appropriate to measure the depth of the channel bed to a similar distance upstream of the debris blockage as well, but movement of the boat over the blockage was not possible, and the upstream side was therefore inaccessible.

Once formed, the debris blockages are colonised by plant species; a process which leads to their consolidation and stabilisation. In contrast however, decomposition processes decrease the stability of these blockages. The net effect of these two opposing processes, dependant on current velocity, determines their longevity.

2.5 The dynamics of debris blockages

The extent to which debris blockages were colonised was evaluated by estimating the mean shoot density of all living plant species present in six randomly placed 2m x 2m quadrats.

The rate of decomposition of papyrus debris was estimated by placing measured quantities of debris (wet mass) into litter bags with a mesh size of 2mm. Larger holes were made in the bags (5mm) to enable access by small invertebrates. Three samples were air-dried initially. The remainder were placed in a debris blockage. Triplicate samples were removed on three subsequent occasions over a period of twenty-six weeks, which was the approximate timespan of the longest-lived debris blockage. Samples were immediately air-dried, and subsequently oven-dried at 80°C for 48 hours before being weighed.

2.6 The fate of debris blockages

Decomposition of the plant material in channel blockages over the period of the decomposition studies was far from complete. The dislodged debris is transported further downstream as large rafts, and is deposited in areas where current velocity is greatly reduced. Dxerega lediba is the first to interrupt flow along the Nqoga-Maunachira river system. The shrinkage of the mouth of this lediba appears to be due largely to the deposition of papyrus debris, and has been estimated by comparison of vertical aerial photographs taken in 1969 and 1983.

2.7 Shortcomings of the methods used

Despite the emphasis on determining relationships between biotic and abiotic characteristics in the growth and demographic studies, they were of limited extent and duration. Similarly, the number of blockages observed, despite being the total number that formed along the Nqoga and Maunachira rivers during the study period, were of limited extent and duration. Caution would therefore need to be taken in extrapolating these data over longer time periods and to different areas.

CHAPTER 3

THE CHANNELS OF THE LOWER NQOGA - MAUNACHIRA RIVER SYSTEM

3.1 A floristic classification of channel vegetation

The two-way phytosociological table which represents output from the TWINSPAN cluster analysis (Table 3.1), highlights the basis for division in the hierarchical classification of stands (Fig. 3.1). Six major groups were recognised. The first division was characterised by the indicator species *Vossia cuspidata* (Roxb.) Griff. which occurred in all the stands in one of the groups (n = 9+), albeit at low cover (less than 20%), and was absent from the remaining stands (n = 50-). The smaller group (n = 9+) was characterised by a low species diversity with only five species (Table 3.1), of which one was the bottom rooted *V. cuspidata*, which was present on the convex side of channel bends. The remaining species in this group were the emergent channel fringe species *Cyperus papyrus*, *Miscanthus junceum*, *Phragmites australis* and *Thelypteris interrupta* (Willd.) K. Iwats. (Table 3.1), which were rooted in submerged peat deposits.

At the second level of division these nine stands were divided into two groups based on the indicator species *Miscanthus junceum*, which was present with a cover of greater than 20% in only two stands (Group E), and was absent from the remaining seven stands (Group F). The further division of these seven stands was due to minor variations in the contributions of species which also occurred in other groups, and it was therefore retained as a single entity.

TABLE 3.1 The percentage-cover abundance, on the TWINSPAN scale, of each species that was present in each of the stands. The groups of stands identified in the floristic classification are indicated

species	plot number					
	33333111 111112	2222	1122222	7666755666666777	56	5555555
	3401203591246904567	1231234	87856789	4123045456789123	90	6780123
Rotala myriophylloides	55---3-------------	5555555	--------	----------------	--	-------
Nesaea crassicaulis	--------4----------	5554454	4-------	----------------	--	-------
Nymphoides indica	----------------213	2113333	---11--1	----------------	--	-------
Ceratophyllum demersum	-------------------	11234--	-------2	----------------	--	-------
Ficus verruculosa	5555555555555555555	5555555	55522223	----------------	--	-------
Brasenia schreberi	--33341--222-------	---3322	--------	1--2------------	--	-------
Typha latifolia	--111122-321-24144-	1132222	-------2	----------------	--	-------
Miscanthus junceum	5555555555555555555	5555555	55555555	5545555545555555	55	-------
Ottelia ulvifolia	--2324435554534---3	--34511	55523334	344433322221222-	--	-------
Nymphaea caerulea	324444244332---444-	2223333	4--22343	32333--111111---	--	-------
Ottelia muricata	-------------------	-------	---22233	----------------	--	-------
Eichhornia natans	-------------------	-------	---33322	4------2222232--	--	-------
Lagarosiphon verticillifolius	-------------------	-------	------22	3---1-----------	--	-------
Najas pectinata	-------------------	---3333	------32	3123423---------	--	-------
Cyperus papyrus	-----444-----------	---5533	55555555	5555555555555555	55	5555555
Vossia cuspidata	-------------------	-------	--------	----------------	44	4444444
Phragmites australis	---------12--------	-------	--------	-----22---1112--	12	111----
Thelypteris confluens	1111133333343433333	4334444	3-333333	3223333222222222	22	2222222
Group identified in floristic classification	a	b	c	d	e	f

TABLE 3.1 The percentage-cover abundance, on the TWINSPAN scale, of each species that was present in each of the stands. The groups of stands identified in the floristic classification are indicated

species	plot number					
	33333111 111112	2222	1122222	7666755666666777	56	5555555
	3401203591246904567	1231234	37856789	4123045456789123	90	6780123
Rotala myriophylloides	55---3-------------	5555555	--------	----------------	--	-------
Nesaea crassicaulis	--------4----------	5554454	4-------	----------------	--	-------
Nymphoides indica	----------------213	2113333	---11--1	----------------	--	-------
Ceratophyllum demersum	------------ ------	11234--	-------2	----------------	--	-------
Ficus verruculosa	5555555555555555555	5555555	55522223	----------------	--	-------
Brasenia schreberi	--33341--222-------	---3322	--------	1--2------------	--	-------
Typha latifolia	--111122-321-24144-	1132222	-------2	----------------	--	-------
Miscanthus junceum	5555555555555555555	5555555	55555555	5545555545555555	55	-------
Ottelia ulvifolia	--2324435554534---3	--34511	55523334	344433322221222-	--	-------
Nymphaea caerulea	324444244332---444-	2223333	4--22343	32333--111111---	--	-------
Ottelia muricata	-------------------	-------	---22233	----------------	--	-------
Eichhornia natans	-------------------	-------	---33322	4------2222232--	--	-------
Lagarosiphon verticillifolius	-------------------	-------	------22	3---1-----------	--	-------
Najas pectinata	-------------------	---3333	------32	3123423---------	--	-------
Cyperus papyrus	-----444-----------	---5533	55555555	5555555555555555	55	5555555
Vossia cuspidata	-------------------	-------	--------	----------------	44	4444444
Phragmites australis	---------12--------	-------	--------	-----22---1112--	12	111----
Thelypteris confluens	1111133333343433333	4334444	3-333333	3223333222222222	22	2222222
Group identified in floristic classification	a	b	c	d	e	f

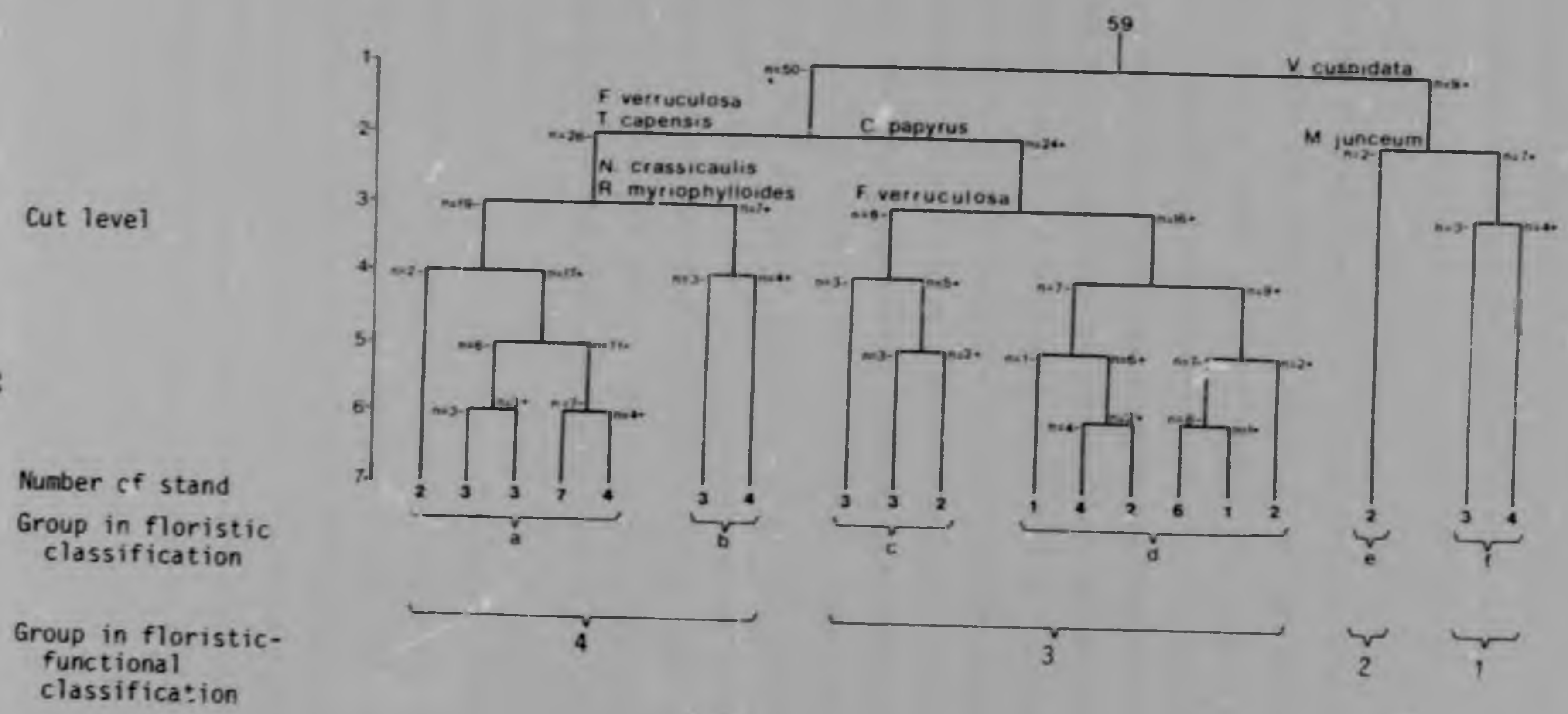


FIGURE 3.1 Hierarchical classification of stands derived from a Two Way Indicator SPecies ANalysis (TWINSPAN)

ations in the contributions of species which also occurred in other groups, and it was therefore retained as a single entity. The presence of *M. junceum*, with relatively high cover in the stands in group E, was considered sufficient to distinguish this group from group F in which *M. junceum* was absent, even though it was represented by only two stands.

The stands in Groups E and F were located upstream of Dxerega lediba, Group F along the lower Nqoga river and the Crosscut channel, and Group E on the Maunachira river between its confluence with the Crosscut channel and Dxerega lediba (Fig. 1.2). In contrast, the fifty stands which formed the group on the other side of the dichotomy at the first level of division were all located downstream of Dxerega lediba. They were characterised by a high species diversity (n = 17), including twelve bottom rooted channel species. The submerged *Najas pectinata*, *Nesaea crassicaulis* (Guill. & Perr.) Koehne, *Rotala myriophylloides*, *Ceratophyllum demersum* L., *Ottelia muricata* (C.H. Wr.) Dandy, and *O. ulvifolia* (Planch.) Walp., and the floating-leaved *Brasenia schreberi*, *Eichhornia natans* (Beauv.) Solms-Laub., *Nymphaea caerulea* Sav. and *Nymphoides indica* were important bottom rooted channel species associated with this group of stands. In addition the emergent channel fringe species *Ficus verruculosa* Warb. was restricted to this group.

At the second level of division these fifty stands were divided into two major groups. *Ficus verruculosa* with a cover of greater than 10%, and *Typha capensis*, were identified as the indicator species of one side of this dichotomy (n = 26-), and *Cyperus papyrus* with a cover of greater than 20% was the indicator species which characterised the other group (n = 24+). This division was between those stands situated between Dxerega and Gadikwe madiba (n = 24+), and those between Gadikwe and Xakanaxa madiba (n = 26-), with the exception of three stands which were located downstream of Gadikwe lediba but were classified together with those between Dxerega and Gadikwe madiba. The presence of *C. papyrus* with a cover of greater than 20% in these three stands has contributed to their inclusion in the group of stands upstream of Gadikwe lediba. This suggests that although the presence of papyrus as the dominant species of the channel banks is largely confined to the channels upstream of Gadikwe lediba, it does occur as a site specific dominant downstream of this. Preferential species associated with the twenty-six stands on channels downstream of Gadikwe lediba were *Rotala myriophylloides*, *Nesaea crassicaulis*, *Nymphoides indica* and *Brasenia schreberi*.

At the third level of division, the twenty-six stands between Gadikwe and Xakanaxa madiba were further divided into two groups. Whereas the stands in Group A (n = 19-) were not characterised by any particular indicator species, those in Group B (n = 7+) were grouped on the basis of the indicator species *Nesaea crassicaulis* which occurred with a cover of greater than 10% in all of the stands in this group, and in only one stand in Group A. *Rotala myriophylloides* was also identified as an indicator species of this group; it was present with a cover of greater than 20% in all of the stands in Group B, and only in two in Group A. Other species which were identified as preferentials and associated with stands in Group B, were *Nymphoides indica* and *Ceratophyllum demersum*.

The division between these stands represents those on the Maunachira river itself between Gadikwe lediba and an island downstream of this, known to the author as "Peter Pan" (Fig. 1.2; Group B), and those on smaller distributary channels which arise from the Maunachira river (Group A). The former channel is large, and is characterised by extensive beds of the red-leaved *N. crassicaulis* and *R. myriophylloides*. The distributary channels which arise from this however, are smaller, and not characterised by the same abundance of submerged macrophytes. Further divisions were based on minor differences in species abundances, and these two groups have therefore been retained as Groups A and B in the cluster analysis (Fig. 3.1).

The twenty-four stands characterised by the indicator species *Cyperus papyrus* at the second level of division (Fig. 3.1), and which represented channels between Dxerega and Gadikwe madiba, were also characterised by a number of preferential species. They were the bottom rooted channel species *Eichhornia natans*, *Ottelia muricata*, and *Najas pectinata* (Table 3.1). These stands were further divided at the third level of division based on the indicator species *Ficus verruculosa* which was present in the eight stands in Group C, but was absent from the sixteen stands which make up Group D. In addition *O. muricata* was identified as a preferential species associated with Group C, which were located on channels between Xobega and Gadikwe madiba (Fig. 1.2), with the addition of the three stands on minor distributary channels downstream of Gadikwe lediba in which *C. papyrus* was present with a cover of greater than 20%. Those in Group B however, were on channels between Dxerega and Xobega madiba, of which several were located on tributary and distributary channels. Further divisions were once again based on minor species differences, and Groups C and D were therefore retained (Fig. 3.1).

The six major groups of stands derived from the TWINSPAN cluster analysis are clearly related to their distribution along the Nqoga river - Crosscut channel - Maunachira river systems. This has provided a useful framework for the development of a broad functional classification of channel types within the study area, which has incorporated the floristic characteristics described above, as well as aspects of channel morphology, hydrology, and inferred patterns of sediment transport and deposition. An examination of these features has resulted in the recognition of four major channel types within the study area.

3.2 A floristic-functional classification of channels

3.2.1 Sandy bottomed channels flanked by *C. papyrus* (Group 1)

This channel type includes the active portion of the lower Nqoga river and the Crosscut channel as far downstream as its junction with the Maunachira river, and is represented by the stands in Group F of the TWINSPAN cluster analysis (Fig. 3.1). The fringes are dominated by tall, dense stands of *C. papyrus* with small amounts of the fern *T. interrupta*, both of which are rooted in peat which constitutes the channel banks (Fig. 3.2). With the exception of *V. cuspidata*, which occurs on the convex sides of channel bends, there is an absence of bottom rooted vegetation. The channel beds are thus sandy, although seldom visible due to the presence of suspended material.

The channels are between eight and twenty metres wide, have mean depths of approximately 3,5m, and mean mid-channel current velocities generally greater than 0,6m.s^{-1} (Table 3.2). These velocities were the highest measured in the study area. The depth to the sand beneath the peat deposits flanking the channels is similar to the mean channel depths, giving the impression that the channels are neither erosional nor depositional.

The water level within these channels, exemplified by the depth gauge at Hamoga island, is seasonally stable but shows a gradual rise over the period 1978 to 1984 (Fig. 3.3). The same phenomenon has been documented at Xaenga island (McCarthy et al., 1986b) which is on the

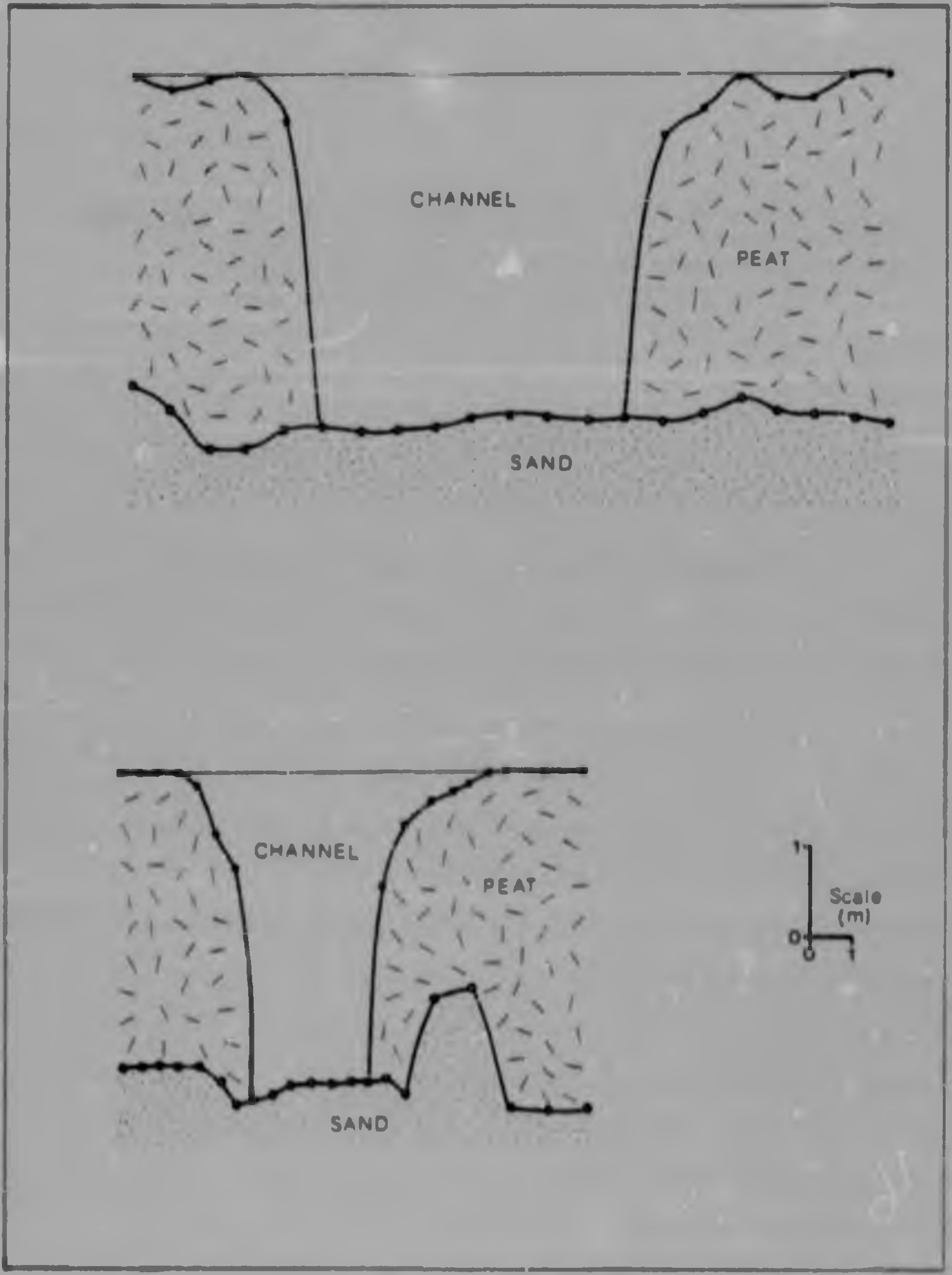


FIGURE 3.2 Channel dimensions and the depth to the sandy substratum of the lower Nqoga channel upstream of Hamoga island (a) and on the Crosscut channel (b), both of which are examples of Group 1 channels

TABLE 3.2 The range of mean channel dimensions and current velocities, and an indication of water clarity, within the four channel types identified in the floristic-functional classification

Floristic-functional channel group	Range of mean channel widths (m)	Range of mean channel depths (m)	Range of mean current velocities $(m.s^{-1})$	Water clarity
1	8,7-19,3	3,4-3,7	0,60-0,64	turbid
2	12,4-16,2	3,3-3,7	0.42-0,51	turbid
3	6,2-22,2	2,2-3,7	<0,03-0,30	clear
4	6,5-16,6	1,7-2,8	<0,03-0,20	clear

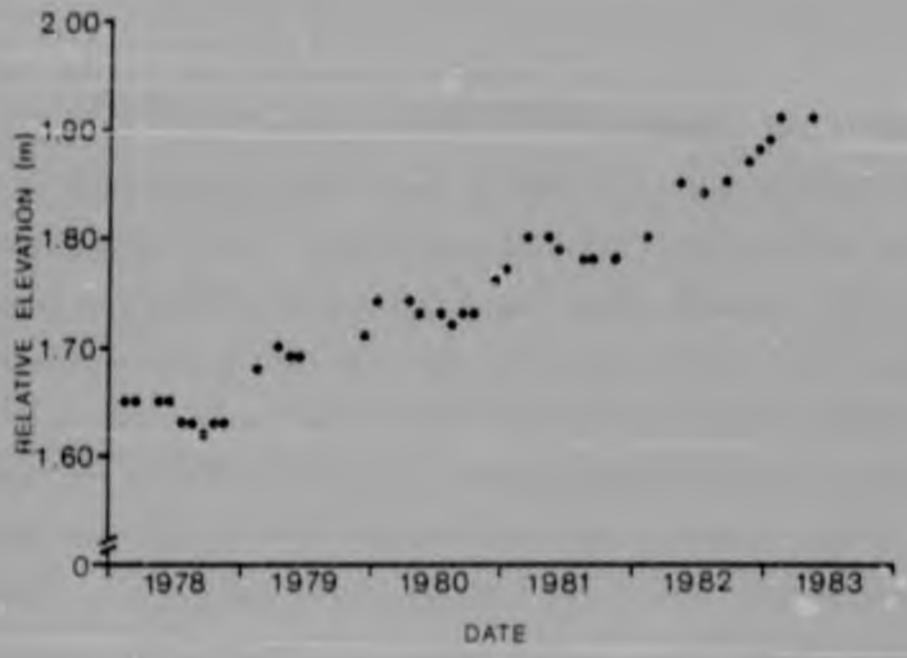


FIGURE 3.3 The water level recorded on the hydrological benchmark on the lower Nqoga river at Hamoga island from 1978 to 1983

Nqoga river approximately fifteen river kilometres upstream of Hamoga island (Fig. 1.2). The water level at both localities, as indicated by the slopes of the lines, appears to be rising at approximately 6cm.a^{-1}, and has not been accompanied by any change in width of the Nqoga channel itself.

3.2.2 Sandy bottomed channels flanked by C. papyrus and M. junceum (Group 2)

This channel type includes the Maunachira river downstream of its junction with the Crosscut channel and upstream of Dxerega lediba, and is represented by the stands in Group E of the TWINSPAN cluster analysis (Fig. 3.1). It receives its water both from the Crosscut channel as well as from the filter area east of Hamoga island which arises as overspill from the Nqoga river (Fig. 1.2). At the junction of these two rivers, the turbid waters of the Crosscut channel are mixed with the clear (filtered) water of the Maunachira river. Although this dilutes the suspended material somewhat, it is still present in sufficient quantities to prevent visibility of the channel bed. The absence of bottom-rooted vegetation within these channels, with the exception of *V. cuspidata*, is therefore considered due to a combination of unstable channel beds and low light availabilities at or close to the channel floor.

These channels are larger than the smallest of the sandy-bottomed channels flanked by *C. papyrus* (Group 1), due to their receiving the combined flows of the Crosscut channel and the Maunachira river upstream of this. They are approximately 15m wide, 3,7m deep and have a mean current velocity between 0,42 and 0,51m.s^{-1} (Table 3.2), which is slightly lower than measured in the previous channel type. The channel bed is at a greater depth than the sandy substratum flanking the channel, suggesting that the channel is incised. The presence of depressions in the sandy substratum on either side of the channel itself (Fig. 3.4) indicates that the channel has been larger in the past, and also that incision into the substratum was greater than at present, and that partial infilling has taken place.

3.2.3 Channels with vegetated beds and flanked by C. papyrus and M. junceum (Group 3)

This channel type is represented by the Maunachira river upstream of its junction with the Crosscut channel, as well as the Maunachira river between Dxerega and Gadikwe madiba (Fig. 1.2), and includes Groups C and D of the cluster analysis (Fig. 3.1). The water in these channels is extremely clear, and the beds are generally vegetated by species such as *E. natans*, *O. muricata*, *O. ulvifolia* and *N. caerulea*. Mean current velocities vary from being too slow to measure (less than 0,03m.s^{-1}) to 0,30m.s^{-1} which is less than in either of the previously described channel types (Table 3.2). The dimensions of these channels are extremely variable. Mean widths are between 6 and 20m, and mean depths vary from 2,2m to 3,7m. Despite the variation in mean channel depths, the depth to the substratum within areas flanking the channels are generally constant at between 1,5 and 2,0m, which suggests that many of these channels have eroded into the pre-channel substratum (Fig 3.5). The absence of hydrological bench-marks on these channels prevents determination of the seasonal and long-term water level fluctuations. A single bench-mark located at Xugana lediba, which is on the middle reaches of these channels (Fig. 1.2), however, indicates small seasonal water level fluctuations of less than 0,3m, and there has been no consistent rise over the period from 1974 to 1982 (Fig. 3.6).

Plant species characteristic of the channel margins are *C. papyrus* and *M. juncem* which are generally dominant on convex and concave

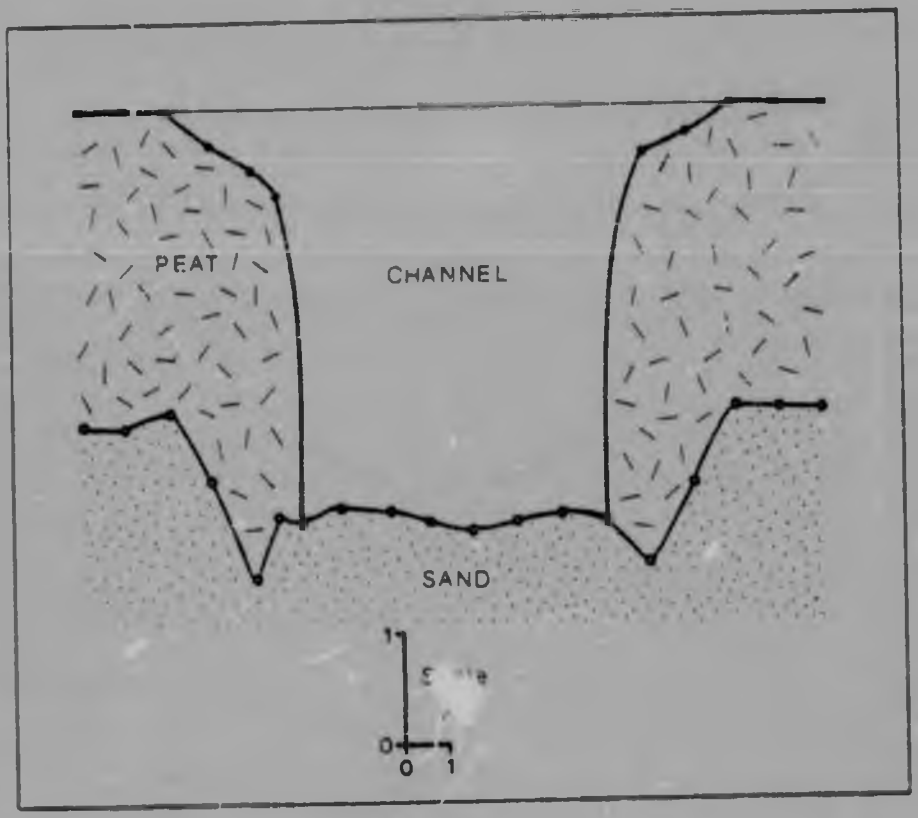


FIGURE 3.4 Channel dimensions and the depth to the sandy substratum of the Maunachira river several hundred meters downstream of its junction with the Crosscut channel, an example of a Group 2 channel

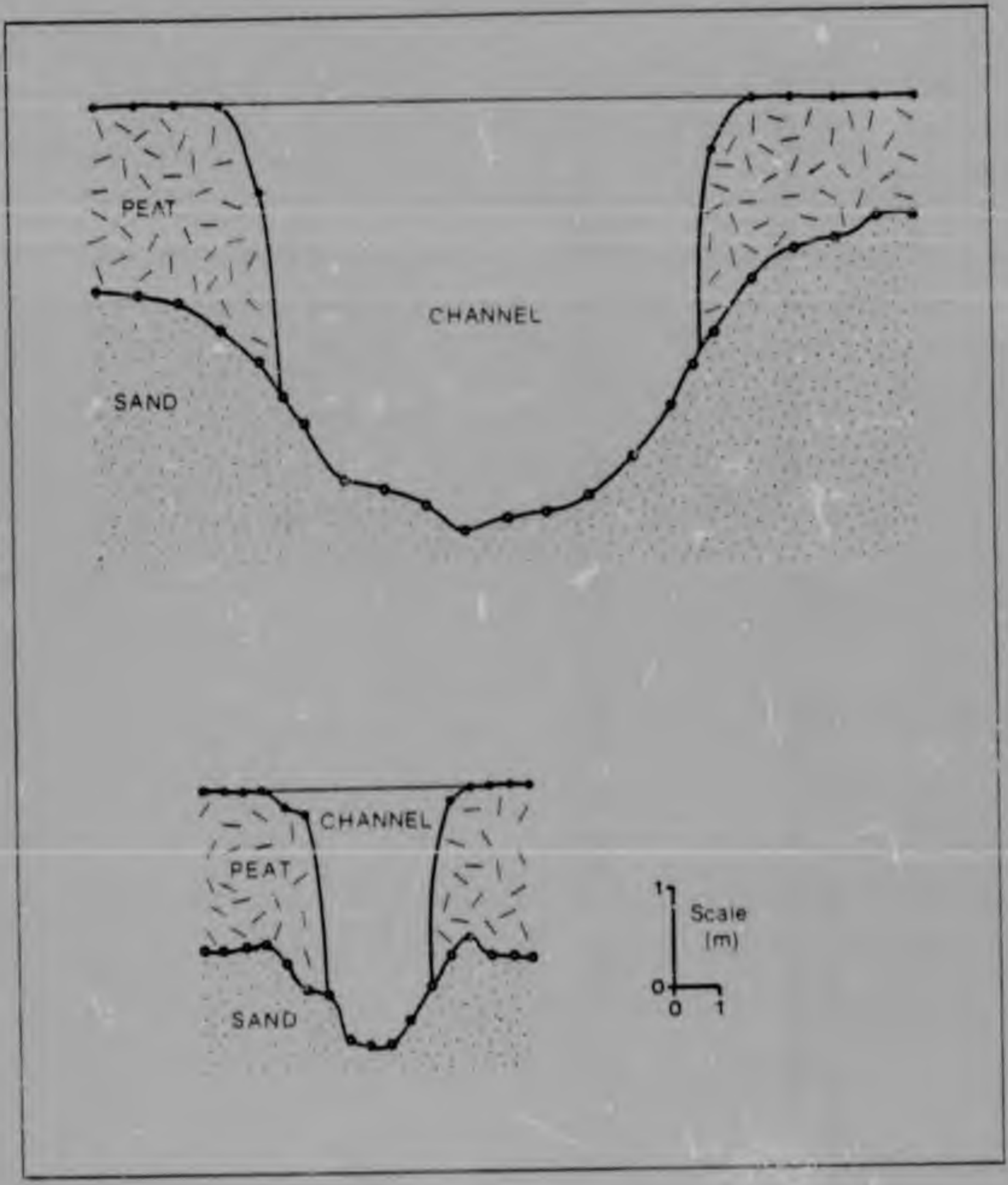


FIGURE 3.5 Channel dimensions and the depth to the sandy substratum of the Maunachira river between Dxerega and Gadikwe madiba, both of which are examples of Group 3 channels

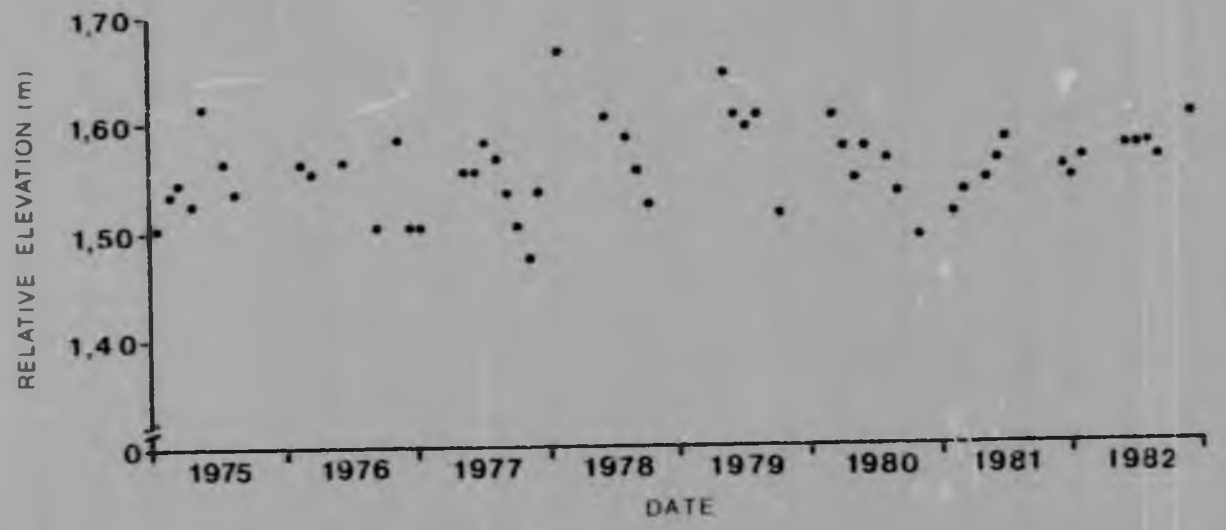


FIGURE 3.6 The water level recorded on the hydrological bench-mark on the Maunachira river at Xugana lediba from 1975 to 1982

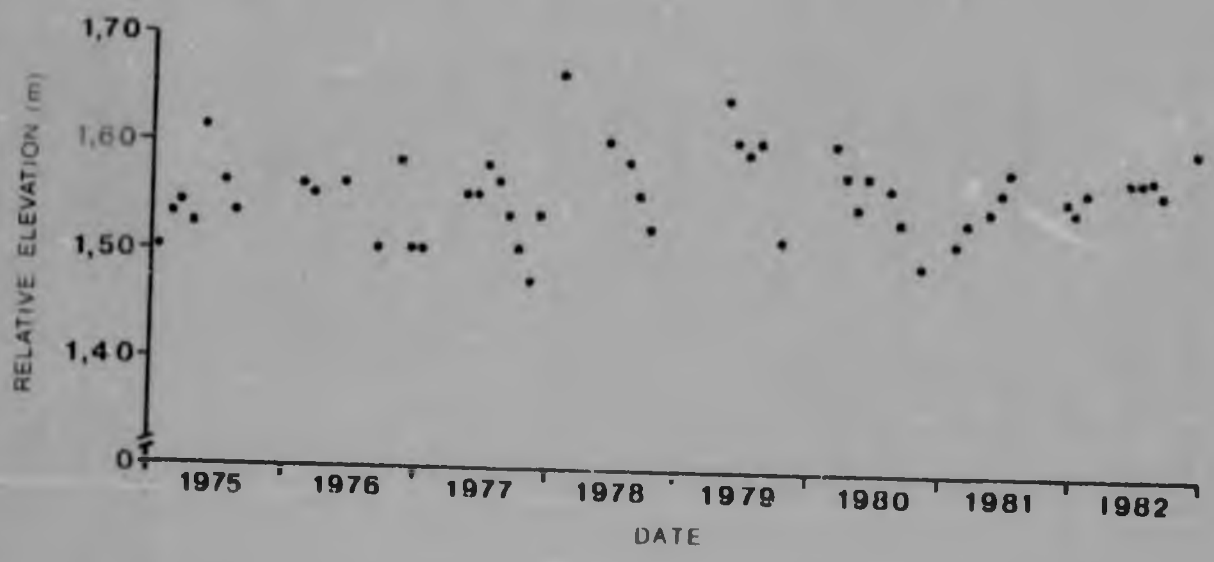


FIGURE 3.6 The water level recorded on the hydrological bench-mark on the Maunachira river at Xugana lediba from 1975 to 1982

banks respectively. Generally banks alongside straight channel sections are dominated by *C. papyrus*

3.2.4 Channels with vegetated beds and flanked by *F. verruculosa* and *M. junceum* (Group 4)

This channel type is represented by channels of the Maunachira river system downstream of Gadikwa lediba (Fig. 1.2), and is indicated by Groups A and B of the TWINSPAN cluster analysis (Fig. 3.1). Their waters are extremely clear and they generally support a large standing crop of submerged and floating-leaved aquatic plants, including beds of *N. crassicaulis* and *R. myriophylloides* as well as the floating-leaved *B. schreberi* and *N. indica*. *Cyperus papyrus* is however virtually absent from the fringes of these channels, which are dominated by *F. verruculosa* and *M. junceum*.

Similar to the previous channels, the channel dimensions are extremely variable; mean widths vary from less than 7m to greater than 15m, and mean depths from less than 2m to almost 3m (Table 3.2). Mean channel velocities also vary from being too slow to measure to approximately 0,2m.s^{-1}. The level of the channel bed in relation to the level of the substratum in areas flanking the channel shows the channel bed to be at the same level or incised into the pre-channel substratum. (Fig. 3.7).

The hydrological regime generally varies less than 30cm.a^{-1}, although in some years it varies up to 40cm as indicated by the water levels measured on the bench-mark at Xakanaxa lediba (Fig. 3.8). These variations are due to increased water levels in the summer months and illustrate the importance of local rainfall in contributing to the hydrology of these lowermost channels. The presence of bottom-rooted aquatics in abundance within these channels sug-

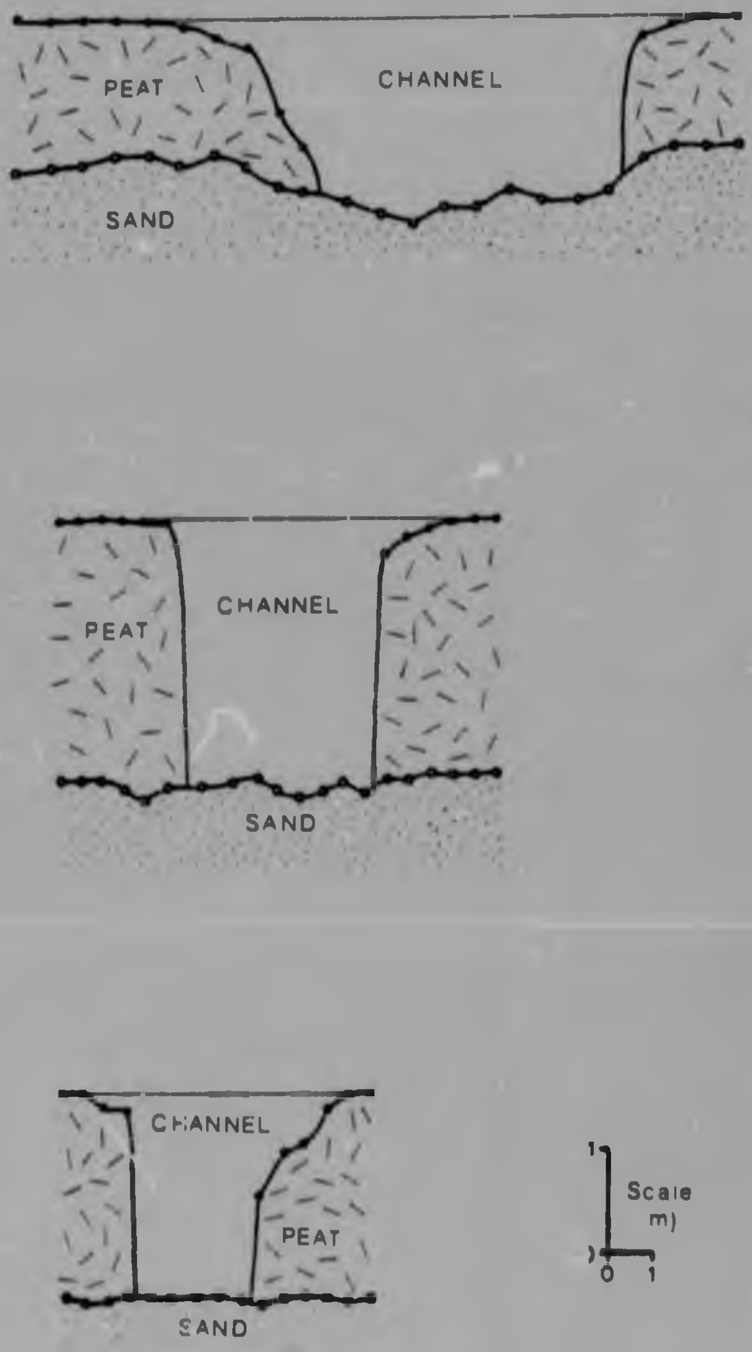


FIGURE 3.7 Channel dimensions and the depth to the sandy substratum of the Maunachira river between Gadikwe and Xakanaxa madiba, all of which are examples of Group 4 channels

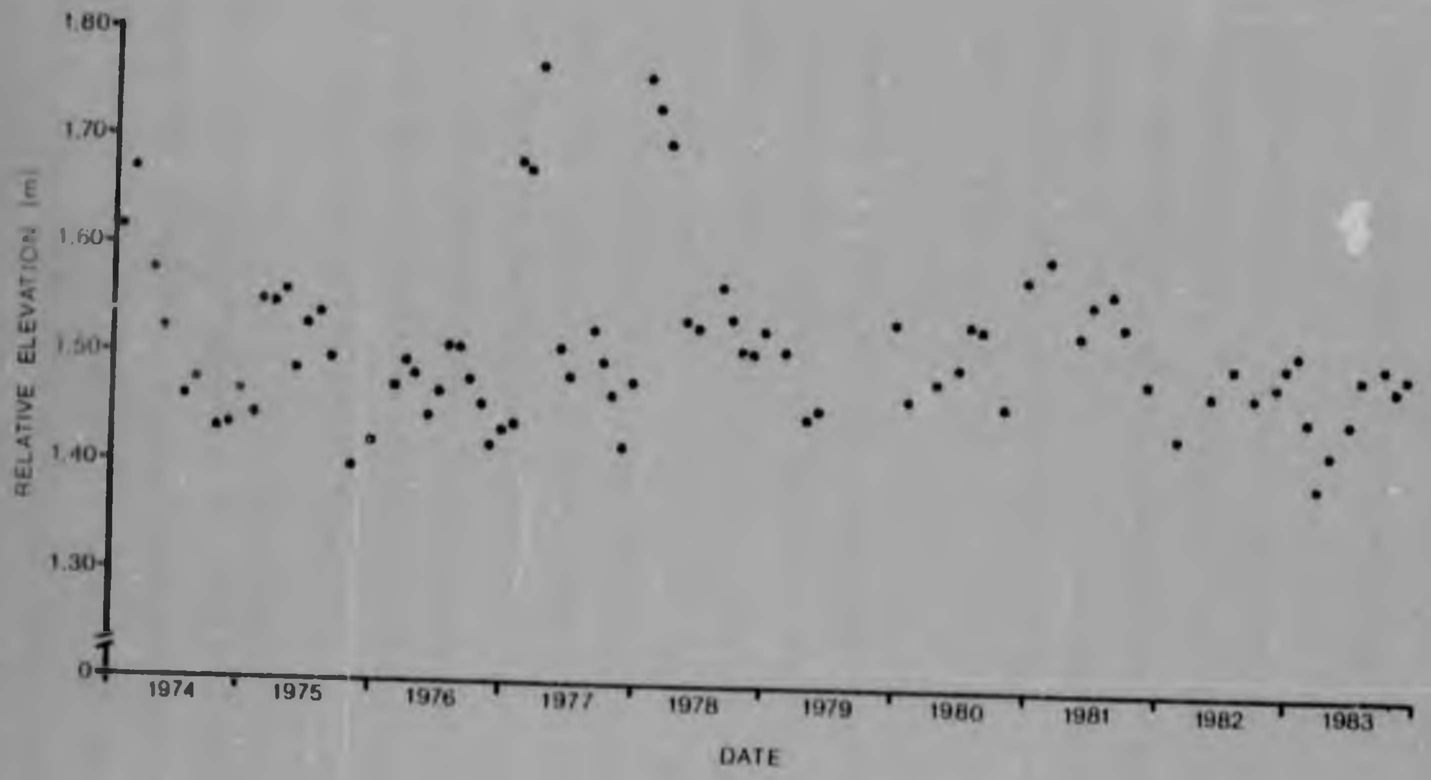


FIGURE 3.8 The water level recorded on the hydrological benchmark on the Maunachira river at Xakanaxa lediba from 1974 to 1983

gests that their beds are stable, and that the movement of bed-load sediments along the channel floors is negligible.

3.3 Discussion

3.3.1 The confinement of water flow, channel-bed erosion and sediment deposition by vegetated peat banks

Channels throughout the study area generally have beds of fine sand which may or may not be vegetated. The banks consist of dense stands of vegetation rooted in submerged peat deposits, which are also underlaid by sand. These vegetated banks appear highly resistant to erosion, and may account for their long term (decades) stability (Wilson, 1973).

Vegetation growth and the concomitant formation of peat in the Okavango Delta appears to lead to a reduction in the area of open water (Ellery, K., 1987), and is a process which may lead to the formation of channels (Gorham, 1957; Breen et al., in prep.). Channels within the study area experience a greater current velocity than areas flanking the channel (McCarthy et al., in press b), and the channels therefore function as canals which are flanked by stable, vegetated peat banks. This has important consequences for the confinement of channel-bed erosion and bed-load sediment deposition to areas within the channels themselves.

The relatively recently increased inundation of the Maunachira river system must have been accompanied by an increase in the rate of water movement in channels in this area. The consistency in the pattern of the depth to the sandy substratum being greater in channels compared to the areas flanking the channels downstream of Dxerega ladiba suggests that erosion in these channels has been confined almost entirely to in-channel areas.

Not only do the vegetated peat banks of the Okavango Delta appear to confine flow and erosion, but they also appear to confine the deposition of bed-load sediments to in-channel areas. Whereas water flow in the Delta takes place to some extent outside river channels, sediments transported as bed-load do not appear to escape from the channels themselves (McCarthy et al., 1986b). Sediments introduced into the Delta each year from source areas as bed-load are therefore confined to those channels directly connected to the Okavango river. The Nqoga River is presently the major offtake of the Okavango river, and it would therefore be expected to receive large quantities of bed-load sediments from source areas. This may account for the gradual rise in water level at Xaenga island (McCarthy et al., 1986b) as well as at Hamoga island (Fig. 3.3).

Despite the apparent deposition of large quantities of sediment along the channel floor of the Nqoga channel, its channel bed is not raised above that of the surrounding pre-channel substratum (Fig. 3.2). This is because major distributary channels are probably erosive before they become directly connected to the Okavango river, such as the Maunachira river downstream of Dxerega lediba.

The boundary between channels which appear to be dominated by erosional processes and those which are predominantly depositional is Dxerega lediba. Presently this lake represents a discontinuity to the transport of bed-load sediments introduced from source areas along the continuous Okavango-Nqoga-Crosscut and Upper Maunachira channel, which are all predominantly depositional. The reduction in current velocity which occurs as water enters Dxerega lediba, results in the deposition of all the bed-load sediments transported this far downstream from source areas. This has led to the formation of a large sand-bar which protrudes into the lediba from the mouth (McCarthy et. al., 1986b). Sediments introduced into the delta from source areas therefore do not enter the Maunachira river downstream of Dxerega lediba, and these latter channels are therefore predominantly erosional.

The presence of Bokoro lediba on the Crosscut channel prior to 1969 (Wilson, 1973) similarly prevented the movement of bed-load sediments into the upper Maunachira river, which at that time must therefore have been erosional. Subsequent to the closure of Bokoro lediba due to infilling by a combination of sedimentation and encroachment by vegetation (Wilson, 1973), bed-load sediments have been introduced into the Maunachira river system between its junction with the Crosscut channel and the next lediba, Dxerega. The introduction of sediments to the Maunachira river upstream of Dxerega lediba since 1969 appears to have greatly influenced the vegetation dynamics of this river system. This is illustrated by a comparison of the present classification of channels with Wilson's (1973) classification.

3.3.2 A comparison of two channel classifications: recent channel changes in the study area

Based on observations as well as aerial photographic interpretations, Wilson (1973) also distinguished between channels with vegetated and unvegetated beds. He referred to the channels with unvegetated beds as 'upper' channels and these were typified by the Okavango-Nqoga river as far downstream as Letenetso island (Fig. 1.2). They were recorded as being bounded predominantly by *C. papyrus*, as having strong flow (typical current velocities were 0,6m.s^{-1}), and as being stable. These appear to correspond to the channels classified in the present study as depositional and flanked by *C. papyrus* (Group 1). Wilson (1973) also recognised two channel types with vegetated beds, 'middle' and 'outlet' channels. These two channel types correspond to the channels classified in the present study as Group 3 and Group 4 channels respectively. A similar distinction between these two channel types has also been described by Gibbs Russel and Biegel (1973).

There are two major differences between the present classification of channels and Wilson's (1973) classification. The first is the extension of the 'upper' (Group 1) channels to include the Crosscut channel since Wilsons (1973) description. It is suggested that the deposition of both bed-load sediments and *C. papyrus* debris along this section between the time of Wilsons (1973) description and the present classification, have resulted in the transformation of the Crosscut channel to a typical 'upper' channel. These processes have also resulted in the closure of a number of open water bodies along the Crosscut channel, of which the most noteworthy is Bokoro lediba (Wilson, 1973).

The second major difference between the present classification and Wilsons (1973) classification is the inclusion of a channel type (Group 2) which was not previously recognised. This channel type appears to be transitional between 'upper' (Group 1) channels and 'middle' (Group 3) channels, both in terms of its species composition and its channel morphology. The Group 2 channels have unvegetated channel beds, which is characteristic of 'upper' (Group 1) channels, but the occurrence of *C. papyrus* and *M. junceum* in their channel margins is a characteristic of 'middle' (Group 3) channels. Furthermore the previously eroded channel bed appears to be in the process of infilling (Fig. 3.4).

A similar change appears to have taken place along the Nqoga river since the early part of this century. Stigand (1923) visited this region of the Delta in the 1910's, and took a photograph of an island on the Nqoga river from the channel itself. It shows a small clump of *Phoenix reclinata* Jacq., and flanking the channel was a dense fringe of *M. junceum*. The island today has well developed stand of *P. reclinata*, and the channel fringe is an extremely dense stand of *Cyperus papyrus* (Smith, P.A. 1976). The transformation of the channel fringe from being dominated by *M. junceum* in the early part of this century to being dominated by *C. papyrus* appears to represent the transformation of what was probably the equivalent of a channel with a vegetated bed flanked by *M. junceum* in association with perhaps either *C. papyrus* (Group 3) or *F. verruculosa* (Group 4) to a depositional channel flanked by *C. papyrus* (Group 1).

The regulation of water movement, erosional processes and the deposition of bed-load sediments by vegetation processes is a feature well illustrated in the present study. The reciprocal effects of each of these processes on the distribution and dynamics of vegetation is also illustrated. Central to these processes is the interaction at the interface between the open water of the channel, and the adjacent swamp communities. The next part of this study was thus aimed at investigating the growth and demography of *C. papyrus* within the channel margins, with an emphasis on biotic and abiotic factors which influence its rate of encroachment into channels.

CHAPTER 4

THE GROWTH CHARACTERISTICS AND DEMOGRAPHY OF CYPERUS PAPYRUS WITHIN THE CHANNEL MARGINS

4.1 Introduction

The high growth rate, guerilla growth form, and ability to grow either rooted or floating are attributes of *Cyperus papyrus* growth which appear to enable its encroachment into channels from the banks. Wilson (1973) however suggested that current velocities may reduce the encroachment of this species into channels. This aspect of the study was therefore aimed at comparing the growth characteristics, demography, and encroachment of *C. papyrus*, within the margins of as wide a range of channel types and flow conditions as possible. Based on these investigations the potential of this species to reduce channel width and modify channel planform geometry has been evaluated.

4.2 The growth characteristics of C. papyrus within the channel margins

The ability of *C. papyrus* to encroach into the channels and modify channel planform geometry was considered to be related to attributes of its growth characteristics. An estimation of plant vigour was made by determining the maximum culm height per rhizome, the mean number of rhizomes per unit cha[illegible]l margin length, the rate of biomass production per rhizome and per unit channel margin length (Fig. 4.1).

There was a downstream decrease in the mean maximum culm height per rhizome for both the concave and straight margins (Fig. 4.1a). Similar downstream trends were recorded in the concave and straight margins for the mean number of rhizomes per unit channel margin length (Fig. 4.1b), the mean rate of biomass production per rhizome (Fig. 4.1c) and the production of biomass per unit channel margin length (Fig. 4.1d). Within the channel margins on the convex side of channel bends however, there was not a systematic downstream decrease in the values of any of these variables. Current velocity in the channel margins decreased systematically downstream for both the concave and straight channel margins, but for the convex margins, the current velocity in the lower study site was greater than in the upper two sites (Fig. 4.1e). This appears to be due to the development of strong eddy currents on the convex side of channels in the upper two study sites, but not in the lower site. In the upper study site, flow along the convex margin was in fact in the opposite direction to that in the main stream.

The results indicate that current velocity may contribute to the downstream decrease in papyrus vigour within the concave and straight channel margins. It is suggested however that the observed trends in papyrus vigour may also be related to a downstream decline in nutrient availability. There appears to be no relationship between current velocity and the vigour of papyrus on the convex banks, and it is likely that the eddy currents on these banks of the upper two study sites cause papyrus to respond in a different way from the other channel margins.

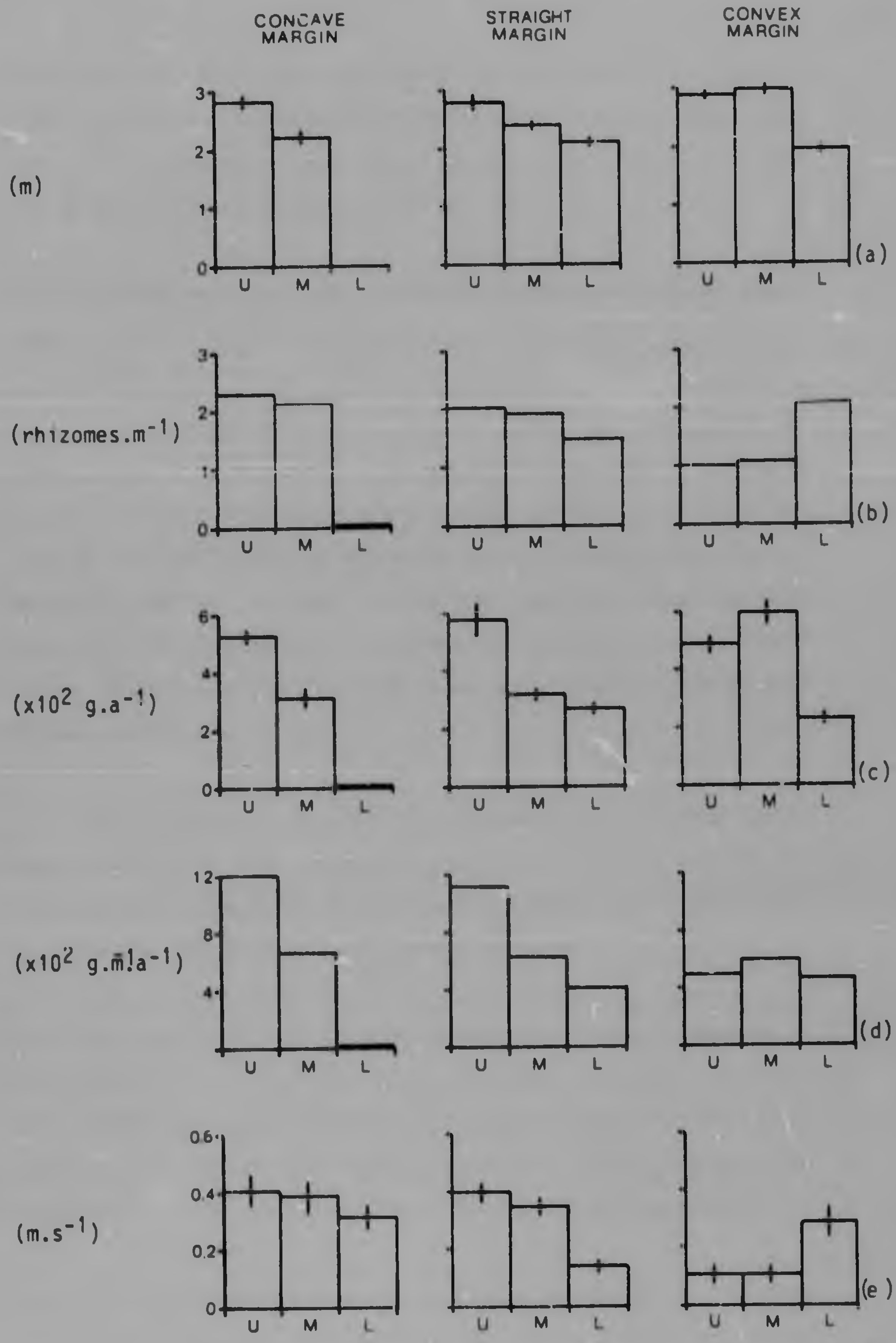


FIGURE 4.1 Changes in *C. papyrus* mean maximum culm height per rhizome (a), the mean number of rhizomes per unit channel margin length (b), the production of biomass per rhizome (c), the production of biomass per unit channel margin length (d) and current velocity (e) within the channel margin of concave, straight and convex banks of the upper (U), middle (M) and lower (L) study sites. Bars indicate std. error

Based on these growth characteristics it would seem that papyrus vigour was greater in the upper two study sites, than the lower study site. It may therefore seem likely that the upper channels are more susceptible to encroachment by this species.

4.3 Encroachment of C. papyrus from the channel banks into channels

The rate of encroachment of *C. papyrus* from the banks into the channels could be expected to be related to its rate of extension growth. If all the rhizomes extended into the channel at right angles to the bank, then the values of these variables would be expected to coincide, as indicated by the "expected" relationship in Fig. 4.2. The protrusion of rhizomes at an angle however, would reduce the slope of the line, but it would still be expected to pass through the origin.

The rates of extension growth and encroachment were in fact poorly correlated (r = 0,495), and the slope of the line which best fitted the spread of points was greater than expected (Fig. 4.2). Furthermore the line did not pass through the origin.

The flow rates within the channel margins have been superimposed on the points representing each of the plots in the study area (Fig. 4.2). Under low flow conditions the observed value is relatively close to the expected value, but as current velocity increases, the difference between the expected and observed values increases.

Mean rates of encroachment were negatively correlated (r = -0,875) with current velocity - with the exception of the plot in the channel margin of the convex bank of the upper study site (*, Fig. 4.3) which had a low negative rate of encroachment as well as a low current

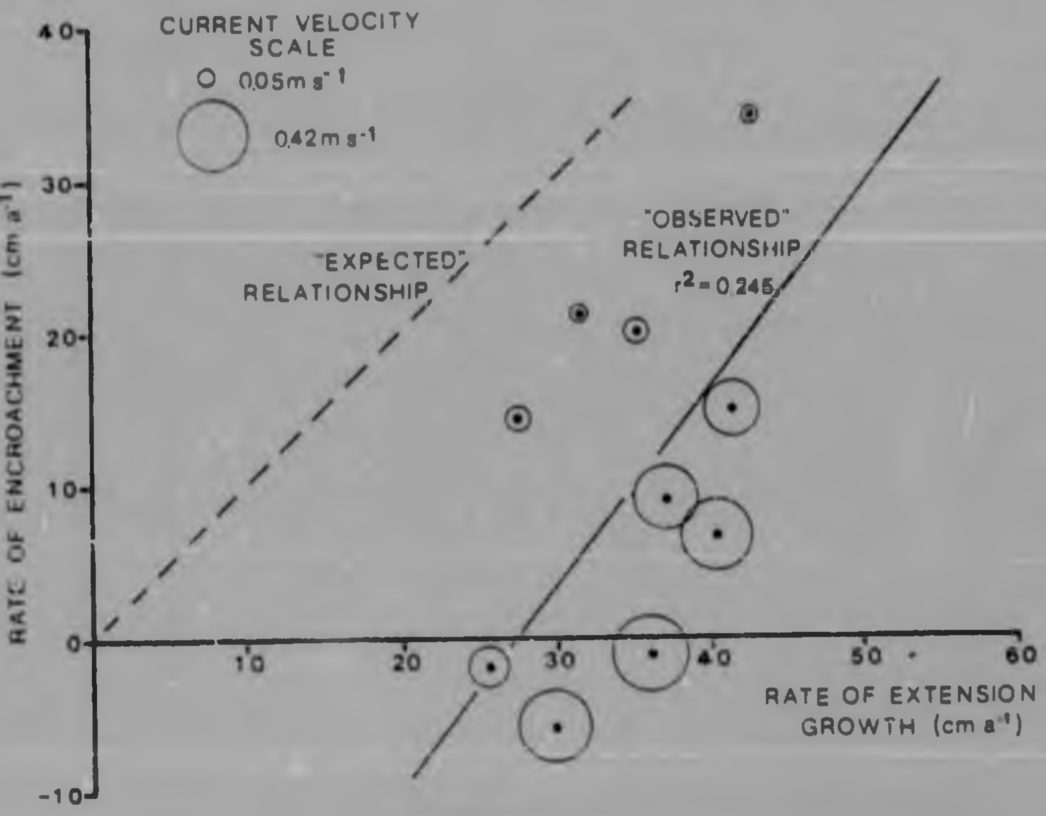


FIGURE 4.2 The expected and observed relationships between the rate of encroachment of *C. papyrus* from the banks into channels and its rate of extension growth. The diameter of the circle around each point is proportional to the current velocity ($m.s^{-1}$) within the channel margin

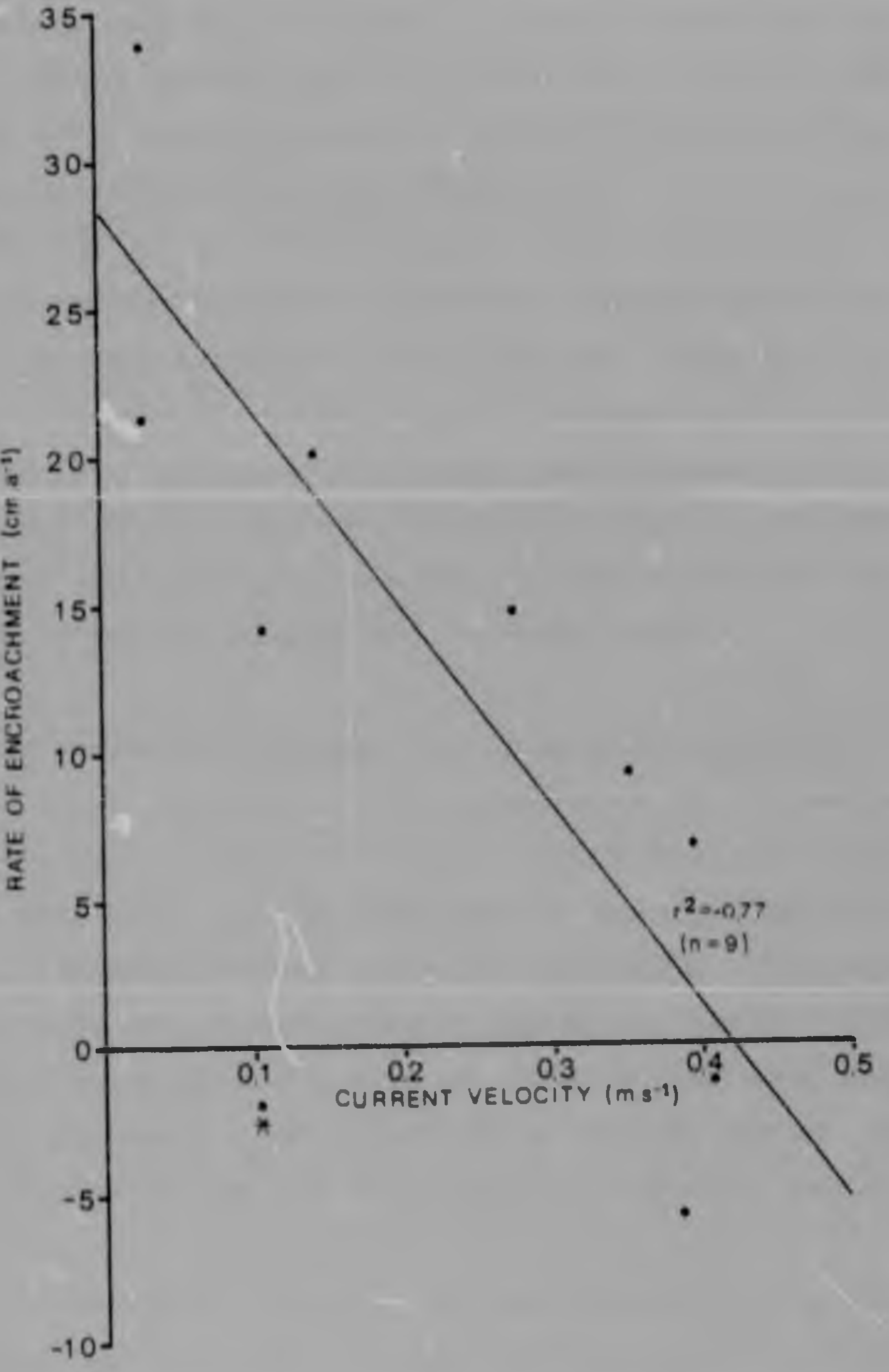


FIGURE 4.3 The relationship between the rate of encroachment of C. papyrus from the bank into the channel (cm a^{-1}) and current velocity (m s^{-1}). The asterisk denotes the value for the plot in the convex margin of the upper study site and was omitted from the regression (see text)

velocity (Fig. 4.3). As indicated previously there was a well developed eddy current on the convex side of this channel, with flow in the margin being in the opposite direction to that in the main channel. This is the only plot in the study area in which this was the case, and it appears to account in some way for the reduced rate of encroachment within the channel margin.

The linear equation which best describes the spread of points (excluding the upper convex bank) is net extension growth ($m.a^{-1}$) = -0,67 x current velocity + 0,28 (r = 0,875) and suggests that in the absence of flow, rhizomes would encroach into the channel at approximately $0,28 m.a^{-1}$. Current velocities are likely to restrict encroachment both by forcing the rhizomes to move towards the bank, as well as by removing rhizomes from the channel margin.

The vector representing the mean rate of horizontal movement of rhizomes towards the bank, with the exception of the plot on the upper convex bank, is well correlated (r = 0,930) with mean current velocity (Fig. 4.4). Water movement therefore appears to cause the movement of rhizomes towards the bank, and accounts for the upstream decrease in the rate of encroachment of papyrus into channels. Once again the eddy current in the convex margin of the upper study site appears to increase the rate of movement of rhizomes towards the bank, despite the current velocity itself being relatively low.

The results for rhizome recruitment and loss in relation to flow rate are illustrated in Fig. 4.5. The line which joins points in which recruitment = loss indicates that the number of rhizomes per unit channel margin length would remain constant over time. Points above this line indicate that recruitment is greater than loss, while points below the line indicate loss being greater than recruitment. With the exception of the plot in the convex margin of the upper

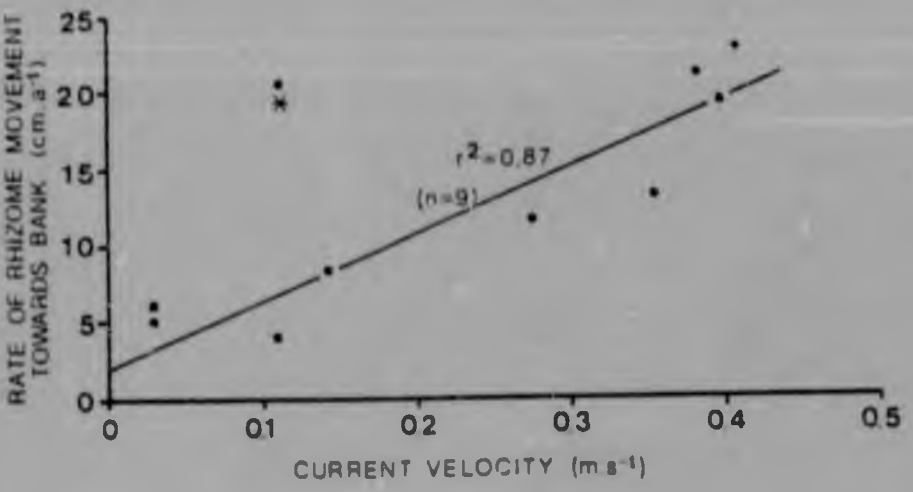


FIGURE 4.4 The relationship between the rate of movement of *C. papyrus* rhizomes towards the bank (cm a^{-1}) and current velocity (m s^{-1}). The asterisk denotes the value for the plot in the convex margin of the upper study site and was omitted from the regression (see text)

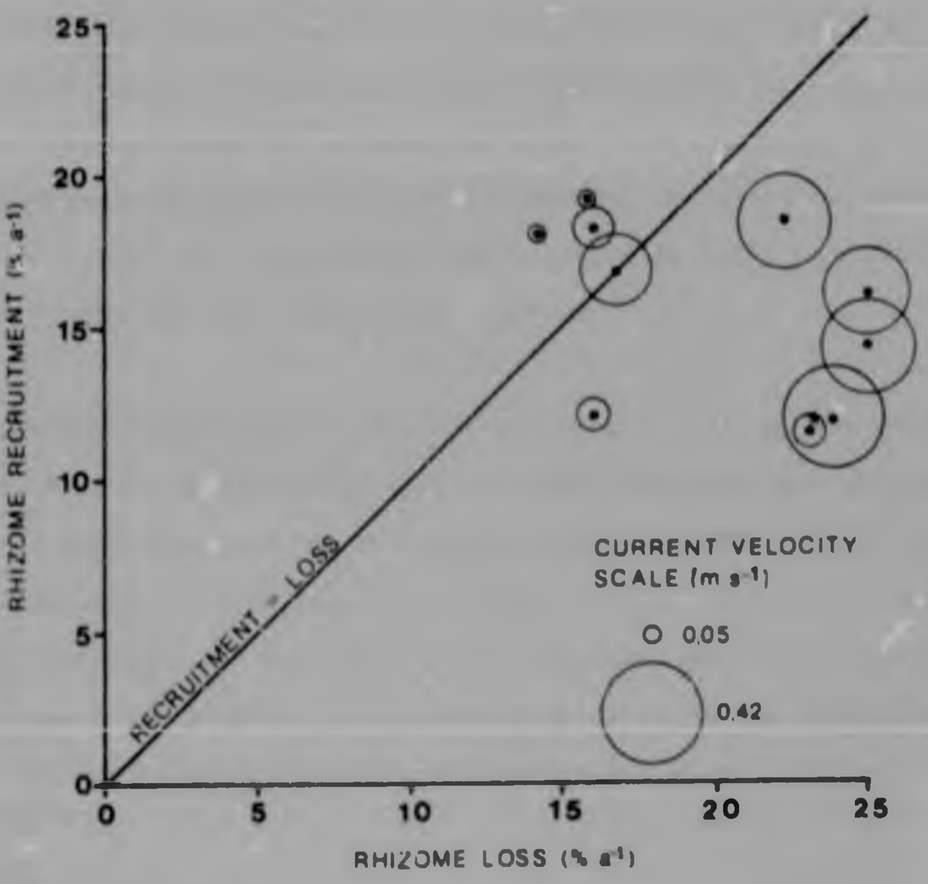


FIGURE 4.5 The relationship between *C. papyrus* rhizome loss and rhizome recruitment. The diameter of the circle around each point is proportional to the current velocity (m s^{-1}) within the channel margin. The asterisk denotes the value for the plot in the convex margin of the upper study site. This is the only plot which does not appear to show the same pattern as the others.

study site - which once again is the exception to the rule - the results indicate that while rhizome recruitment was not related to current velocity, the proportional loss of rhizomes from the channel margin increased with an increase in current velocity. This suggests that the physical force of the current contributes to the removal of rhizomes from the channel margin. Furthermore, plots in the channel margin which had a greater loss of rhizomes than recruitment, were generally those in which current velocities were high, while plots in which recruitment was greater than loss were those in which current velocity was low. Plots in which recruitment was greater than loss would be expected to result in channel constriction, wheras those in which loss was greater than recruitment would be ecpected ve their banks slowly eroded by the current.

Although the examination of growth characteristics of papyrus in the channel margin has suggested that the upper channels may be more prone to encroachment than the lower channels, studies on the rate of encroachment of this species from the bank into the channel have in fact indicated the reverse. It is therefore concluded that the encroachment of channels by *C. papyrus* is lower in the channels of the upper two study sites, than the lower study site.

4.4 Discussion

The features of *C. papyrus* growth which were considered to be related to plant vigour, and which appeared to decrease downstream are:-

- the maximum (potential) culm height per rhizome

- the rate of biomass production per rhizome

- the rate of biomass production per unit channel margin length.

Although there appears to be some degree of correlation between these growth characteristics and current velocity, it is suggested that a downstream decrease in nutrient availabilities may also be a contributing factor. Talling (1957) recorded such a decline in the swamps of the White Nile, evidently due to the removal of nutrients by plant communities further upstream. Furthermore, the removal of nutrients by papyrus swamps has been recorded elsewhere in Africa (Gaudet, 1977; 1978; 1982). This is a subject which requires further investigation in the Okavango Delta, as it has important consequences for the dynamics of channels and their fringing plant communities.

Despite the downstream decrease in these attributes of vigour, this component of the study has indicated that encroachment into channels increases downstream. This appears to be due to a downstream decrease in current velocity, and supports the suggestion by Wilson (1973) that current velocity is of overriding importance with regard to the rate of encroachment of papyrus into channels from the banks.

One of the mechanisms by which encroachment into channels may be reduced by the current is the removal of rhizomes from the channel margins. Observations in the study area further indicated that newly formed blockages were composed almost entirely of papyrus debris, and that they were restricted to the lower Nqoga River and Crosscut channel. The following investigations were therefore concerned with the origin of the debris, the mechanisms involved in its aggregation into rafts sufficiently large to become lodged within channels, as well as the dynamics and ultimate fate of debris blockages.

CHAPTER 5

THE ORIGIN, INITIATION, DYNAMICS AND FATE

OF CYPERUS PAPYRUS DEBRIS BLOCKAGES

5.1 Introduction

Rafts of *Cyperus papyrus* have been recorded to block channels in a large number of African swamps, including the Okavango Delta (Wilson, 1973; Smith, P.A., 1976). At present the lower Nqoga river and Crosscut channel are the sites of blockage formation (Smith, P.A., 1976). This component of the study was aimed at determining the mechanisms involved in the formation of debris blockages within the lower Nqoga river and Crosscut channel. The spatial and temporal dynamics of debris blockages within this channel section, and the eventual fate of debris blockages have also been investigated.

5.2 The formation of C. papyrus debris blockages

The formation of debris blockages requires the production of large quantities of debris, and its aggregation into rafts sufficiently large to become lodged within the channels as they become progressively narrower downstream (Wilson, 1973).

The collection of debris flowing downstream along the lower Nqoga river at Hamoga island revealed that greater than 95% of the debris consisted of *C. papyrus* plant parts. This debris appears to be generated by the removal of rhizomes from the channel margin as described in Section 4.2. If the proportional loss of rhizomes from the channel margins (Fig. 4.5) constitutes debris, then the production of debris for each of the concave, straight and convex banks decreases markedly downstream (Table 5.1). This would appear to be due to the downstream decline in papyrus productivity, as well as in current velocity, both of which appear to contribute to the quantity of debris produced (Fig. 5.1).

The amount of debris flowing within a given channel section is not simply related to the amount produced further upstream, but also to the interception of debris along the channel course. This is illustrated by a consideration of the amounts of debris flowing into the lower Nqoga channel downstream of Hamoga island, and out of the Crosscut channel, this being a continuous, unbranched section of channel. The amount flowing into the upstream end of this channel was greater by more than an order of magnitude than the amount flowing out from the downstream end (Table 5.2), with the exception of a single sampling date in July, 1985. On this occasion the quantity of debris was too large to measure; several tons drifted past the sampling station in less than 15 minutes.

The episodic, large scale debris flow observed in July 1985, consisted of rafts of debris up to 6 m in diameter, and was caused by the release of a debris blockage further upstream. This indicates the importance of blockages in aggregating individual pieces of debris into large rafts. The question arises as to how individual pieces of debris become aggregated in the first place to form rafts sufficiently large to become lodged in a channel wider than 8m, which is the approximate width of the narrowest section of the Ngoga-Crosscut channel. Based on observations in the study area it was

TABLE 5.1 The change in mean rates of *C. papyrus* debris production per unit channel margin length ($g.m^{-1}.a^{-1}$), in relation to the location and position of plots in the channel margins within the study area

	Rate of papyrus debris production per unit channel margin length ($g.m^{-1}.a^{-1}$)		
Plot position \ Study site	Upper	Middle	Lower
Concave bank	286,4	149,3	0,0
Straight bank	293,4	158,0	64,1
Convex bank	116,9	103,4	81,4
Low flow 1			46,7
Low flow 2			74,3

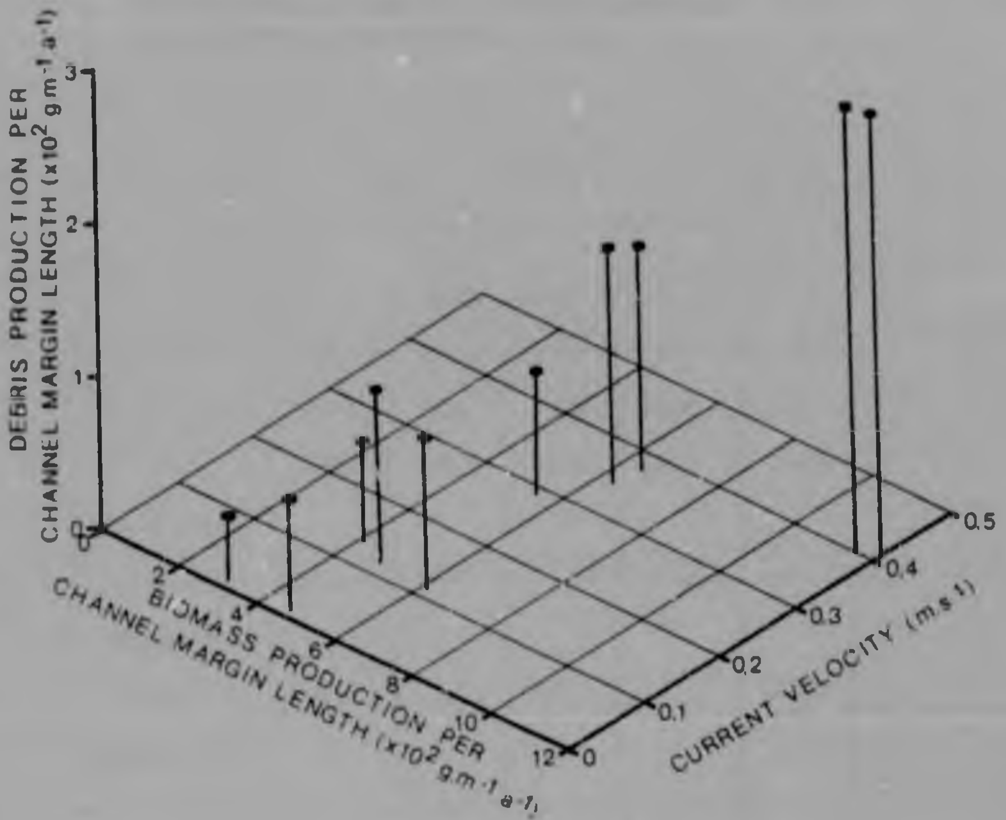


FIGURE 5.1 The relationship between C. papyrus debris production per unit channel margin length (g m a^{-1}) and papyrus biomass production per unit channel margin length (g m a^{-1}) and current velocity (m s^{-1})

TABLE 5.2 Changes in the rates of debris flow (kg.h^{-1}) between the Nqoga river at Hamoga island and the lower reaches of the Crosscut channel on 5 sampling dates during the study period (* = debris flow too large to measure. Estimated to be several tons).

	Debris flows (kg.h^{-1})				
Date Locality	March 1985	May 1985	July 1985	Sept. 1985	Dec. 1985
Nqoga R. at Hamoga Is.	88,6	48,4	20,7	28,2	94,6
Lower Crosscut Channel	8,3	1,9	*	1,4	5,3

proposed that the gradual accumulation and episodic release of vegetation debris on the convex side of channels with well developed eddy currents, was one mechanism which enabled the formation of rafts large enough to become lodged in the channels as they become progressively narrower downstream. One such bank was mapped on the lower Nqoga river to determine its pattern of accumulation and release.

At the time of the first visit the debris bank was approximately 10,5m long, had a maximum width of 1,6m and a surface area of approximately 9,8m^2 (Fig. 5.2a). It increased gradually in length and width (Fig. 5.2 b & c), until in May, 1985, it covered an area of approximately 43,4m^2. At the time of the next visit eight weeks later, the entire structure had disappeared. The pattern of the gradual increase in the size of the debris bank, and its sudden release over a much shorter timespan suggests that it may have been released as a single entity. A circular debris mat with a surface area of 43,4m^2 would have a diameter of 7,4m which is much the same as the minimum width of portions of the Crosscut channel. This raft of debris could therefore have become lodged within the lower reaches of the Crosscut channel, and illustrates a possible mechanism which leads to the aggregation of debris into rafts large enough to become lodged within channels.

Although they have been considered to promote channel blockage and abandonment, the effect of debris blockages on channel morphology and flow conditions has never been investigated. Does the presence of a papyrus blockage lead to a reduction in channel cross-sectional area, and thereby reduce flow? An investigation of the morphology of the channel bed beneath a small debris blockage has shown that the channel bed becomes eroded, and that some of the material removed from the channel bed is deposited on the downstream side of the

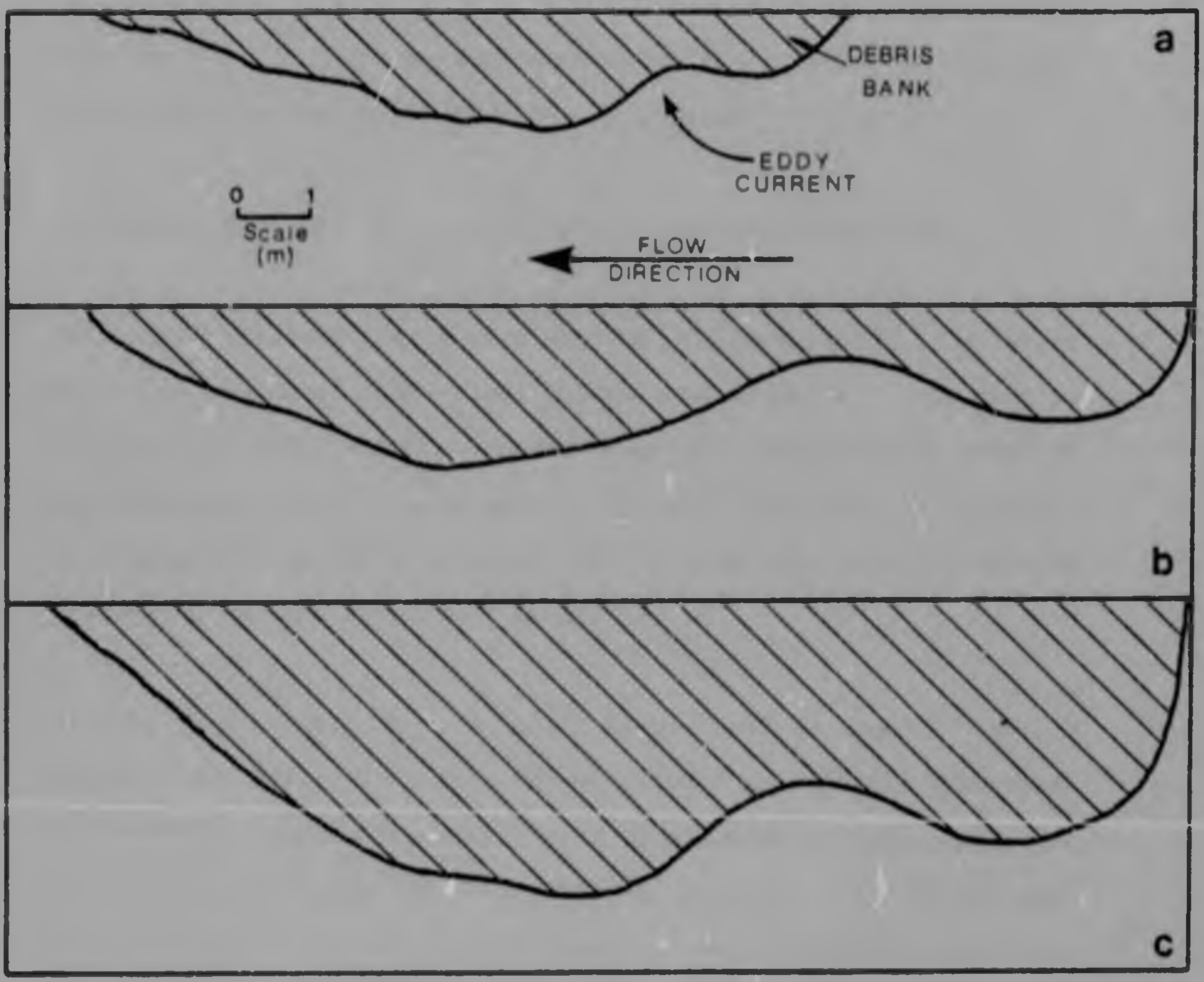


FIGURE 5.2 The gradual accumulation of C. papyrus debris on a convex bank on the lower Nqoga river, as demonstrated by the size of the debris bank in February (a), March (b) and May (c). The entire debris bank had disappeared by July

blockage (Fig. 5.3). An aerial view of a larger debris blockage clearly demonstrates the deposition of eroded material material on its downstream side (Plate 5.1). Despite the presence of debris blockages within these channels, therefore, cross sectional areas and water flows are likely to be maintained or reduced only slightly. The suggestion that debris blockages become rooted in the channel bed (Brind, 1955) therefore appears unlikely under the present hydrological conditions within the study area.

5.3 The spatial and temporal dynamics of debris blockages

Only five debris blockages were observed to form in the study area, all along the lower Nqoga river (downstream of the man-made channel at Hamoga island) and the Crosscut channel. These either broke up and reformed further downstream or else were deposited in the inlet of Dxerega lediba which is the first to interrupt the flow of the Okavango river and its direct extensions.

On the first visit to the lower Nqoga river in August, 1984, a blockage was observed to form in the channel immediately downstream of Letenetso island (Fig. 5.4a). It formed when a large number of floating rafts of papyrus debris many of which were 6 - 8m in diameter, became lodged within the channel where its width suddenly decreased due to the presence of an island in mid-channel. Once this debris had thus lodged in the channel, it formed a plug and the remainder of the debris banked up against it (Plate 5.2). This blockage was approximately 80m long, 20m wide and had a depth of approximately 2m. The shoot densities were not estimated on the occasion of its formation, but based on photographic evidence and on the first observation of each of the subsequent debris blockages, were estimated to be 0,25 culms.m^{-2} in the case of *C. papyrus*, and 0,10 and 0,05 shoots.m^{-2} in the case of *Vossia cuspidata* and

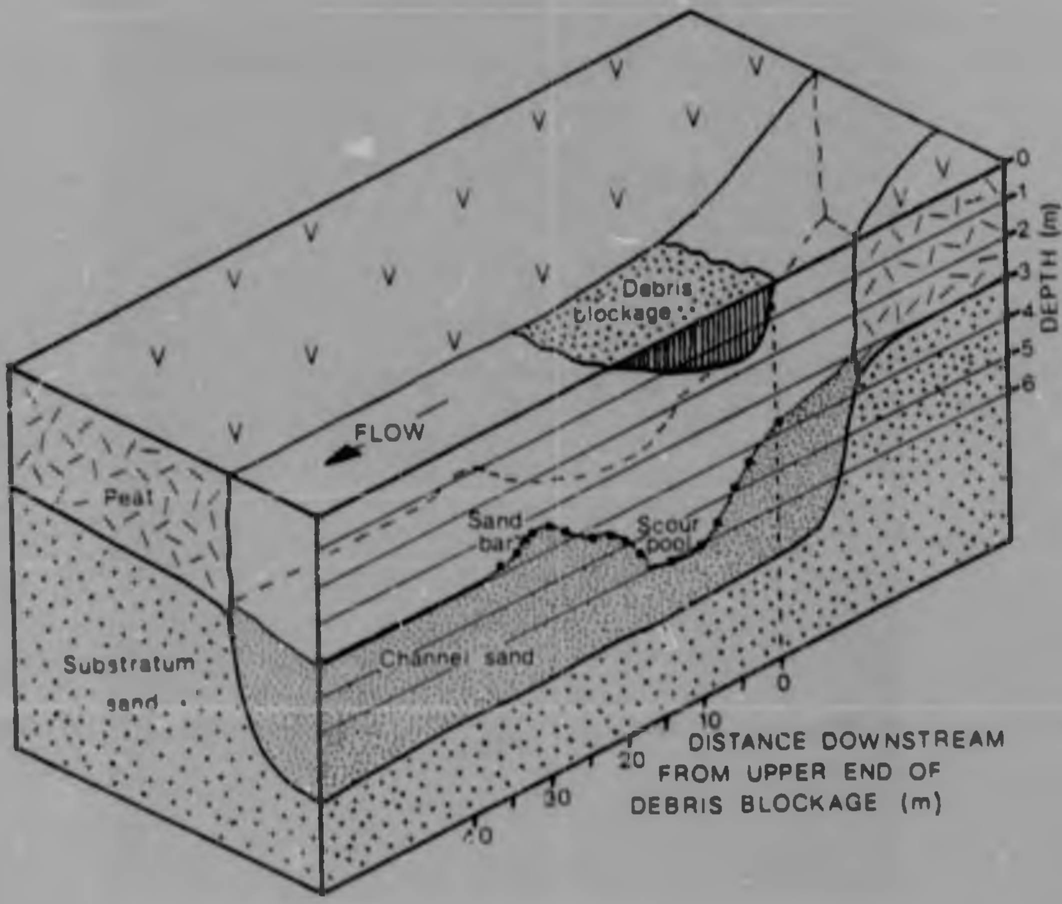


FIGURE 5.3 Scouring of the channel bed beneath a debris blockage accomadates water flow along the channel, and results in the formation of a sand bar on the downstream side

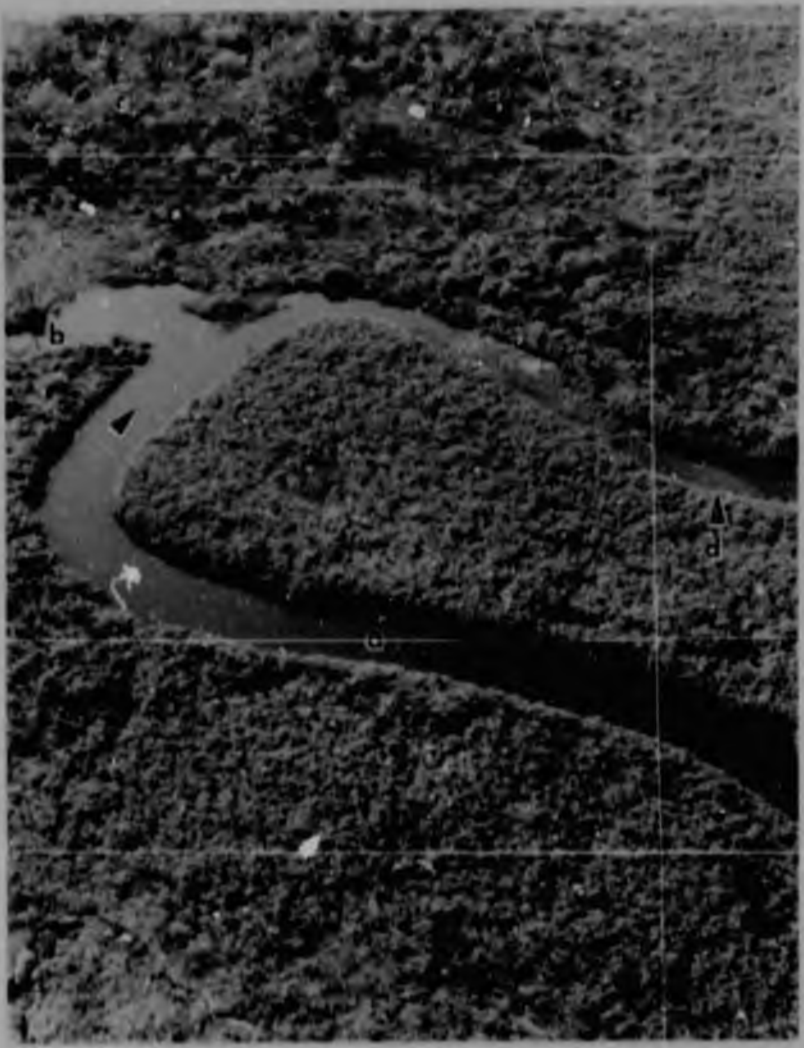
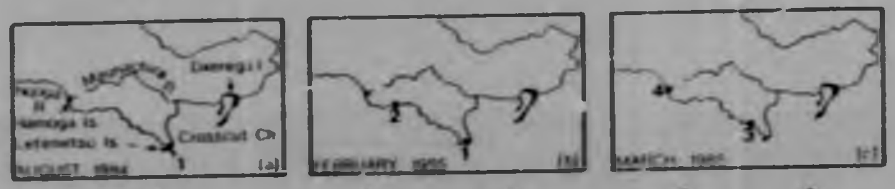


PLATE 5.1 A debris blockage downstream (arrow indicates flow direction) of the junction of the Nqoga river (a) and man-made channel (b) at Hamoga island (c), and the formation of a sand-bar (d) on the downstream side

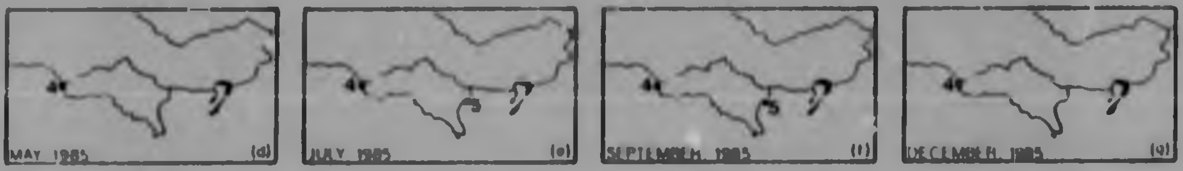


-Blockage number	1	1	2	3	4
-Length (m)	80	10,5	50	20	20
-Width (m)	20	20	20	15	20
-Depth (m)	>2	0,72	>2	>2	>2
-Shoot density (m^{-2})					
± std. dev.					
C. papyrus	c. 0,25*	4,33±1,03	0,23±0,06	0,26±0,09	5,21±0,10
V. cuspidata	c. 0,10*	11,00±2,14	0,11±0,08	0,08±0,06	0,10±0,06
P. australis	c. 0,05*	2,58±0,92	0,05±0,01	0,05±0,02	0,05±0,03

-Blockage number	4	4	5	4	5	4
-Length (m)	60	45	25	100	20	120
-Width (m)	20	20	12	20	12	20
-Depth (m)	>2	>2	>2	>2	>2	>2
-Shoot density (m^{-2})						
± std. dev.						
C. papyrus	0,20±0,09	0,23±0,14	0,26±0,11	0,24±0,11	**	0,25±0,12
V. cuspidata	0,[illegible]±0,02	0,09±0,05	0,05±0,03	0,10±0,05	**	0,11±0,05
P. australis	[illegible]±0,03	0,05±0,03	0,05±0,03	0,05±0,03	**	0,05±0,03

FIGURE 5.4 Positions, dimensions and shoot densities of all the plant species present on C. papyrus debris sudd blockages observed in August, 1984 (a); February, 1985 (b); March, 1985 (c); May, 1985 (d); July, 1985 (e); September, 1985 (f); and December, 1985 (g). * = estimates based on photographic evidence. ** = estimates not made due to a recent surface fire

	(a)	(b)	(b)	(c)	(c)
-Blocl.age number	1	1	2	3	4
-Length (m)	80	10,5	50	20	20
-Width (m)	20	20	20	15	20
-Depth (m)	>2	0,72	>2	>2	>2
-Shoot density (m^{-2}) ± std. dev.					
C. papyrus	c. 0,25*	4,33±1,03	0,23±0,06	0,26±0,09	0,21±0,10
V. cuspidata	c. 0,10*	11,00±2,14	0,11±0,08	0,08±0,06	0,10±0,06
P. australis	c. 0,05*	2,58±0,92	0,05±0,01	0,05±0,02	0,05±0,03



	(d)	(e)	(e)	(f)	(f)	(g)
-Blockage number	4	4	5	4	5	4
-Length (m)	60	45	25	100	20	120
-Width (m)	20	20	12	20	12	20
-Depth (m)	>2	>2	>2	>2	>2	>2
-Shoot density (m^{-2}) ± std. dev.						
C. papyrus	0,20±0,09	0,23±0,14	0,26±0,11	0,24±0,11	**	0,25±0,12
V. cuspidata	0,06±0,02	0,09±0,05	0,05±0,03	0,10±0,05	**	0,11±0,05
P. australis	0,05±0,03	0,05±0,03	0,05±0,03	0,05±0,03	**	0,05±0,03

FIGURE 5.4 Positions, dimensions and shoot densities of all the plant species present on C. papyrus debris sudd blockages observed in August, 1984 (a); February, 1985 (b); March, 1985 (c); May, 1985 (d); July, 1985 (e); September, 1985 (f); and December, 1985 (g). * = estimates based on photographic evidence. ** = estimates not made due to a recent surface fire

PLATE 5.2 A surface view of the *C. papyrus* debris blockage which formed in the Nqoga river at Letenetso island in August, 1984

Phragmites australis respectively. The area was subsequently visited six months later, at which time a blockage had formed in the channel between Hamoga and Letenetso islands (Fig. 5.4b). Its formation had prevented the addition of any further debris to the first formed blockage, which had shrunk to just 10,5m in length and 0,72m in depth (Fig. 5.4b). This must have been due to decomposition as well as the removal of some of the partly decomposed debris by the current. Despite this shrinkage, plant growth had led to its consolidation, to the extent that from the boat it was almost indistinguishable from the bank (Plate 5.3). *Cyperus papyrus* was present at a density of 4,3 culms.m^{-2} while *V. cuspidata* had increased to 11 shoots.m^{-2} and *P. australis* to 2,6 shoots.m^{-2}. The increase in shoot density of *V. cuspidata* was two orders of magnitude and in the case of debris blockages appears to be important in their initial rapid consolidation. *Phragmites australis* shoot density had a[illegible] increased by two orders of magnitude, but its lower initial density makes it less important as an early coloniser. The cul[illegible]nsity of *C. papyrus* increased by an order of magnitude. I[illegible] greater robustness however, would make it important in the long term consolidation of sudd blockages.

Despite the colonisation and consolidation of this blockage by vegetation, it had broken up entirely by the time of the next visit, as had the blockage which had formed upstream of it (Fig. 5.4c). A portion of the upper blockage had become lodged further downstream, and on the sampling date in March a blockage had formed at Hamoga island downstream of the man-made offtake (Fig. 5.4c). This continued to increase in size from 20m in length in March to 60m long in May (Fig. 5.4d), at which time there were no other blockages present in the study area. Its increase in size was due to the gradual addition of debris to its upstream end. A portion of its downstream end however, had become detached after May and was de-

PLATE 5.3 A surface view of the *C. papyrus* debris blockage at Letenetso island in February, 1985. Colonisation by plants made the blockage (a) almost indistinguishable from the bank (b)

posited in the Crosscut channel (Fig. 5.4e). The subsequent gradual increase in size of the upstream blockage was due to the continuous input of debris to its upstream side, while the shrinkage and eventual disappearance of the lower debris blockage was due to its decomposition, the removal of some of the debris by the current, in the absence of any addition of new material. It was not possible to estimate the densities of plants on this blockage in September due to the above-ground portions having been burned in a surface fire. The remaining blockages however, did not show a marked increase in shoot densities of the species which colonise them (Fig. 5.4c-g), this being a reflection of the continuous input of material to their upstream ends and the removal of material from their downstream ends.

The ephemeral nature of debris sudd blockages or of portions of them during the study period is attributed to decomposition processes which lead to a reduction in both their mass as well as their stability. Based on the decomposition experiments *C. papyrus* debris lost approximately 26% of its mass over a period of 26 weeks, (Fig. 5.5). The rate of mass loss typically declined progressively over time. Since most blockages did not remain intact for periods longer than 30 weeks, decomposition appears to be more important in breaking down rigid plant tissue which becomes soft and fluid with the waterlogging which follows initial decay. This leads to the collapse of the blockage which is broken up by the current and transported downstream.

5.4 The fate of debris: closure of Dxerga lediba

Aerial photographs of Dxerega lediba taken in 1969 and 1983 reveal that its mouth has shrunk considerably during this period. Comparison of the reduction in the surface areas of the portions of the

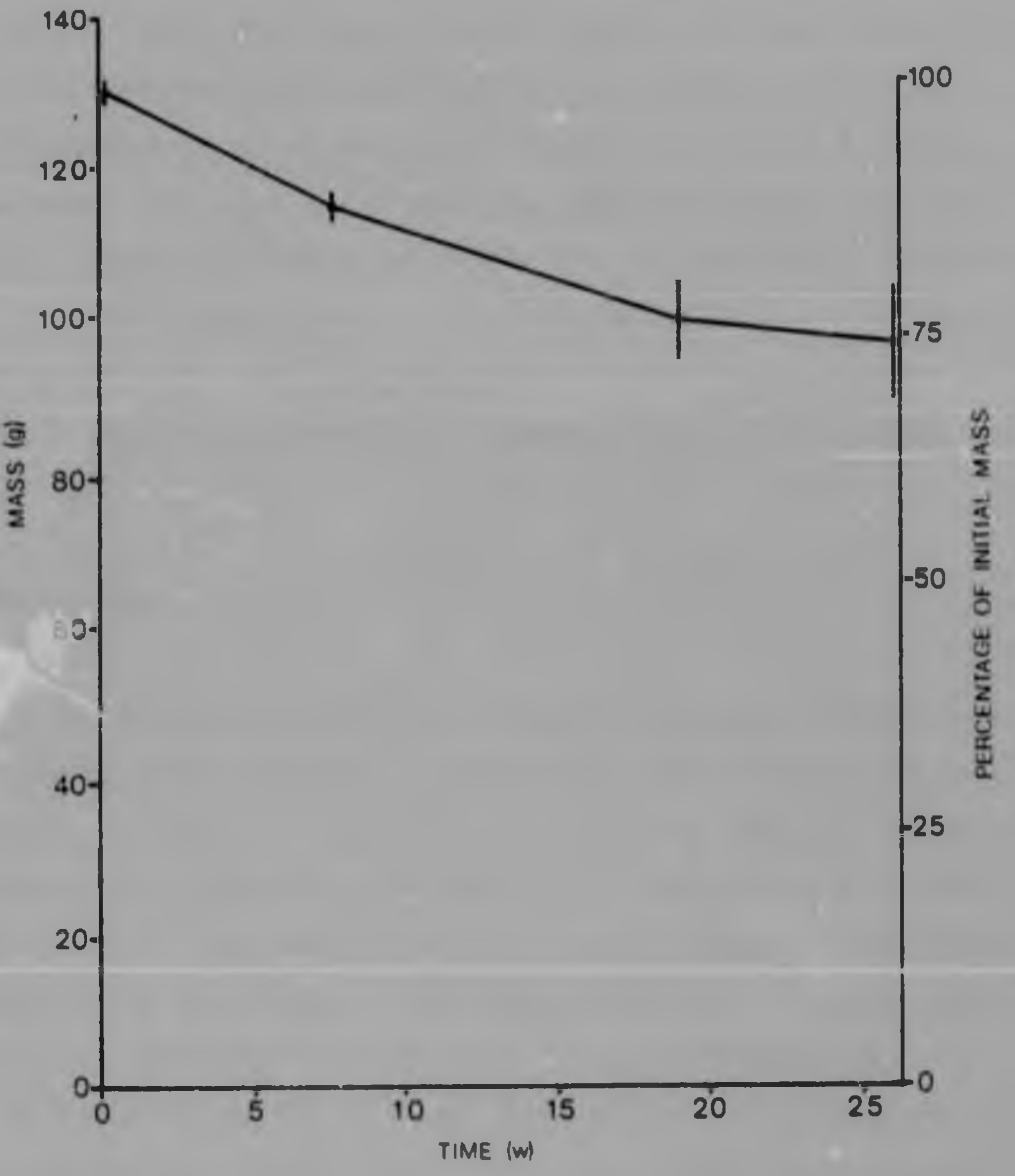


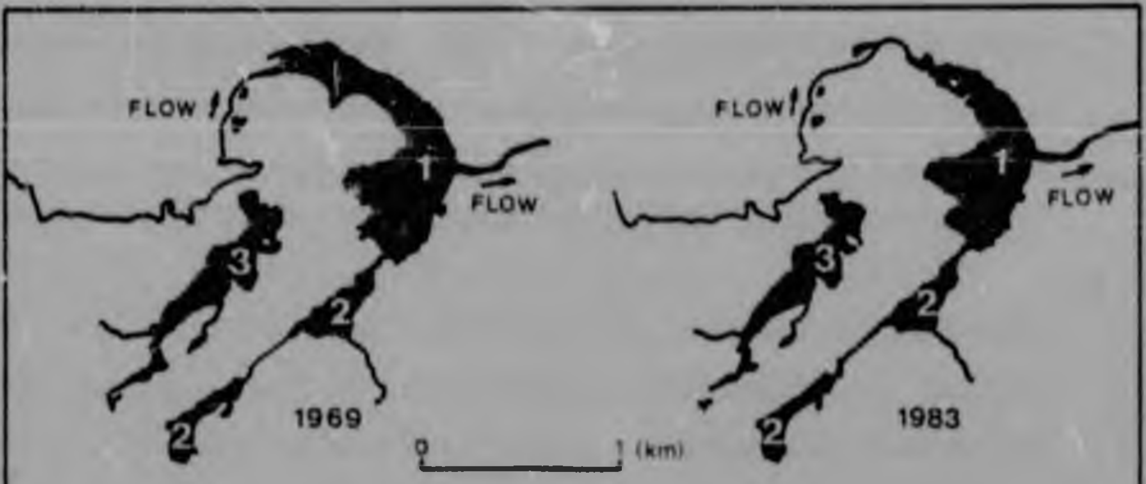
FIGURE 5.5 Decomposition of *C. papyrus* debris over a period of 26 weeks as indicated by the loss of mass (g) as well as a percentage of the initial mass. Vertical bars indicate standard deviations

lediba linked directly to the inlet channel, with those portions not linked directly to the inlet channel illustrates the contribution of vegetation debris to lediba shrinkage, as opposed to shrinkage caused by the more widespread processes of plant succession (Ellery, K., 1987). The surface area of the portion of the lake which is linked to the inlet channel had shrunk from approximately 43,8ha in 1969 to approximately 32,0ha in 1983 (portion no. 1; Fig. 5.6) which represents a 27% reduction. The areas not connected to the inlet channel, namely portions 2 and 3 (Fig. 5.6), have shrunk by 3% and 7% respectively. The greater shrinkage of the portion of the lediba which receives its water directly from the inlet channel appears to be due largely to the deposition of papyrus debris in the mouth of this lediba.

5.5 Discussion

During photosynthesis a variety of organic compounds are produced of differing molecular sizes, complexities, solubilities and resistances to decomposition. The more labile compounds are readily transformed by respiratory processes into the biomass of higher trophic levels and some is lost as carbon dioxide. The more refractory compounds persist for longer periods and are either exported from the system or else accumulate in particulate and dissolved form (Rogers, 1983). Swamp ecosystems are recognised to be net exporters of organic matter, and the rivers draining swamp watersheds are responsible for the export of large quantities of organic carbon (Mulholland & Kuenzler, 1979; Mulholland, 1981).

The extent of removal and transport of *C. papyrus* from the channel margins of major distributaries of the Okavango Delta appears to be related to current velocity, and illustrates the importance of attributes of the hydrological regime in determining rates of organic



Surface Area (ha)

Area no. 1 = 43,8
Area no. 2 = 14,5
Area no. 3 = 19,8

Surface area (ha)

Area no. 1 = 32,0
Area no. 2 = 14,1
Area no. 3 = 18,4

FIGURE 5.6 Shrinkage of the surface area of Dxerega lediba in the portion linked to the inlet of the Maunachira river (1) as well as in the portions not linked directly to the inlet (2 and 3) based on aerial photographs taken in 1969 and 1983 matter export. In other African lakes and rivers seasonal fluctuations in the water level cause the detachment of floating islands of *C. papyrus* from their margins (Thompson, 1985) and these may be transported downstream. Newhouse (1929) observed an increase in the numbers of floating papyrus islands in the upper Nile swamps during periods of peak discharge, and a similar phenomenon has been recorded in the Lualaba river in Zaire (Thompson, 1976b). The lodgement of papyrus islands and rafts in rivers and channels has been widely reported as being an obstacle to navigation, but only in the Okavango swamps have they been considered to cause channel avulsion by becoming rooted in the channel beds (Brind, 1955; Grove, 1969).

The vegetation blockages within the study area are surface phenomena, and appear to have little effect on flow conditions. Furthermore, they appear to be short-lived under the present hydrological conditions. The term 'blockage' with respect to the floating rafts of debris which become lodged in the channels of the Okavango Delta is therefore not considered entirely appropriate. The Arabic word 'sudd' was originally used to describe floating papyrus rafts which became lodged in the channels of the 'Sudd' region of the Nile river. It has since been used to describe any floating mat of vegetation (Thompson, 1985), and the term is presently used in this context. The term 'channel sudds' as a descriptive term for the rafts of debris which become lodged within the channels of the Okavango Delta is therefore considered more appropriate.

Under the present hydrological regime in the active portion of the lower Nqoga river, channel sudds cause scouring of the channel floor. Furthermore they become increasingly unstable over time and eventually appear to be broken up by the current. Brind's (1955) description of the development of a blockage on the Thaoge river, in which, *under conditions of very low flow*, a previously floating mat of *C. papyrus* became rooted in the channel floor (my own underlining), supports the present view that the development of permanent *C. papyrus* blockages (Brind, 1955; Grove, 1969; Wilson, 1973) are a consequence and not a prior cause of reduced flows. In his consideration of channel abandonment Wilson (1973) raised an important question namely, why does a channel system which for decades remained clear, suddenly start to block with vegetation? The present study has provided sufficient evidence for the development of a conceptual model for channel avulsion, which has been supported by several visits to the abandoned lower Nqoga river (McCarthy et al; in press a).

CHAPTER 6

DISCUSSION

Channels within the study area which are considered most prone to blockage and abandonment appear least subject to encroachment by the dominant fringe species *Cyperus papyrus* under the present hydrological regime. Furthermore, it is evident that although channel sudds are largely restricted to those channels which are most prone to blockage and abandonment, they are surface phenomena, and do not appear to have a large effect on hydrological conditions. They are also short-lived, and under the present hydrological regime do not appear capable of rooting in the channel bed as described by Brind (1955). It is therefore suggested that the vigorous growth habit of papyrus, and the development of channel sudds within those channels which are in the process of blockage and abandonment (Smith, P.A., 1976), are symptoms but not the cause of channel deterioration.

The description and classification of channels within the study area (Chapter 3) has been particularly valuable in providing a basis for the evaluation of processes which may be important in channel blockage and abandonment. These include the confinement of rapid flow, and bed-load deposition to in-channel areas.

6.1 Vegetation growth and the confinement of flow, erosion, and bed-load deposition to within channels

Within the study area, channel planform geometry appears to be regulated by the interactions between plant growth and current velocity. Based on the present study there does not appear to be any evidence that channel banks dominated by *C. papyrus* are being significantly eroded ($p=0,95$) by the current, even in those plots in the channel margin which are subjected to relatively high current velocities (greater than $0,4m.s^{-1}$). In a study by Smith, D.G. (1976) in Alberta, Canada, the reduction of erosion of channel banks by plants has been quantitatively demonstrated to be related to the root volumes of plants rooted in the banks. In the margins of channels in the study area, the reduction of erosion of the channel banks also appears to be related to the extension of papyrus rhizomes at different distances out from the banks, and at different depths, as these reduce current velocities within the channel margins themselves. These factors appear to account for the long-term (decades) stability of channels reported by Wilson (1973).

One of the consequences of the presence of erosion resistant channel banks in the channels in the study area is the confinement of erosion of the channel bed to in-channel areas. This is evident in the channels which do not receive a large sediment supply from source areas, namely the Maunachira river downstream of Dxerega lediba. Channels upstream of Dxerega lediba however, receive sediments from source areas via the Okavango river. The confinement of these sediments to the channels appears to have resulted in the aggradation of the channel bed of the Nqoga river as illustrated by the gradual rise in water level at both Gaenga (McCarthy et al., 1986b) and Hamoga (Fig. 3.3) islands.

In terms of channel morphology and sediment transport, the channels in the study area bear some resemblance to the anastomosed channels of the Alexandra river in Banff, Alberta, Canada, which have been described by Smith & Putnam (1980), Smith & Smith (1980) and Smith (1981). An anastomosed river is defined as a system comprising an interconnected network of low-gradient, relatively deep and narrow, straight to sinuous channels composed of stable banks of silt, clay and vegetation (Smith & Putnam, 1980). Deposits result from vertical aggradation within the channel (Smith & Putnam, 1980), rather than from the lateral migration of the channel system as a whole as is the case in meandering systems (Friedman & Saunders, 1978). Vertical aggradation of the channel bed of channels in the Okavango Delta which receive sediments from source areas, appears to be accompanied by the vertical accretion of the papyrus dominated banks. The combination of these 2 processes is considered to contribute to channel avulsion, and has been the basis for the proposal of a conceptual model which has been developed in conjunction with members of the Geology Department of the University of the Witwatersrand (McCarthy et al., 1986b).

6.2 A model for channel avulsion in the Okavango Delta

Much of the water entering the Okavango Delta is lost from the channels by overspill and seepage through the vegetation flanking the channels (Wilson & Dincer, 1976). This is accompanied by a downstream decrease in the channel width (Wilson, 1973), as well as a decline in the ability of channels to transport bed-load sediments (McCarthy et al., 1986b). As they cannot escape due to the presence of vegetated peat banks, these sediments are deposited within the channels, and lead to the aggradation of the channel beds.

Overspill promotes plant growth on the channel banks due to increased nutrient supply, and the aggradation of the channel bed is accompanied by aggradation of the channel flanks. The formation of such vegetation levees results in the channel becoming progressively raised relative to its surroundings (Fig. 6.1). This leads to a steepening of hydraulic gradients at right angles to the channel

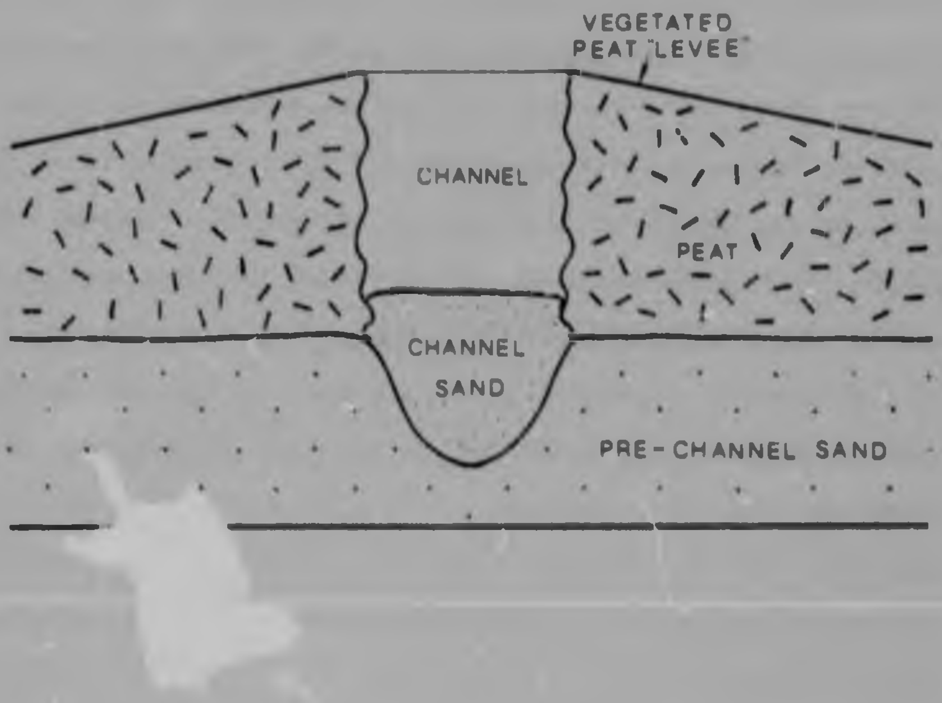


FIGURE 6.1 A cross-section of a mature channel showing the distribution of sand and peat (from McCarthy et al., 1986b)

axis. Water shed laterally from the aggrading channel through the flanking vegetation will seek out new paths, which may be provided by hippopotamus trails (Stigand, 1923). Water entering such a path will be free of bed-load sediments, and given a suitable hydraulic gradient, will begin to erode a new channel.

At some stage channel sudds form in the deteriorating channel. Extensive encroachment by *Vossia cuspidata* is a further indicator of channel deterioration. The channel sudds that form are initially short-lived due to decomposition processes, and the removal of undecomposed plant material by the current. As larger volumes of water are diverted to the new channel, current velocity in the old channel declines, and channel sudds become more permanent. Eventually they become sufficiently consolidated to 'block' the channel. The continuous input of debris to the semi-abandoned river course at this stage results in the progressive upstream invasion of the river by plants, and the formation of a 'channel blockage' such as has been described in the case of the Thaoge river during the last century (Brind, 1955), as well as the abandoned section of the lower Nqoga river (Wilson, 1973). Once this stage is reached, bed-load sediments enter the new channel and a new cycle of aggradation begins.

6.3 Conclusions

In the light of all the information available, the conceptual model appears to satisfactorily account for the process of channel blockage and abandonment which occurs at an interval of approximately every 100 years. The model is conceptual, and has not yet been directly tested or verified. A regional study including the Okavango, Nqoga and Maunachira rivers, in which hydrological characteristics, sediment transport, channel elevations relative to the surrounding swamps, elevations of the channel beds relative to the sands flanking the channels and the vegetation distribution and growth characteristics within and flanking channels are investigated, would contribute greatly to an understanding of the importance of each of these processes in channel avulsion.

In addition to such a regional study, the question of the differences in the distribution and growth characteristics of *Cyperus papyrus* within the Nqoga and Maunachira river systems requires further investigation. Is the downstream decrease in papyrus stature and productivity simply due to the more recent invasion of the Maunachira river system by this species as suggested by Smith P.A. (1976), is it related to current velocity, or is there a systematic downstream decrease in the concentration or availability of one or more essential plant nutrients? Such a downstream change in water quality was reported in the swamps of the White Nile river in the Sudan (Talling, 1957), but the author did not record the effects of this on the distribution and dynamics of the biotic component of that system. The effect of plant communities in the upper reaches of the Delta, particularly the filter communities described by Wilson (1973) and Smith P.A. (1976), appear to be important in determining the distribution and dynamics of the biota further downstream, and therefore to exert a major influence on ecosystem functioning.

A question of a more theoretical nature which arises as a result of this study, regards the consequences of desiccation in the region of abandoned channels, as well as the increased flooding in the region of newly formed channel systems. Peat formation constitutes a nutrient sink (Moore & Bellamy, 1974) and within the recently inundated Maunachira river system, plant succession and the formation of peat therefore leads to the storage of a large nutrient pool. Upon desiccation subsequent to abandonment, subsurface peat fires destroy the former peat deposits. This has been recognised to produce a flush of nutrients (Tallis, 1983), the benefits of which were recognised by Stigand (1923) who observed peat fires in the region of Lake Ngami in 1915. When he visited the same area again in 1922, he recorded that a hard soil had been produced on the floor of the former lake, and that this had formed a smooth, lush "golf-course-like" flat covered with grass. The question regarding the consequences of channel avulsion for the functioning of the ecosystem as a whole is one that is worthy of pursuit, particularly from the point of view of the future management of the Okavango Delta as a whole. If it is recognised that the blockage and abandonment of channels within the Okavango Delta is an important aspect of the maintenance of a diversity of habitats in different stages of wetting and drying, then the functioning of the ecosystem as a whole would be detrimentally affected by stabilising the hydrological regime. Furthermore, an increase in the rate of change of channel switching by increased bed-load sediment transport, which could accompany development of the catchment for example, may also be detrimental to the ecosystem as a whole.

The present study has not only contributed to an increased understanding of the causes of channel blockage and abandonment, but it has also provided some insight into the key determinants and processes of ecosystem functioning, and highlighted these for future research. In the case of the Okavango Delta, it is evident that to an extent the adage of Alphonse Karr is applicable; "The more things change, the more they stay the same".

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