Modelling Ecosystem Response to Flooding: a Remote Sensing Approach.

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EXTENDED ABSTRACT

Modelling the impact of river regulation on large floodplain wetland ecosystems is essential for long-term management of these systems. Understanding the response to hydrological events is critical to developing conceptual models, while appropriate data is required to calibrate, test and validate models. In the Gwydir wetlands, NSW, Australia, satellite-derived normalised difference vegetation index (NDVI) has been used to assess flood response. This paper firstly compares the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) with NOAA Advanced Very High Resolution Radiometer (AVHRR) NDVI for use in long-term temporal profile analysis and then explores the use of these data to identify the flood response from wetland ecosystems.

Terra MODIS 16-day maximum value composite (MVC) NDVI data at a pixel resolution of 250 m^2 is stacked temporally for the period 29 September 2000 to 26 June 2005 for the study area. The NOAA AVHRR High Resolution Picture Transmission (HRPT) dataset (1 km^2) was extracted for the period 21 March 1992 to 26 June 2005 and an MVC algorithm applied to correspond to the MODIS 16-day periods. Both MODIS and AVHRR data are used to determine the flood response using two sites, an internationally recognised wetland site and an adjacent native grassland site. Rainfall and inflow data were extracted from Bureau of Meteorology and NSW Department of Natural Resources databases respectively at daily resolution and the cumulative total for each 16-day antecedent period calculated.

For both the wetland and grassland site, the AVHRR NDVI value was lower overall than for MODIS NDVI for the 109 composite periods analysed. A simple linear regression model explained over 80% of the variation between the AVHRR and MODIS data for both sites, although the intercept was higher for the wetland site. Mean NDVI was significantly higher in the wetland site compared to the grassland site but both sites can reach similar peak values following large rainfall or flood events. The NDVI time-series has significant auto-correlation at lags of 1 to 4 (64 days). Cross-correlation between NDVI, rainfall and inflow was generally significant at lags up to 80 days.

Events were extracted from the AVHRR 16-day time-series where peak wetland NDVI exceeded 0.45. The mean NDVI for the event, initial NDVI, antecedent rainfall and inflows (80 days) were calculated for each event. Multiple regression analysis indicated that pre-event NDVI and antecedent inflows accounted for over 79% of the event NDVI for the wetland site. Neither rainfall nor inflows were significant for grasslands.

This exploratory analysis of events indicates that the modelling of NDVI response is possible for small wetland sites using the AVHRR satellite data and can be compared to higher resolution MODIS data to provide a level of confidence when scaling from field sites to MODIS to AVHRR. Further investigation of modelling approaches using time-series may strengthen the analysis. More research is required to provide confidence in the sensitivity of models and data to small differences in event NDVI that separated highly productive wetlands from normal seasonal greening responses. This work must also be coupled with field monitoring to validate the NDVI results and determine the target event NDVI response required to maintain wetland vegetation communities in a healthy state.

Despite some limitations and the need for further analysis, the results of this paper show promise for application to water management. These types of models can be used to estimate the water requirements to achieve a pre-determined NDVI response under a variety of antecedent conditions (as indicated by pre-event NDVI).

1. INTRODUCTION

Understanding the water requirements of floodplain wetlands is critical to management of environmental flows. Floodplain wetland water requirements have been assessed using direct relationships between hydrology and ecological response (Kingsford and Auld, 2005) or by linking hydrological or hydrodynamic models with ecological process knowledge (Mawhinney, 2003; Whigham and Young, 2001). These approaches require information on both the hydrological and ecological response of the wetland system.

Remote sensing of flood distribution has been used extensively in large wetland systems (Gumbricht et al., 2004; Shaikh et al., 2001). Approaches such as density slicing of near infrared (NIR) wavelengths and unsupervised classification have been effective in large systems with persistent expanses of open water flooding. These approaches were applied to the Gwydir wetlands, Australia (Powell, 2005); a floodplain wetland system dominated by shallow, macrophyte-dominated water meadows. Due to the rapid emergence of vegetation, shallow and turbid floodwaters and shorter duration of flooding, methods for detecting open water are not as effective in these types of systems.

The use of remotely-sensed temporal vegetation response is proposed as an alternate approach to modelling of environmental flow requirements in these types of systems. Vegetation responds to water availability and season in cycles of growth and dormancy described by the phenological cycle (Zhang *et al*., 2001). This temporal information can be extracted from multitemporal satellite imagery, such as the NOAA series of Advanced Very High Resolution Radiometer (AVHRR) or the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) sensors, in the form of readily available vegetation indices. The Normalised Difference Vegetation Index (NDVI) response to antecedent rainfall can be modelled using simple linear regression (Eklundh, 1998). Temporal NDVI has also been used to extract phenological indicators to monitor land-cover change.

In this paper, the suitability of AVHRR and MODIS NDVI is assessed in relation to sites of interest within the Gwydir Wetlands, NSW Australia. The relationship of time-series NDVI phenological indicators will be explored in relation to inflows, rainfall and antecedent conditions.

1.1. Study Area

The Gwydir wetlands of north-western NSW, Australia (Figure 1), is one of the largest inland wetlands in Australia and is recognised internationally (Ramsar Convention Secretariat, 2004). The wetlands are formed as an inland delta at the end of the Gwydir catchment and are under increasing pressure from water resource development, diversion and extractions. Understanding the relationships between catchment inflows and vegetation response is vital to the management of water resources under competing demands in this catchment.

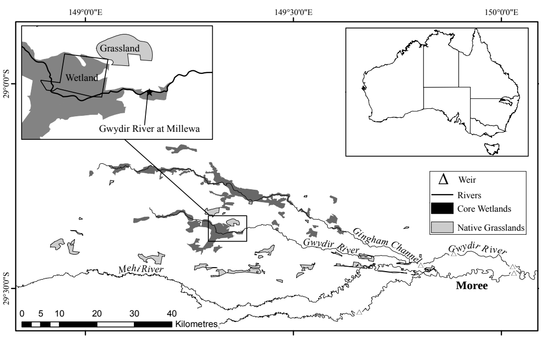

Figure 1. Map showing location of study area, areas of core wetlands and major channels. Also shown (inset) is the wetland and grassland sites and the location of the Gwydir River at Millewa gauging station.

The wetland system divides into two main channels, the Lower Gwydir River to the south and the Gingham Channel to the north. The 'Old Dromana' Ramsar site is a privately owned wetland on the Lower Gwydir River covering an area of approximately 600 hectares as shown in Figure 1 and, along with an adjacent native grassland, is the focus of analysis in this paper.

2. METHODS

The methods include the extraction and processing of remotely-sensed NDVI for the purpose of temporal response modelling, and the subsequent exploratory statistics for model development.

2.1. Data and pre-processing

Satellite Data: The level 3, MODIS 16-day, 250m NDVI (MOD13Q1) is stacked for the period 29 September 2000 to 26 June 2005 and clipped to the study area. The MODIS data processing stream for this product includes a cloud mask and a maximum value composite (MVC) to create the 16-day product (Barrett et al., 2005; Huete et al., 1999). Cloud masking provides a more reliable data product, but it may also detect flooded pixels as being invalid due to low NDVI values. Hence this product may not be sensitive to the expected drop in NDVI values caused by flooding. Similarly the 16-day period will only detect flooding that persists for this period. Daily resolution AVHRR and MODIS NDVI products were evaluated. It was found that the errors introduced through different satellite angles and atmospheric contamination, particularly for the AVHRR product discussed below, and the volume of data required to analyse long periods, make the data impractical for the purpose.

The NOAA AVHRR High Resolution Picture Transmission (HRPT) dataset has a nominal 1 km^2 pixel size and daily overpass. In reality, the pixel size at nadir is 1.1 km^2, while at the edge of the swath might exceed 5 km^2. The HRPT dataset is archived for Australia from 1992 to present (King, 2003). One of the significant problems with the AVHRR datasets for use in multi-temporal studies is the relatively large variation in view zenith and direction of illumination due to the large geographical coverage of the satellite and significant orbit drift (Chopping, 1998). These problems can be reduced by applying a Bidirectional Reflectance Distribution Function (BRDF) correction and using temporal composites. To overcome the problems of the standard MVC algorithm invalidating flooded pixels, the AVHRR datasets were extracted by CSIRO Marine and Atmospheric Research as maximum value 16-day composites with no cloud masking. Low or negative values may then need to be examined manually to determine whether they are likely to be flooded pixels or are a result of cloud contamination or sensor errors.

Both MODIS and AVHRR data are used in this study to determine the flood response. Although MODIS is of higher spatial resolution and has more consistent viewing angles, it is only available from 2000. AVHRR provides a longer-term record, with almost complete HRPT (1 km^2) coverage currently processed from 1992 in a consistent manner. There remains the issue of different sensor calibration and drift between NOAA satellites. Given the strong absorption by water, these artefacts are likely to be small.

All data are extracted as summary statistics (mean, minimum, maximum and standard deviation) for all pixels within sites of relatively homogenous vegetation types for each composite period. This was chosen as it is representative of an operational feasible approach to examining large numbers of sites over large time periods.

Rainfall and evaporation: Rainfall data is obtained from the Bureau of Meteorology. The closest rainfall station is Moree (stations 053115 and 053048). For temporal analysis and comparison to the MVC NDVI, climate data is calculated as the cumulative 16 days **prior** to the start of the NDVI MVC interval.

Inflows: Daily flow is extracted from the Pineena database (Department of Infrastructure Planning & Natural Resources, 2004) for the Gwydir River at Millewa (418066). As for climate data, inflows are calculated as the cumulative flow for the 16 days prior to the start of the NDVI MVC interval.

2.2. Data analysis

Comparison of sensors: The mean 16-day MVC NDVI composites for AVHRR and MODIS, at 1km^2 and 250m^2 resolution respectively, were extracted for all pixels within selected sites. The temporal profiles were compared visually, and the relationship between the sensors was represented using a simple linear regression model.

$$N_M = \beta_0 + \beta_1 N_A + \varepsilon, \quad (1)$$

where N_M is the MODIS NDVI, N_A is the AVHRR NDVI, β_0 is the intercept, β_1 is the slope and ε is the residual error.

The residuals will be examined for systematic errors. As the AVHRR MVC dataset is processed without the cloud masking algorithms that are used in the MODIS dataset, it is possible that the residuals are either due to cloud contamination in the AVHRR dataset, or due to flooding that it masked as cloud in the MODIS dataset. Alternatively there may be resolution effects due to the different spectral bandwidths of the two sensors.

Response modelling: To understand the NDVI response to inflows as compared to temperature and rainfall influences, it is first relevant to establish that the NDVI response for the wetland site is significantly different from the adjacent grassland site. A simple t-test was be used to test whether the difference between the two population means was significant assuming a normal distribution. Examination of the NDVI residuals for a range of vegetation types indicates that this condition is not always met. The non-parametric sign test is therefore used to compare the sites.

In relation to phenology characteristics, the analysis in still in the exploratory stage and will be discussed in terms of general patterns and observations, rather than formal statistical tests. This paper suggests some of the key concepts for summarising the differences and relating these to flood response and modelling in relation to phenological indicators such as those proposed by Zhang *et al*. (2001) (Figure 2).

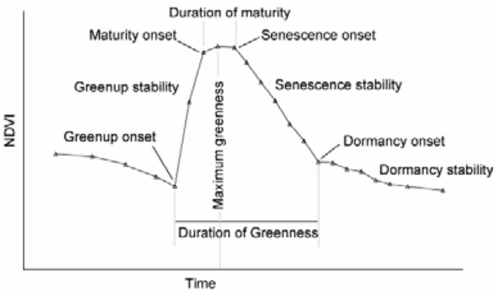

Figure 2: Phenological indicators from an NDVI time series.

The influence of both rainfall and inflows on vegetation response is highly likely to be both lagged and cumulative. In addition, NDVI is highly auto-correlated. Both aspects will be evaluated in relation to multiple regression modelling of the NDVI response.

3. RESULTS AND DISCUSSION

3.1. Comparison of sensors

For both the wetland and grassland site, the average (whole of site) AVHRR NDVI value was lower than for MODIS NDVI over the 109 composite periods analysed (Table 1). Ranges were similar, as was the standard error.

Table 1. Summary statistics of wetland and grassland (whole of site) AVHRR and MODIS NDVI over 109 composite periods.

Site	Sensor	n	Mean NDVI	Range NDVI	standard error
Wetland	MODIS	109	0.60	0.53	0.013
	AVHRR	109	0.36	0.57	0.013
Grassland	MODIS	109	0.42	0.57	0.014
	AVHRR	109	0.27	0.51	0.011

Temporal profiles of the AVHRR and MODIS NDVI composites (Figure 3) show that MODIS values are consistently higher than AVHRR, but that the temporal patterns are very similar. This is most likely due to the narrower spectral passbands of MODIS (Barrett et al., 2005).

The linear relationship (Figure 4) between the mean 16-day MVC for MODIS and AVHRR for both wetland and grassland shows a significant difference ($p<0.001$) from 0 for the intercept, and from 1 for the slope. Over 80% of variation is accounted for by this simple linear equation for both wetland and grassland sites (Table 2). Evaluation of residuals indicated that they are normally distributed throughout the NDVI range.

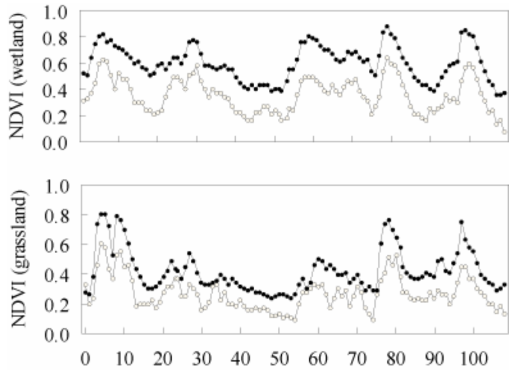

Figure 3: Time-series comparison of Terra MODIS (●) and NOAA AVHRR (○) NDVI time-series for wetland and grassland sites (29 September 2000 to 26 June 2005).

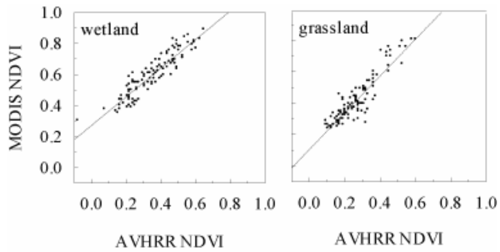

Figure 4: AVHRR and MODIS 16 day MVC NDVI for wetland and grassland showing linear regression.

Table 2. Results of regression analysis of temporal MODIS (N_M) and AVHRR (N_A) NDVI for a wetland and grassland.

Site	β_0 estimate and standard error		β_1 estimate and standard error		r^2	n
wetland	0.272	(0.014)	0.922	(0.037)	0.85	109
grassland	0.105	(0.015)	1.170	(0.052)	0.82	109

Barrett *et al*. (2005) and Gallo *et al*. (2005) showed significant linear relationships between MODIS and AVHRR NDVI and that the relationship was dependant on land cover types. For non-tree cover types, intercepts (slopes) ranged from 0.002 (1.029) for grasslands to 0.068 (0.963) for pastures (Gallo et al., 2005). Interestingly mixed forests had much higher intercepts of 0.110. The intercepts were much higher in this study, particularly so for wetlands but the r^2 values were similar. Barrett *et al*. (2005) also found r^2 in the range 0.82 to 0.85 for tussock grasslands and cereal crops.

The higher intercept values may be due to the heterogeneity of the wetland site which includes a range of flood distributions from almost permanently wet areas of high biomass to irregularly flooded areas more similar to adjacent grasslands. Huete *et al*. (2002) found that MODIS and AVHRR NDVI were very similar in arid and semi-arid sites but AVHRR was significantly lower than MODIS during wet intervals of the growing season. This was attributed to the different spectral properties of the two sensors in the NIR channel.

3.2. Vegetation response to flooding

There is a significant difference between the NDVI of wetland and grassland sites for both AVHRR and MODIS data. The boxplots (Figure 5) of wetland and grassland values for AVHRR and MODIS demonstrate that the difference is both in relative NDVI values and in the distribution of the data, with high NDVI values in grasslands representing outliers. Peak values are similar for both vegetation types, suggesting that the difference in means is not due to the vegetation characteristics, rather the greater availability of water in the wetland site.

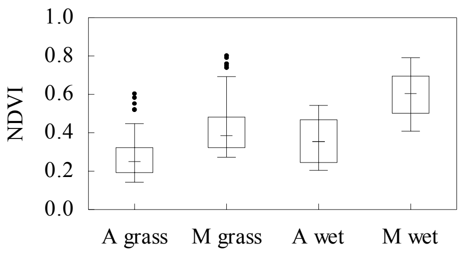

Figure 5: AVHRR (A) and MODIS (M) 16 day MVC NDVI for wetland (wet) and grassland (grass) sites. Boxplots showing median, quartiles, non-outlier range (10th and 90th percentiles) and outliers (> 1.5 the height of the box) (●).

Visual comparison of the MODIS wetland and grassland temporal NDVI (Figure 6) indicates that the wetland site has higher values at maturity and the duration of greenness is longer. Rate of greenup is similar but rate of senescence is greater for grasslands. Dormancy NDVI is also markedly lower in grasslands which approximate bare soil (approximately 0.2 MODIS NDVI for study area). Grassland maturity values only approximate wetland peaks when associated with larger rainfall events (as in composite periods 0-10 and 95-100, Figure 6) or large flood events (composite periods 0-10 and 75-80, Figure 6) and are of shorter duration. There is noticeable deviation in the wetland and grassland maturity during moderate inflow periods (20-30 and 60-70, Figure 6). This can be attributed to flood inflows to the wetland site with insufficient local rainfall for a strong greening response in unflooded grassland. The same patterns were observed in the AVHRR record.

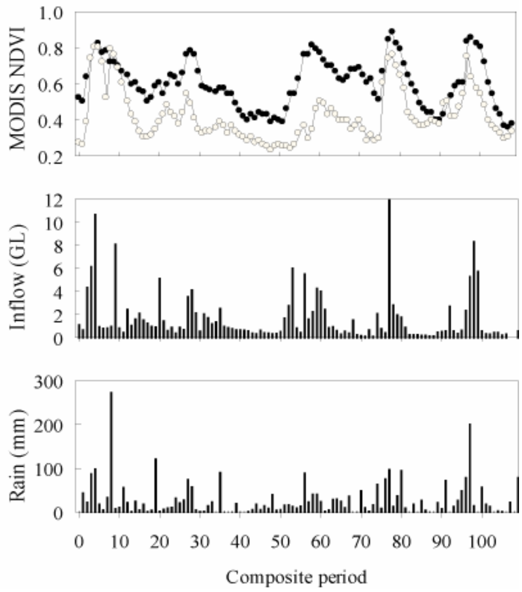

Figure 6: MODIS 16 day MVC NDVI for wetland (●) and grassland (○) compared to the 16 day cumulative antecedent inflows (Gwydir River at Millewa gauge) and rainfall (Moree) for the period 29 September 2000 to 26 June 2005.

Time series analysis: All NDVI timeseries were significantly autocorrelated at lag intervals 1 to 4 (64 days). Inflow was significantly autocorrelated at lag 1 only, while there was significant auto-correlation of rainfall only at lag 0. Cross-correlation between NDVI and rainfall or inflow was generally significant for up to five lag intervals (80 days). There was also significant cross-correlation between rainfall and inflows at lags -1 and 0. As the rainfall and inflows were calculated for the antecedent 16-day period of the MVC period for NDVI, this indicates that the lags of particular interest in relation to regression modelling of response include the MVC period itself and the four preceding intervals. The significant rainfall lag periods of up to 80 days is similar to that found by Eklundh (1998).

Preliminary regression modelling of the NDVI time-series indicated that rainfall accounts for less than 35% of variation, and that the analysis is confounded by the significant autocorrelation of NDVI. This was also found by Eklundh (1998). As the purpose of this study is to understand the flood response, an event-based approach is proposed for the exploratory analysis.

Event analysis: The entire MODIS record shows 5 distinct events for the wetland site (figure 6). To increase the number of events for exploratory modelling of response, the AVHRR timeseries from 1992-2005 is used (320 composite periods as shown in (Figure 7).

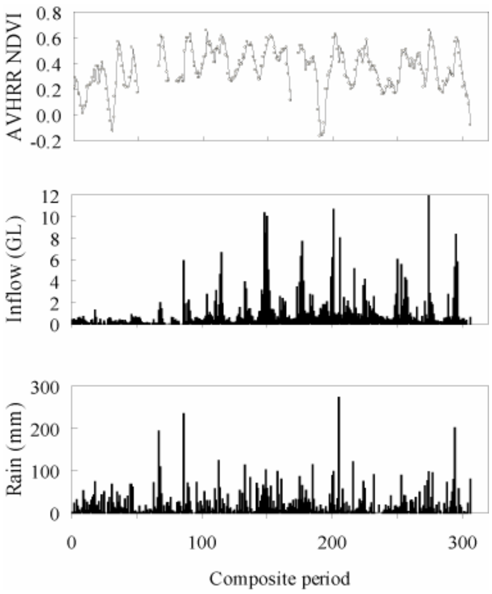

Figure 7: 16-day MVC time-series AVHRR for wetland site and 16 day cumulative antecedent inflow (Gwydir River at Millewa gauge) and rainfall (Moree) for the period 21 March 1992 to 26 June 2005.

To extract the signal due to events, peaks greater than 0.4 NDVI separated by at least 5 composite intervals (as shown previously, NDVI has significant auto-correlation for lags of 0 to 4) are included in the analysis. Antecedent rainfall and inflow were calculated for the MVC period corresponding to the peak and the preceding four lag periods. Visual examination of the phenology curves indicate that five cumulative periods following the peak generally account for most of the senescence. For this reason, the NDVI over 10 periods (160 days in total) is representative of the duration of greenness and the mean is used to describe the event NDVI (N_e).

Extracting the pre-greenup NDVI and event NDVI for a range of rainfall and/or inflow events allows preliminary analysis of a multiple linear regression model such that

$$N_e = aN_i + bQ + dR + c \qquad (2)$$

where N_e is the event NDVI, N_i is the pre-event or initial NDVI, Q is inflow, R is rainfall and a, b, c and d are the parameter values.

It was found that rainfall was not significant. This is likely due to vegetation response to inflows originating from headwater rainfall rather than local rainfall. Alternatively it may be due to the event analysis approach as it could be expected that most peaks are vegetation responding to local rainfall to some degree, and there is generally a correlation between rainfall and inflows. This is a disadvantage of the event-based approach that requires further consideration. Setting the rainfall coefficient, d, to 0 gave an adjusted r^2 of 0.52, with parameter values as shown in Table 3.

The analysis was repeated for events with peaks greater than 0.45 (n=16) and 0.5 (n=13) NDVI. The regression model was significant in all cases ($p<0.001$), explaining over 79% of the event NDVI for peaks greater than 0.45 (Table 3).

Table 3. Results of regression analysis of AVHRR NDVI for a range of event peaks. Rainfall coefficient was not significant.

Peak NDVI	n	*A*	*b* x10^{-6}	*c*	r	adj. r^2
> 0.4	20	0.21	3.72	0.31	0.75	0.52
> 0.45	16	0.23	3.27	0.32	0.79	0.57
> 0.5	13	0.25	3.04	0.32	0.79	0.56

When the analysis is repeated for the grassland site, only the intercept and initial NDVI are significant in the model. This is expected as peaks in NDVI are generally rainfall driven. By only including peaks, the sensitivity to insufficient rainfall is lost. In a distributed lag model of monthly time-series NDVI and rainfall in East Africa, Eklundh (1998) found that although the models were statistically significant, the relationships did not explain more than 36% of the variation in NDVI. The difference between a poor seasonal response to moisture availability and an excellent response when all conditions are favourable may only be small in terms of peak or event NDVI. The sensitivity of the modelling approach to this small difference requires further investigation.

4. CONCLUSION

The results of the comparison of sensors indicate that, despite the small size and heterogeneity of the study site through space and time, AVHRR and MODIS show similar temporal NDVI profiles and can be compared using a simple linear regression model. This enables further research based on higher resolution MODIS data and field work to be applied to historical AVHRR datasets. It may also provide a level of confidence when scaling from field sites to MODIS to AVHRR.

This exploratory analysis of events indicates that multiple regression modelling of NDVI response is possible for small wetlands sites using the AVHRR satellite data. Further investigation of modelling approaches using the whole time-series (rather than parts limited to events) and the difference between wetland and dryland sites may strengthen the analysis. And more research is required to establish that the models and data are sensitive to small differences in event NDVI that separate highly productive wetlands from a normal seasonal greening response. This work must therefore be coupled with field data to validate NDVI results and phenology, and to determine the ideal NDVI response for healthy wetland communities.

Despite limitations and the need for further analysis, the information presented here shows promise for application to water management. These types of models can be used to estimate the water requirements to achieve a pre-determined NDVI response under a variety of antecedent conditions (as indicated by pre-event NDVI).

5. ACKNOWLEDGEMENTS

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