Monitoring transitions in vegetation cover to detect long-term trends in ground water resources

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ABSTRACT

This paper provides a simple methodology to detect long-term trends in groundwater resources by using multi-date remotely sensed imagery and in-situ observations to monitor transitions in vegetation in and around Lake Ngami's emergent floodplain environment in the distal reaches of Botswana's Okavango Delta. Covering a period of 34 years between 1967 and 2001, trends emerging from this reconstruction point to a sustained shift from a perennial wetland to an intermittently flooded dryland environment, significant increase in drought tolerant woody species notably *Acacia mellifera* and *Acacia erioloba*, and sustained contraction of groundwater resources. With transitions in the distribution of these and other indicator species mimicking changes in hydrological conditions, it is apparent that spatial and temporal variations in their distribution can be used to provide long-term trends in groundwater resources. In view of the general lack of time-series data on regional trends in aquifer storages in arid and semi-arid areas, remote-sensing-based monitoring of vegetation can be exploited to provide proxy measurements and useful insights that can be used to guide the formulation of informed interventions potentially capable of enhancing our capacities to cope with decreasing supplies in areas where signals of climate change point to the inevitability of increased scarcities.

Key words: groundwater, long-term trends, remote sensing, arid/semi arid areas, drying sequences

INTRODUCTION

In arid and semi arid areas where groundwater is exploited for direct consumption and the sustenance of a wide range of human activities, it is difficult to obtain reliable estimates of quantities available because of the complex linkages between recharge and withdrawal. Though local rainfall in these areas plays an important role in determining recharge its influence is mediated by evapotranspiration and human exploitation. Because rainfall and these withdrawals are spatially and temporally variable (Declan et al., in press), estimates that are based on monitoring recharge and losses through natural and non-natural pathways are bound to be guesstimates that do not reliably capture long-term trends in groundwater resources. This is particularly so in water stressed areas where exclusive abstraction from surface sources is incapable of meeting the growing demands of rapidly increasing populations (VanderPost and McFarlane, 2007). In the majority of these areas, shortages are aggravated by persistent decrease in rainfall (Hamandawana et al., 2005; Steenekamp and Bosch, 1995). This phenomenon has become a dominant feature of southern Africa's climate (Hulme et al., 2001), with long-term trends pointing to increasing aridity (Hamandawana et al., 2008) while modelled projections of hydrological conditions predict substantial deterioration during the remaining decades of the 21st

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century (Murray-Hudson et al., 2006). Though some areas continue to receive high rainfall large portions of the sub-region receive amounts well below 500mm/annum most of which is not utilizable because of high annual evaporation rates approximating 4 000mm. This scenario has substantial implications on reliable access to adequate supplies with estimates projecting continued decrease in per capita availability (DFID, 2003) as escalating demands and climate induced contraction reinforce each other to increase stress on declining supplies. That supplies are contracting is corroborated by sustained floodplain desiccation (Hamandawana, 2007) and climate predictions of decrease in rainfall by >10% (Nyong, 2005) and surface flow by 23%-78% for different catchments in this region by the end of this century (de Wit and Stankiewicz, 2006). Though it is generally accepted that water is becoming scarcer, approaches to water resources planning continue to be supply-driven, with most countries trying to meet increasing demands by expanding abstractions from surface sources and aquifers. While surface sources are generally easy to monitor through devices such as stream gauging and quantitative estimation of dam and lake volumes, groundwater requires more costly techniques that have traditionally depended on water-table monitoring to estimate recoverable quantities in different aquifers. Cost constraints are further aggravated by the inability of the same techniques to provide informative insights on long-term trends due to lack of time-series data over similar temporal scales and fragmented spatial coverage where such data are available. These limitations are complicated by stochastic variations in withdrawals and recharge that make localised measurements unreliable indicators of trends at sub-regional/regional levels. These shortcomings pose serious challenges as characterizations cannot be confidently transferred from one spatial scale to another. Though groundwater resources in this sub-region have been investigated by many, most of the efforts have been focused on identifying exploitable aquifers (DWA, 2002; 1998; IUCN, 1992; SMEC, 1987) and estimating transpirative losses (Ringrose, 2003) and anthropogenic pollution (BRGM, 1986). This bias creates an information gap that makes it difficult to regulate levels of exploitation in tandem with aquifer potentials. Since our understanding of trends in groundwater remains equivocal, conservative estimates should be made on how natural and non-natural externalities are impacting on reserves at our disposal.

Without reliable information on how groundwater is responding to climate variability and human exploitation, forward planning to ensure sustainable provision of adequate supplies remains a major policy issue requiring comprehensive exploration of appropriate monitoring strategies. Though boreholes and wells have traditionally been used for this purpose, they are generally incapable of providing regional-scale coverage because they require high density distributions and commitment of substantial resources. Similar limitations apply to related techniques such as aero-magnetic surveys that need to be validated by costly field investigations. One way of overcoming these constraints is by monitoring long-term changes in vegetation distribution. In stressful environments characterised by high rates of evapotranspiration and low and erratic rainfall, temporal and spatial variations in the distribution of dimorphic species (those that utilize both deep and shallow water) provide reliable expressions of trends in groundwater resources. This relationship allows remote sensing-based characterisations of vegetation to be used for monitoring trends in groundwater resources at multiple spatial scales. Though remote sensing is potentially useful for this purpose, investigations that exploit vegetation’s informative expression of groundwater conditions are uncommon. In recognition of this shortcoming, the objective of this paper is to illustrate how remote sensing can be used to detect long-term trends in groundwater resources by reconstructing trends in vegetation distribution and relating the same trends to *in-situ* observations of surface and sub-surface hydrological conditions.

THE REFERENCE AREA

The reference area comprises a 900km^2 sample site providing footprint of coverage of Lake Ngami and its immediate environs (Figure 1). The Lake is a terminal sump of the Okavango Delta that perennially flooded to inundate an area averaging 800km^2 during and before the first half of the 19th century from inflow via the Thaoge River and other supply channels that include the Nhabe and Kunyere (Shaw, 1983; Stigarnd, 1922; Oswell, 1849).

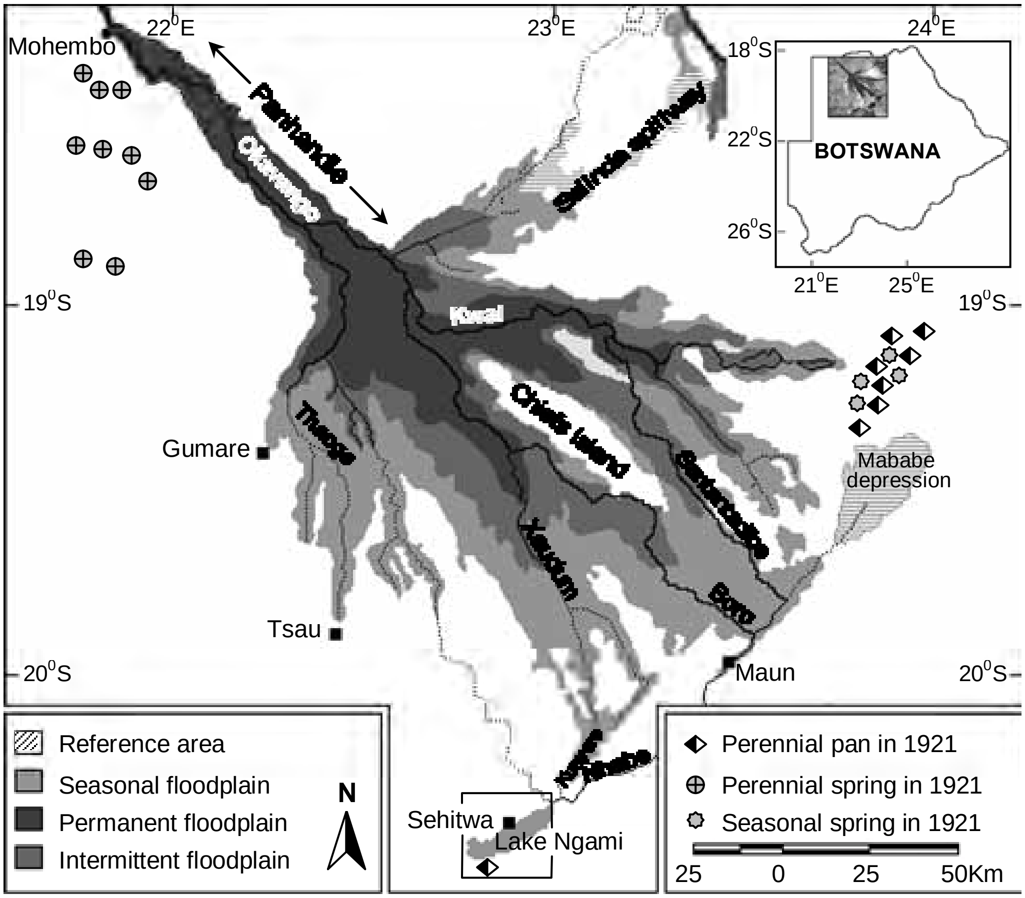


Figure 1 Location of the reference area in the distal reaches of Botswana's Okavango Delta

Though Lake Ngami features in the literature and maps showing this region's surface hydrology, it started drying up during the second half of the 19th century (Shaw 1985; Tlou, 1972) and is exempted from being classified as a fossil lake because it occasionally floods during periods of exceptionally high rainfall in the Delta's major catchment areas in Angola and Namibia. At the local level, the area has a semi-arid climate with rainfall averaging 453mm year^{-1} (Ringrose et al., 2007) and is among those worst affected by drying sequences (Hamandawana et al., 2007a).

Over time during the recent historical past, flood failures translated into sustained desiccation and successive colonization of the Lake's emergent environment by different types of vegetation. Because of marginal rainfall vegetation largely consists of bush savanna dominated by a narrow range of drought tolerant species. Surface drainage is dominated by intermittent streams and rivers that flow when floods in the Delta are high enough to sustain discharge from the wetland. The human population is largely confined to nucleated villages due to the need for centralized provision of water from boreholes. The major source of livelihood is livestock farming which is also dependent on borehole water. Arable farming has substantially declined due to sustained decrease in rainfall and drying sequences that have undermined rain-fed and flood recession cultivation. The area is therefore confronted by serious water challenges and the situation is likely to worsen as climate change continues to diminish the limited resources available.

MATERIALS AND METHODS

The materials that were used include CORONA photographs of 1967, Landsat Thematic Mapper (TM) and Landsat Enhanced Thematic Mapper (ETM) mosaics of 1989 and, 1994 and 2001 respectively, a 1m-resolution ortho-photo mosaic of August 2000 and aerial-photo mosaics of August 1991. Table 1 describes the temporal sequencing and characteristics of these images.

Table 1 Temporal coverage and characteristics of images that were used

***CORONA MOSAIC:** Source – USGS					
Acquisition date	**Scene ID**	**Acquisition date**	**Scene ID**	**Instrument**	**Spatial resolution**
15 Sep1967	D153-061	15 Sep1967	D153-063	KH4B-FW	2m
15 Sep1967	D153-062	15 Sep1967	D153-064	KH4B-FW	2m
****LANDSAT MOSAICS:** Source – USGS					
Acquisition date	**Scene ID**	**Acquisition date**	**Scene ID**	**Instrument**	**Spatial resolution**
04 Sep 1989	P174R073	04 Sep1989	P174R074	TM	30m
01 Aug1994	P174R073	01 Aug 1994	P174R074	TM	30m
28 Aug2001	P174R073	13 Sep 2001	P174R074	ETM	30m
AERIAL PHOTO MOSAICS: Source – Department of Surveys and Mapping, Botswana					
Acquisition date	**Scene ID**	**Acquisition date**	**Scene ID**	**Type**	**Spatial resolution**
***August 2000	****	***August 2000	****	Panchromatic	1m
***August 1991	****	***August 1991	****	Panchromatic	1: 50 000

*Key Hole (KH) designators were used to index the photographs that were acquired in stereo by forward (FW) and backward looking cameras. Frames used were acquired by the FW looking camera. **Landsat scenes are given by path (P) & row (R) numbers. ***Acquired on different days of August.

These images were extracted from a geo-database (Hamandawana et al., 2005) that was compiled to monitor environmental changes in and around the Okavango Delta (Hamandawana, 2006). The CORONA mosaic was compiled from 2m-resolution intelligence satellite photographs declassified by the United States in 1994. Hamandawana et al., (2007b) provide a detailed discussion on how these photographs were processed and merged with Landsat imagery. The aerial photo-mosaics (used as ancillary sources of ground truth during image classification) were also compiled from dry-season coverages to enhance close temporal correspondence with satellite images. The next subsections (sub-sections 3.1-3.3) describe how reference information used to guide supervised classification was collected, how CORONA and Landsat images were classified and procedures that were used for classification accuracy assessment (CLACAS).

Field compilation of reference data

During field investigation, reference data were compiled from 170 ─ 30m x 30m quadrats that were located by using a Garmin III Global Positioning System with a rated accuracy of 4m±. These quadrats were systematically selected on the basis of a 30-class field-guide map prepared from unsupervised classification of the 2001 ETM subset. In running unsupervised classification, the red, green and blue composite of bands 4, 3 and 2 was used. Band combinations were determined by selecting the least correlated and most appropriate bands for land use and land cover mapping. The former was accomplished by running the image through band correlation analysis in ERDAS IMAGINE 8.4 (Erdas Inc, 1999) and suitability criteria obtained from Lillesand and Kieffer (2000). For each of the 30 cover types in the field guide map, 3 quadrats were intensively investigated and class labels assigned on the basis of consistent criteria that include species type, tree-height and density distribution and canopy closure. However, identification by species type was considered unnecessary for herb cover because its classification on this basis was not possible. For this information class, the percentage of cover in individual quadrats was determined by using the quadrat charting technique (Hamandawana, 2002). In this procedure, the proportion of each quadrat under herb cover was visually determined and then expressed as a percentage i.e. 3/4 coverage = 75% cover. For woody cover, canopy closure was determined by estimating the tree-shaded proportion of each quadrat and expressing this estimate as a percentage of the total area and a physical count of individual plants by species type used to determine dominant species. To expedite representative sampling, at least 4 geolocated hand-held camera photographs were also acquired for each cover type following the procedures described above. Thereafter, all field data were entered in a database file in Excel (statistical software, Microsoft® Office 2003) and class-labeled quadrats and photo-standards relationally linked to their coordinate locations. This georeferenced information, was then converted to point themes in ArcView 3.2 (GIS software, Neuron Data Inc, 1991), with 2/3 of this data being set aside for supervised classification and the remaining 1/3 being reserved for CLACAS. Though non-woody information classes were not used to infer trends in groundwater distribution, these were also mapped to facilitate the isolation of all cover types.

CORONA image classification

CORONA photographs were classified on the basis of an improvised step-wise density slicing procedure that involves digital classification by segmentation and visually guided gray-scale-coding (DCSVGGC). In the preceding contraction, DC indicates digital manipulations that were used during image classification. S shows that the image was classified on the basis of segments interactively delineated into broad information classes. VG denotes the classification component in which consistent criteria and ground-truth were simultaneously used to guide visual feature discrimination and interactive assignment of pixels to information classes. The terminal GC conveys how similar features were grouped through computer-aided discretization of spectrally homogeneous pixels in user-defined segments through successive symbolization (i.e. pixel colour shading) of individual gray levels to obtain information classes corresponding to simplified equivalents of Landsat imagery. The main steps involved can be summarized as comprising: 1) image segmentation into broad homogeneous cover types, 2) identification and colour-coding of distinct information classes in the same segments and refining these classes through secondary segmentation to isolate and reclassify misclassified features with overlapping brightness values and, 3) progressive recoding of all segments into classified subsets and overlaying the individual subsets to build a composite map output. Details on how these procedures were undertaken are described elsewhere (Hamandawana et al., 2006).

Landsat image classification

Landsat images were classified by subdividing the three datasets into two groups comprising the more recent ETM mosaic of 2001 and the historical TM mosaics of 1989 and 1994. The 2001 mosaic was classified on the basis of data compiled during a field investigation in March 2004 and collateral information from the 2000 ortho-photos. The historical 1989 and 1994 subsets were classified on the basis of the 1991 aerial-photo mosaics that were used as sources of ground truth in lieu of field data and information on habitat preferences of individual species.

Signature extraction and supervised classification

The same band combination used during unsupervised classification was used for the supervised classification of Landsat imagery. In classifying the 2001 ETM subset, the point themes created in ArcView were overlaid on the same image subset to guide the compilation of signatures from 2 x 2 pixel windows which was further boosted by use of the 2000 ortho-photos as an ancillary source of ground-truth. The latter was accomplished by displaying both images in geographically linked viewers and using the Linked Cursor tool to confidently identify different cover types in the ortho-photos under appropriate magnification. The same procedure was also used with the 1991 aerial photographs to guide classification of the historical 1989 and 1994 images. In addition, ancillary information on preferred habitats by individual species was further used to enhance confident compilation of training statistics. For example, *A. mellifera* is more tolerant of soil-water deficits compared to *A. erioloba* and was therefore expected to be dominant in upland areas while the latter's preference of wetter soils was reasoned to bias its distribution toward low-lying areas and riparian corridors where water tables are higher compared to upland areas. After compilation of signature files, the Mahalanobis distance classifier was used to run all classifications after a series of test trials in which this classifier yielded the best results compared to maximum likelihood and minimum distance classifiers. Table 2 shows information classes that were mapped from CORONA photographs and Landsat images by time slice and data list names used to describe them in Excel.

Table 2 Information classes that were mapped from CORONA and Landsat images

Cover type name	**Data list name**	**Year period and executed process by cover type**			
		1967	**1989**	**1994**	**2001**
Mixed bush	Mb	Mapped	Mapped	Mapped	Mapped
Mixed woodland	Mw	Mapped	Mapped	Mapped	Mapped
Acacia erioloba	Ace	Mapped	Mapped	Mapped	Mapped
Acacia mellifera	Acm	Mapped	Mapped	Mapped	Mapped
Open grassland	Opg	Mapped	Mapped	Mapped	Mapped
Overgrazed grassland	Ovg	Mapped	Mapped	Mapped	Mapped
Bare ground	Bg	Mapped	Mapped	Mapped	Mapped
Scrub and shrubs	Ss	Mapped	Mapped	Mapped	Mapped
Water	Wat	Mapped	Mapped	Mapped	Mapped
Wetland	Wtd	Mapped	*Not mapped	*Not mapped	*Not mapped

* There was no wetland from 1989 onward because of drying sequences

Classification accuracy assessment (CLACAS) of Landsat map outputs was carried out by using field-compiled ground truth reserved for the purpose during supervised classification and collateral information from aerial-photo mosaics of 1991 and 2000 to calculate the global accuracy and the kappa (K) coefficient. CLACAS of the CORONA map-output was conducted by assessing the accuracy of the classification technique (DCSVGGC) rather than the map output because of the historical nature of this dataset (Hamandawana et al., 2007a). The level of accuracy for the 1967 CORONA map output was 69.05%, K = 0.69. Accuracy levels for the 1989 and 1994 Landsat TM and, 2001 Landsat ETM map outputs were 73.86%, K = 0.74; 71.23%, K = 0.71 and 67.42%, K = 0.67 respectively.

RESULTS

Results are presented in the form of graphs and map outputs that show the field observed distribution of 1) major woody species that were identified during field investigation and hand-dug wells and boreholes and, 2) temporal variations in information classes that were mapped from satellite imagery.

Field observed distribution of major woody species

For woody cover, the position of quadrats that were investigated is shown by latitude in order to accommodate the area’s hydrological gradient that is characterised by a north-south decrease in the influx of overflow from the Delta.

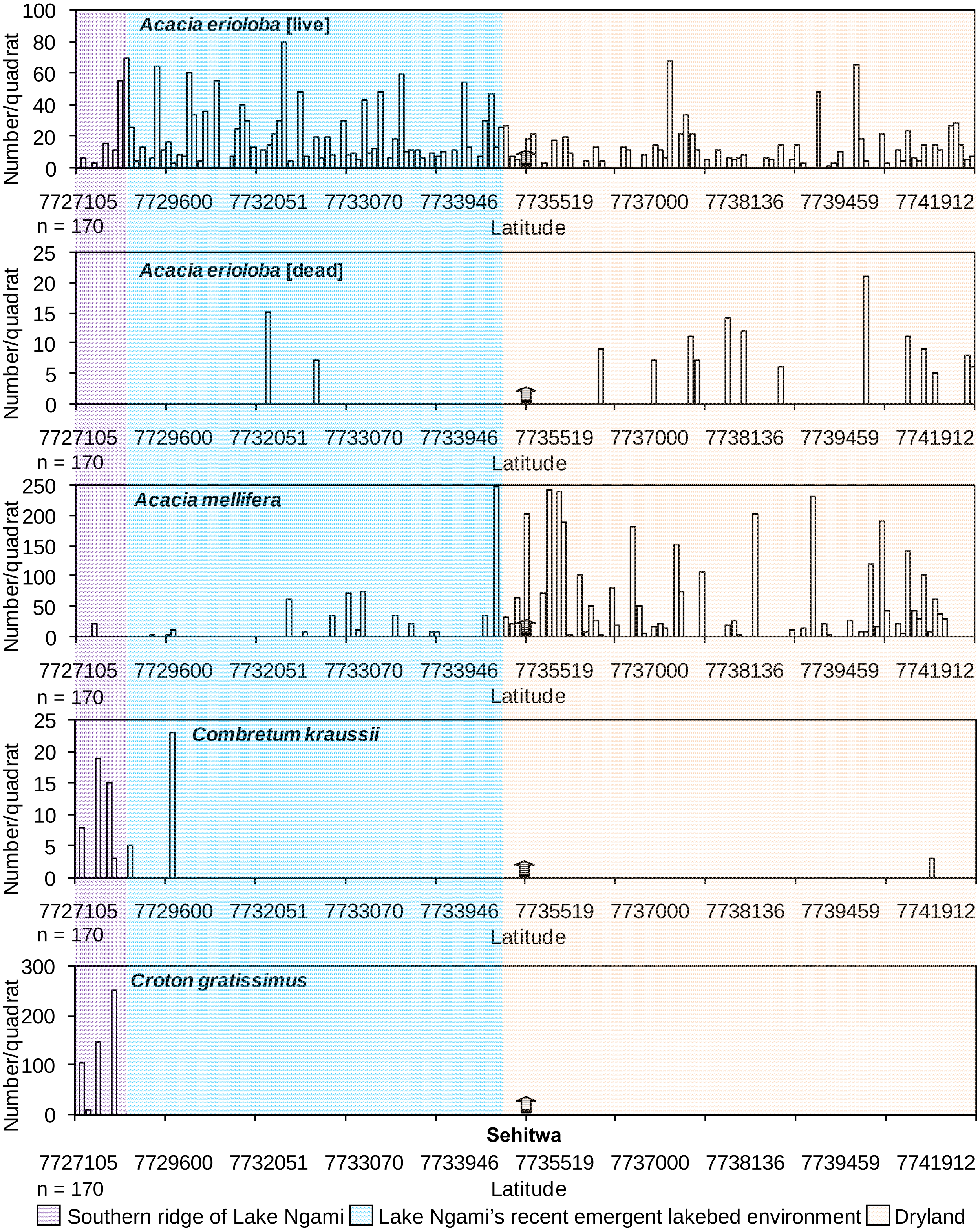


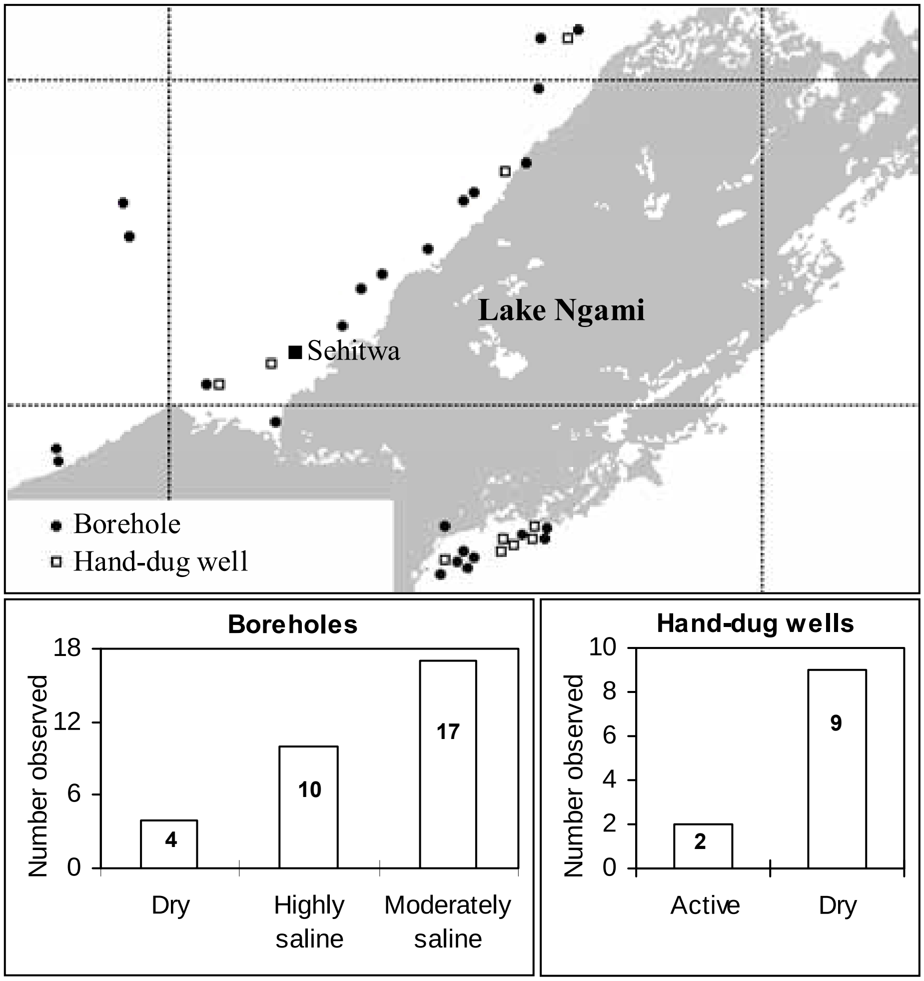
Figure 2 Density distributions of woody species around Lake Ngami

The major woody species that were identified during field investigation include *Acacia erioloba*, *Acacia mellifera, Combretum kraussii,* and *Croton gratismus*. The spatial distribution of these species reflected the influence of topographic variations with *A.erioloba* tending to be dominant in low lying areas while the remaining species were largely confined to upland areas. Observed densities in the distribution of *A. erioloba* were stratified into categories comprising live and dead trees. The former exhibited substantial spatial variations with the highest densities occurring in margins of the emergent lake bed and its adjoining areas where robust and mature specimens were observed while juveniles were more populous along margins of the lake's more recent flood limits. In upland areas, densities were high along corridors of fossil channels and very low in localities with pronounced elevation above the floodplain environment. This distribution is indicative of succession sequences closely correlated to the punctuated dry-down of Lake Ngami. Dead individuals exhibited bimodal distribution with substantial dieback being observed in elevated dryland areas where age and declining water tables appear to be the main drivers while fire was evidently the primary cause of this phenomenon on islands and interfluves within the lake's emergent floodplain environment. For *A. mellifera*, the highest densities were observed in elevated dryland with areas close to margins of the Lake's recent shorelines exhibiting noticeable dispersion while complete absence was observed in the Lakebed environment. While low densities in the lakebed environment suggest *A. mellifera's* general intolerance of periodic flooding, higher densities in upland areas suggest opportunistic expansion by out-competing species poorly adapted to water deficit conditions. Spatial distribution north of the lake appears to reflect variations in soil type, with sparse and dense communities occurring in sandy and consolidated soils respectively.

Combretum kraussii was exclusively observed on foot-slopes of Lake Ngami's southern ridge in association with scattered occurrences of other less common species that include *Dichrostachys cinerea, Terminalia sericea* and *Boscia albitrunca*. This confinement suggests adaptation of these species to prolonged soil water deficits. *Croton gratissimus* appears to be extremely habitat selective and was exclusively observed on the southern ridge of Lake Ngami. High densities of *Pechuel loeschea* were observed in abandoned arable landholdings, around boreholes and along roads in different localities. The species described above (excluding *A. mellifera* and *A. erioloba*), were observed in co-occurrence with other less common types that include *Berchemia discolour, Diospyros lycioides, Grewia flava, Diospyros lycioides, Berchemia discolour, Terminalia prunioides, Ximenia Americana, Ximenia caffra, and Ziziphus mucronata.* Because of substantial mixing in different communities, discrimination by species type was not possible and they were collectively classified as mixed woodland.

Field observed distribution hand dug wells and boreholes

Numerous water points comprising boreholes and hand-dug wells were identified around Lake Ngami during field investigation (Figure 3). Though they were extensively used during the 1960s, such use disappeared during the late 1970s when these water points dried up and were replaced by deeper boreholes. This shift explains their clustered and paired distribution around the Lake's recent floodplain environment.



Borehole (Bh)

x y	Status	x	y	Status
682296 7729077	□ 68	2381	7738921	□□□
683886 7729550	□ 68	4444	7741912	□□□
684666 7729820	□ 68	2390	7738825	□□□
671207 7732051	□ 68	4123	7739869	□□□
684500 7743297	*□* 68	1392	7737537	□□□
685460 7743545	*□* 68	0180	7736851	□□□
681784 7728585	*□* 67	9545	7736468	□□□
677200 7732800	*□* 68	2655	7729000	□□□
675500 7733758	*□* 68	2484	7728961	□□□
684400 7729636	*□* 68	2645	7729007	□□□
684507 7729803	*□* 68	2406	7728918	□□□
673076 7738835	*□* 68	1867	7729901	□□□
684267 7729642	□□□ 67	3235	7737851	□□□
679013 7735368	□□□ 67	1313	7731700	□□□
675296 7733782	□□□			
684013 7729618	*□*			
684267 7729603	*□*			

Hand-dug well (Hdw)

x	Y	Status
684267	77296 42	□
683501	7729472	□
683575	7729472	□
684418	7729738	□
675533	7733796	□
677140	7734380	□
683535	7739687	□
685480	7743555	□
681853	7728990	□
683909	7729453	□□□
683501	7729450	□□□

Source type	**Percentage**
Dry-Hdw 82	
Active-Hdw 18	
□Dry 13	
□ Highly saline	32
□□□ Moderately saline	55

Figure 3 Observed distribution boreholes and hand-dug wells in around Lake Ngami

Temporal variations in information classes that were mapped from satellite imagery
Figure 4 summarizes trends in the distribution of different woody cover and other information classes that were mapped 1967, 1989, 1994 and 2001.

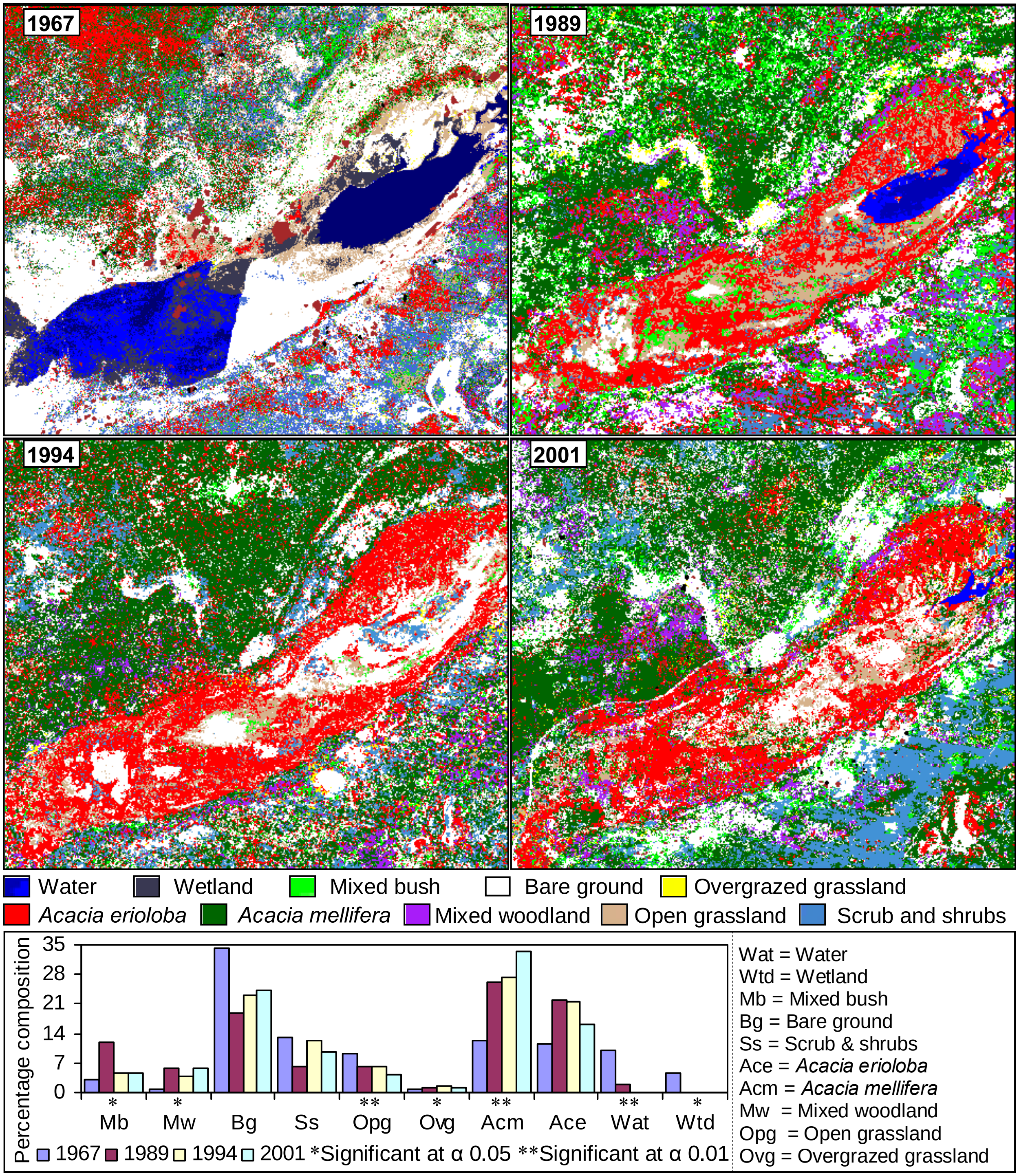


Figure 4 Temporal variations in information classes mapped from satellite imagery

The specific changes characteristic of the major cover types between 1967 and 2001 include:

- Marginal decline in mixed bush by nearly 2% with the overall trend showing major increase between 1967 and 1989 and a pronounced decrease thereafter up to 2001.
- Noticeable expansion in mixed woodland, with the greatest amount of increase being observed during the 22 years before 1989 after which there was a major decline in the 5 years before 1994 which evened off thereafter up to 2001.
- Substantial increase in *A. erioloba* by 13% between 1967 and 1994 and noticeable 8.7% decrease thereafter that suggests the interaction of several drivers in determining the direction of change. Possible factors explaining this trend include age-induced mortality, natural variability in key determinants such as rainfall and groundwater supplies and human interventions/resource use practices.
- A significant increase in *A. mellifera* by 21.1% during the 34 years between 1967 and 2001 that points to inception of favourable conditions for this species.
- Significant decrease in open grassland by 5% during the same period that is indicative of bush encroachment on account of the non-selective expansion characteristics of *A. mellifera*.
- Accelerated increase in overgrazed grassland for the period between 1989 and 1994 with marginal decline thereafter suggesting the intervening influence of other factors not directly related to changes in open grassland.
- High temporal variability in scrub and shrubs with overall trends showing a decrease by 3.5% during the 34 years between 1967 and 2001 that was inversely related to temporal variations in *A. mellifera*.
- Initial decrease in bare ground due to bush encroachment and a terminal increase on account of the desiccation of Lake Ngami.
- Pronounced decrease in surface water distribution with a down-trending situation that suggests the persistence of drying sequences and reduced flow into Lake Ngami. Though the lake flooded in 1989 and 2001, these floods were ephemeral with the disappearance of all wetland after 1967 pointing to major regime shifts in surface hydrology and a transition into sustained drying sequences.

DISCUSSION

Though changes in cover distribution between 1967 and 2001 point to opportunistic expansion of vegetation into emergent floodplain areas; the same trends provide informative insights on groundwater conditions in this environment. During the late 1960s, much of Lake Ngami's immediate environs were open country with bare ground covering more than 34% of total area (Figure 4). This phenomenon cannot be a coincidental occurrence ascribable to dry season acquisition of the CORONA photographs that were used to reconstruct the land cover situation in 1967. A survey of the Okavango Delta region in the 1950s reported that *there was hardly any bush to be seen for miles in the widest part of open area south and southwest of Sehitwa* (Brind, 1955). This report confirms the non-seasonal character of extensive bareness during the 1960s which is indicative of an emergent floodplain whose accelerated dry-down created a hospitable environment for the establishment of different types of vegetation.

Though drying sequences provided a window of opportunity for colonisation of emergent floodplains by woody vegetation, groundwater tables remained high because of residual storage from high floods of the historical past. That water tables were high during the inception of drying sequences is supported by the numerous hand-dug wells that provided perennial sources of portable water before the 1970s (Figure 3). Though the depths of these wells are variable, all of them are shallower than the boreholes which replaced them during the early 1980s in order to facilitate continued withdrawal of supplies as water tables declined. As desiccation persisted, woody species tolerant of 'high' water tables invaded the emergent floodplains. This opportunistic expansion explains the significant increase in mixed bush and the inversely related trend in bare ground (Figure 4). Woody vegetation fast colonised emergent floodplain areas with this expansion being more pronounced for *A. mellifera* which increased persistently by more than 21% between 1967 and 2001. Though overgrazing facilitated this encroachment by excluding fire (Hamandawana at al., 2007a), declining water tables appear to have played a decisive role by creating a hospitable environment for successful establishment and subsequent expansion of species adapted to dryland conditions. The important insight from these trends is that in semi arid areas, changes in vegetation distribution can provide dependable expressions of surface and sub-surface hydrological conditions. While an inverse relationship between *A. Mellifera* and groundwater is evident from the drying up of hand-dug wells as woody cover increased, similar inference can be made from temporal variations in the distribution of *A. erioloba* whose distribution around Lake Ngami suggests colonization of the emergent floodplain environment in successive phases. In the northern peripheries of Lake Ngami that correspond to the coterminous extend of the ancient floodplain; substantial dieback of old trees is evident in dryland areas (Figure 2). This phenomenon is conspicuous northeast of Sehitwa in the vicinities of boreholes and dry hand-dug wells. On inner margins of the more recent low lake levels are dense middle-age stands in a well defined ring formation that coincides with the inner shoreline of the central lake bed environment where juveniles of the same species are increasing. If one allows for a chronology in which colonisation progressed in pulses coinciding with similar decline in lake levels, trends in the distribution of *A. erioloba* can be explained in terms of phased expansion during three periods comprising; the recent past, the immediate past and the present past.

The recent past can be conveniently delimited as spanning the period between the 1950s and late 1970s. For the 1950s, colonial documents report that Lake Ngami was full in August of 1951 (Brind 1955: 31) while oral evidence confirms a major flood in 1955 and perennial water residence on account of sedentary presence of hippos and crocodiles in the Lake (Hamandawana et al., 2007a). As confirmed in CORONA imagery, a substantial amount of water was still in the Lake by the end of 1967 (Figure 4). Thereafter floods persistently failed and lake levels receded, giving way to colonisation of the emergent floodplain by *A. erioloba* which increased by 13% between 1967 and 1994. This period and successive years before it is likely to have been associated with pioneer establishment of *A. erioloba* in upland areas where substantial dieback of this species is presently evident. Immediate-past is here taken to be the period between the early 1980s and late 1990s. During this period, progressive flood failures, prolonged and successive drought periods of 1981-1984, 1985-1987 and 1991-1992 (Solway, 1994) reinforced each other to initiate the complete dry-down of Lake Ngami (Figure 5).

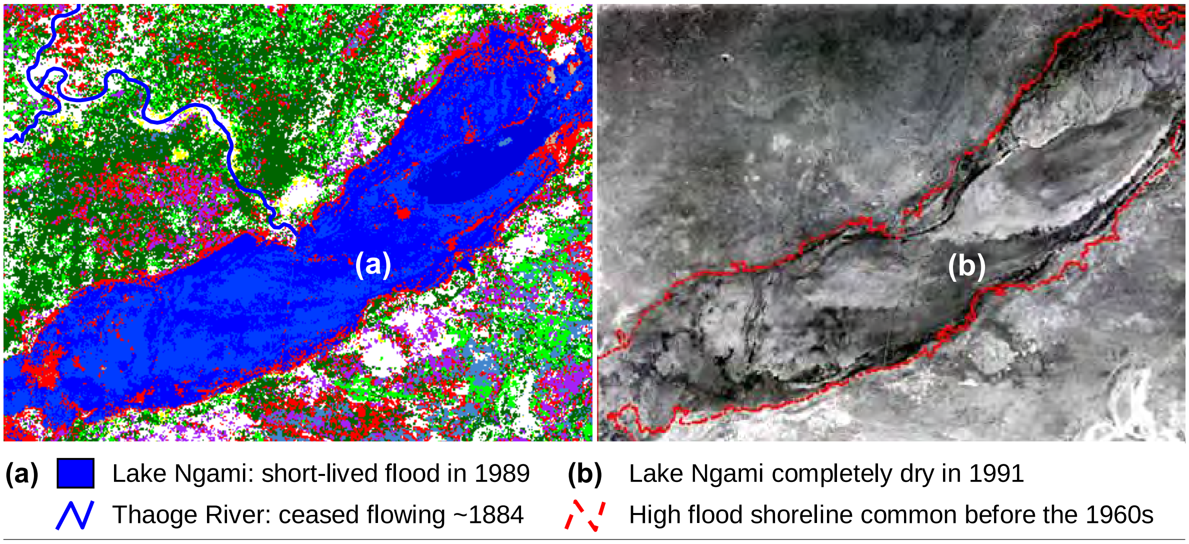


Figure 5 A short-lived high flood (1989) and dry lake bed (1991) illustrating the normal extend of Lake Ngami before the second half of the twentieth century

As happened during the recent past, retreating water levels left an intermediate emergent zone between higher ground in the dryland upland and the central lake bed. Given the dominance of middle age, actively growing stands in this environment and on mid-lake islands at similar levels above the lake bed; it is possible that the *A. erioloba* woodland around the central lake bed (Figure 4) colonized this area in early 1980s. The present-past is here taken to cover the period between 2000 and 2005. Progressive desiccation during this period, punctuated by short-lived floods in 2001 and 2004, has allowed the establishment of actively growing *A. erioloba* bush in the lake bed environment. The near stable trend observed in the distribution of this species between 1989 and 1994 can thus be explained as a ceiling in terms of expansion imposed by progressive decline in ground water tables due to persistent flood failures, declining rainfall and over-extraction from boreholes that might have accelerated natural dieback of pioneer woodlands in upland areas. Though this dieback has been the subject of speculation by many, historical evidence shows that some of the dead *Acacias* in this locality have been standing there for the last 150 years. Brind (1955: 28) observed that *not far from Sehitwa, on the northern fringe of the area inundated in good flood years, there are a number of large dead tree trunks, which are not to be found anywhere else in the Lake area* [and there is] *little doubt that, they are the same trees seen and remarked upon by Livingstone* [in 1849] *'A number of dead trees lie in this space'*. This observation confirms early inception of this dieback with failure to reestablish and out-competition by *A. mellifera* pointing to increased environmental resistance after initial establishment as water tables declined.

As observed during field investigation dieback is quite substantial, with dead trees still in bark indicating continued mortality in more recent years. Though this spatially confined dieback might be indicative of the combined influence of numerous factors, declining water tables appear to be responsible for most of the mortality. Age-driven dynamics fail to explain this dieback because, rather than affecting the entire cohort through out this area as expected, this phenomenon is spatially confined to borehole-dominated localities. With evidence pointing to abundance of equally old species in Shakawe and Gumare amidst succession trends characterised by extremely low mortality compared to Sehitwa's Lake Ngami environment (Hamandawana et al., 2007c), climate driven lowering of ground water tables offers the most plausible explanation of initial expansion and terminal decrease in *A. erioloba*. The hypothesis on climate driven contraction of groundwater reserves is supported by the complete dry-down of perennial springs that were mapped by colonial authorities during the early 1920s (Figure 1) and the more recent drying up hand dug wells (Figure 3). Though boreholes have replaced shallow wells, their distribution and water yield characteristics provide additional insights on long-term trends groundwater conditions. Where these are clustered, such clustering consists of dry boreholes, those decommissioned because of hyper-saline yields and those that are active though yielding saline water. The decommissioned boreholes are shallower than their recently established counterparts. Given the depth-dependent-salinity characteristics of water from these boreholes, it is reasonable to suggest that over-extraction of water from the older and shallower boreholes has initiated salt-water intrusion, with naturally induced thinning of aquifers appearing to exert an equally important influence on the high salinity levels of water from these boreholes. Similar levels of salinity are characteristic of water from all boreholes in upland areas north of the emergent lake bed. Climate change is further corroborated by significant increase in the number of arid years between 1934 and 2004 that points to increasing aridity (Hamandawana et al., 2008) which explains the recent contraction of *A. erioloba* and persistent increase in the more drought tolerant *A. mellifera* which has been associated with noticeable decrease in groundwater levels in the semi arid areas of Namibia (Bayer et al., 1999). These scenarios indicate that in this environment, trends in the distribution of *A. mellifera* and *A. erioloba* provide reliable indicators of regime shifts in the hydrology of aquifers. The former taps shallow seated water because of its shallow rooting system while the latter extracts deep-seated water because of its deep rooting physiology (Muñoz et al., 2008). These characteristics allow temporal variations in their distribution to be used as surrogate indicators of changes in groundwater at multiple levels.

CONCLUSION

This paper has attempted to provide a methodology that can be used to detect long-term trends in groundwater resources by using multi-date remotely sensed imagery to monitor transitions in vegetation distribution. With major trends revealing close relationships between changes in the distribution of *A. mellifera* and *A. erioloba* and groundwater resources, it is evident that spatial and temporal variations in the distribution of selected indicator species can be used to provide dependable estimates of groundwater resources at multiple spatial scales. In view of the general lack of time-series data on regional trends in aquifer storages in arid/semi-arid areas, it is apparent that remote-sensing-based monitoring of vegetation can be used as suggested, to provide informative insights that are potentially capable of enhancing sustainable use of groundwater resources by guiding the formulation of informed policy interventions. Apart from meriting serious consideration because of its ability to provide information on long-term trends, the methodology is also worth trying because it is better able to provide large-scale coverage at reasonable costs compared to conventional groundwater monitoring techniques.

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