The use of satellite image analysis in long-term monitoring of the effects of water extraction from a coastal subtropical wetland.

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Abstract – This paper concerns the use of remote sensing as a tool for monitoring the health of a natural, remote, coastal, groundwater-dependent wetland on a large subtropical sandy island. Monitoring was aimed at detecting any effects of extraction of groundwater on vegetation. The Normalised Difference Vegetation Index (NDVI) has been used annually since 1984. Two remote methods were used: (i) the proportional representation of three stratified activity bands over the whole area, and (ii) the average NDVI at a range of discrete sites. The results were compared with prevailing environmental conditions, groundwater levels, and vegetation measurements.

The duration of monitoring presented significant technical challenges, as has the nature of the feature being monitored. The hypothesis that water logging restricts vegetation activity and growth, and hence NDVI, was supported. The NDVI data were not easy to interpret, and both methods were found useful. The interplay between on-ground and remote measurements proved vital.

Keywords: NDVI, monitoring, wetland, groundwater, coastal, vegetation health.

1 – INTRODUCTION

Remote sensing as a tool in the detection of change in boundary and area of vegetation coverage is common (Masek 2001, Marlen et al. 1999, Schulz 2001), and it is also used for the detection of change in vegetation activity or health (Coveny and O'Donovan 2001, Ramsey et al., 2001, Peters et al. 2002) or a combination of the above. Examples of its use as a tool for actual long-term monitoring are less common, as might be expected due to the youth of the technology.

The Normalised Difference Vegetation Index (NDVI: Nightingale and Phinn, 2003) has great potential for the assessment of vegetation health, due to its close relationship (indeed causal relationship) with photosynthetic activity and biomass (Erhlich et al. 1994, Ramsey et al. 1997, Specht and Specht 2002). In a lentic (wetland or lake) system, the presence of excess water reverses the usual positive relationship between NDVI and water. In a lentic system, the amount of standing water can be such that terrestrial vegetation fails, the major defining factors being the depth, frequency, and duration of standing water. Such standing water impedes growth, hence NDVI is limited in such systems (Figure 1).

Vegetation activity is primarily due to the horizontal area of leaves covering the ground, and their photosynthetic activity. This, in turn, is directly affected by the amount of water available and the immediate past activity, which results in carbohydrate production, and hence stem, leaf and root growth (which have their own effects on NDVI: Nightingale and Phinn, 2003). In a wetland, where water levels are often such that conditions of 'ecophysiological drought' prevail (waterlogging is prohibitive), water is frequently unavailable, restricting photosynthesis, and hence reducing NDVI. When water levels fall, availability of water to plants increases, with resultant photosynthetic increase and biomass production.

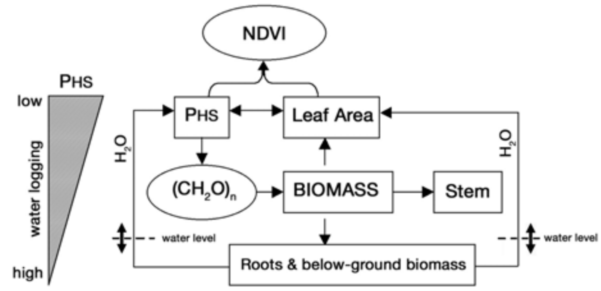

Figure 1. A diagrammatic illustration of the relationship between water level in a lentic (wetland) system and NDVI. PHS = photosynthesis, $(CH_2O)_n$ = carbohydrate formed from the process of photosynthesis.

Time series analysis of multispectral and multisensor Landsat data (MSS, TM5 and TM7) has been used since 1984 as part of an integrated monitoring program related to water extraction from a coastal freshwater wetland (Eighteen Mile Swamp) at North Stradbroke Island in south-eastern Queensland, Australia (Figure 2). Stradbroke Island is a largely unpopulated, sandy island off the central eastern coast of Australia, the major disturbance until recently being sand mining for heavy minerals at a number of locations on the Island. It is representative of several similar low nutrient, deep sandy systems along the east coast of Australia which formed during a series of quaternary low sea levels.

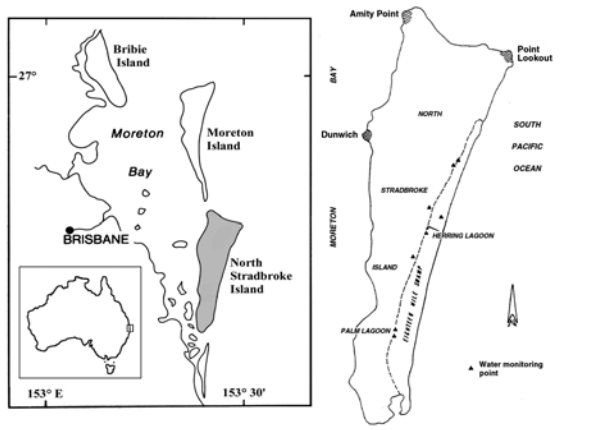

Figure 2. Location map of Stradbroke Island, showing Eighteen Mile Swamp along the eastern linear face of the Island.

The Swamp is a 32.76 square kilometres window in the groundwater aquifer of the island. It is largely vegetated, with low relief (maximum of 10m elevational change). Changes in vegetation from wet heath, to *Melaleuca quinquenervia* open-woodland, to sedgeland are largely due to undulations in levels

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** this project was supported throughout by Redland Shire Council.

of surface and subsurface sand, and constrictions to the southward flow of the surface water.

Since the 1950s, water has been extracted from the Swamp at several locations for use in heavy mineral sand mining. In recent years extraction has been from Herring Lagoon (to the present day) and Palm Lagoon (between 1992 and 1997). In 1992 Redland Shire Council began to export water from Herring Lagoon to the adjacent mainland. In anticipation of this, biological monitoring of Eighteen Mile Swamp was commissioned by the Shire in 1988 to detect any adverse changes to the ecosystems occurring there, and to assist in the identification of thresholds and triggers beyond which extraction should cease (Dutton et al., 1993). The managing water authority changed in 2007 and monitoring ceased, although extraction has not, neither by the Shire (now City) nor the mining industry.

This paper describes analysis of remotely sensed information between 1984 and 2005/6, with particular focus on the utility of the Normalised Difference Vegetation Index (NDVI), calculated from the near infrared and red wavelength bands (Nightingale and Phinn, 2003), as a tool for the detection of wetland change in response to a changing environment, both natural and anthropogenic. We reflect on the challenges of long-term monitoring using such remote sensing techniques.

2 – METHODS

All images were acquired from the Australian Centre for Remote Sensing (ACReS), now GeoScience Australia, and were obtained on cloudfree days in June-July. These months were chosen because of minimal vegetation flowering, and fewer cloudy days in the dry subtropical winter than in other seasons. All images were taken from the Landsat satellites along path 89 and row 79. The scene nadir is centred near Brisbane and the subset including Stradbroke Island covers approximately 15 x 40 km. All available bands (four for the MSS images, seven for TM) were acquired.

Several different Landsat platforms have been used over the study period, starting with Multispectral Scanner (MSS) in 1984, with 90m pixel resolution, replaced by the more refined TM5 images (30m pixels) and, for three years by ETM+ (TM7). This latter satellite encountered hardware component failure in 2003 causing missing data in the image, necessitating a return to TM5 in 2003. Transition between satellite sources was executed by comparing them visually to correlate the density slicing for each NDVI image, and semi-quantitatively using site information. Three images were used to facilitate calibration between MSS and TM images.

In the final suite of analyses, all images were rectified against the TM7 image of 2001. The images were resampled to 25m pixels to ensure uniformity across years. They were then clipped around the area of interest. Each band in the image was then histogram-matched to its corresponding band in the TM7 image of 2001 to decrease across-year variations caused by differences in satellite calibration. TM (and ETM+) bands 3 and 4 (red and near infrared) and bands 2 and 3 of MSS were used to calculate NDVI.

The NDVI was rescaled from –1 to +1 to 1-255 (with 0 NDVI = 127). This scale range has been used throughout the study, and is chosen to enable comparison with the original processing done in MicroBrian (Harrison and Jupp, 1993). The NDVI values were then classified by density slicing into three classes whose nature was determined by comparison with the vegetation maps prepared for reporting (Specht, 1989) and from 1:8000 colour aerial photographs in 1998 (Specht 1998) and on the basis of a histogram plot of the NDVI values for the image (Table A). All data were processed using ERDAS Imagine version 8.5 (ERDAS Imagine Tourguides, and ERDAS Imagine Field Guide, 1997).

Mapped comparisons with time (i.e. difference images) were attempted in the early years, but due to the coarse resolution of the satellite data available for the duration of the study, the elongated shape of the swamp, and the study goals, these were discontinued. Whole of swamp and specific location data were examined to detect any changes in vegetation activity that could not be explained by reference to climatic or other natural phenomena.

Table A. The three classes of the Normalised Difference Vegetation Index (NDVI) obtained by the density slicing technique.

activity class	NDVI value	ground interpretation
low	1-42	deep water, water, open sand, little vegetation to inactive vegetation, waterlogged or droughted vegetation
medium	43-180	slightly waterlogged or droughted vegetation
high	181-255	actively growing, healthy vegetation

The percentage cover occupied by each NDVI class across all images (1983-2005) was then calculated. This gives an overall picture of the change in vegetation activity and water content throughout the Swamp. It does not, however, give a good picture of the distribution of the classes within the swamp over time, except by visual comparison.

The NDVI of the vegetation was also followed at several defined areas of the Swamp as a way of examining the spatial and temporal variation in conditions and vegetation activity in the swamp. These sample areas were selected to cover the range of key locations and topographical morpho-types occurring in the Swamp: hind dune (4 sites); core swamp (2 sites); "Palm Lagoon" (2 sites); western swamp edge (4 sites); and "Herring Lagoon" (1 site). Some non-swamp sites (high dune >200m ASL, and dune face ~10m ASL on the frontal dunes) were added, the high dune sites after 1996. The average number of pixels per site group ranged from a minimum of 107 pixels to a maximum of 561. ERDAS Imagine was used to generate the total, maximum, minimum and average NDVI for each site. The mean and standard error of the NDVI for each morpho-vegetation type was calculated, and the results plotted. All site categories were compared using analysis of variance in the Statistical Package for the Social Sciences (SPSS) version 11.

3 – RESULTS

The spatial changes in NDVI in the Swamp show that there are zones where low activity is common throughout the years, and others where consistent high activity is recorded. Higher activity generally corresponds to more structurally developed vegetation. In the later years of the study there was a marked increase in vegetation activity in the Swamp.

An increase in activity in the last few years throughout the Swamp is clearly shown in the plot of the percentage of activity levels throughout the Swamp (Figure 3). The percentage of pixels with high activity increased from around 20% in 2001-2002 to 70% by 2005, compensating for a marked decline in medium-level activity, although there is some contribution from very low activity (areas of sand and water with no or little vegetation).

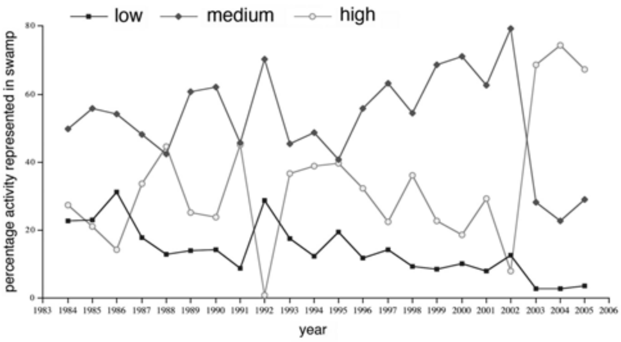

Figure 3. The percentage of the area of the Swamp in the three activity bands of the NDVI from 1984 until 2005.

Preliminary examination of the relationship between these figures and rainfall suggests that after more than one year of low rainfall the percentage of the Swamp with high activity drops (1986, 1992, 2002). In the case of 1992, this low activity might have continued but for a major fire at the end of that year resulting in new growth in the subsequent autumn, recorded by the satellite. Conversely, prolonged high rainfall periods saturate the substrate, resulting quickly in eco-physiological drought (low activity) as illustrated by low activity levels in 1989-90, 1996-97, 1999-2000. The water relations of the Swamp are complex, however: seepage from the high dunes to the Swamp arrives well after the rain, the base material (sand and peat) has poor water retention when dry, and the north-south flow of surface water is interrupted due to narrow passages or sand blows.

The residual rainfall plot shows a consistent decline in rainfall calculated as the long-term average since 1980 (Figure 4). High NDVI activity follows an overall declining trend to 2003, when activity suddenly increases. This may represent a threshold of water level, below which all water logging effects are relieved, and adequate water is achieved where the roots of the vegetation can reach the water table, but not be limited by it. If the water level continues to fall, perhaps limiting water will be arrived at, and the NDVI will fall again.

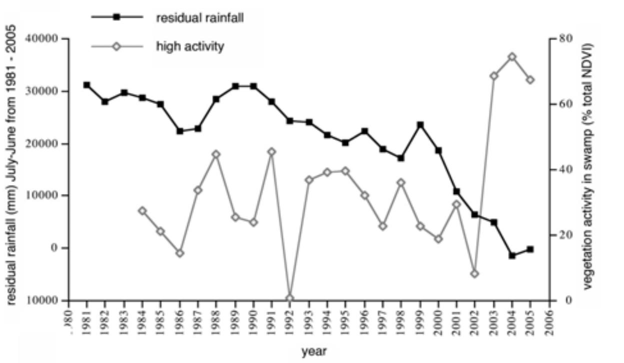

Figure 4. The percentage area of the Swamp in the highest activity class of NDVI plotted with the residual annual rainfall calculated between 1981 and 2006. The rainfall intervals are from July to June to coincide with the image dates.

For most years the activity in the dune face site was consistently lower than in the main part of the Swamp, but not always significantly (Figure 5). A general increase in activity after 2003 was consistent with the whole swamp analysis (Figure 3). By 2003, three groups of sites emerged (analysis of variance, p=0.000, Tukey's HSD test at alpha ≤ 0.05): high dunes, swamp proper, and dune face (from high to low activity).

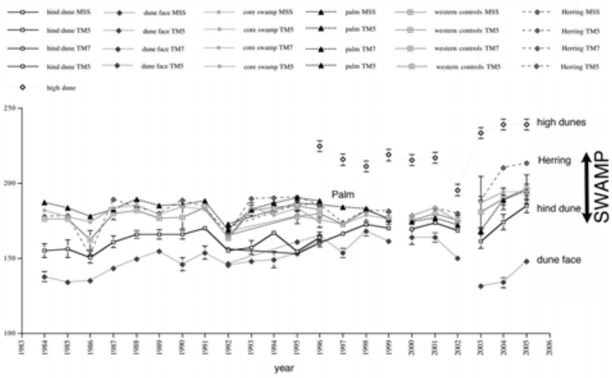

Figure 5. Average total NDVI (on a scale of 0 – 255) for each site type considered from 1984 until 2005. Within-swamp sites are indicated.

The site analysis highlighted other features. The hind dune sites, which experience frequent periods of water logging due to the microtopography of the Swamp, were generally lower in activity than the other swamp sites. The site with current extraction by 2003, Herring Lagoon, showed a strong upward trend in activity compared to the other swamp sites and previous measures for that site.

4 –DISCUSSION

The advantages of a remote technique like NDVI in monitoring are several, including providing a means of integration between on-ground point and quadrat measurements, and providing an alternative to expensive and time-consuming on-ground measurements, particularly in the physically difficult wetland context (Harvey and Hill, 2001). These benefits can only be realised if there is a meaningful and accurate outcome from the measurements.

At the start of a monitoring study decisions need to be made about the selection of measurements that subsequently have to be maintained with some consistency throughout a study, perhaps for many years. In the example presented in this paper, not only have image types changed from the same provider (Landsat), but so have image analysis systems, necessitating several re-analyses and the purchase of additional, duplicate and retrospective images. Sometimes the cross-matching of image types (with different resolutions) is imprecise, especially in areas where there are few on-ground reference points. This adds to the expense of a monitoring program, which can become prohibitive and out of the reach of any but the most sophisticated laboratory.

The utility of a monitoring method depends on its link to the question being asked and the matter being monitored, but also to the precision of the method: does it show accurately enough what we need to know? This was a major question in this study, for which at the start in 1988 there were few precedents. Natural variation can be high, masking real changes, especially when the error of measurement is also high. Numerous methods to refine and improve the image and image analysis have emerged, including atmospheric correction. As these were not available at the beginning, nor could we retrace our steps in that regard, does this mean that the results obtained are worthless? Consistency of method, and good knowledge of the nature and function of the study area can compensate for many errors (Gibbes et al., 2009), and this has to be relied upon.

Given these concerns, the data show that this is a swamp that has relatively variable activity levels with time (Figure 3). The NDVI recorded is high compared to that recorded elsewhere (e.g. Chen et al., 2006, Gibbes et al., 2009 and Nightingale and Phinn, 2003). The typology of the swamp NDVI, however, is reasonably distinct (Figure 5), and consistent with the model hypothesised at the start of the study (Figure 1), namely that water logging decreases vegetation activity. Unfortunately the hydrological measurements and models available are not sufficient to confirm this, so this has to be a tentative conclusion at this stage, although a potentially strong one (Chen et al., 2006). The identification of a threshold in rainfall, and hence water level in the Swamp, is important, and although the opportunity has not been provided for formally confirming the effect of this, there is ample casual evidence that the woody species, *Melaleuca quinquenervia*, significantly increased in size (and hence activity) in the Swamp between 2003 and 2006 (Figure 6).

NDVI is useful if it is consistent with on-ground measurements, and although Palm Lagoon did not have markedly higher activity than other sites in the Swamp for much of the observation period, it did in 1997. In that year at Palm Lagoon *M. quinquenervia* became extraordinarily dominant due to excessive water extraction between 1992 and 1998. By 2002, waterlogging returned (confirmed by local piesometer measurements), reducing NDVI to average levels. It appears that major changes may be triggered by short-term episodes.

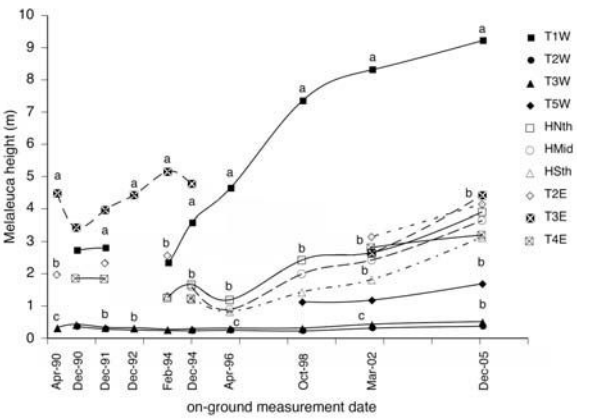

Figure 6. Height of *Melaleuca quinquenervia* at ten on-ground transects monitored in Eighteen Mile Swamp from 1990 until December 2005. Small letters indicate significant differences between transect heights using Tukey's HSD at each date.

The hypothesis that waterlogging supresses vegetation activity has been supported in space and time. The conjoint use of on-ground and remote measurements greatly enhances the interpretation. On-ground measurements provided the understanding and interpretation, while remote sensing provided the opportunity to link discrete sites, and to monitor at more frequent and regular intervals when access to field sites was not possible. One without the other would be suboptimal.

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