The use of SPOT imagery in the study of environmental processes of the Okavango Delta, Botswana

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Computer-processed multispectral SPOT satellite images covering part of the Okavango Delta provide an extremely useful tool for studying this large, remote wetland. In particular, a transformed vegetation index (TVI) was found to be semi-quanitatively related to standing crop. Vegetation standing crop is, in turn, related to resource availability and, hence, indirectly to local hydrological regime. The TVI images therefore provide a synoptic view of water dispersal in the Delta. Careful examination of the images further reveals the widespread development of lineaments, presumably of tectonic origin. The TVI images are ideal for studying such lineaments.

The Okavango Delta of northern Botswana (Fig. 1) is one of Africa's largest wetlands. For some years an interdisciplinary group from the University of the Witwatersrand has been studying the dynamics of the wetland with a view to obtaining a comprehensive understanding of the functioning of this unique ecosystem.

Due to its remote location, and until recently the presence of tsetse fly, the region is in an essentially pristine state, with little in the way of physical infrastructure. Airfields belonging to safari lodges provide access to limited areas within the wetland and, importantly, to the larger distributary channel systems, which are navigable. However, the backswamp areas, which comprise most of the Delta, are inaccessible. Logistical difficulties associated with research in the Delta are immense. Moreover, the Delta covers a vast area, consisting of about 6 000 km^2 of permanent swamp and a further 6 000 to 12 000 km^2 of seasonal swamp. Several hundred kilometres of channelways traverse the swamp. Field studies can at best sample only a small fraction of this large area and there are great problems associated with selecting suitably representative areas for field work.

Remote-sensing techniques are clearly of value in this situation and extensive use has been made of conventional panchromatic aerial photographs in the course of the research. These provide excellent morphological information, but their usefulness in studying aquatic vegetation is limited. The authors were afforded the opportunity of examining the applicability of multispectral satellite imagery to this problem. Two images covering the areas shown in Fig. 1, acquired by the French Satellite Probatoire pour l'Observation de la Terre (SPOT), were obtained by courtesy of the Satellite Applications Centre of the CSIR and SPOTIMAGE of France.

Image-processing techniques

Multispectral SPOT data are collected in three wavebands: green visible (0.50–0.59 μm), red visible (0.61–0.68 μm) and near infra-red (NIR, 0.79–0.89 μm), with a ground pixel resolution of 20 × 20 m at nadir. Data for the present study were collected by the SPOT 2 satellite on 8 October 1991; scene reference numbers are 118.388 and 119.388. Bands 1 and 2 (green and red visible) in both scenes were badly striped, apparently as a result of defective sensor calibration algorithms (Ike Marais, pers. commun.). No preprocessing was done to remove this striping, however, because the spectral band ratioing techniques used in this study are unaffected by albedo differences. Image processing of the data was carried out on a 486 personal computer with the Map and Image Processing System (MIPS) software package.

Jensen[1] has provided a useful summary of the application of vegetation indices derived from remote-sensing data. These reflect vegetation canopy characteristics, such as percentage ground cover, biomass, leaf area and productivity. A number of standard vegetation indices were tested on the 119.388 data set, for use as the main component in the final interpretation image. These included a simple band ratio (NIR/red), a transformed vegetation index {100 × sqr.rt [(NIR – red)/(NIR + red)]}, and a leaf area index (41.325 × green/red – 42.45 × green/NIR). In addition, examination of the eigenvector matrix after a principal-component analysis showed that the second principal component is mostly due to the spectral reflectance of vegetation, and an image of this was compared with greyscale images of the above indices. Overall, the TVI image portrayed the most detail, and this index was therefore chosen for production of the final colour image. Prior to incorporation into the final image, the TVI image was interactively scaled to achieve optimum contrast over a specific area of interest within the general study area, where ground control was very good.

The final colour image for interpretation was compiled in intensity–hue–saturation (IHS) colour space, using an interactively scaled first principal component to represent intensity (a general albedo image), and the TVI to represent both hue and saturation. Bright (highly saturated) blue and magenta colours portray high vegetation indices on this image; reds, oranges and yellows portray moderate indices; and light, pale (weakly saturated) greens portray low indices. The advantage of generating a colour composite image in IHS colour space is that topographic detail is preserved, but colour is controlled by only one image component (in this case, the TVI).

Results and discussion

Interpretation of spectral response

Areas of the images where detailed ground studies have been completed[2] were examined in order to assess the significance of the colour scale produced by the processing technique. This revealed that the hue is related primarily to the standing crop of vegetation and is not influenced by the species composition of the vegetation. In stands of *Cyperus papyrus*, for which quantitative estimates of biomass are available,[3] hue was found to be related directly to biomass (Fig. 2).

A critical factor promoting growth of aquatic plants is turnover of water. Aquatic plants growing in slow-flowing or stagnant water deplete the nutrients and become stunted. Water flow can prevent this from occurring. The spectral signature can therefore be used to analyse water-flow patterns.

It has been shown that there are changes in the species composition of channel-flanking vegetation along the channel system. These changes are believed to reflect the differing

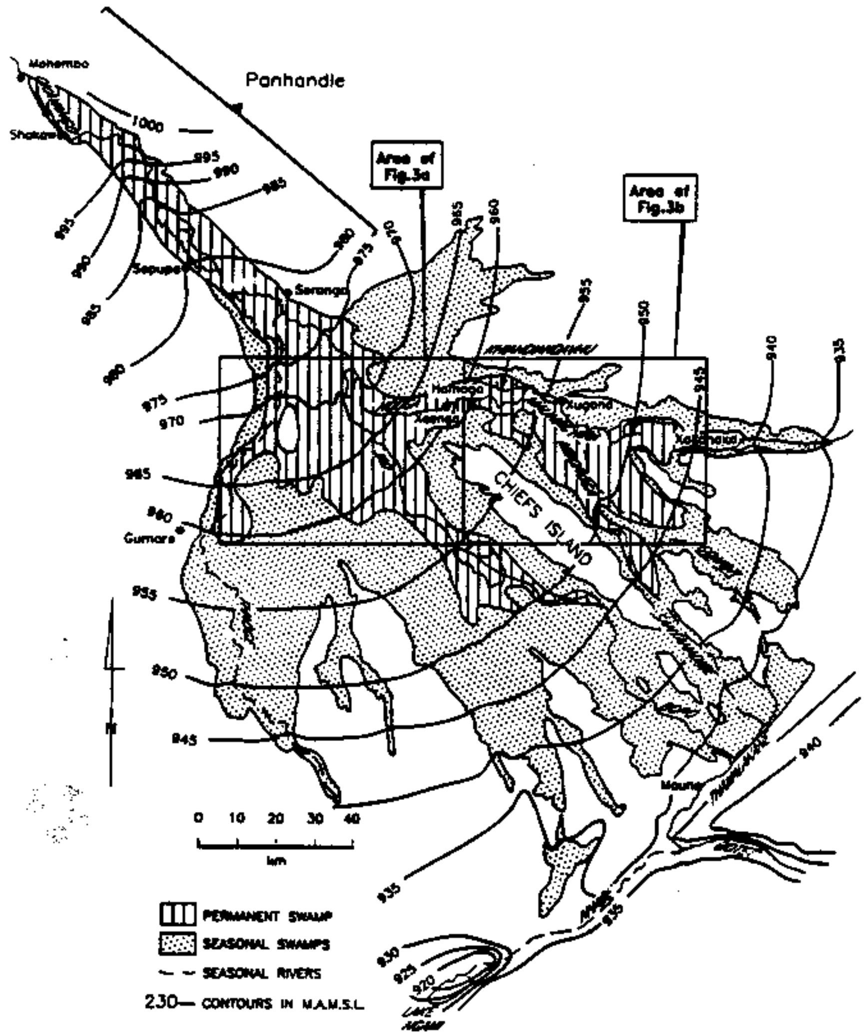

Fig. 1. Location of the SPOT images studied in this work.

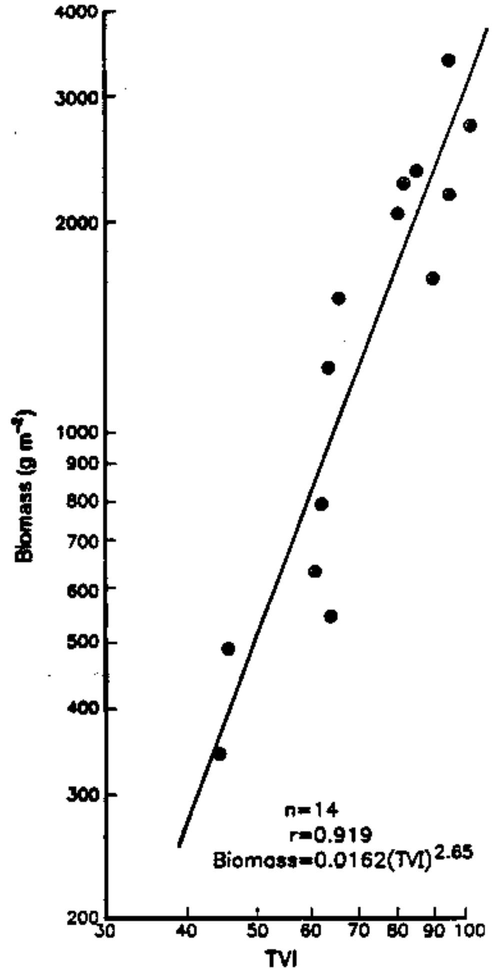

Fig. 2. The relationship between biomass and transformed vegetation index (TVI) in papyrus stands along the Nqoga and Maunachira channels.

nutrient requirements of the various species. Different species appear to have a similar TVI response, and species composition cannot be easily determined from the processed images. However, it is not known whether the relationship between TVI and biomass as shown in Fig. 2 is the same for all species.

Open water bodies or recently burnt wetland communities appear black on the image, while grassland is characterized by pale colours. Bare soil appears white. As the images were collected before the onset of the summer rains, chlorophyll levels over most terrestrial environments were low. This would undoubtedly be different for a mid- to late-summer image.

Regional gradient

Cursory examination of the images (Figs 3*a* and *b*) reveals that the upper reaches of the permanent swamp are in general characterized by yellow or reddish hues, while the distal reaches are marked by greens and blues, indicating a generally higher level of biological activity in the upper reaches of the swamps. This most probably reflects a regional gradient in nutrient level. Within this overall gradient, ribbons of enhanced vegetation growth are discernible, invariably associated with distributary channels.

Channel systems

Detailed study has revealed that channels can be classified into various categories on a basis of fluvial processes operating within them. In general terms, two broad types of channel can be identified in the region of swamp covered by the images:

a) Primary channels are those which receive water and sediment from the Okavango River. These are aggradational and generally leak water to the surrounding swamps. The water level in these channels is elevated relative to that in the surrounding swamp and is maintained by levees of dense aquatic vegetation.[4] Primary channels have a limited life because they experience aggradation as a result of bedload accumulation.[5,6] These channels fail progressively from their distal ends.

b) Secondary channels receive water lost from primary channels (or other secondary channels) by flow through the swamp, but they receive no sediment. In their upper reaches these channels are erosional and they deposit the eroded sediment downstream and lose water to the surrounding swamp.[6]

Primary channels which are losing water are characterized by a wide, highly coloured fringe on the image (Fig. 4*a*). Outflow of nutrient-carrying water promotes vegetation growth on the immediate channel fringe. Water loss is sometimes asymmetrical, with one margin showing more prolific growth than the other.

The image covering a primary channel reach which is currently experiencing failure is particularly informative (Fig. 4*b*). Water is known to be spilling from the channel and dissipating in the flanking swamp immediately upstream of the failing reach (A in Fig. 4*b*).[6] This phenomenon is clearly visible on the SPOT image. In the failing reach itself, prolific growth is limited to a very narrow zone along the constricted channel.

Secondary channels have a rather different appearance on the images. These channels draw water from the surrounding swamp. The water is already depleted in nutrients and consequently no vegetation anomaly is developed along the channel

Fig. 3. Two complete processed SPOT scenes: the colours of the western image, *a*, are in general brighter than those of the eastern image *b*, indicating a generally higher level of biological productivity in the west.

margins (B and C in Fig. 4*b*; A in Fig. 4*c*). Although secondary channels gain water and are erosional in their upper reaches, they become aggradational downstream and lose water. This phenomenon can be clearly seen on the image of the upper reaches of the Khiandiandavhu and Maunachira channels (D and E, respectively, Fig. 4*b*).

Many small channels in the distal reaches of the swamp are marked by a continuous, brightly coloured fringe on the images (Fig. 4*d*), which cannot be readily related to regional water-flow patterns. These narrow channels are hippopotamus trails.

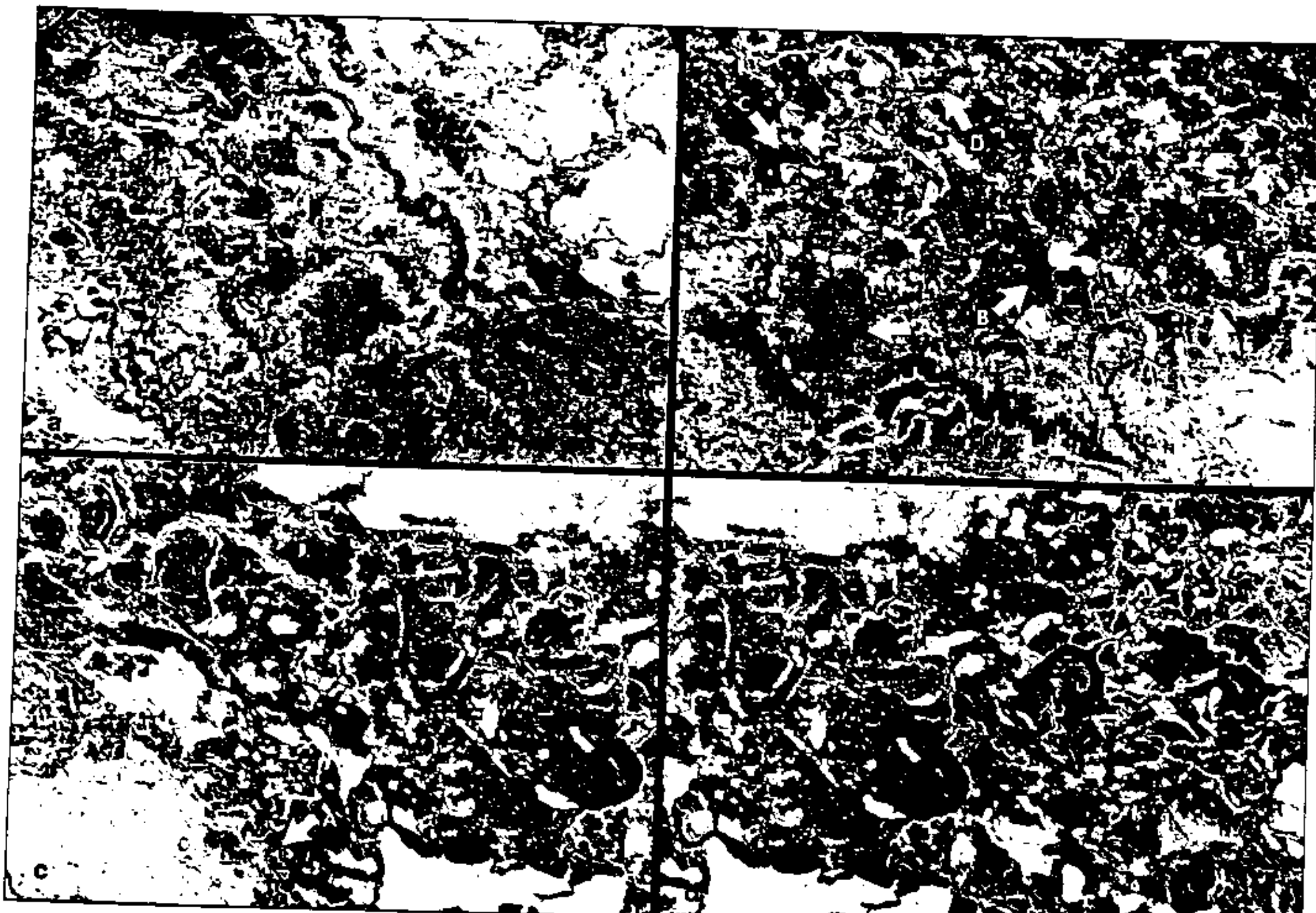

Fig. 4. *a*, Processed SPOT image showing a section of the Nqoga channel (arrowed) which leaks water to the surrounding swamp, producing a dense vegetation fringe which appears as a magenta zone flanking the channel. *b*, Processed SPOT image of the failing end of the Nqoga channel, where water dissipates into the surrounding swamp, creating dense vegetation growth (A). The area is drained by two secondary channels, the Maunachira (B) and the Khiandiandavhu (C). These do not have dense fringing vegetation in their upper reaches but develop a dense fringe downstream, such as along the Khiandiandavhu (D) and along the Maunachira (E). *c*, Processed SPOT image of the lower reaches of the Maunachira channel. The large oxbow lake on the right is Gobega. The Mboroga channel (A) draws its water from the surrounding swamp and has no dense vegetation fringe. *d*, Processed SPOT image of the lower reaches of the Maunachira channel. The large lakes (black) are (from left to right) Gobega, Gadikwe and Xhamu. Most small distributary channels along the lower Maunachira channel are characterized by a vegetation anomaly. The field of view in each image is approximately 13 × 9 km.

These animals probably introduce nutrients into the channel system and the disturbance caused by their passage spreads this into the flanking swamp, creating a broad fringe of higher vegetation standing crop, which can readily be seen on the image.

Islands

Many of the islands in the area of permanent swamp covered by this survey are characterized by trona ($Na_2CO_3.NaHCO_3$ $2H_2O$) accumulations, a product of transpiration and evaporative pumping.[7,8] These islands have a narrow fringe of broad-leaf evergreen trees and shrubs, which passes abruptly into a barren interior zone in which soil alkalinity is so high that no plants are able to grow.[7,9] These islands are clearly visible on the SPOT image. On the processed image, the dense evergreen vegetation produces a magenta fringe around the white bare soil of the island interior (Fig. 4*b*). These islands have higher albedo than dry grassland because of the presence of white efflorescent crusts of trona on the surface. The contrast between these two types of terrain is likely to be greater for images produced using data acquired after the summer rains. It appears that data obtained during late winter or early spring are unsuitable for analysing dryland settings, but this period is probably optimal for studying wetland vegetation patterns, as the contrast between dry and wetland situations is so pronounced.

Neotectonics

The Okavango Delta is situated in a half-graben,[10] which is an extension of the East African Rift system.[11] The area is seismically active[12] and a magnitude 6.7 earthquake occurred in the area in 1952.[13] Seismicity is currently centred in the area south-west of Maun.[12] Fault traces are evident on the surface, in the form of fault scarps which control the terminal drainage along the south-eastern margins of the Delta. These are clearly visible on satellite images of the area.[14,15]

Careful examination of the SPOT images reveals numerous, subtle lineaments, defined by linear chains of islands, straight channel reaches or linear offshoots of swamp. Three orientations occur (Fig. 5). The most prominent is parallel to a major WNW-striking dyke swarm, while a second set strikes subparallel to the Panhandle (Fig. 1). These observations suggest that small faults abound in the Delta and may have considerable influence on water distribution. The images processed in the manner described here provide a potentially powerful tool in the study of the role of tectonics in wetland systems.

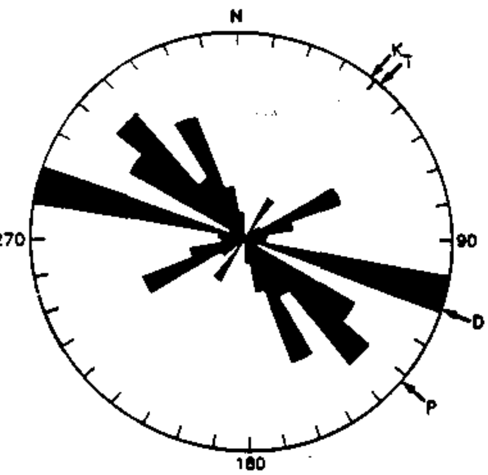

Fig. 5. Rose diagram showing the orientation of lineaments measured in the easterly SPOT image: K, Kunyene fault; T, Thamalakane fault; D, dyke swarm; P, Panhandle.

Comparison of SPOT imagery with panchromatic aerial photography

Conventional aerial photographs have superior resolution to SPOT imagery. However, the transformed vegetation index used in this study provides information not obtainable from conventional photographs. This can be clearly seen by comparing Fig. 6 with Fig. 4*b*, which cover essentially the same area. The processed SPOT image provides important vegetation and, by inference, hydrological information and is a useful supplement to conventional aerial photography. However, the superior definition of aerial photography renders it more useful in geomorphological analysis.

SPOT imagery as an aid in regional reconnaissance

During the course of this investigation, several large areas were observed in which vegetation growth was anomalously prolific. We were not previously aware that these areas were in any way abnormal and the reasons for these features are unknown. In view of the relationship between vegetation growth and hydrology, it seems likely that these anomalous areas reflect unusual hydrological conditions. SPOT imagery processed in the manner described here is clearly useful in reconnaissance investigations of wetlands, as areas of potential interest and importance are highlighted.

Conclusions

Wetland plant communities are particularly sensitive to the nutrient status of the water in which they grow and moreover respond to turnover of the water mass. Plant growth is therefore sensitive to the hydrological sub-environments within the wetland. This investigation has shown that a transformed vegetation index calculated from high-resolution SPOT imagery yields information on the density of chlorophyll and hence provides a means of imaging the vegetation response to nutrient supply. This indirectly provides hydrological information.

Detailed ground studies carried out over a number of years have revealed that certain channels of the Okavango Delta leak water to the surrounding swamp. SPOT images have not only confirmed this finding but also revealed exactly where the water is being lost. Studies have also shown that certain channels gain water from the surrounding swamps. These can also be recognized on the images. An added advantage is that the images provide information about areas which are not accessible to ground study. Winter images seem to be especially useful, as grassland signatures are suppressed. The processed SPOT images provide a synoptic view and highlight

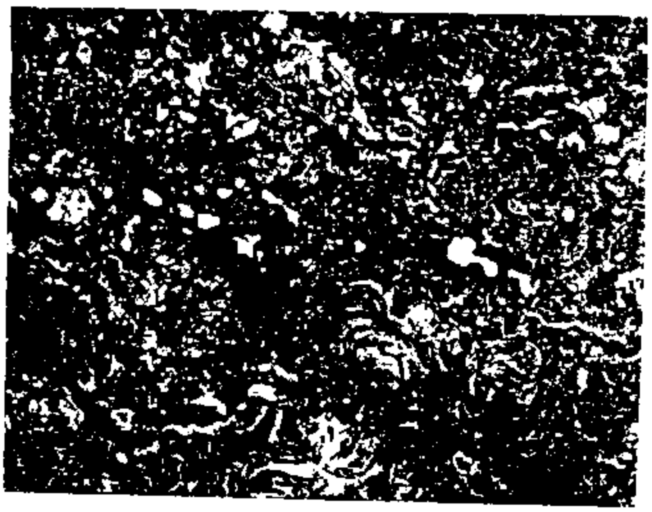

Fig. 6. Panchromatic aerial photograph covering approximately the same area as shown in Fig. 4*b*.

areas of enhanced activity, a useful feature during the planning phase of wetland research programmes. However, SPOT imagery is not a substitute for panchromatic aerial photography, but it does form a useful supplement, providing data which cannot be obtained by any other means.

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