Indicators of desiccation-driven change in the distal Okavango Delta, Botswana

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Abstract

This work seeks to determine whether riparian woody plant variables respond to drying and salinity regimes in the semi-arid distal Okavango Delta, northern Botswana. Structural and compositional variables were obtained from 47 field sites. Mapping using satellite imagery illustrated differences in the character of riparian zones in terms of species composition and provided data on flood frequency. Salinity data plots show increases downstream. Results imply that woody plant variables respond to desiccation-driven change due to water-table lowering (reduced recharge) and increased salinization through distinct changes in tree and shrub height, plant density and species richness. In the wetter, intermediate distributaries, key biotic indicators of ecosystem change comprise structural variables such as decreases in canopy cover per cent and tree height and increases of shrub height, which are indicative of mainly ground-water declines. Biotic indicators in the less frequently flooded receiver channels comprise plant density and species richness increases involving mainly brackish ground-water-tolerant and dryland species which are indicative of both ground-water declines and/or salinization. These indicators could provide useful parameters for use in long- and short-term monitoring aimed at assessing desiccation-driven change in different parts of the Okavango Delta and possibly other semi-arid wetlands. The indicators are important as a less-expensive alternative to drilling as a means of verifying ground-water declines and/or salinization.

Keywords: Semi-arid riparian zones; Compositional and structural variables; Water-table lowering; Salinization

1. Introduction

This work aims to identify and map the distribution of riparian woody species in the broad context of decreased levels of flow (resulting in ground-water lowering) and trends in increasing salinity in the distal Okavango Delta. Specifically the work seeks to determine how woody plant variables are responding to desiccation-driven change. The so-called Delta

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is an under researched semi-arid alluvial fan in northern Botswana, with a water surface area of about 8500km2 incurring evapo-transpiration (ET) losses through the woody riparian vegetation cover of up to 85–90% of the entire wetland water loss (e.g. Dincer et al., 1987; SMEC, 1987; Ringrose et al., 1988, 2003a; McCarthy and Ellery, 1994). Surface water evaporation and ET from floodplain vegetation leads to a shift in ionic spectrum from calcium–sodium–bicarbonate at the Delta inflow, to sodium–calcium– bicarbonate in distal areas (Cronberg et al., 1996). Riparian rims prevent the flooding of riparian zone woody species which persist above the flood level and are sustained by ground-water. As flow throughout the Delta has been recently declining in volume and extent, it is probable that the semi-deciduous riparian zones were developed historically during periods of higher flow levels, such as those resulting from higher than average rainfall during the early 1970s (cf. Aston and Neale, 2002). Drying takes place as a result of natural cyclical processes but is locally exacerbated by off take upstream and/or changes in flow patterns as a result of channel blockages or neotectonic events (summarized in Ringrose et al., 2003a). This has led to distinct changes in soil chemistry in both the floodplains and riparian rims (Huntsman-Mapila et al., 2003).

Long-term ecological monitoring frequently uses remotely sensed data as part of overall monitoring regimes, although this is frequently applied in conjunction with ground-based data. Recent work on the value of remotely sensed data to assess parameters of ecological significance has been discussed in Kerr and Ostrovsky (2003) and Turner et al. (2003) with lidar systems appearing particularly promising for vegetation structure mapping (Lefsky et al., 2002). Where ground-water occurs close to the surface it may be co-incident with particular patterns of tree growth, assuming that the natural vegetation cover has not been disturbed (e.g. Meyboom, 1967; Ringrose et al., 1997, 1998). The need to obtain long-term data is crucial to our understanding of environmental change, as it informs management especially in sensitive, semi-arid wetlands (e.g. Gosz, 2000; Andersson et al., 2003; Junk, 2003). In the literature the effects of drying have mainly been reported as they relate to decreases in crop production (e.g. Williams et al., 2002) with relatively little work assessing the impacts of drying in naturally vegetated semi-arid watercourses. Changes in structure (trees to shrubs) and function (water use) may be assessed in complex natural ecosystems through the use of biotic indicators (Papadimitriou, 2002) such as changes in species composition. However ecosystem complexity especially evidenced in wetland environments needs to be reduced to a few key variables in order to facilitate monitoring (Cole, 2002).

This work aims to provide preliminary information directed towards mapping the distribution of riparian woody species and developing data on species composition in the distal Okavango Delta. The overall aim is to establish relationships between Delta drying (manifesting as ground-water lowering and/or salinity increases) and downstream species and compositional changes, in order to demonstrate how woody plant variables are responding to desiccation-driven change. Once identified, relevant desiccation indicators are proposed for use in long- and short-term monitoring.

2. Study area

The study area covers part of the drier distal reaches of the Okavango Delta, characterized by riparian rims surrounding remnant islands adjacent to major floodplains (Fig. 1). The Delta is located in the northern Botswana Kalahari sands and comprises a series of dispersed distributaries, a sub-sample of which are analysed in the present work (Fig. 2). The study area covers 4403km^2, has a mean annual rainfall of 453mm (range ca. 444–472 mm) and a Class A pan evaporation rate of about 2700mmyear^{-1} (range ca. 2100–3005mmyear^{-1}) (SMEC, 1987). In a downstream direction the Delta comprises areas of permanent swamp, followed by floodplains incurring seasonal and intermittent flow and extensive dry former floodplains in the distal zone. The flow extent is at its maximum in August, having taken 6 months to drain from the central Angola highlands, some 800 km to the north. Floodwaters pass through the distal Delta using a series of low

Fig. 1. Woodland riparian zones and adjacent shrubland in the distal Delta (Gomoti distributary).

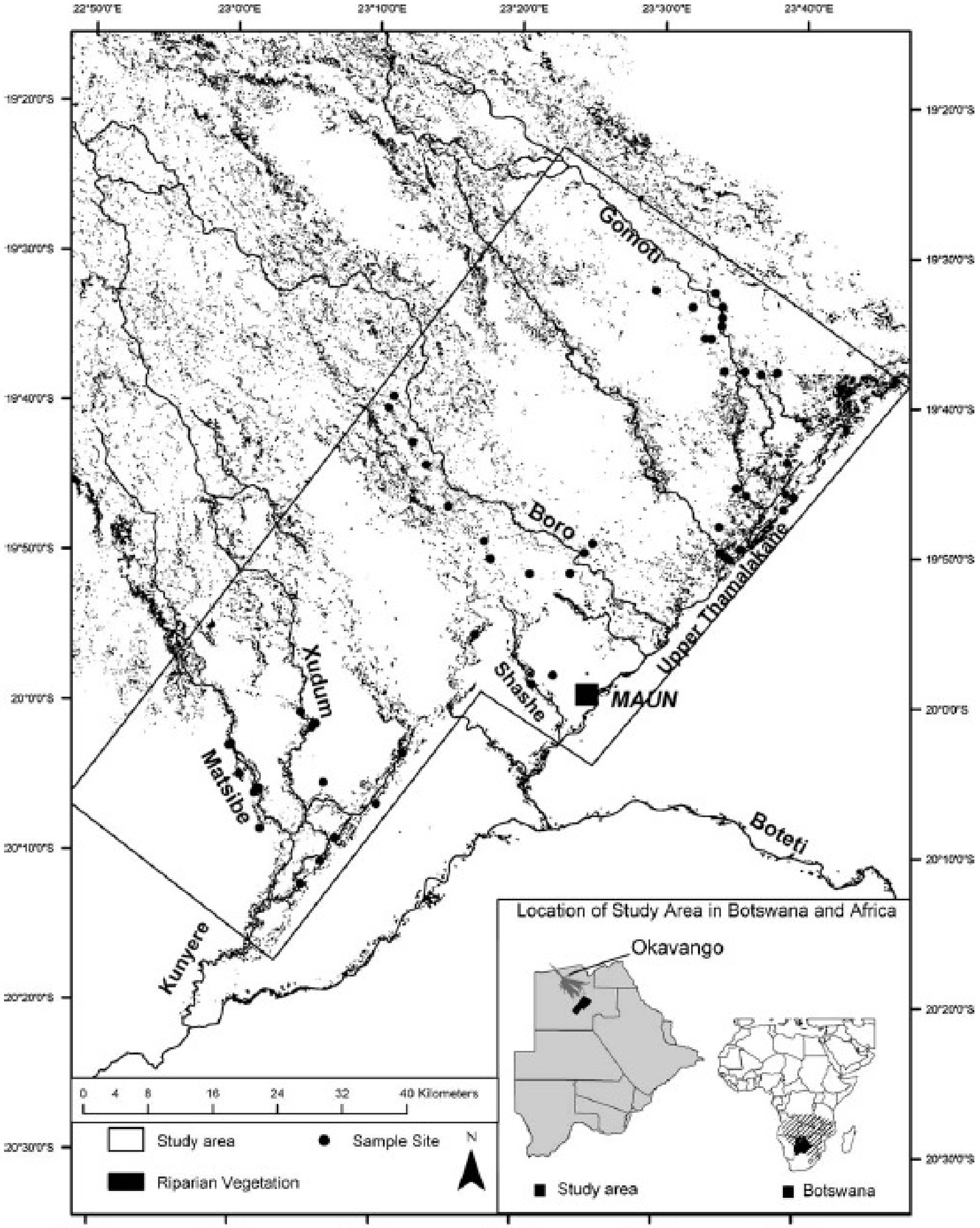


Fig. 2. Study area and mapped spatial extent of distal Okavango Delta riparian zones in northern Botswana from Enhanced Thematic Mapper imagery. The intermediate distributaries terminate at their confluence with the receiver channels. The extent of the Zambezian vegetation zone is shown on the inset map.

flow anastomosing intermediate distributaries which feed into faultline-controlled receiver channels towards the terminus of the Delta during high flow years. The exoreic drainage continues during high flow years towards the Makgadikgadi Pans. Groundwater sustained riparian zones occur peripheral to the main distal distributary systems. The floodwater passes laterally under the riparian rims as ground-water seepage (Wolski and Savenije, 2006). The riparian woodlands extend 100–1000m landward and are elevated on island rims 1–4m above the adjacent floodplains. The riparian substrate comprises rich humic fine sandy soils under dense woody cover in their upstream portion with humic poor, calcareous sandy soils under sparser cover downstream. While ground-water from the annual flood is essential for riparian woodland sustainability, the contribution of seasonal rainfall is also important as some woody species appear to fruit and flower in response to flooding while others respond to the onset of the summer rains (Ringrose, 2003). The woody riparian species are not unique to the Delta but are endemic to the semiarid mid-Kalahari portion of the Zambezian province of southern Africa (Africa shown as grey shading on the inset Africa map in Fig. 2) (White, 1983; Cowling and Hilton-Taylor, 1994).

3. Methods

Riparian zones adjacent to seven distal distributaries (the Gomoti, Boro, Shashe, Xudum, upper Thamalakane, Matsibe and Kunyere) were mapped using image interpretation processing techniques (Jellema et al., 2002). The mapping involved supervised classification using Landsat Enhanced Thematic Mapper (ETM+) imagery from April, 2000. The ETM+ instrument provided image data from eight spectral bands with a spatial resolution of 30m for the visible and near-infrared (bands 1–5 and 7) which comprised the six bands used in this work. The approximate scene size is 170 x 183 km. The image was supplied at (Level 1G) comprising Systematic Correction of both radiometric and geometric attributes. The image data was sampled as 8-bit unsigned integer values. The original image was geometrically corrected on the basis of Global Positioning System (GPS) collected ground control points resulting in an accuracy of 100m or better.

The image (located on path 174 row 074) was classified using the maximum likelihood classifier in Erdas Imagine 7.6 (Erdas, 1999). Information used in the acquisition of training sites included video imagery, over-flights and field location data. Supervised classification required the development of signature files for all vegetation classes in the distal Delta. Specifically this involved the development of vegetation-type files which were taken from all observable reflectance categories (Erdas, 1999; Foody and Culter, 2002; Jellema et al., 2002). Once a point (or series of points) was selected, the region growing tool was applied to ensure spectral homogeneity and spatial continuity of the training sets. Riparian zones were specifically targeted for this work and it was noted that their reflectance properties differed throughout the distal Delta. The maximum likelihood classifier was first run through a feature space sub-routine (non-parametric rules) and resulted in 44 separate vegetation classes over the entire image. The spectral integrity of each class was checked by using class histogram procedures in Erdas. The amount of noise over the classified image was reduced through the use of a 3 x 3 majority filter. Once complete, the riparian zone classes were excised from the remaining vegetation cover for the present analysis. Data from field transects were added to affect class interpretation, particularly with respect to species content (cf. Ringrose and Matheson, 2001). Limited use was made of vegetation indices (VIs) to further amplify relationships between mapped vegetation cover and spectral characteristics (cf. Lillesand and Kiefer, 1994). While VIs vary in their complexity, positive use in Botswana has been derived from the use of simple ratios often involving the red and near infrared bands (Moleele et al., 2002; Ringrose et al., 2003a). The TM4/3 vegetation index was applied as it uses a combination of near infrared (TM4) and red (TM3) reflectance to indicate the vigour of plant growth.

Field transects were developed perpendicular to the linear riparian woodland from the floodplain margin, during 1999–2000. At each site, three 90m transects were paced along a compass bearing perpendicular to the floodplain margin at 5 km intervals. The unit area of the three transects comprising one field site is 8100m2 (cf. Ringrose and Matheson, 1991). Data from 47 sites included the recording of all woody species types, canopy extent and tree and shrub height along each of the 90m transects. Canopy extent was calculated from the canopy diameter which was measured under specific trees. Species identification resulted in species lists of woody cover being systematically developed (cf. Tiner, 1999). Tree height was calculated using geometrical procedures while shrub height was measured using a vertically held tape (Kent and Coker, 1996). The differentiation of trees and shrubs is taken here at the 4.0m limit, as described in Setshogo and Venter (2003). Canopy cover percent is the total measured canopy per site area. The calculation of plant density and species richness included all the species at a given site, divided into site area (Rebelo, 1994). The recruitment index was calculated as the total number of species-specific shrubs (same species recruits of the tall riparian trees) divided into the total number of riparian trees of the same species, per site.

Flow frequency mapping was undertaken to determine the extent to which floodplains adjacent to study area riparian zones were recharged over a 15 year period (cf. Wolski et al., 2003). This procedure was necessary because of the absence of gauge data on the distributaries and because recently formulated long-term drying trends apply to the Okavango Delta as a whole and not to individual distributary systems (Aston and Neale, 2002; Ringrose et al., 2003a). NOAA-Local Area Coverage imagery from 1985 to 2000 was used for this analysis (cf. Remboldt et al., 2001). The NOAA images were georectified using standard image-processing techniques (e.g. Erdas, 1999) and classified by applying supervised procedures into flow/no flow classes. Flow maps were stacked to give a representation of maximum flow area for each of the analysed years. The number of flow years was determined for each pixel and the flow frequency map obtained by dividing the number of flow years by 15. This was converted to flow frequency percentage. Further details regarding the sequential flow cycles are available in Gumbricht et al. (2004a).

Ground-water electrical conductivity (EC) data were taken from the limited existing measurements along the major distal distributaries. Samples were taken from 10 to 60m depth immediately following the drilling of observation and pumped wells in the floodplains adjacent to the riparian zones (Republic of Botswana, 2003). Data were derived from two main sources, an older data set (1975–2002) involving a number of pumped boreholes in which some mixing of the fresh and saline aquifers may have taken place, and younger data sets (2003) based on observation wells where drilling stopped at the first water surface, which was often fresh. The ground-water rest level was also recorded. The data were plotted in ARC/GIS to determine whether relationships could be established between EC data and deep rooting tree species in the riparian zones using a 4 km buffer around the boreholes.

Statistical analyses associated image data, flow frequency, salinity and riparian structural and compositional variables (SPSS statistical software; Norusis, 2002). Pearson and Spearmans rank correlation techniques were both used to assess the likelihood that riparian structural and compositional data could be resolved into specific drying response characteristics. Factor analysis was applied using interval scale compositional and structural variables to identify underlying factors which explain the pattern of correlations within the set of observed normally distributed variables (Zar, 1999). Data reduction procedures were required to identify a small number of factors that explain most of the variance observed. The methods used involved principal component analysis as the method of data extraction with no rotation and one tailed significance testing to provide feasible distance measures for feature separation.

4. Results

4.1. ETM+ imagery and field data analysis

The classification of ETM+ image 174-074 led to the sub-division of the distal Delta study area into 44 vegetation classes from which two major riparian zones were excised. These two comprise the wetter, intermediate distributary riparian zones characterized by mixed *Acacia nigrescens* Oliver (Mimosoideae)/*Combretum imberbe* Wawra (Combretaceae) woodlands in association with *Combretum imberbe/Lonchocarpus capassa* Rolfe (Papilionoideae) woodlands and shrublands. Their common names are Knobthorn/Leadwood woodlands which were mapped in association with Leadwood and Raintree woodlands and shrublands. The second major riparian zone class is located along the drier receiver channels and is characterized by mixed *Combretum hereroense* Schinz (Combretaceae)/*Croton megalobotrys* Meuell. Arg. (Euphorbiaceae) woodlands and shrublands (Fig. 3). In terms of their common names these are Russet Bushwillow/ Feverbush woodlands and shrublands. The extent of these different riparian zones within the distal Delta study area is mapped as 155.4 and 191.7km^2 respectively. The accuracy of the classification was checked by comparing the spatial distribution of classes with aerial photography. The accuracy levels attained reached 73–75% overall producers–users accuracy, with the accuracy for the two riparian zone classes standing at 88% users accuracy and 73% producers accuracy. The reason for the variability in accuracy levels results from the fact that the digital values of riparian woodlands are similar to those of emergent macrophytes and dense dryland vegetation cover, leading to class overlap. However, the accuracy levels attained are generally regarded as being acceptable in terms of conventional remote-sensing analyses (cf. Foody and Culter, 2002).

4.2. Flow frequency and electrical conductivity analysis

Flow frequency analysis was conducted using NOAA imagery over the entire Delta for the period 1985–2000. The results show that flow in distal distributary floodplains varies considerably both in time and in space (Fig. 4). Annual flow is important in this context as it recharges the ground-water table by lateral seepage under the floodplains and adjacent levees to the riparian root zone to an average depth of 4–8m (cf. Ellery and Ellery, 1993; Ringrose, 2003, Wolski and Savenije, 2006). Because of recent trends towards enhanced drying, downstream reaches of the Delta experienced little or no flow between 1985 and 2000. In the intermediate distributaries river flow occurred between 20% and 50% of the time, although only the Boro River experienced flow during 8 years between 1985 and 2000. The other intermediate distributaries (namely the Gomoti, Xudum and Matsibe Rivers) were inundated up to 20% of the time in their upstream reaches during the 15 years

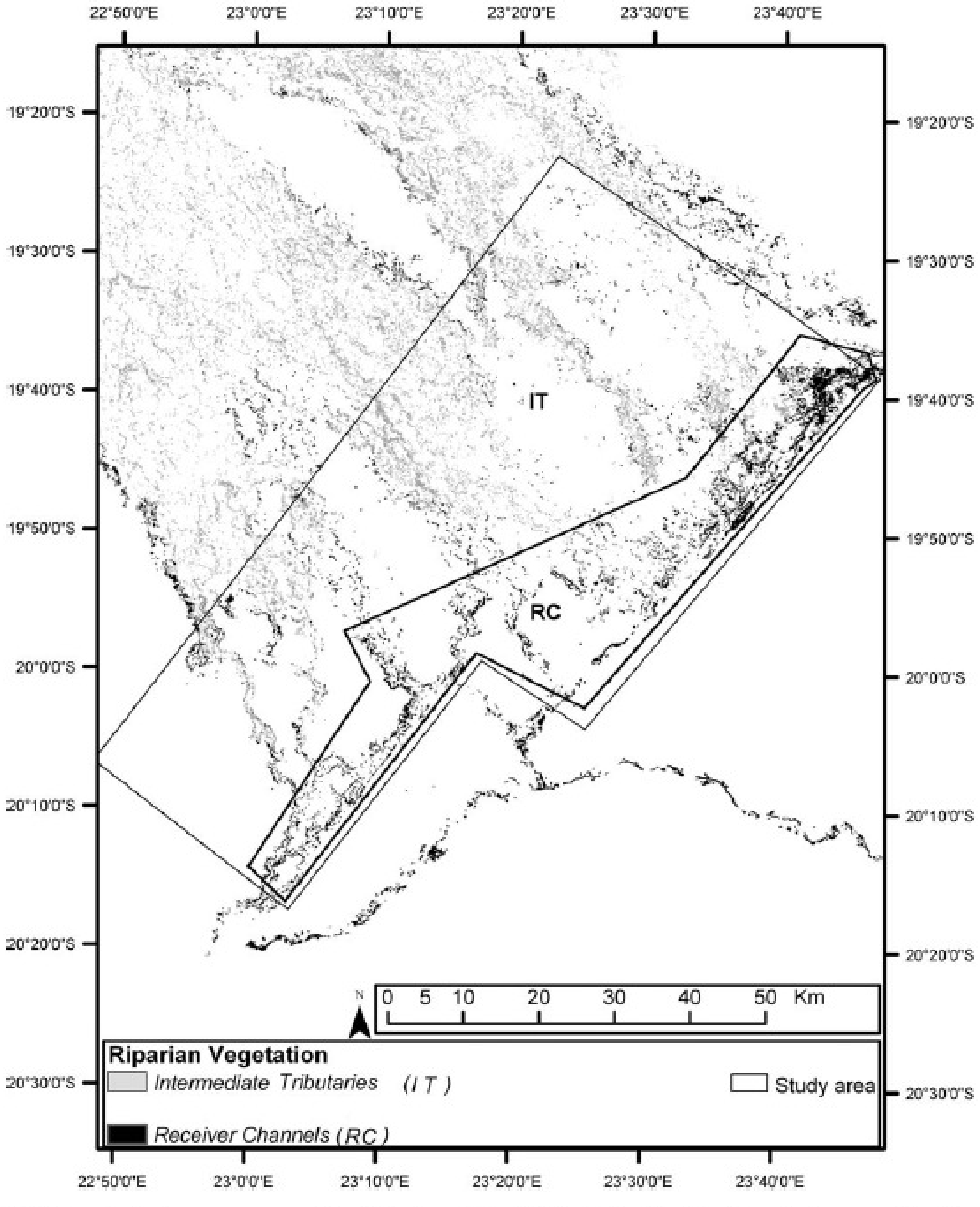


Fig. 3. Mapped riparian zones comprising (in intermediate distributaries-IT) mixed *Acacia nigrescens*/*Combretum imberbe* woodlands in association with *Combretum imberbe*/*Lonchocarpus capassa* woodlands and shrublands and (in receiver channels-RC) mixed *Combretum hereroense*/*Croton megalobotrys* woodlands and shrublands.

under consideration. The terminal receiver channels (the Shashe, upper Thamalakane and Kunyere Rivers) obtained significantly less water as flow events occurred only 0–10% over the 15 years. Hence fresh ground-water recharge under most of the riparian zones in the distal Delta is infrequent but varies throughout the distributaries under consideration with recharge water recurring more frequently in the intermediate distributaries.

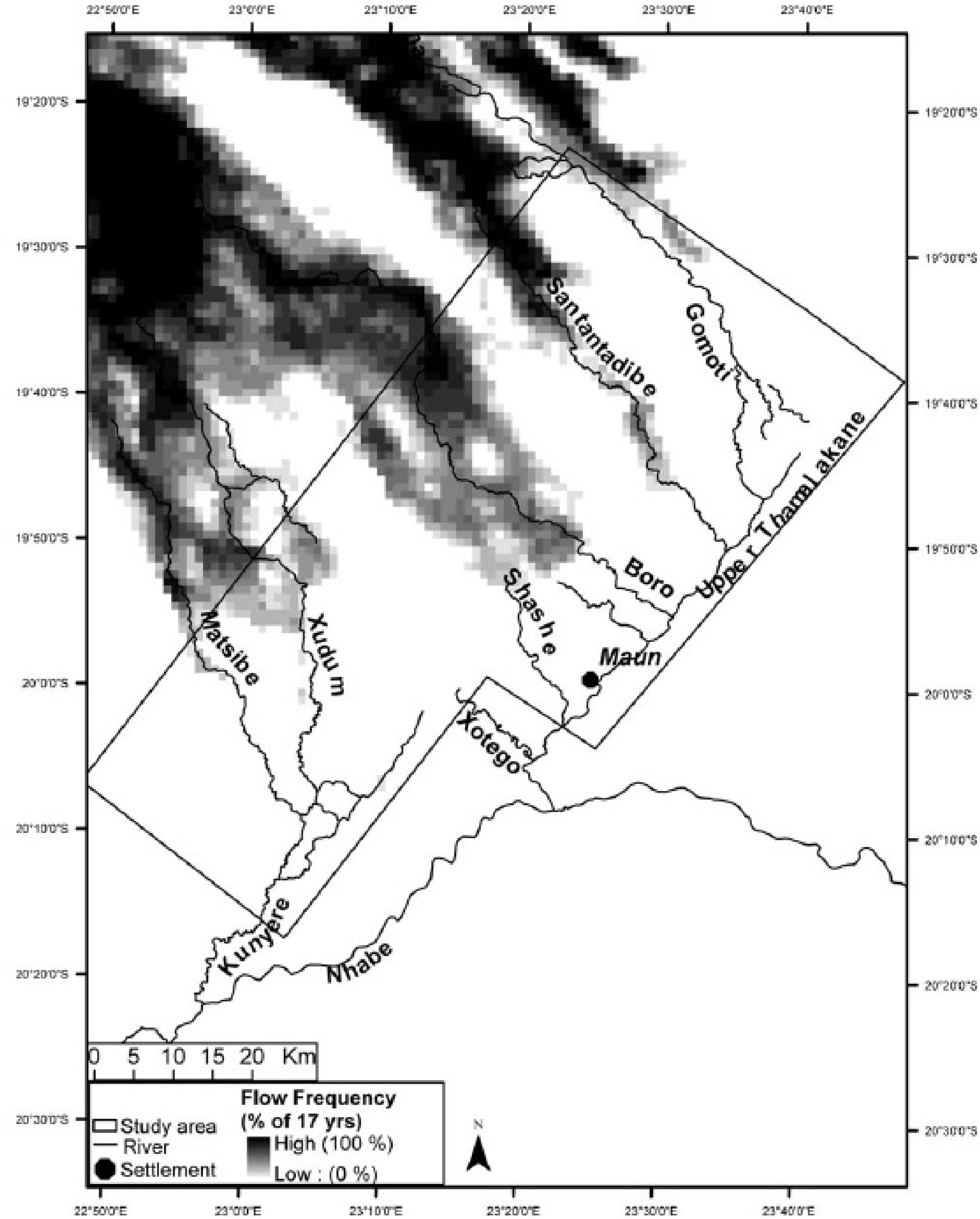


Fig. 4. Flow frequency through the distal Okavango Delta mapped from NOAA AVHRR imagery over 1986–2000.

Recent work has shown that due to the sandy nature of the aquifer and floodplain deposits in the Okavango Delta, ground-water is hydraulically linked to the surface water in permanently flooded areas, or recharged by surface water in intermittently flooded areas to the extent that the ground-water table under inundated area rises to the surface. Ground-water in the Delta forms a semi-continuous regional ground-water mound. The role of regional ground-water flow is, however, limited due to low regional ground-water

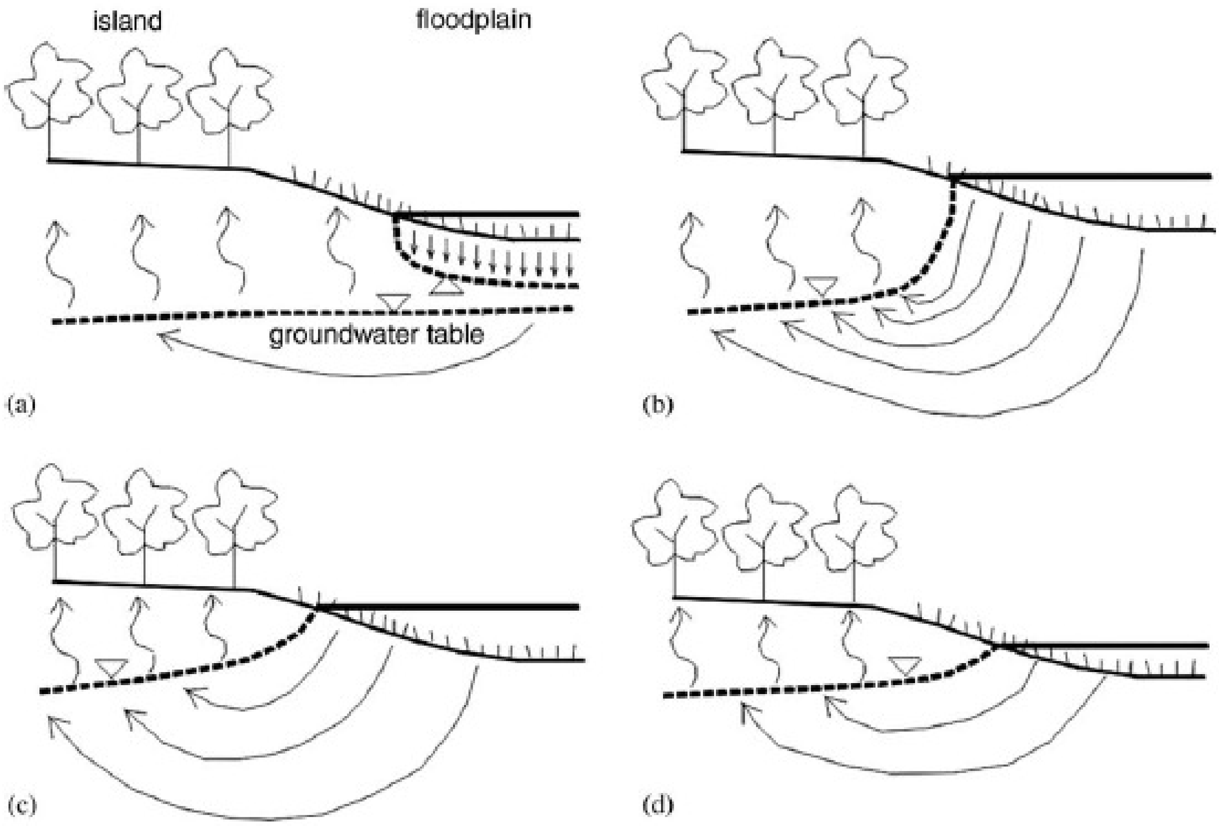


Fig. 5. Scheme of seasonal dynamics of surface water–ground-water interactions and floodplain–island ground-water flows in the Okavango Delta showing the relationship with riparian tree ground-water uptake (after Wolski and Savenije, 2005).

gradient (in order of 1:3600), and the domination of local ground-water flow systems. Local flow systems develop between the floodplains and islands/interfluves, where floodplain–island ground-water table gradients are often in order of 1:100. These flow systems are caused by the localization of recharge and discharge zones, with floodplains being the recharge and interfluves/islands the discharge zones. Discharge occurs due to transpiration by island/interfluve riparian vegetation through processes illustrated in Fig. 5.

Results of ground-water analyses show rest water levels ranging from 2.2 to 14.3m below the floodplains immediately adjacent to riparian zones. Salinity increases generally in the downstream direction in the distal Delta as indicated by EC values which increase from 643 to about 3010 μScm^{-1} (Fig. 6). The spatial distribution is irregular with higher salinity levels (>6660 μS cm^{-1}) interspersed with low levels (331 μS cm^{-1}) suggesting that pockets of saline ground-water occur between freshwater lenses under the floodplains (Linn et al., 2003). Mapping salinity data for individual boreholes in ARC/GIS shows that lower salinity ground-water is mainly concentrated along the wetter intermediate distributaries (Fig. 6). More highly saline ground-water (>6000 μm cm^{-1}) in contrast appears most frequently in association with the terminal receiver channels which coincidentally are subject to less-frequent flow (Fig. 4).

4.3. Development of riparian compositional and structural variables

Fieldwork results led to the identification and listing of 900 riparian trees along with 3300 shrubs throughout seven Okavango distal rivers. Major tree and shrub species are

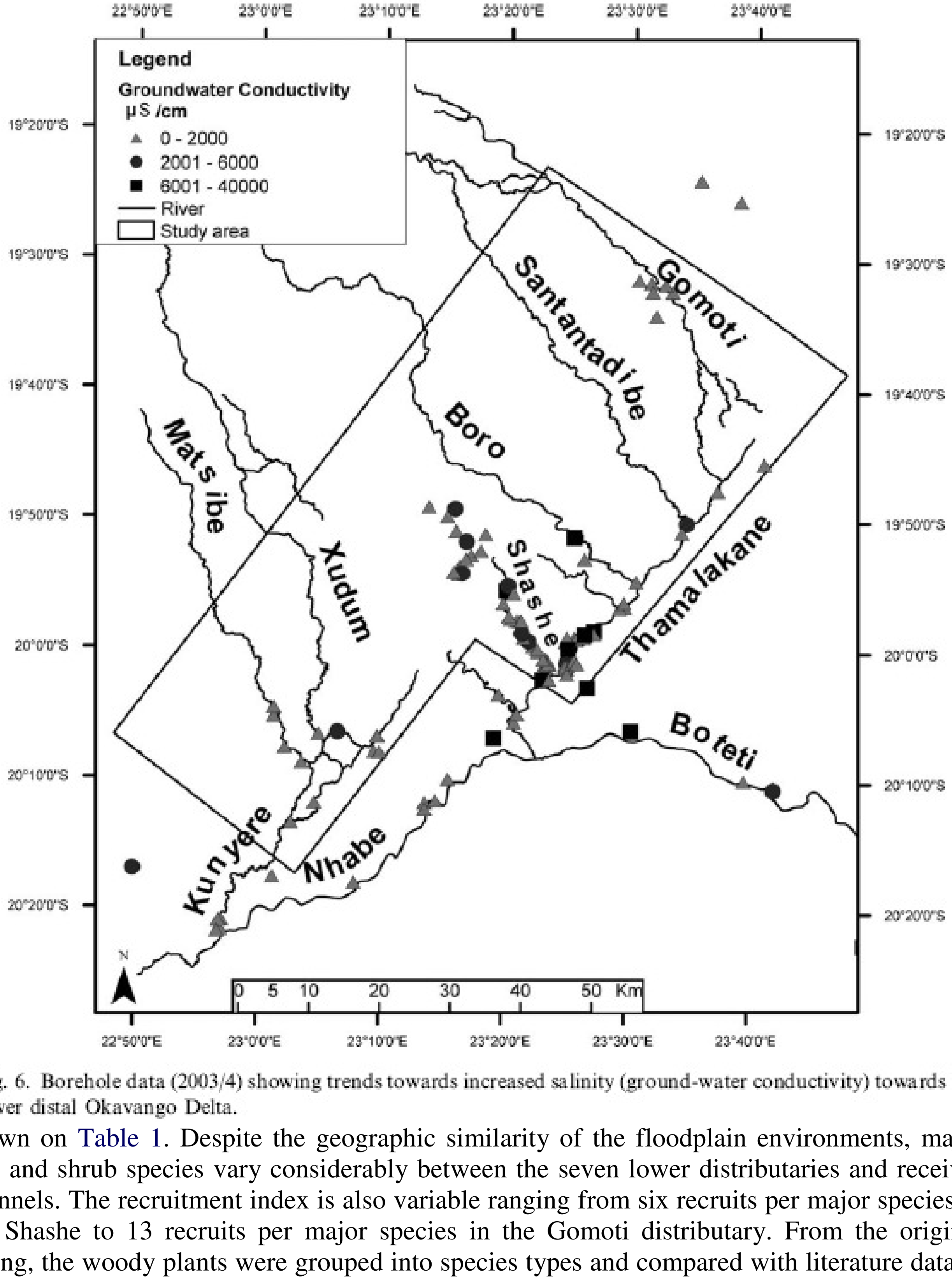


Fig. 6. Borehole data (2003/4) showing trends towards increased salinity (ground-water conductivity) towards the lower distal Okavango Delta.

shown on Table 1. Despite the geographic similarity of the floodplain environments, major tree and shrub species vary considerably between the seven lower distributaries and receiver channels. The recruitment index is also variable ranging from six recruits per major species in the Shashe to 13 recruits per major species in the Gomoti distributary. From the original listing, the woody plants were grouped into species types and compared with literature data to establish which of the species was normally deep rooted and fresh ground-water preferring, and which could adjust to, or tolerate more brackish conditions (cf. Palgrave, 1981; Roodt, 1995; Ellery and Ellery, 1997). Other dryland species (mainly shrubs) were regarded as being shallower rooted relative to the deeper rooting riparian trees (Ringrose et al., 2003b). Summarized results show examples of typical riparian tree

Table 1
Summary of major riparian tree and shrub species with recruitment characteristics in the intermediate distributaries (IT) and receiver channels (RC)

River (number of sample sites)	Main tree species (number and total woody plants)	Main shrub species (number and total woody plants)	Recruitment index
Gomoti (14) IT	*Acacia nigrescens* (59/228), *Acacia erioloba* (35/228) *Lonchocarpus capassa* (34/228)	*Hyphaene petersiana* (126/1015), *Combretum mossambicense* (83/1015) *Pecheul-loeschea leubnitziae* (83/1015)	13
Boro (12) IT	*Croton megalobotrys* (57/164), *Combretum imberbe* (32/164), *A. erioloba* (29/164),	*Maytenus senegalensis* (153/890) *H. petersiana* (141/890), *P.l. leubnitziae* (114/890)	10
Matsibe (10) IT	*Combretum imberbe* (40/201), *Combretum hereroense* (31/201) *Croton megalobotrys* (27/201)	*Diopsyros lycioides* (122/494) *D. cinerea* (91/494) *Grewia bicolor* (54/494)	8
Xudum (4) IT	*Croton megalobotrys* (22/88), *A. erioloba* (20/88) *L. capassa* (16/88)	*D. lycioides* (70/258), *Rhus tenuinervis* (26/258) *P.l. leubnitziae* (26/258)	6
Thamalakane (7) RC	*Combretum hereroense* (22/58) *L. capassa* (16/58)	*C. mossambicense* (114/384) *P.l. leubnitziae* (94/384),	2
Kunyere (5) RC	*Croton megalobotrys* (22/118), *A. erioloba* (22/118) *Combretum imberbe* (19/118)	*P.l. leubnitziae* (80/317) *Rhus tenuinervis* (33/73)	7
Shashe (4) RC	*L. capassa* (25/104) *Croton megalobotrys* (19/104) *Combretum hereroense* (17/104)	*L. capassa* (79/372) *Grewia flavescens* (54/372) *D. lycioides* (48/372)	6

and shrub species along the wetter intermediate distributaries and then along the drier receiver channels (Table 2) in terms of their assumed responses to fresh or brackish ground-water. These species are typically found elsewhere in the northern Botswana Kalahari but normally associated with ephemeral watercourses. The dryland trees and shrubs are normally not found in association with surface water features. A wide variety of species was listed in each major distributary, which is partly attributable to successional changes downstream. The Gomoti distributary for example, shows a higher frequency of fresh ground-water preferring tree species upstream and while mixed species are present, there is a tendency for more brackish tolerant species to occur more frequently towards the terminus (Table 3).

A second data set derived from the field sites led to the characterization of structural vegetation properties. This involved listing each woody plant in terms of canopy cover per cent, tree height and shrub height. The number of plants per unit area provided an index of plant density. Summary results demonstrate that the distal distributaries vary widely in terms of their canopy cover percentages, the highest being the Boro river (range 59–76%) and the lowest being the Shashe river (range 33–42%) (Table 4). Field data indicate that average canopy cover per cent and tree height decrease downstream along study area distributaries. Shrub height and plant density show tendencies to increase downstream.

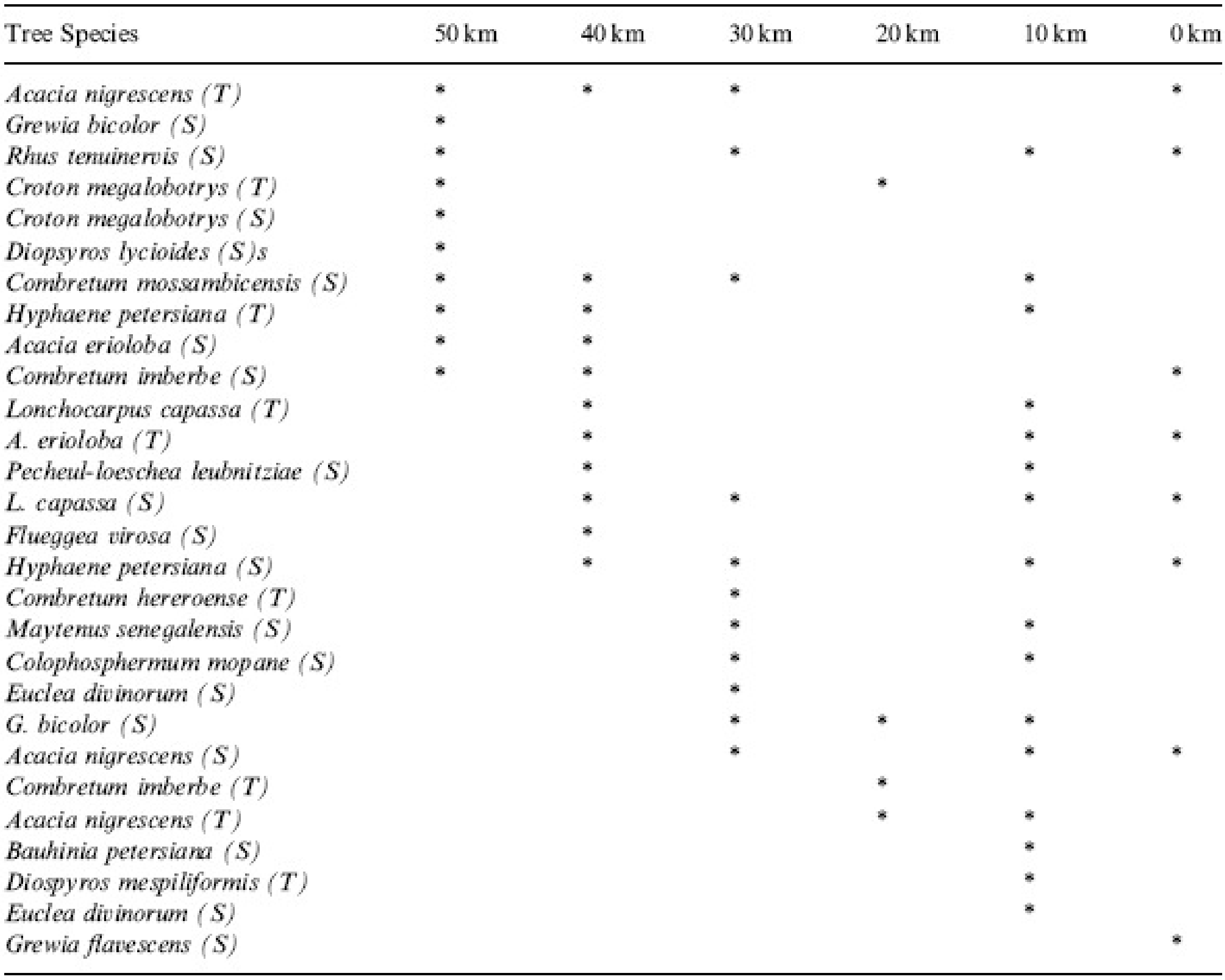
Table 2
Examples of fresh ground-water preferring, brackish ground-water and dryland tree and shrub species from riparian zones in the intermediate distributaries (IT) and receiver channels (RC)

IT	Gomoti River	Boro River	Matsibe/Xudum Rivers
Examples of fresh ground-water preferring tree and shrub species	*Acacia nigrescens*	*Ficus sycamorus* L., (Moraceae)	*Berchemia discolor*
	Acacia erioloba *Lonchocarpus capassa* *Diospyros mespiliformis* Hochst. Ex A. DC. (Ebenaceae) *Berchemia discolor* (Klotzsch) Hemsley (Rhamnaceae)	*Kigelia africana* (Lam.) Benth (Bignoniaceae) *Diospyros mespiliformis* *A. erioloba*	*Gardenia volkensii* K. Schum. (Rubiaceae), A. erioloba
Examples of brackish ground-water-tolerant tree and shrub species	*Hyphaene petersiana* Klotzsch, (Arecaceae)	*Croton megalobotrys* Meuell. Arg. (Euphorbiaceae), *Combretum imberbe* Wawra (Combretaceae)	*Croton megalobotrys*
	Pechuel-loeschea leubnitziae (Kuntze) O. Hoffm. (Asteraceae)		*Combretum hereroense*
Examples of dryland tree and shrub species	*Terminalia prunioides*, C. Lawson (Combretaceae), *Boscia albitrunca* (Burch.) Gilg & Benedict (Capparaceae)	*Sclerocarya birrea* (A. Rich.) Hochst. (Anacardiaceae)	*Terminalia sericea* Burch. Ex
			DC. (Combretaceae) *Lonchocarpus nelsii* (Shinz) Shinz ex Heering & Grimme (Papilionoideae)
		R. tenuinervis Engl. (Anacardiaceae) *P.-l leubnitziae*, *Grewia bicolor*, Juss. (Tilicaceae)	*B. albitrunca* *Diospryos lycioides* Desf. (Ebenaceae)
	Bauhinia petersiana Bolle. (Caesalpinioideae)		
RC	Shashe	Upper Thamalakane	Kunyere
Fresh ground-water preferring tree and shrub species	*Ziziphus mucronata*	*A. nigrescens*, *Albizia versicolor*, Welw. Ex Oliver, (Mimosoideae), *A. sieberiana* var. *sieberiana* DC., (Mimosoideae),	*Croton megalobotrys*

Table 2 (*continued*)

IT	Gomoti River	Boro River	Matsibe/Xudum Rivers
	Willd. (Rhamnacae)	*Combretum mossambicense*, *A. erioloba*	*A. erioloba*
			Garcinia livingstonei T. Anders. (Celastraceae).
Brackish ground-water-tolerant tree and shrub species	*L .capassa*, *Combretum hereroense* *Croton megalobotrys*	*Combretum hereroense*	*C. imberbe*
	Combretum imberbe	*L. capassa*	*L. capassa*
	P.-l leubnitziae	*H. petersiana* *P.l. leubnitziae*	*P.l. leubnitziae*
Examples of dryland shrub species	*Grewia flavescens* Juss. (Tiliaceae). *Acacia mellifera*, *Colophospermum mopane* (Kirk ex Benth.) Kirk ex J. Leonard (Caesalpinioidae)	*B. albitrunca*,	*R. tenuinervis* Engl. (Anacardiacae)
	Grewia bicolor,	*Dichrostachys cinerea*,	*A. fleckii* Schinz (Mimosoideae)
	Rhus tenuinervis,	*G. bicolor*, *X. americana*,	*A. tortilis* (Forsk.) Hayre (Mimosoideae)
	Ximenia americana L (Olacaceae)	*B. petersiana*, *Maytenus senegalensis*	*G. flavescens* Juss. (Tiliaceae) *P.l. leubnitziae*

Table 3
Distributional range of species (frequency >5) along lower Gomoti intermediate distributary from 50 km upstream to the receiver channel confluence, see Fig. 2. (T = trees and S = shrubs)



Tree Species	50 km	40 km	30 km	20 km	10 km	0 km
Acacia nigrescens (T)	*	*	*			*
Grewia bicolor (S)	*					
Rhus tenuinervis (S)	*		*		*	*
Croton megalobotrys (T)	*			*		
Croton megalobotrys (S)	*					
Diopsyros lycioides (S)s	*					
Combretum mossambicensis (S)	*	*	*		*	
Hyphaene petersiana (T)	*	*			*	
Acacia erioloba (S)	*	*				
Combretum imberbe (S)	*	*				*
Lonchocarpus capassa (T)		*			*	
A. erioloba (T)		*			*	*
Pecheul-loeschea leubnitziae (S)		*			*	
L. capassa (S)		*	*		*	*
Flueggea virosa (S)		*				
Hyphaene petersiana (S)		*	*		*	*
Combretum hereroense (T)			*			
Maytenus senegalensis (S)			*		*	
Colophosphermum mopane (S)			*		*	
Euclea divinorum (S)			*			
G. bicolor (S)			*	*	*	
Acacia nigrescens (S)			*		*	*
Combretum imberbe (T)				*		
Acacia nigrescens (T)				*	*	
Bauhinia petersiana (S)					*	
Diospyros mespiliformis (T)					*	
Euclea divinorum (S)					*	
Grewia flavescens (S)						*

Statistical analyses were undertaken to provide insight into riparian compositional and structural characteristics relative to the flood frequency and salinity data. Analyses were also undertaken to establish functional relationships to show how specific variables may be responding to change both spatially and in relationship to one another. In this way specific variables may be identified as indicators of desiccation-driven change.

4.4. Statistical analyses of distal delta variables

The inherent complexity of the Okavango Delta distal riparian zones requires reduction of the structural and compositional components to a few key functional variables to facilitate monitoring (cf. Cole, 2002). Initially correlation analysis was run between structural and compositional components and the imagery derived Delta flood frequency record for the years 1985–2000. Flood frequency is taken as being indicative of groundwater recharge hence the absence of flooding infers ground-water table lowering. Correlation analysis revealed coefficients such as 0.329 (p= 0.01) when flood frequency was plotted against canopy cover. Flood frequency against average tree height resulted in a

Table 4
Ranges in main riparian woody plant structural and compositional variables (IT = intermediate distributary; RC = receiver channel, gw = ground-water)

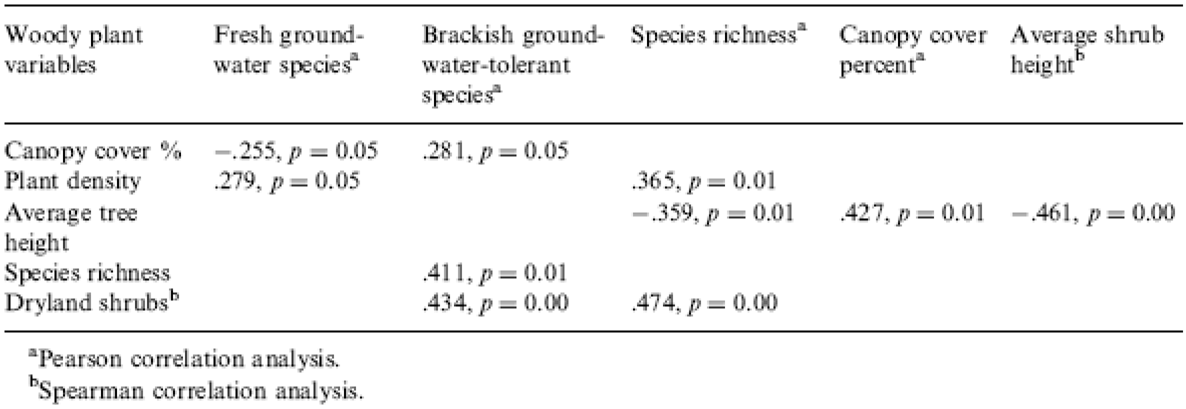
Riparian zone structural variables	Average canopy cover%[a]	Tree height in meters (m)[a]	Shrub height in meters (m)[b]	Plant density[b]
Gomoti IT	63.2–67.0	10–12	1.3–1.8	0.28–0.38
Boro IT	59.3–76.2	10–14	0.75–1.5	0.15–0.21
Matsibe IT	49.8–73.3	7–12	1.5–2.5	0.12–0.31
Xudum IT	56.9–65.7	9–12	1.5–2.0	0.15–0.25
Thamalakane RC	37.3–51.8	7–11	1.6–1.7	0.2
Kunyere RC	57.1–65.5	9–10	2.0–2.5	0.15–0.25
Shashe RC	33.2–42.2	8	1.3–1.7	0.14–0.31
Riparian zone compositional variables	Number of fresh gw species	Number of brackish gw species	Number of dryland shrubs	Species richness
Gomoti IT	17–23	13–20	15–27	0.02
Boro IT	14	14	10–21	0.019–0.02
Matsibe IT	7–22	11–27	15–65	0.022–0.024
Xudum IT	12–17	12–20	40	0.017–0.019
Thamalakane RC	5–16	18	8–17	0.017–0.026
Kunyere RC	8–12	13–22	24–29	0.023
Shashe RC	15–27	9–27	24	0.02

[a] Field data shows trend towards decrease downstream.
[b] Field data shows trend towards increase downstream.

coefficient of 0.39 ($p = 0.02$) and flood frequency against average shrub height revealed a coefficient of –0.264 ($p = 0.04$). Similar analyses were run with the salinity data but this also resulted in low correlation coefficients. However a correlation coefficient of 0.447 ($p = 0.05$) resulted when species richness was related to ground-water rest levels. Also a relatively high negative correlation coefficient of 0.489 ($p = 0.05$) emerged when EC values were plotted against the TM4/TM3 vegetation index derived from ETM+ data suggesting that areas of higher salinity may cause a decline in vegetation vigour.

Further associations were sought by running the field site compositional and structural variables ($n = 47$) through standard correlation analyses to determine whether trends could be developed both within and between the data sets. Results show significant correlations (at the $p = 0.01$ level) between canopy cover and average tree height (Table 5). Further results indicate that the average tree height and species richness association is negative such that as tree height decreases species richness increases, implying that further downstream more species per unit area may be anticipated (Table 5). Plant density also increases with species richness ($p = 0.01$), suggesting an increase in both plant variables in a downstream direction (Table 4). Similarly increases in species richness parallel increases in the numbers of woody plants which tolerate brackish ground-water conditions ($p = 0.01$) suggesting that brackish ground-water trees and shrubs may be found in areas with a large variety of species. This is considered rational in the light of the downstream drying gradient which results in extensive openings in the riparian canopy and the introduction of increasing numbers of invasive shrubs. A relatively strong negative

Table 5
Downstream trends in woody plant structural and compositional variables for entire distal Delta ($n = 47$) showing correlation coefficients obtained from either Pearson and Spearman Rank correlation techniques but listing significant correlations only



Woody plant variables	Fresh ground-water species[a]	Brackish ground-water-tolerant species[a]	Species richness[a]	Canopy cover percent[a]	Average shrub height[b]
Canopy cover %	−.255, $p = 0.05$	.281, $p = 0.05$			
Plant density	.279, $p = 0.05$		.365, $p = 0.01$		
Average tree height			−.359, $p = 0.01$	.427, $p = 0.01$	−.461, $p = 0.00$
Species richness		.411, $p = 0.01$			
Dryland shrubs[b]		.434, $p = 0.00$	.474, $p = 0.00$		

[a] Pearson correlation analysis.
[b] Spearman correlation analysis.

relationship was also found between average tree height and average shrub height with tree height decreasing in a downstream direction, while shrub height increases (Table 5).

Riparian structural and compositional variables were input into factor analysis in an attempt to detect and identify groupings of interrelated variables (Shaw and Wheeler, 1985). This analysis resulted in the dataset being characterized by four components, which when combined accounted for 69% of the variability. While there is a high degree of scatter, most (56%) variability lies on the first three components. The results in terms of factor loadings indicate that canopy cover per cent and average tree height are significantly loaded on the first component suggesting that these two variables in combination are important components in the desiccation processes. Species richness and numbers of brackish ground-water preferring species are loaded on the second component again suggesting that they provide a degree of association with respect to overall drying. Average shrub height and plant density are loaded on the third component. Hence it appears that as tree height and canopy cover per cents both decrease downstream (Table 4) this association suggests a symptomatic decline in optimal growing conditions. The relationship between brackish species and species richness confirms observations that brackish ground-water tolerating species are more readily developing in the distal Delta. Increases in dryland invasive species also contribute to increasing plant density and species richness values.

Results so far recognize important changes in structural and compositional variables downstream which appear indicative of peripheral Delta drying. However associations suggesting functional relationships could be enhanced if upstream–downstream relations were analysed more closely. This focusing of apparent desiccation-driven change was also undertaken to develop more location-specific data for future environmental monitoring. The data set was therefore spatially sub-divided on the basis of the ETM+ mapped predominant species distributions into the more frequently flooded intermediate distributaries and slightly drier receiver channels (Fig. 2). The intermediate distributaries sub-set (n = 33) comprised sample sites along the Gomoti, Boro, Xudum and Matsibe Rivers with the terminal receiver channel subset (n = 14) comprising sample sites along the upper Thamalakane, Kunyere and Shashe Rivers.

The intermediate distributary sub-set was run through Pearson's correlation analysis to re-assess relationships between structural and compositional variables. In this part of the study area, canopy cover per cent was again positively correlated with average tree height and negatively correlated with average shrub height at the $p = 0.01$ level (Table 6). This appears to confirm the overall trend, that as canopy cover decreases downstream, shrub height increases (cf. Table 4). In this sub-set however a strong negative relationship emerged between fresh ground-water deep rooting tree species and brackish ground-water tolerating tree species suggesting a distinct separation of these tree types in terms of preferred locations. This contrasts with results from the receiver channel part of the study area where fresh ground-water preferring species are less evident. In the receiver channels, brackish ground-water tolerating species are strongly positively correlated with plant density and species richness (Table 6), as inferred from earlier analyses of the entire area (Table 5). Factor analysis was run on both sub-area data sets to determine whether different variables may be associated with the drying processes in different parts of the study area. Results now show that 70% of the variance is resolved into four components in the intermediate distributary subset (Table 7). In this case, fresh ground-water preferring species and canopy cover per cent strongly contribute to component one suggesting a strong association between these variables. Species richness and average shrub height are also significant on component two (Table 7). Brackish tolerating species show a relatively low significance in components three and four. Interestingly results of factor analyses on the receiver channels' riparian sub-set show different groupings with four variables contributing to component one, including brackish ground-water-tolerant species, plant density, species richness and canopy cover per cent in the lowermost reaches of the Delta (Table 7).

In terms of biotic indicators of desiccation-driven change, key indicators include declines in the extent of canopy cover along with decreases in tree height downstream as these are the most responsive variables reflecting reductions in ground-water recharge hence watertable lowering in the distal Delta. Similarly flood frequency and shrub height are negatively correlated and so also appear to be symptomatic of ground-water reduction in the entire distal Delta. In the intermediate distributary sub-set biotic indicators of ground-water lowering in this slightly more frequently flooded area comprise mainly structural variables such as decreased canopy cover per cent and tree height along with increases in shrub height. It appears that these changes would mostly take place in fresh ground-waterpreferring species. In contrast, biotic indicators responding to ground-water changes in the less frequently flooded receiver channels comprise mainly increases in plant density and species richness which occur along with increases in brackish ground-water-tolerant species. These increases take place as more dryland species invade the riparian zones and are believed to relate to more persistent ground-water lowering. Increases in brackish ground-water-tolerant species also reflect the increasing incidence of saline ground-water in the more downstream reaches of the Delta.

5. Discussion

Work on riparian zone characteristics in relation to fluctuations in river flow worldwide tends to concentrate on species distributions as both flow and flood events influence dispersal, recruitment and competition (Michener and Houhoulis, 1997; Turner et al., 1998; Vervuren et al., 2003). Flood events bring moisture and nutrients to ecosystems (e.g.

Table 6
Relationships between riparian plant structural and compositional variables in the intermediate distributaries ($n = 33$) and receiver channels ($n = 14$) showing Pearson correlation coefficient and listing significant correlations only

Intermediate distributaries sub-set	Fresh ground-water species	Brackish ground-water-tolerant species	Dead	Species richness	Canopy cover percent
Canopy cover	$-.373, p = 0.05$		$-.377, p = 0.05$		
Plant density	$.521, p = 0.01$				
Average tree height				$-.387, p = 0.05$	$.412, p = 0.01$
Average shrub height					$-.432, p = 0.01$
Species richness		$.361, p = 0.05$			
Brackish ground-water-tolerant species	$-.317, p = 0.01$				
Receiver channels sub-set	Brackish ground-water-tolerant species	Dead	Plant density	Dryland shrubs	Species richness
Canopy cover		—		$.503, p = 0.05$	
Plant density	$.653, p = 0.01$				$.684, p = 0.01$
Average tree height		$-.387, p = 0.05$			
Average shrub height					
Species richness	$.712, p = 0.01$		$.579, p = 0.01$		
Dryland shrubs	$.365, p = 0.05$				

Table 7
Component loadings using factor analysis comparing statistical variability in the intermediate distributaries ($n = 33$) and receiver channels ($n = 14$)

Intermediate distributaries sub-set	Component 1 Variability 24%	Component 2 Variability 21%	Component 3 Variability 15%	Component 4 Variability 11%
Fresh ground-water species	.721			
Brackish ground-water-tolerant species			.767	.563
Plant density				
Species richness		.696		
Canopy cover %	−.799			
Average shrub height		.675		
Receiver channels sub-set	Variability 29%	Variability 22%	Variability 15%	Variability 11%
Brackish ground-water-tolerant species	.917			
Plant density	.715			
Species richness	.783			
Canopy cover%	.742			
Average tree height			.645	
Dead			.695	
Dryland shrubs		.783		
Average shrub height				.779

Lyttle, 2001; Baker et al., 2003) even in Okavango riparian zones which derive moisture and nutrients through lateral ground-water seepage. In the Okavango Delta many trees have responded uniquely to the presence of near surface ground-water through historic or even geological time spans (Huntsman-Mapila et al., 2003; Gumbricht et al., 2004b).

Most riparian tree species are deep rooted and contribute to high ET rates especially in the distal Delta (Ringrose, 2003; Bauer et al., 2004). In a drying situation, this has the effect of depleting the upper fresh cone of ground-water thereby drawing more saline water towards the surface (McCarthy et al., 1991; Linn et al., 2003; Wolski et al., 2003). As Delta distributaries experience desiccation, a number of deep-rooted riparian woody species have been shown to adapt to increasingly brackish conditions, while simultaneously the riparian zones are being invaded by dryland (shrub-shallow rooted) life-forms (cf. SMEC, 1989; Ringrose et al., 1998, 2003b).

This work demonstrates that a decrease in flow frequency which leads to water-table lowering and salinization is detectable as structural and compositional changes in the riparian woody plants. Ground-water salinity results (measured as electrical conductivity) show general increases downstream commensurate with an overall drying regime. Since water-table lowering and salinization are significant in a semi-arid regime in terms of ground-water availability and potability, the inferences drawn here may assist in facilitating detection of changed or changing ground-water conditions in the Delta periphery, thereby minimizing the need for extensive (and intrusive) drilling operations. In order to achieve this some continuity in terms of recording specific variables needs to be instituted which is normally operationalized as long- (or short-) term monitoring endeavours (Gosz, 2000; Dale and Beyeler, 2001).

The riparian zones along seven Okavango distal distributaries are maintained by fresh ground-water which is recharged periodically. However such recharge is intermittent resulting in changes to specific structural and compositional variables including the increased incidence of more brackish tolerant tree species. Overall results suggest that longer term (ca. 100 plus years) drying trends may be reflected in decreases in the average extent of canopy cover along with changes in tree and shrub height as these are the most responsive variables to flooding. These associations are particularly apparent in the intermediate distributary sub-set where results indicate that monitoring could take place using these riparian variables to detect systematic ground-water declines. In contrast, monitoring in the less frequently flooded receiver channels could emphasize a wider range of structural and compositional variables such as plant density and species richness increases which occur where ground-water declines are associated with increasing salinization. In this sub-area, increasing salinization may be detected by the increase in brackish ground-water-tolerant woody species. Riparian zone woody vegetation cover is also subject to water-table lowering below the effective root depth. This leads to community responses by invasions of relatively shallow rooted woody vegetation (mainly shrubs) referred to here as dryland species (cf. Ringrose and Matheson, 2001). Monitoring could also take place by quantifying dryland shrub increases. Short-term (up 50 years) changes may be best captured by repeated measurements of changes in structural components, while longer-term (centuries) changes might best be quantified by increases in the numbers of brackish tolerant tree species and dryland shrub species. Longer-term changes might best be observed by decreases for instance, in the numbers of fresh water preferring species (e.g. *L. capassa*) and concomitant increases in brackish tolerant groundwater species, like *Croton megalobotrys*. Repeated measurements (in enclosures) of changes in tree and shrub height in relation to species richness could also take place along all the major distributaries. In this way both shorter-term structural trends along with longer-term compositional trends could be quantified and inferences drawn with respect to whether desiccation-driven change is mainly taking place in the form of ground-water table drawdown or as increases in potential salinity in any given area.

6. Conclusions

1. Riparian woody species distributions can be mapped using ETM+ imagery from which two riparian zone classes prevalent in different parts of the distal Okavango Delta, are spectrally distinguishable. The first class is found by the slightly more frequently flooded intermediate distributaries where the species composition includes mixed *A. nigrescens/Combretum imberbe* woodlands in association with *Combretum imberbe/L. capassa* woodlands and shrublands. The second class is found in the drier receiver channels and mainly comprises mixed *Combretum hereoense/Croton megalobotrys* woodlands and shrublands.
2. While riparian woodland characteristics infer that these are the products of major flow events over historical time spans, flow/drying data from 1985 to 2000 demonstrate that both intermittent and zero flow commonly occur in the distal Delta.
3. While known incidences of high ground-water salinity are intermittent in the distal Delta, salinity is known to be locally high due to evapo-transpiration losses.
4. Riparian variables in the distal Delta appear to be responding to drying regimes through changes in compositional and structural variables. Key compositional variables entail downstream changes in relative proportions of fresh versus brackish groundwater riparian species. Key structural variables mainly entail decreases in canopy cover

and increases in species richness, while tree height decreases and shrub height increases downstream mainly in response to water-table lowering.

5. In terms of riparian zone functioning, results indicate that significant desiccation-driven ecological change is taking place in the distal Delta as ground-water is becoming increasingly brackish and/or ground-water tables drop.
6. Both shorter term structural trends and likely longer-term compositional trends could be monitored in the distal Delta and elsewhere such that inferences can be drawn with respect to ground-water table drawdown and potential increases in salinity.

While parameters derived from riparian zone woody plant data may provide significant indicators to show where differential drying is taking place, more work is required to determine indicator conditions which would denote specific environmental thresholds (e.g. toxic salinity levels) in the Delta. It is important to independently assess long-term flow trends in all the distributaries as ground-water deficiencies may eventually become more pervasive with negative impacts on water supplies for the local populations. It is anticipated that the indicative results obtained here may however help Botswana's water management policy, for instance by providing research inputs for various initiatives including the Okavango Delta Management Plan (Republic of Botswana, 1991; Turton, 1999; Government of Botswana, 2001).

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