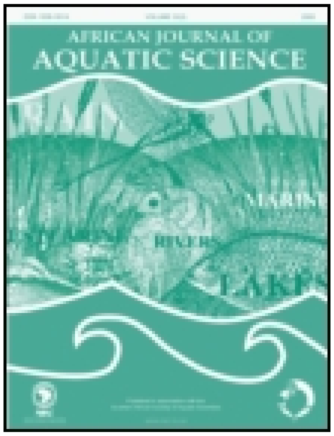

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An analysis of plant species distributions on the floodplain of the Okavango River, Namibia, with respect to impacts of possible water abstraction

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The proposed abstraction of water from the Okavango River in Namibia could potentially result in significant changes in the vegetation of floodplains downstream of the abstraction point. Direct gradient analysis was used to determine the distribution of the most common floodplain plant species in relation to elevation above the water surface and distance from the channel, and therefore to the depth and duration of flooding. Species could be ranked and scored according to their distribution in relation to both elevation and distance from the channel, reflecting a gradient from species intolerant of flooding to those that withstand prolonged flooding. In general, as distance from the channel increased, the elevation at which each of the species occurred decreased, but there was a great deal of variation in the range of elevations over which each species occurred, primarily as a consequence of the irregular topography of these floodplains. Furthermore, several ruderal species were restricted to elevated sites in close proximity to the channel, occurring on recently formed point bars which are the product of fluvial processes. Disturbance in the form of sediment deposition on point bars is thus an important determinant of species distribution on floodplains of the Okavango River. Given these patterns of species distributions it is difficult to predict with accuracy the effect of abstraction on vegetation distribution.

A preliminary analysis of possible changes in the hydrological regime after abstraction has also been attempted as part of this study. This was achieved by comparing mean stage heights before and after abstraction assuming a constant rate of abstraction of 3 cumecs, and based on historical daily records from Rundu and Mukwe. Uniform abstraction would have a greater impact at low flows than at medium and high flows. Should abstraction proceed, it would therefore be more appropriate to remove water during periods of high discharge. However, since the Okavango River in Namibia recharges local and possibly regional groundwater, its discharge declines downstream. Rates of water loss from the river thus need to be determined prior to any decision being made about whether or not abstraction should take place, or where to locate the point of abstraction.

Keywords: Okavango River, floodplain wetlands, water abstraction, fluvial disturbance

Introduction

The boundaries between terrestrial and riverine systems have been recognised as riparian wetlands (Mitsch and Gosselink 1986). These wetlands have been described as transitional systems by Mitsch and Gosselink (1993), in that they are transitional in the amount of water that they store and process, and are periodically influenced by fluctuations in water level in the riparian zone. The hydrological regime, particularly the depth and duration of flooding, is an important determinant of vegetation distribution in riparian wetland ecosystems. Wetland systems contain a mosaic of emergent and submergent plant species, and small changes in hydrological regime can result in significant biotic changes (Mitsch and Gosselink 1993). Physicochemical properties of the system (including nutrient availability, soil salinity, sediment properties and pH) are easily altered by changes in hydrologic conditions and have a direct impact on the biotic response in wetlands.

The issue of water abstraction from the Okavango River in Namibia to increase water supply to Windhoek has received much public attention in southern Africa and elsewhere. The possible impact on the natural environment of the floodplains of the Okavango River in Namibia (Figure 1) has been of some concern. The terminal region of the drainage basin, the Okavango Delta, may however be most affected. The purpose of this study was to determine the relationship between plant species distributions and the hydrological regime in order to determine the nature and magnitude of possible impacts of abstraction on the floodplain vegetation in Namibia. In order to achieve this the distribution of a number of common species was determined in relation to elevation and distance from the river, as these are considered surrogates for the frequency, depth and duration of flooding. A preliminary analysis of some changes in the hydrological regime as a consequence of abstraction was also undertaken.

In order to predict the effects of water abstraction on wetland vegetation distribution, the impacts of abstraction on the depth and duration of flooding are considered. Several features related to abstraction are important from the perspective of vegetation, as indicated in a simple conceptual model (Figure 2). Firstly, it is possible that some areas which were infrequently flooded or were flooded for extremely

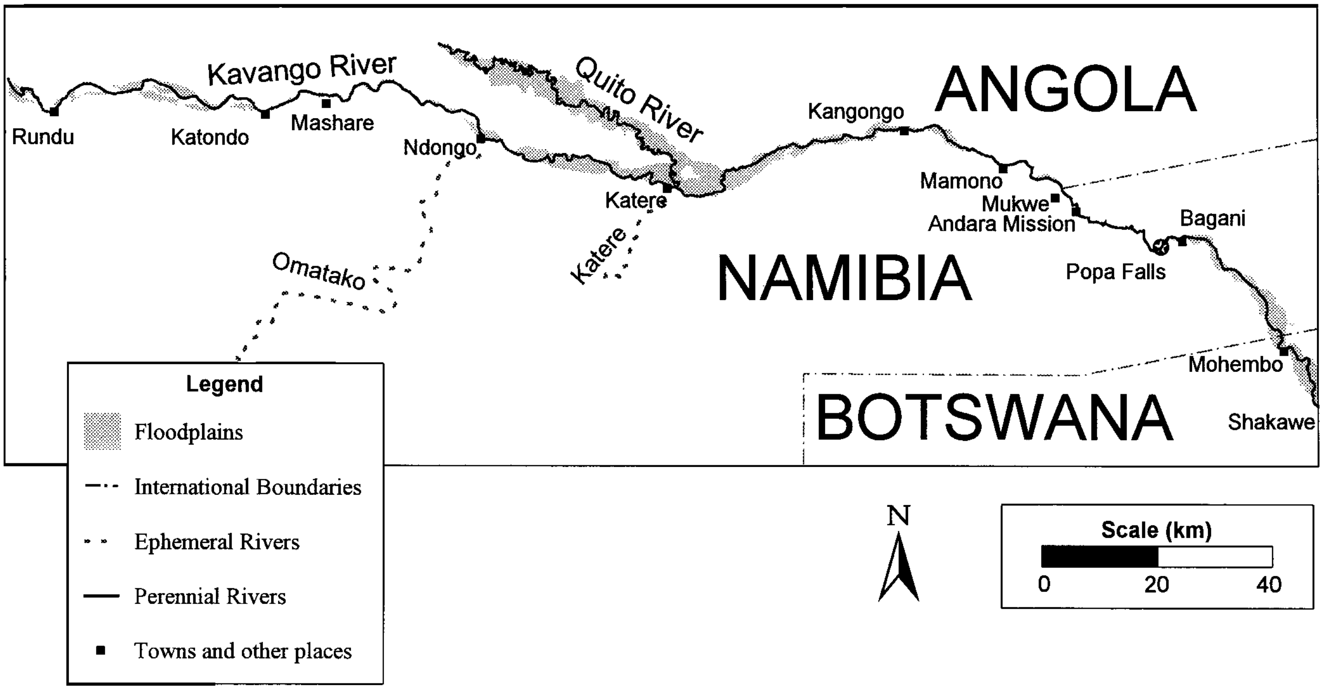

Figure 1: Map of the study area showing the two main distributary channels, distribution of floodplains and location of some towns and villages adjacent to the floodplain

short periods only will not be flooded at all after abstraction. The region A (Figure 2) represents the difference in stage height between pre- and post-abstraction flooding regimes, and A^1 the period over which an area that was previously inundated during the high flood prior to abstraction will not be inundated following abstraction. Secondly, some areas that were flooded continuously prior to water abstraction are likely to be aerially exposed after abstraction. Region B (Figure 2) represents the difference in stage height between pre- and post-abstraction flooding regimes, and B^1 (Figure 2) the duration over which an area that was previously flooded continuously during periods of low flow prior to abstraction will be aerially exposed following abstraction. Finally, at stage heights between these two extremes (C, Figure 2) a reduction in the duration of flooding will be experienced as the flood wave arrives later ($C^1$1, Figure 2) and recedes earlier ($C^1$2, Figure 2) than it would if there were no abstraction.

Following a preliminary environmental impact assessment, and subsequent to good rains in the region, the proposed abstraction of water from the Okavango River has been shelved. Nevertheless, it is hoped that this publication will promote discussion of some of the issues relevant to predicting the impacts of these sorts of issues, particularly as they are likely to recur in a region where water demand for human development is greater than supply. The regional drainage commission (OKACOM) is proposing, and seeking funding for, the development of an integrated management plan for the drainage basin as a whole. This would ensure that issues related to human development and the environment are addressed jointly and holistically and also that the concerns of each of the countries with an interest in the water resources of this system can be addressed.

Study Area

The Okavango River forms part of an internal drainage basin known as the Kalahari Basin (Smith 1976). The river itself rises in the highlands of central Angola which is drained by the Okavango and Quito Rivers, which join in the vicinity of Katere in Namibia (Figure 1). The Okavango River forms the boundary between Angola and Namibia for approximately 415 kilometres, after which it crosses the Caprivi in a south-easterley direction. Downstream of Popa Falls in Namibia the floodplain widens considerably in the upper reaches of the Panhandle of the Okavango Delta, and the river crosses the border with Botswana at the town of Mohembo in Botswana.

Although the Okavango River is perennial, it is subject to immense variations in flow volume. The fluvial style is meandering with the section between Mukwe and Popa Falls appearing braided as a consequence of bedrock control.

The present study focuses on the floodplains along the stretch of river from Rundu in Namibia, which is the proposed point of abstraction, to Mohembo in Botswana (Figure 1). The ecology of these floodplains has received little attention in the scientific literature, with the exception of a general description of the wetlands that was accompanied by a comprehensive plant species list (Bethune 1991).

Methods

Data collection

Two environmental gradients were chosen along which the plant species on the Okavango River floodplains were believed to be distributed: elevation above the water surface

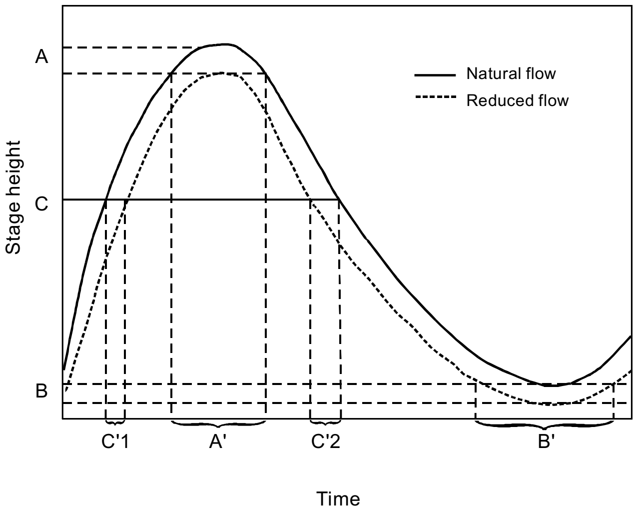

Figure 2: Conceptual model of the relationship between pre- and post-abstraction flooding regimes. Refer to the text for an explanation of notation

and distance from the channel. The importance of these with respect to the floodplain vegetation is as follows:
Elevation: The elevation of a species above the water surface determines the frequency, duration and depth of flooding that plants will experience (Rogers 1985). A change in flood height will affect these variables directly. This change in flood height is predictable if rates of abstraction are known (Hupp and Osterkamp 1985).
Distance: The distance of a species from the channel will determine the amount of sedimentation to which the plants are subjected (Rogers 1985). Plants closer to the channel will be subjected to a greater amount of sedimentation as overbank deposits than those further away from the channel. Changes in sediment characteristics owing to changes in stage level are difficult to predict.

The data used in the study was collected during October 1996. Measurements of elevation above the channel and distance from the channel were made in the form of a series of transects across the Okavango River floodplain. Elevation and distance were measured in relation to the existing water level at the time of the survey.

Vegetation was sampled at each point where elevation was measured, with 308 sample plots being laid out at approximately 30 localities. The vegetation was sampled in circular sample plots with a five metre diameter for herbaceous vegetation and a twenty metre diameter in woodlands. In each sample plot all the species encountered were recorded and an estimate of cover was made using a cover-abundance scale based on the Braun-Blanquet technique (Mueller-Dombois and Ellenberg 1974). Cover intervals were between 0, 2, 5, 10, 25, 50, 75 and 100 percent.

Data Analysis

Species Cover

The thirty most frequently encountered species in the survey were selected for analysis. In order to analyse the species distributions in relation to elevation above and distance from the channel, species cover values were plotted in relation to elevation above and distance from the channel. The transect elevations and distances were plotted to create a visual impression of the topography at each sample point.

Direct Gradient Analysis

In order to calculate plot scores based on species composition, each species was given a score that reflected its position along the most important environmental gradient(s). Only species which appeared to be ecologically useful were used (25 out of 30) since species that are ecological generalists are not useful as they cover a wide range of environmental conditions. Species that occurred close to the channel and at low elevations were allocated low species scores, while those at higher elevations and close to the channel, or at a lower elevation far from the channel received higher species scores. Species scores were thus directly related to absence of flooding, with low species scores being typical of species tolerant of prolonged and frequent flooding, and high scores typical of species intolerant of flooding.

Plot scores, reflecting the ecological score of each plot based on the species composition, were calculated from the species indicator scores using the following formula:

Plot score = $(x_1y_1 + x_2y_2 + ... x_ny_n) / (y_1 + y_2 + ... y_n)$, where x = species score and y = species abundance (Jongman *et al*. 1995).

Hydrological Analyses

A superficial analysis of the effects of a constant abstraction rate of 3 cubic metres per second, which is similar to the proposed abstraction rate specified by the Department of Water Affairs, Namibia, has been attempted here, based on the historical set of hydrological data available for Rundu and Mukwe (courtesy of Department of Water Affairs, Namibia). This was done by comparing the following:

- mean annual (C, Figure 2), mean maximum (A, Figure 2) and mean minimum (B, Figure 2) stage heights before and after abstraction,
- number of days per annum where the water level prior to abstraction was higher than the maximum level reached after abstraction (A^1, Figure 2),
- number of days per annum on which the water surface was lower after abstraction than the minimum water elevation prior to abstraction (B^1, Figure 2),
- number of days by which flooding was reduced by abstraction at the mean stage height during a rising ($C^1$1, Figure 2) and falling ($C^1$2, Figure 2) flood cycle.

Results

Topographic profiles

Floodplain topography varies considerably along the length of the study area. In some areas the floodplain is relatively narrow and elevation increases with increasing distance from the river (Figure 3a). In some cases there is a single ridge of high elevation running sub-parallel and immediately adjacent to the channel, giving way to a depression, following which the elevation increases again with increasing distance from the channel (Figure 3b). In many areas the topography is complex, with a series of elevated ridges and low-lying depressions which run sub-parallel to the channel (Figure 3c). Areas of high elevation in Figures 3b and 3c represent scroll bars which are the result of sediment deposition on the point bars (on convex banks) of a meandering river during particularly high flows.

The typical appearance of the floodplain as seen in aerial photographs varies in a similar way to that described above. The river may be confined in a narrow valley (Figure 4a), or alternatively it is a meandering river with distinctive depositional features known as point bars on the convex banks, and erosional features known as cut banks on the concave banks (Figure 4b).

The elevation of the land surface may vary markedly on either side of the river in the meandering reaches, reflecting erosional and depositional processes which characterise meandering rivers. The river course typically migrates downstream by eroding into areas of relatively high elevation on the down-valley side of the river, in which case the bank is steep and exceptionally high. We were unable to survey onto the bank on the northern side of the river in the meandering reaches as it was in Angola, but the bank on the up-valley side of the river was always shallow compared to the down-valley side of the river in these settings (Figure 5). The overall topography and flooding regime of the meandering sections of the Okavango River is illustrated schematically in Figure 5.

Species scores in relation to elevation and distance from the channel

An attempt was made as part of this study to relate the distribution of species to elevation and distance from the channel, as these are widely recognised as the most important determinants of vegetation distribution in floodplain wetland environments (Gosselink and Turner 1978, Mitsch and Gosselink 1993).

In view of the complex floodplain topography and the considerable variation in floodplain width, it was not possible

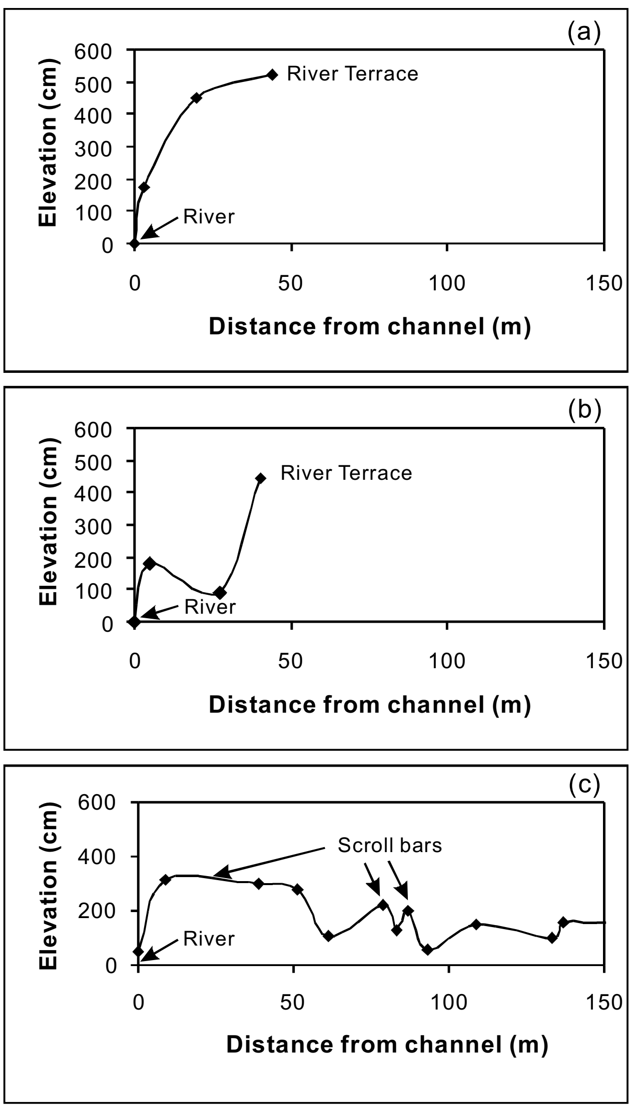

Figure 3: Topographic profiles away from the Okavango River at Andara Mission (a), Mashare (b) and downstream of the Quito confluence (c)

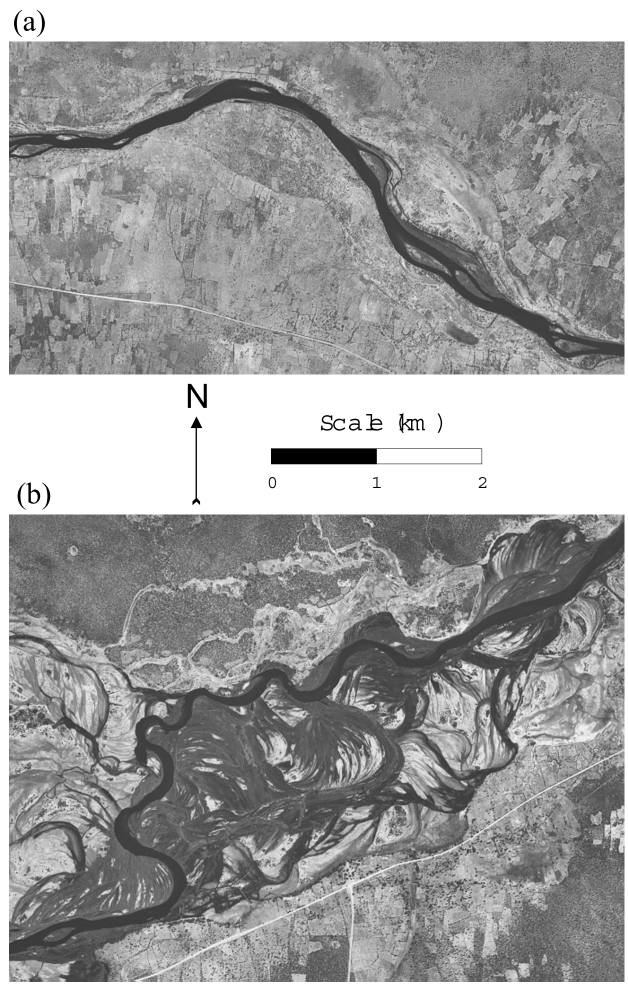

Figure 4: Aerial photographic views of the floodplains of the Okavango River between Kangongo and Mamono (a) and downstream of the Quito confluence (b)

to relate the distribution of species to distance from the channel or elevation above the water level in a simple way. However, it was possible to detect patterns in the distribution of species when these variables were considered jointly. The following patterns of species distribution were distinguished in relation to elevation above and distance from the channel:

i. Several species were restricted to areas of high elevation irrespective of distance from the channel, including *Acacia erioloba, A. hebeclada, Diospyros lycioides, Grewia occidentalis, Jasminum fluminense, Maytenus senegalensis, Peltophorum africanum* and *Terminalia sericea*. These species are clearly intolerant of flooding and occur on the floodplain in areas that have not been flooded for many years, or are infrequently flooded for short periods of time.
ii. Some species showed a pattern of occurring at high elevations close to the channel and at increasingly lower elevations with increasing distance from the channel. These species include: *Bergia pentheriana, Cynodon dactylon, Eragrostis porosa, Panicum maximum* and *Setaria sphacelata.* These species are likely to tolerate higher flooding frequencies or flooding of a longer duration than those mentioned previously, but they are generally intolerant of prolonged flooding.
iii. Other species showed a pattern whereby they were distributed at moderate or high elevations relatively close to the channel, but they were seldom found far from the channel. These species include: *Eragrostis bicolor, E. trichophora, Sesbania* sp.*, Trachyandra laxa, Tragus racemosus* and *Wahlenbergia* sp. These species appear unable to tolerate frequent or prolonged flooding. Their distribution close to the channel suggests that they colonise the most recently formed scroll bars. These are ruderal species which indicate recent disturbance, and our interpretation is that they occurred largely on the most recent scroll bars which are the product of fluvial processes.
iv. Several species occurred over a wide range of distances but at relatively specific elevations. These include *Brachiaria eruciformis* (low to moderate elevation), *Ischaemum fasciculatum* (low elevation), *Phragmites mauritianus* (low to moderate elevation), *Polygonum limbatum* (low elevation), *Vetivaria nigritana* (moderate elevation) and *Vossia cuspidata* (low elevation). These species appear to tolerate flooding to various extents, with flooding tolerance indicated by their distribution in relation to elevation.
v. Species occurring at a very low elevation and close to the channel include *Aeschynomene fluitans, Leersia hexandra, Ludwigia stolonifera* and *Pycreus mundii.* These species tolerate frequent and prolonged flooding of the root zone.
vi. The remaining species selected for analysis were too sparsely distributed to determine any pattern in their distribution. They have therefore been omitted from further analysis.

Based on these distribution patterns in relation to elevation above and distance from the channel it was possible to score species on a scale of 1 to 5 based on their perceived tolerance of flooding (Table 1).

Several interesting features emerge from this analysis. Generally, for each species for which there was sufficient data for analysis, as distance from the channel increased there was a decline in elevation as reflected by the slope on the regression line of elevation against distance (Table 1). Despite this trend, individual species covered an extremely wide range of conditions with respect to both elevation above and distance from the channel, as reflected in the low values for the correlation co-efficients of distance and elevation (Table 1). This is probably a result of the complex topography that typifies much of the floodplain. Certain areas, at low elevation for example, are not flooded as frequently as their elevation might suggest because they constitute a depression between two scroll bars, and are therefore surrounded entirely by land at higher elevation. Such depressions would require the water to reach the elevation of the lowest point of the surrounding high lying ground before the depression itself was flooded. Furthermore, variability in flooding conditions (discharge and therefore stage height) from year to year could contribute to these patterns in species distributions.

A further environmental variable that is clearly important, but which has not been taken into account in the present direct gradient analysis, is disturbance, particularly the formation of depositional features associated with fluvial processes. Several species were found to occur on recently-formed scroll bars. As such, they were found close to the channel but at high elevations above the channel. The distribution of these species has little to do with the hydrological regime (depth and duration of flooding), but is primarily related to disturbance history, particularly by disturbance associated with fluvial processes.

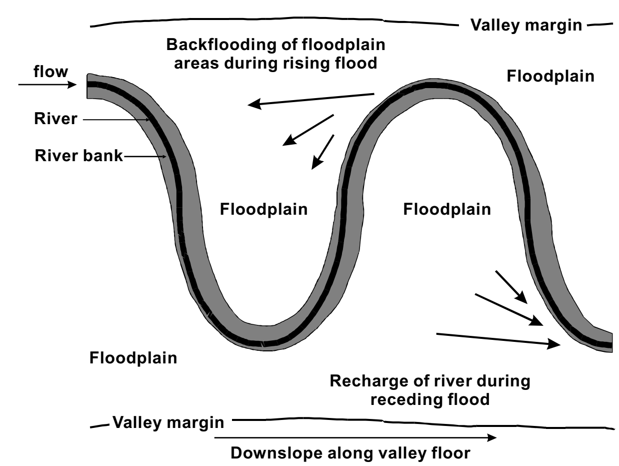

Figure 5: Schematic illustration of floodplain elevation in relation to the river and river valley, and an interpretation of flooding patterns during a rising and falling flood wave

Sample scores in relation to elevation and distance from the channel

Sample scores varied between >1 and <5, but when rounded to the nearest 0.5 they included the full range of values. The distribution of plot scores in relation to distance from the

Table 1: Species scores, slope of linear regression equations, y-intercepts and correlation co-efficients for different species in relation to distance (x-axis) and elevation (y-axis) on the floodplains of the Okavango River, Namibia

SPECIES	Species score	Slope of regression equation	y-intercept	Correlation co-efficient (R^2)
Pycreus mundii	1.5	-0.148	104.4	0.024
Aeschynomene fluitans	2	-0.178	76.9	0.122
Ischaemum fasciculatum	2	0.065	73.5	0.029
Leersia hexandra	2	1.252	33.2	0.333
Ludwigia stolonifera	2	0.039	77.5	0.004
Vossia cuspidata	2	0.083	108.6	0.008
Phragmites mauritianus	2.5	0.166	107.1	0.048
Polygonum sp.	2.5	-0.039	131.9	0.004
Setaria sphacelata	3	-0.099	188.8	0.023
Eragrostis bicolor	3.5	0.483	157.5	0.295
Trachyandra laxa	3.5	-0.225	174.7	0.342
Vetivaria nigritana	3.5	0.043	181.9	0.011
Bergia pentheriana	4	-0.437	295.8	0.613
Cynodon dactylon	4	-0.168	210.2	0.068
Eragrostis porosa	4	-0.382	264.8	0.582
Eragrostis trichophora	4	-0.090	215.1	0.010
Tragus racemosus	4	-0.074	194.5	0.013

channel and elevation above the water surface reflects the general pattern of increasing plot scores with increasing elevation and distance from the channel (Figure 6). A similar situation of decreasing elevation with increasing distance was evident for plots as it was for species, once again with a great deal of variation as reflected in the poor correlation co-efficients for linear regression of elevation against distance from the river (Table 2).

The impacts of water abstraction on the hydrological regime

The Okavango River is a perennial river with peak flows late in the southern summer (March – April), and low flows early in summer (October – November) at both Rundu and Mohembo (Figure 7a, b). Peak flows at Rundu are in the vicinity of 1 000 x 10^6m^3 in April, with a total mean annual flow of 5.5 x 10^9m^3, while at Mukwe the peak flows are approximately 1 500 x 10^6m^3 in April, with a total mean annual flow of 10.0 x 10^9m^3. The difference between these flows is due to the Quito River joining the Okavango River between Rundu and Mukwe, and this seems to contribute approximately 50% of the flow downstream of the confluence.

Comparison of the elevation of the water surface (stage height) before and after abstraction over the period of record reveals that the impact of water abstraction is greatest at low flows, and that the impact of abstraction decreases as discharge and therefore stage height increases. If there was no difference in stage height the line representing the relationship between pre- and post-abstraction stage heights would have a slope of 1, and a y-intercept of 0. The equations of the linear regression illustrating this relationship for both Rundu and Mukwe have slopes greater than unity, and a negative y-intercept, suggesting that at high flows the regression line converges on the line of no difference (Figure 8a,b). However, at low flows the difference between these two lines becomes increasingly great. Thus, at high flows there would little or no difference in stage height before and after abstraction, but at low flows the difference would be great.

This is supported by a more detailed analysis of differences in stage heights before and after abstraction for

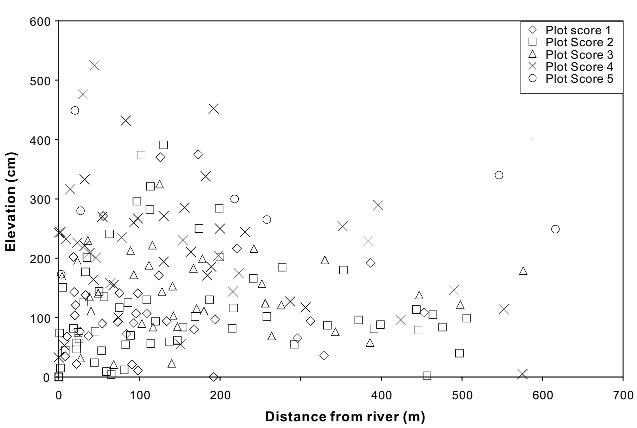

Figure 6: Distribution of plots with differing plot scores (rounded to the nearest whole number) in relation to elevation and distance from the river

Table 2: Slope of linear regression equations, y-intercepts and correlation co-efficients for different plot scores in relation to distance (x-axis) and elevation (y-axis) on the floodplains of the Okavango River, Namibia

Plot score	Slope of regression equation	y-intercept	Correlation co-efficient (R^2)
1	0.043	113	0.003
2	-0.03	115.4	0.005
3	-0.028	145.1	0.004
4	-0.228	252.1	0.099
5	-0.028	303.8	0.006

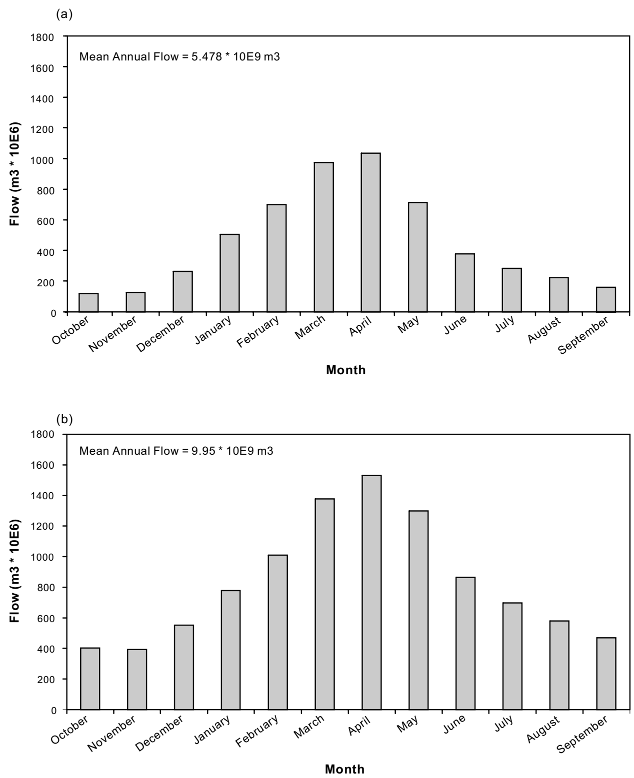

Figure 7: Mean monthly flows for gauging stations at Rundu (a) and Mukwe (b)

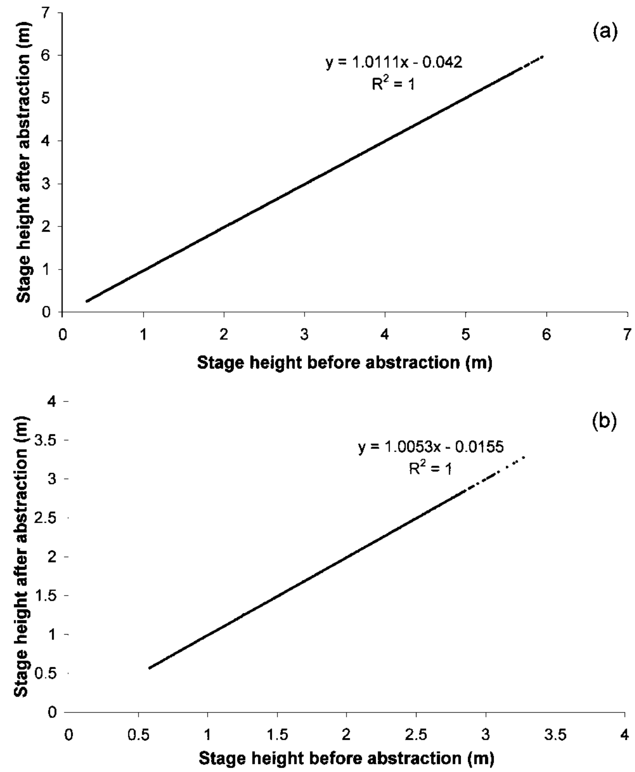

Figure 8: Relationship between pre- and post-abstraction stage heights, assuming a constant abstraction of 3 cubic metres per second at Rundu (a) and Mukwe (b)

Rundu and Mukwe (Table 3). The mean maximum stage height at Rundu is 5.4mm higher following abstraction than it was prior to abstraction (Table 3). This is related to minor inaccuracies in calculating stage height from discharge, and is indicated in the comparison of water elevations before and after abstraction (Figure 8a). In contrast to Rundu, the maximum stage height at Mukwe was 2.5mm lower after abstraction. The mean stage heights for pre- and post-abstraction regimes differed by 23.3mm for Rundu and 8.8mm for Mukwe, while the minimum values differed for these locations respectively by 33.9mm and 9.7mm. The reason for these differences is due to the fact that the Quito River joins the Okavango River between Rundu and Mukwe, and the impact of abstraction is considerably less at the station which receives higher flows at any given time.

Based on the present analysis of the duration of flooding at 3 stage heights (Figure 2), it is clear that the most significant impacts occurred during periods of low flow. During periods of peak flow for both Rundu and Mukwe, the water level prior to abstraction was higher than the maximum level reached after abstraction (A^1, Figure 2). However, for those areas no longer flooded after abstraction, the duration of flooding before abstraction (days per annum) only lasted 1–2 days. Based on the variability in discharge, and therefore stage height, from year to year, this is considered an insignificant impact. The delay in the arrival of the flood at the mean stage height ($C^1$1 Figure 2), and its decline below the mean stage height ($C^1$2 Figure 2), were less than 2 days. This suggests that abstraction would not materially affect vegetation on the floodplain at elevations of the mean stage height either. However, following abstraction, during each flood cycle there was lengthy exposure of areas that would not have been exposed prior to abstraction. The mean duration of exposure of such areas was 17.5 days at Rundu and 6.0 days at Mukwe. The duration of exposure of these areas was variable between years, with standard deviations of 10.1 and 5.4 respectively, indicating that there is a high year to year variability in the pattern of flood wave recession.

Discussion

Patterns of vegetation distribution

The distribution of vegetation on the floodplain of the Okavango River in Namibia is complex, reflecting the complex topography of the floodplain environments, complexity in the patterns of flooding and the importance of disturbance as an environmental variable, particularly disturbance associated with fluvial processes. Nevertheless, the vegetation of the floodplains is already generally disturbed due to the impacts of human activity and grazing by domestic livestock. Furthermore, the absence of any vegetation that indicates perennial flooding outside of the main river channel is striking. The giant sedge *Cyperus papyrus* is present at the confluence of the Okavango and Quito Rivers, as well as immediately above Popa Falls. The hydrological data shows seasonal water level fluctuations in the vicinity of 2m at both sta-

Table 3: Changes in mean stage heights and flooding regime per annum at maximum, mean and minimum stage heights for Rundu and Mukwe (standard deviations in parentheses)

VARIABLE	RUNDU N=50	MUKWE N=44
Difference (before – after abstraction) in mean stage (mm)	23.3 (12.1)	8.8 (2.6)
Difference (before – after abstraction) in annual maximum stage height (mm)	-5.4 (17.8)	2.3 (6.1)
Difference (before – after abstraction) in annual minimum stage height (mm)	33.9 (2.27)	9.7 (0.20)
Duration of exposure of areas flooded at maximum stage height before abstraction that were not flooded after abstraction (days)	1.00 (1.80)	1.52 (1.52)
Delay in flood wave at mean stage height during a rising flood (days)	0.70 (0.78)	0.82 (0.69)
Reduction in flooding duration at mean stage height during a falling flood (days)	1.77 (1.15)	1.61 (0.65)
Duration of aerially exposed vegetation at low flood stage following abstraction that would have been continuously inundated prior to abstraction (days)	17.5 (10.1)	6.0 (5.4)

tions and observations in the region suggest that the river itself is the only area that is permanently flooded. Clearly high current velocities and sediment movement on the river bed prevents the establishment of a significant in-channel flora.

Geomorphic history as a determinant of vegetation distribution

Based on the present study it is clear that patterns of vegetation distribution on the floodplains of the Okavango River in Namibia are not related simply to the hydrological characteristics as described in texts such as Gosselink and Turner (1978) and Mitsch and Gosselink (1993). In the case of the floodplain of the Okavango River in Namibia, geomorphic history is important. The present study demonstrates the widespread occurrence of ruderal species close to the channel with several species occurring only on the most recently formed scroll bars. In order to understand species distributions more clearly in this riparian wetland, one therefore needs an understanding of fluvial processes.

The catchment of the Okavango River comprises primarily aeolian Kalahari sand, although a portion of it is underlain by granite. Weathering of the granite yields kaolinite clay, but otherwise the sediment brought down by the Okavango River is primarily well sorted fine sand (Wilson and Dincer 1976). Given this simple geology and a bimodal particle size distribution of sediments transported by the Okavango River (McCarthy *et al*. 1988), the substratum characteristics of the Okavango River floodplains in Namibia are relatively uniform. Generally the surface of the substratum is clayey. This clay layer often overlies sand at shallow depth (<300mm). Alternatively, sand may be exposed at the surface. In general too, the floodplain tends to be more clayey close to the valley margin than close to the river itself.

Rogers (1995) addresses the issue of hydrogeomorphic determinants of riparian wetlands and recognises that the geomorphology of a river exerts a strong influence on biotic distribution. We contend that in the case of the riparian wetlands of the Okavango River in Namibia, geomorphic history is a significant determinant of vegetation distribution and that it ought to be considered on an equal footing with hydrological considerations. In the case of attempting to understand the impacts of water abstraction, it is therefore evident that it is important to further understand the impacts of reduced flows for fluvial processes related to sediment deposition and erosion. If abstraction is likely to lead to a reduction in unusually high flood events, which typically give rise to the formation of depositional features such as scroll bars, then it should be expected that ruderal colonisers of these features might become locally extinct from the floodplains of the Okavango River in Namibia. It is therefore recommended that, if water abstraction proceeds, it be done in a manner which does not significantly dampen unusually high flows. The present analysis suggests that abstraction during high flows has little impact, and this therefore does not appear to be a significant problem. However, the construction of a dam or weir in the catchment or along the course of the Okavango River may have this effect, and consequently this option is strongly advised against. The method of abstraction must therefore be by pumping.

A more detailed consideration of the hydrological implications for water abstraction

If abstraction is to take place continuously over the annual cycle, impacts would be greatest on the lower floodplain. In contrast, the impacts on the middle and upper floodplain would appear to be small. This combination of circumstances provides a good case for recommending that, should water abstraction proceed, it should take place at times other than during periods of low flow. Based on variability in peak flows from year to year, it seems that abstraction at peak flows is unlikely to have a substantial impact on vegetation distribution, and our opinion is that abstraction would be acceptable at such times.

A further concern related to abstraction of water at low flows is the fact that the Namibian section of the Okavango River leads to a recharge of the local groundwater. This means that the discharge of the river declines downstream as water is continually supplied to the surrounding floodplain as groundwater. The rate of decline of river flow from Rundu to Mukwe is unknown as the Quito River joins the Okavango River between these two stations. It is, however, possible that if abstraction was to take place at low flows, the Okavango River could potentially be converted from a perennial river to a seasonal one — at least between Rundu and its confluence with the Quito River. This would be unacceptable from the points of view of the people living on the floodplains in Namibia, and of the undesirable conversion of perennial rivers to seasonal rivers which, in southern Africa, has been widely recognised as being ecologically disastrous (O'Keeffe *et al*. 1989). This may provide a case for recommending that abstraction take place downstream of the confluence of the Quito River, in which case the possibility of seasonally terminating the flow of the river would be eliminated. Clearly, more information regarding the rate of recharge of groundwater by the river downstream of Rundu needs to be determined prior to determination of an abstraction procedure.

Conclusion

This study reveals that the vegetation of the Okavango River floodplain in Namibia is determined by a complex interaction of hydrology, topography and disturbance history. It also illustrates that uniform abstraction of water would have a greater impact at low flows than at medium and high flows. For this reason abstraction would be best undertaken during periods other than at low flows. This contention is supported by the fact that the Okavango River is a groundwater recharge river and abstraction at Rundu during periods of low flow could potentially cause the reach between Rundu and the Quito River confluence to cease flowing seasonally. This is potentially disastrous and, in the absence of sufficient information on rates of groundwater recharge, it may be advisable to consider removing water from below the Quito confluence should abstraction ever need to take place during periods of low flow.

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