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Modelling Impacts of Environmental Water on Vegetation of a Semi-Arid Floodplain–Lakes System Using 30-Year Landsat Data

Chunying Wu [1,2,3,*], James Angus Webb [1] and Michael J. Stewardson [1]

[1] Department of Infrastructure Engineering, Faculty of Engineering and IT, The University of Melbourne, Melbourne, VIC 3010, Australia; angus.webb@unimelb.edu.au (J.A.W.); mjstew@unimelb.edu.au (M.J.S.)
[2] Australian-German Climate & Energy College, The University of Melbourne, Melbourne, VIC 3010, Australia
[3] Institute of Applied Geosciences, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
* Correspondence: chunyingw@student.unimelb.edu.au

Abstract: River floodplains are among the most dynamic and diverse ecosystems on the planet. They are at risk of degradation due to river regulation and climate change. Environmental water has been delivered to floodplains to maintain environmental health by mimicking natural floods. It is important to understand the long-term effects of environmental water to floodplain vegetation to support its management. This study used Normalized Differences Vegetation index (NDVI) from the 30-year Landsat datasets of the Hattah Lakes floodplain in Australia to investigate the drivers of vegetation dynamics. We developed generalized additive mixed models (GAMM) to model responses of vegetation to environmental water, natural floods, precipitation, temperature, and distance to water across multiple spatial and temporal scales. We found the effect of environmental water on floodplain vegetation to be quite different from that of natural floods in both space and time. Vegetation in most areas of Hattah Lakes will respond to natural floods within one month of flooding, while positive responses to environmental water occur 1 to 3 months after inundation and are more restricted spatially. For environmental water planning, managers need to be aware of these differences. The implementation of new infrastructure to transport or retain environmental water on floodplains needs to be planned carefully, with continuous monitoring of rainfall and natural floods. Whilst environmental floods do not mimic the effect of natural floods, they do provide some positive benefits that can partially offset effects of reduced natural floods.

Keywords: environmental water; vegetation; normalized differences vegetation index (NDVI); generalized additive mixed model (GAMM); Hattah Lakes; climate change

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1. Introduction

River floodplains are among the most diverse, dynamic and vulnerable ecosystems on the earth [1]. They are important to ecology and the economy because of the ecosystem services they provide, including water purification, biodiversity, sediment retention, carbon sequestration, and tourism [2–5]. However, they are at risk of degradation and destruction due to increasing human populations, river regulation and climate change [3,6].

Wetland inundation regimes have been altered because of water resource management, such as the construction of dams or locks, leading to a decline in riverine ecosystem health [7]. Surface flow reductions, agricultural expansion and groundwater mining have cause declines in woody vegetation populations and seedling establishment in western North America, Europe, and Asia [8]. In Australia, due to water resources regulation and climate change, wetlands in semi-arid floodplains and their hydrological connectivity with main river channels are under increasing pressure [9]. For example, anthropogenic influences on river systems combined with the 'Millennium Drought' from 1997 to 2009 led to severe declines in vegetation condition across the floodplains of the Murray-Darling Basin [10,11].

Environmental flows are defined as the volumes of water maintained in rivers to protect and enhance the ecological functions of floodplain, riverine and wetland ecosystems [12]. In this study, environmental water is mainly referred as environmental flow. To restore floodplain ecosystems, mitigate the impact of river regulation and maintain environmental health, increasing numbers of environmental water delivery programs have been implemented around the world [13,14]. These now include engineering-based approaches including inundating floodplains by pumping into canals and then controlling water delivery with regulators to mimic flood events [15,16]. In the Missouri River, USA, flooding was managed and controlled to mainly benefit migrant waterbirds when the annual natural flooding did not occur [14]. Similar infrastructure projects are also proposed to increase seasonal wetland flooding in Poyang Lake wetland, China, which has experienced reduced flooding since the construction of the Three Gorges Dam [15]. In Australia's Murray-Darling basin, environmental water has been pumped into many wetlands such as Chowilla floodplain and Hattah Lakes floodplain to improve the health of vegetation and restore habitat [13]. These examples notwithstanding, using artificial engineering methods to provide water to floodplain is relatively a new practice [15].

The response of vegetation is one important consideration when determining environmental water releases, and improving the richness and abundance of water dependent native vegetation is a common long-term management objective of environmental flow programs [1]. Designing environmental water programmers and requirements to achieve ecological goals for floodplain ecosystems is challenging because of their complex plant communities. Field experiments, ecological modelling and remote sensing technology have been used to detect vegetation response to floods or environmental flows [17,18]. Short-term benefits of a large-scale environmental flow event have been evaluated using a multi-taxon Bayesian hierarchical model based on a single environmental flow event and limited field data [1]. However, long-term effects of environmental flows on floodplain vegetation have not been described because of a lack of longer-term datasets [1,19]. Therefore, long-term effects of environmental water on floodplain ecosystems need to be monitored and modeled to better manage environmental water [20].

To address this research gap, this paper focuses on modelling vegetation response to environmental water based on 30-year Landsat datasets in Hattah Lakes, Australia. Most environmental water programs are based on the assumption that environmental water can be used to mimic natural floods [15,21]. Therefore, comparing the impact of natural floods and environmental water to see if environmental water can achieve the same goal of natural floods is a key objective of this research. The influence of climate factors including precipitation and temperature, lag time are also considered in the modelling. We developed a generalized additive mixed model, combining continuous and categorized data, which is a first attempt in this type of research. The spatial responses of vegetation were then summarized according to different vegetation classes. We conclude by giving technical support and suggestions for government and management to make decisions regarding environmental water release strategies.

2. Materials and Methods

2.1. Study Area

The Hattah Lakes floodplain, located in north-western Victoria, south-east Australia (34°41′14″S, 142°22′54″E), is a semi-arid connected floodplain–lakes system. As part of the floodplain of the Murray River, Hattah Lakes covers an area of ca. 480 square kilometers [22] and floodplain is composed of more than 20 semi-permanent wetlands, including 12 Ramsar-listed wetlands (Figure 1). With an average rainfall of about 250 mm, Hattah Lakes is generally only inundated when the Murray River reaches moderately high flows. These semi-permanent shallow lakes (0.4–2.8 m retained water depth) are important habitats for the floodplain biota [22].

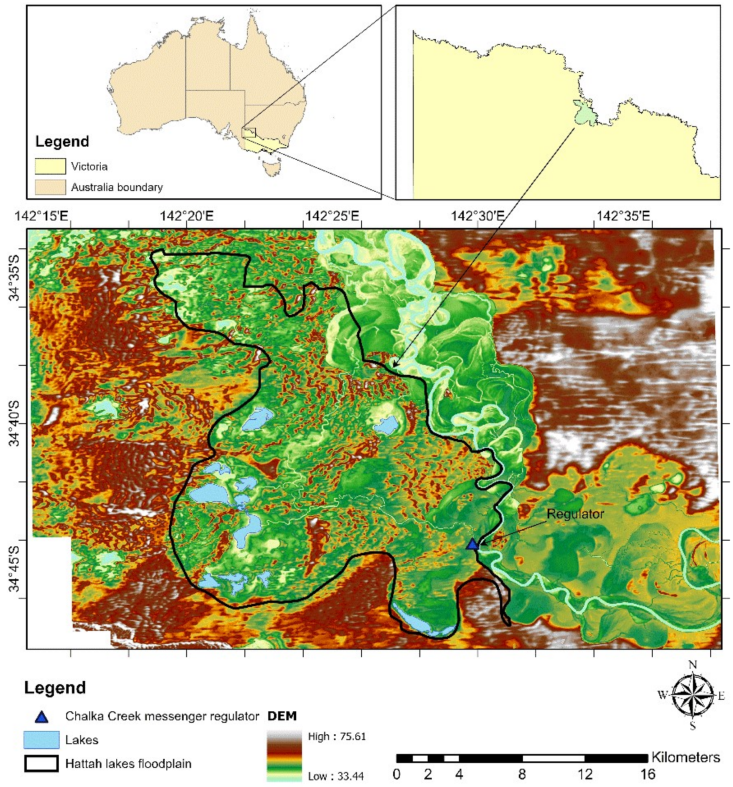

Figure 1. Location and elevation of study area. The floodplain boundary used in this research is extracted from interim Biogeographic Regionalization for Australia version 7 (IBRA7).

The ecological value of Hattah lakes has been affected by river regulation. Discharge at Euston Weir (~70 km upstream of Hattah Lakes) has been reduced by ~50% of natural levels as a result of water extraction in the upstream regions of the Murray River and its tributaries. For Hattah Lakes, these changes have reduced flood frequency and duration by 57% and 65%, respectively. Flood timing has also been delayed from August to September or October [22]. Therefore, most water bodies in Hattah Lakes receive reduced inflow and only maintain wet status for a very short time due to regulation. Between 1996 and 2010, natural floods occurred only in 1996 and 2010, but they would have occurred at least seven times under natural inundation conditions [22].

Environmental water was first pumped into Hattah Lakes in 2005 with the purpose of restoring and improving the health of River Red Gum (*Eucalyptus camaldulensis*) forests threatened by the below-average rainfall during the Millennium Drought. Tree condition was improved by the environmental watering between 2006 and 2010, but the restored area was relatively limited and other trees in Hattah Lakes remained in poor condition [23]. After 2010 and 2011, the condition of River Red Gum greatly improved following above-average precipitation and natural floods. As a result of increasing water availability following high rainfall, flooding events in 2010 and 2011 improved most River Red Gums in Hattah Lakes. At the same time, excess water may recharge groundwater in this region [23]. Low rainfall occurred following this wet season in the Hattah lakes. Between 2013 and 2017, environmental water has been delivered to Hattah Lakes five times through the Chalka Creek regulator (marked as a triangle in Figure 1) [24].

2.2. Datasets

2.2.1. Remote Sensing Data

A 30-year Landsat dataset from 1988 to 2018 was used in this study. Landsat 4, 5, 7, 8 surface reflectance Tier 1 data were accessed through the Google Earth Engine (GEE). The temporal resolution of the dataset is 16 days. These remotely sensed images meet geometric and radiometric quality requirements and have been atmospherically corrected. We removed pixels with clouds and cloud shadows using the 'pixel_qa' band from the pixel quality information, and repaired Landsat 7 Scan Line Corrector (SLC)-off error using the morphological mean filter method in GEE. Values were interpolated from the previous and following images to fill the pixel gaps.

Two vegetation indices were calculated based on the Landsat data. Normalized Difference Vegetation Index (NDVI) is derived from the ratio of near-infrared spectral (NIR) and red spectral (RED) wavelengths reflected by vegetation [25,26]. NDVI has been widely used in research and is strongly related to vegetation distribution, phenology, and productivity [26,27]. We compared NDVI and the Enhanced Vegetation Index (EVI) [28] to compare their effectiveness in representing vegetation condition of the study area. We found that EVI values were generally low over semi-arid sites. In contrast, NDVI shows variation among years and has different patterns for different Ecological Vegetation Classes (EVCs; explained below in Section 2.3.4.) (Figures 2 and 3). Together, these show that NDVI is appropriate to be used to represent vegetation condition in Hattah Lakes.

$$\text{NDVI} = \frac{NIR - RED}{NIR + RED}, \tag{1}$$

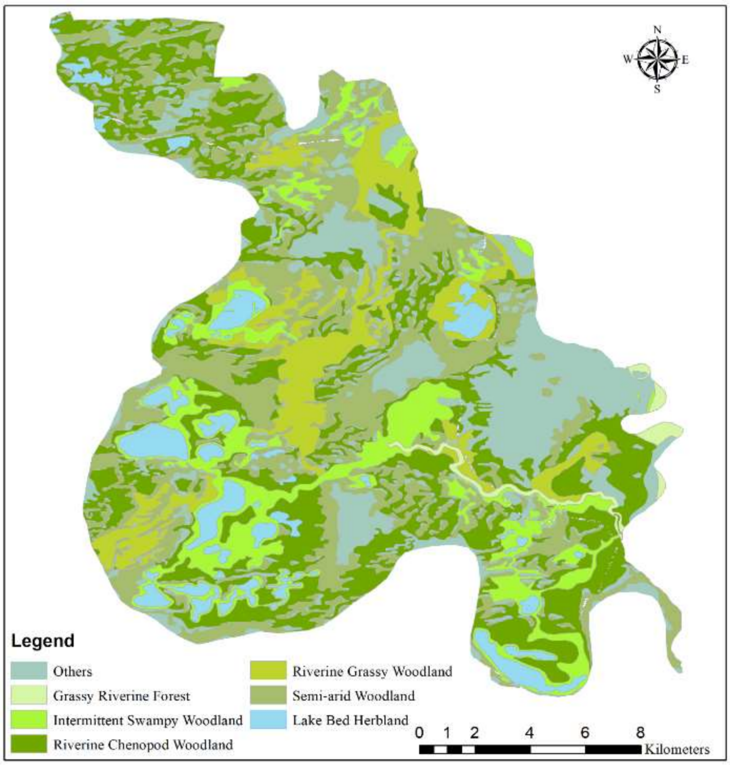

Figure 2. Main ecological vegetation classes in Hattah Lakes.

The modified Normalized Difference Water Index (mNDWI) was calculated from green spectral (GREEN) data and MIR spectral data and was used to delineate open water. MIR refers to the middle infrared band, such as the TM band 5 [29].

$$\text{MNDWI} = \frac{GREEN - MIR}{GREEN + MIR}, \tag{2}$$

The distance to water for each pixel was derived from the mNDWI. Surface water was identified as areas with mNDWI greater than 0. Then, Euclidean distance to the nearest water pixel was obtained for each pixel and each date using the "ee. Image.distance" function in GEE.

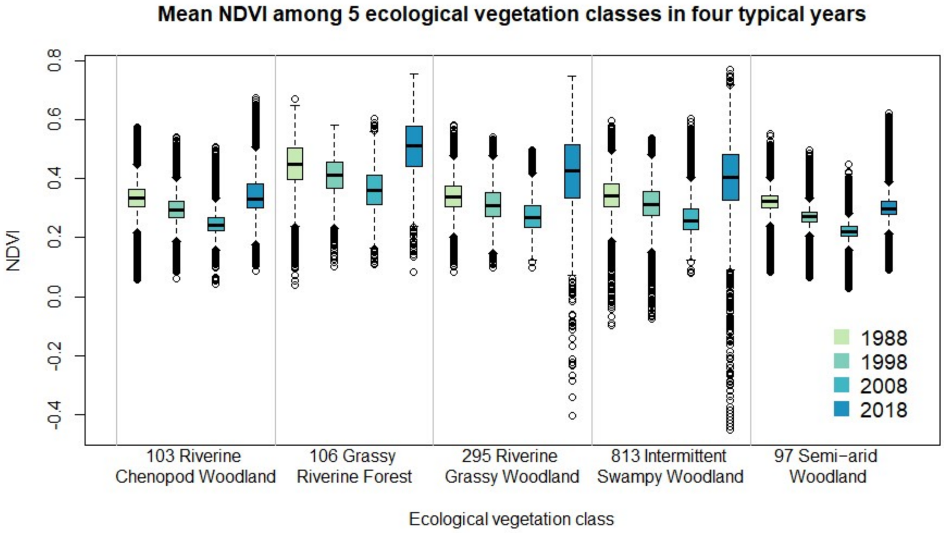

Figure 3. Mean NDVI for five vegetation EVCs, showing various among four typical years.

2.2.2. Climate Data

The AWAPer package [30] was used to extract daily maximum temperature and precipitation data for Hattah Lakes with a spatial resolution of approximately 5 km. The climate data have been developed through the Bureau of Meteorology's Australian Water Availability Project [31]. To match dates of the remote sensing imagery, we calculated maximum temperature on the date the image was taken and accumulated precipitation data for the 16 days before the date.

2.2.3. Hydrological Data

Natural flood records and environmental water records for the Hattah Lakes floodplain were derived from discharge data at Euston Weir and the Chalka Creek regulator. A commence-to-flow threshold of 36700 ML/day was applied to delineate the occurrence of a natural flood [23]. Records of environmental flow inputs have been recorded at the Chalka Creek regulator since 2013, and from pumping records prior to then.

2.3. Model Design and Evaluation

2.3.1. Predictor Variables and Response Variable

Table 1 shows the predictor variables used in this study, including distance to water, precipitation and temperature, all of which are 30-year spatial data. Hydrological variables include concurrent water, water in period 01 and water in period 02. These were categorized as "NN", "NY", "YN", "YY", representing whether environmental water (first letter) or natural floods (second letter) occur or not in the corresponding period and in what combination. The response variable in this model is NDVI, representing vegetation condition.

Table 1. Description of predictor variables used in the model.

Model Terms	Description
Day of year	To represent vegetation phenology
Distance to water	Euclidean distance to the nearest water based on mNDWI dataset
Precipitation	16 days accumulated precipitation
Temperature	Max temperature over the 16-day period
Concurrent water	Environmental water or natural floods occurs or not within one month prior to the image date
Water in period 01	Environmental water or natural floods occurs or not 1 to 3 months prior
water in period 02	Environmental water or natural floods occurs or not 4 to 12 months prior

2.3.2. Generalized Additive Mixed Models (GAMMs)

Generalized additive mixed models (GAMMs) were applied in this study to assess the relationships between NDVI and the multiple independent variables. This approach was selected because it can deal with autocorrelated data likely in time-series. GAMMs can not only model the nonlinear relationship between response variables and explanatory variables, but also include random effects similar to generalized linear mixed models [32,33]. Recently, GAMMs have been increasingly used in the studies of ecology, environments, and linguistics to extract temporal trends or model complex relationships [34].

An autoregressive-moving average (ARMA) correlation structure was selected to model temporal autocorrelation of the time-series data. The model structure used in this research takes the following form.

$$g(\mu_t) = \sum_{i=1}^{m} s_i(X_{ti}) + \sum_{i=1}^{n} X_{ti}\beta_i + ARMA(p,q), \tag{3}$$

$$\begin{aligned} ARMA(p,q) = {} & \sum_{j=1}^{p} \varphi_j \left(g(y_{t-j}) - \left(\sum_{i=1}^{m} s_i(X_{t-j,i}) + \sum_{i=1}^{n} X_{t-j,i}\beta_i\right)\right) + \\ & \sum_{j=1}^{q} \theta_j \left(g(y_{t-j}) - g(\mu_{t-j})\right), \end{aligned} \tag{4}$$

In this equation, $g(\mu_t)$ is the response variable, and g is the link function; $s_i(X_{ti})$ are smoothing parts of the explanatory variables nonlinearly related to the response variable; $X_{ti}\beta_i$ are the linear components of the model, including parameters for linear variables and intercept; $ARMA(p,q)$ is a correlation structure for modelling temporal autocorrelation. After considering the relationships between dependent and independent variables, the variables "day of year" and "distance to water" were modelled using smooth functions, while others were considered as linear terms.

This model was implemented using the "gamm" function from the mgcv package in R. Restricted Maximum Likelihood (REML) estimation was used to estimate parameters for this model [35]. Thin plate regression splines [36] were utilized for smooth terms; they out-perform traditional cubic regression splines but are computationally intensive.

2.3.3. Per Pixel Model

GAMMs were applied independently to each individual pixel of the Hattah Lakes floodplain. Because resolution of Landsat data is 30 m, we resampled the climate data to 30 m resolution. Therefore, the size of pixel is 30 × 30 m and in total we obtained 343,956 pixels for the Hattah Lakes floodplain. To perform model simulation across all pixels, the High Performance Computing system SPARTAN [37] at the University of Melbourne was used to improve the computation time. The function "future_map" in furrr package [38] in R was used to parallelize computations.

2.3.4. Model Evaluation

Before modelling, a variance inflation factor (VIF) test was conducted to check for multicollinearity between the predictor variables. This was done using vif() function from the car package in R. The VIF scores were all less than 1.4. This shows that multicollinearity is not a problem among those predictor variables, and it is not considered further in the results. To evaluate modelling results, we used the adjusted R^2 statistic. The partial autocorrelation function (PACF) was also used to test if autocorrelation in the model was removed (Figure S1).

The results were evaluated and analyzed by looking at the distribution of REML estimates of the regression coefficients across the set of per-pixel models, stratifying by EVCs (Figure 2). EVCs are the principal units used to classify native vegetation and plan land-use and management in Victoria [39,40]. They are distinguished through a combination of floristic, life form and ecological characteristics, and through an inferred fidelity to particular environmental attributes [40]. EVCs were obtained from Victorian Department of Environment, Land, Water & Planning (https://discover.data.vic.gov.au/dataset/native-vegetation-modelled-2005-ecological-vegetation-classes-with-bioregional-conservation-sta, last accessed on 28 December 2021).

3. Results

3.1. Vegetation Composition and Changes in NDVI

Hattah Lakes is mainly covered by five main EVCs (Figure 2). To illustrate how NDVI changes from 1988 to 2018, yearly NDVI was calculated in four typical years with ten-year interval (Figure 3).

NDVI in 2008 shows the lowest value among the different EVCs, coincident with the millennium drought in Australia. The millennium drought occurred from 2000 to 2009, affecting most of southern Australia [18]. *Semi-arid woodland*, composed of non-eucalypt woodland, has a relatively lower value of NDVI. The mean NDVI value of *Grassy riverine forest*, which are mainly River Red Gum forests, is higher than other classes. This type of vegetation occurs along Chalka creek, through which environmental water is delivered to the water bodies in Hattah Lakes. *Riverine chenopod woodland*, *riverine grassy woodland* and *intermittent swampy woodland* have similar NDVI values in each year.

3.2. Vegetation Responses to Natural Floods and Environmental Water

Coefficients of natural floods and environmental water are summarized by the percentage of negative and positive regression parameter estimates across all of Hattah Lakes (Table 2). More than 85% of the pixels of *semi-arid woodland*, *riverine chenopod woodland* and *grassy riverine forest* positively responded to natural floods occurring within one month of the survey date ('concurrent'). The other two types of vegetation also positively respond to concurrent natural floods, but with a smaller percentage of pixels (76% and 79%). Apart from grassy riverine forest, more than 60% of the pixels of other EVCs have on-average slightly negative responses (i.e., positive response rate is <50%) to natural floods occurring 1 to 3 months prior to the survey and have positive responses to natural floods occurring 4 to 12 months previously.

Table 2. Percentages of positive coefficient of watering events for five vegetation classes in Hattah Lakes.

	97 Semi-Arid Woodland	*103 Riverine Chenopod Woodland*	*106 Grassy Riverine Forest*	*295 Riverine Grassy Woodland*	*813 Intermittent Swampy Woodland*
Concurrent natural flood	95%	91%	85%	79%	76%
Natural flood in period 1	40%	35%	64%	35%	33%
Natural flood in period 2	77%	67%	75%	61%	68%
Current env water	21%	22%	9%	24%	21%
Env water in period 1	72%	61%	85%	60%	57%
Env water in period 2	73%	68%	61%	63%	68%
Both occur in period 2 [1]	83%	74%	55%	70%	66%

[1] 'Both' refers to both Natural floods and Environmental water occurring within the same period.

Unlike natural floods, environmental water appears to have a negative influence on vegetation in more than 76% pixels in the month after delivery (concurrent). However, over half the pixels for each EVC show a positive response to environmental water with a lag time more than 1 month (periods 1 and 2). This phenomenon is most apparent in *semi-arid woodland*, where the percentage shifts from more 70% negative during the 'concurrent' period to more than 70% positive when lag time is greater than one month (Table 2).

To further explore spatial influence patterns of natural floods and environmental water, we classified pixels into eight classes according to positive and negative value of coefficients (Table 3). If effects of watering events within one month are positive, then no matter how the effects change with lag time, we describe them as vegetation increasing immediately. If vegetation responds positively to watering events happening 1 to 3 months previously, but negatively to concurrent events, we consider them as vegetation increasing with 1 to 3 months lag time. Other classes are described in the same way (Table 3).

Table 3. Classification of influence patterns of watering events (+ represents positive influence, while − influences negative influence.).

Class of Influence	<1 Month	1 Month to 3 Months	4 Months to 12 Months	Description
1	+	−	−	Increase immediately
2	+	+	−	Increase immediately
3	+	−	+	Increase immediately
4	+	+	+	Increase immediately
5	−	+	+	1 to 3 months lag
6	−	+	−	1 to 3 months lag
7	−	−	+	4 to 12 months lag
8	−	−	−	Negative response

Vegetation in most areas of Hattah Lakes will respond to natural floods immediately within one month (Figure 4a). In the southwestern part of Hattah Lakes, some *riverine grassy woodland* responds to natural floods with a lag time of 1 to 3 months. In some fringing areas around Lake Lockie (red area in Figure 4a), NDVI only increases with natural floods that occurred 4 to 12 months previously.

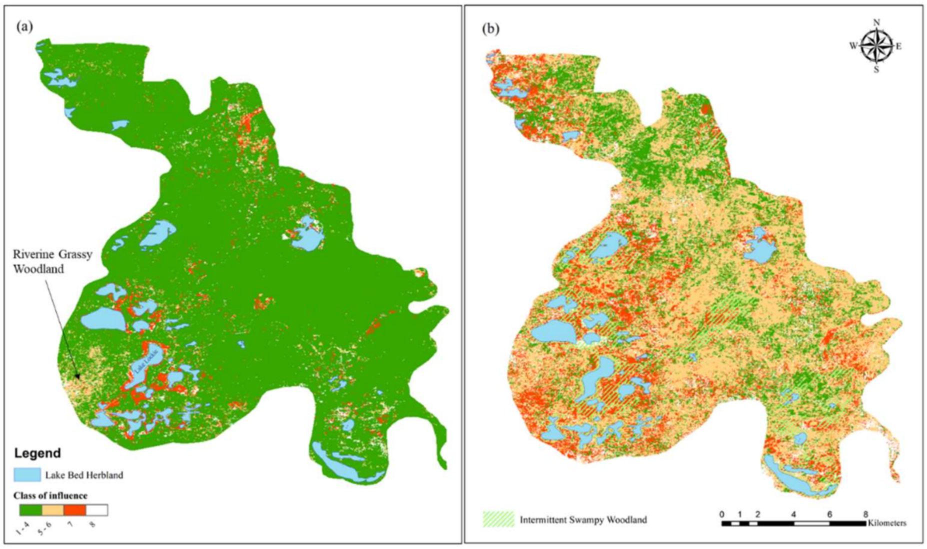

Figure 4. Pattern of vegetation response to (**a**) Natural floods (**b**) Environmental water with different lag time.

Compared to natural floods, the impacts of environmental water are more spatially complex (Figure 4). Environmental water can help vegetation condition immediately in the northern Hattah Lakes floodplain (green area in Figure 4b), while vegetation over most of Hattah lakes will positively respond to environmental water occurring 1 to 3 months prior. *Intermittent swampy woodland* (area with green slash in Figure 4b) shows different patterns, in that environmental water occurring 4 to 12 months earlier has a positive impact. There are only a few pixels classified as class eight (negative response), which means that neither environmental water nor natural floods will improve vegetation health within 1 year of the event.

3.3. Other Explanatory Variables and Model Evaluation

3.3.1. Influence of Climate Factors and Other Variables

Coefficients from the models were used to represent the influences of 16-day accumulated precipitation and maximum temperature on vegetation (Figure 5). The influences are spatially distributed and there are differences among EVCs.

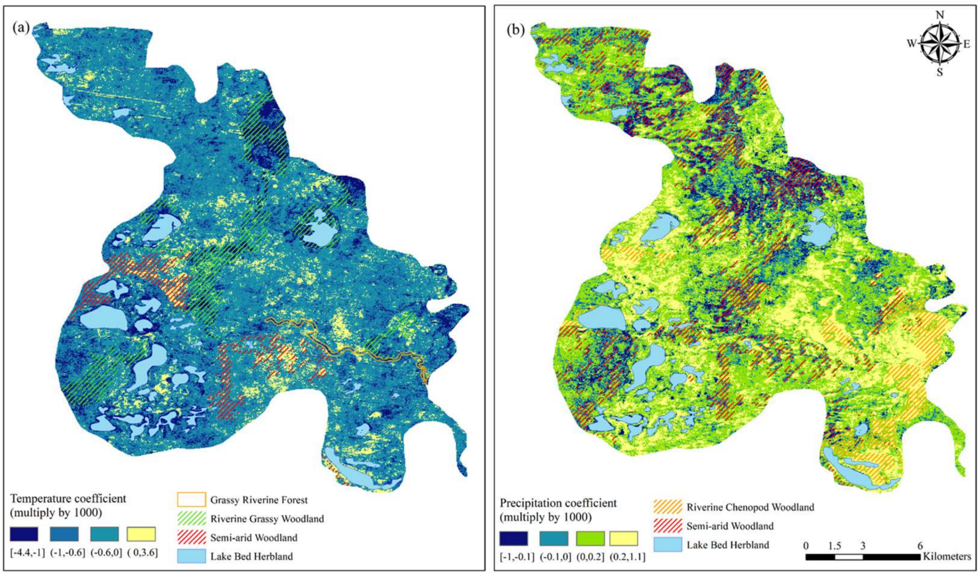

Figure 5. Influence of (**a**) temperature and (**b**) precipitation on vegetation.

Most areas in Hattah Lakes negatively respond to increasing temperature, while a small proportion of semi-arid woodland shows a positive response to temperature. Vegetation along Chalka creek, which is grassy riverine forest, and in riverine grassy woodland, are more strongly influenced by temperature compared to other vegetation types (Figure 5a).

NDVI increases when there is more rainfall in most part of Hattah Lakes, but a major portion of semi-arid woodland responds negatively to precipitation (blue area in Figure 5b). The yellow area with larger precipitation coefficients in the model is covered by riverine chenopod woodland and shows a stronger positive response to precipitation.

The results of the variable 'day of year' indicate that the GAMM model captures vegetation phenology in Hattah lakes successfully. In most pixels, the peak of season is between the 175th and 212th day of the year. Multiple pixels are selected to show the influence curves of distance to water generated by GAMM, and it shows that distance to water has a slightly negative influence on NDVI value.

3.3.2. Model Evaluation

The four maps in Figure 6 illustrate that autocorrelation was largely removed for temporal lags 1 to 4. Autocorrelation was almost completely removed for lag 1 and 2, while there is a small number of pixels that have substantial serial autocorrelation for lag 3 and 4 (blue area in Figure 6c,d). This shows that the ARMA error function performed as hoped.

The mean adjusted R square for all models is 0.52. Models in the drier areas of the landscape, and in particular semi-arid woodlands, have higher R square values (Figure 7). Models in fringing area of the lakes themselves have the lowest adjusted R square values. This is mainly because they are periodically inundated, which influences NDVI value substantially.

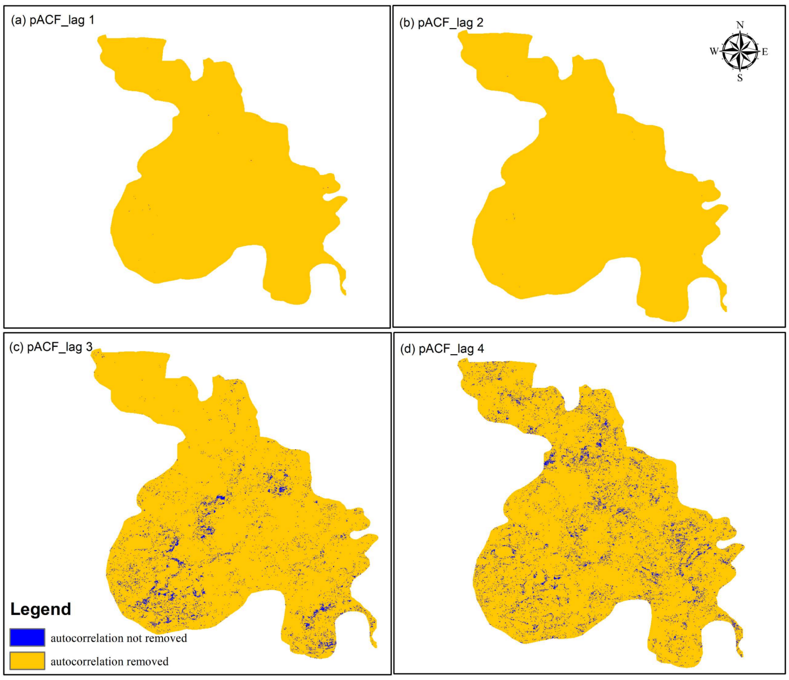

Figure 6. Result of PACF (If the value of Partial autocorrelation is within the 95% interval, the pixel is recognized as autocorrelation removed and vice versa).

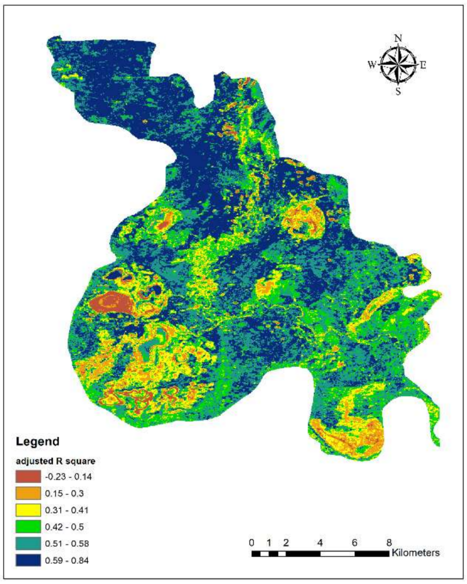

Figure 7. Adjusted R square.

4. Discussion

The results provide new insight to support environmental water management to maintain vegetation health. It is generally assumed that environmental water can be used to provide equivalent outcomes as overbank flows in supporting floodplain vegetation. However, this study found that vegetation responses to environmental water and natural floods were found to be very different in terms of lag time and spatial distribution.

4.1. *Different Effects of Environmental Water and Natural Floods on Floodplain Vegetation*

Our results show that although both environmental water and natural floods have benefits for floodplain vegetation, those benefits are very different in terms of the spatial extent of the effect and to a lesser extent the temporal extent. In general, environmental water takes a longer time (1 to 3 months) to display a positive effect than natural floods, which produce effects within 1 month of inundation.

Despite this important difference, vegetation in the Hattah Lakes floodplain responds positively to both environmental water and natural floods events occurring over the previous year. These results are coherent with previous findings. Both precipitation and flooding are important drivers of vegetation variation in the floodplain [18,41]. In the Narran Lakes floodplains in northern New South Wales, Australia, response patterns are complex and vary among different vegetation communities, but flow remains the main influence on vegetation productivity [42]. NDVI has previously been found to increase up to 19% above non-flood levels and for a period of 13 months following recession of a flood that inundated more than 50% of the Paroo River Wetlands in 2008 [12]. Vegetation recruitment has been shown to respond to a combination of environmental flows and riparian vegetation enhancement [8]. In Hattah Lakes, environmental water has previously been shown to promote short-term positive responses in native vegetation based on data collected in the field [1].

4.2. Why Are There the Differences in the Influence of Environmental Water and Natural Floods?

The most obvious potential reason for the difference in the effects of environmental water and natural floods is that delivery mechanisms vary between the two sources of water. The floodplain will be inundated if natural floods occur, but environmental water is directed along individual channels. This restricts the inundated area for environmental water. The time of occurrence, flooding duration and volume may also differ between natural floods and environmental water. For example, volume of natural floods is larger than environmental water, so that overbank flows occur. These factors influence watering extent and in turn the reproductive processes of vegetation.

There are some spatial differences among the different EVCs. *Riverine grassy woodland* in the western part of the Hattah Lakes floodplain responds to natural floods 1 to 3 months after the overbank event. That area is the greatest distance from the river in the floodplain and in a slightly elevated position where floods are rare [43]. This means that water from natural floods does not reach the areas immediately. Vegetation in the fringing areas, especially around Lake Lockie, is improved 4 to 12 months after natural flooding. Because of the large volume of natural floods, the area around the lakes is flooded and will remain inundated for some time. Standing water will reduce the NDVI value, and at the same time, we will not see an increase in vegetation condition in those pixels around the lakes until after the water recedes. This phenomenon is more apparent in response to environmental water. In most areas of intermittent swampy woodland, which includes fringing area of lakes, environmental water improves vegetation condition 4 to 12 months after delivery. This EVC is mainly *Eucalypt* woodland up to 15 m tall and is close to the path of environmental water. Therefore, it will be inundated and influenced directly when environmental water is delivered.

4.3. Implications for Environmental Water Management

This research provides a counterpoint to assumptions implicit in environmental water management in Australia, and in particular the management of sustainable diversion limits (SDL) in the Murray-Darling Basin Plan. In calculating SDLs, and in particular the ‘Adjustment mechanism’ to increase the amount of water retained for agricultural consumption [44], environmental water is used to replace natural floods. It is assumed that environmental works such as regulators provide ‘equivalent environmental outcomes’ as do overbank flows, but with greater watering efficiency [45,46]. However, our results clearly show that pumping environmental water using regulators does not achieve the same benefits as natural floods. Many projects have been designed to reinstate the natural flooding regime by delivering environmental water [21], and many propose to do so by constructing pumping stations and other regulators. With regard to such projects, we suggest continuing with environmental watering to help vegetation health in the changing climate. However, managers need to be aware that the beneficial effects of such flows will be much more spatially constrained than those of natural floods, and that the time scale of effect may be different to that of natural floods.

Long-term vegetation condition has been modelled in this paper, supporting adaptive management of environmental flows in terms of vegetation monitoring and evaluation [47]. In Hattah Lakes, the release of environmental water will continue to play an important role in maintaining and improving vegetation growth under climate change, as was demonstrated throughout the Millennium drought period. Based on the results from this study, the implementation of new infrastructures needs to be planned carefully. Environmental water benefits accrue more slowly for floodplain vegetation than those from natural floods. If a decreasing trend of precipitation and lack of natural floods are predicted, it is worth considering pumping environmental water into floodplain system in advance of any full-blown drought. According to the distribution of results among EVCs observed here, *intermittent swampy woodland* should be a focus because it shows a longer lag response to environmental water. Monitoring of this area can be more frequency and more research are needed on this EVC.

4.4. Benefit of the Methods and Future Opportunities

This is the first application of GAMM to analysis of environmental water effects of which we are aware. There were several advantages of GAMM for our study. First, it is suitable for qualitative factors, where the watering events were categorized into 3 classes for each date. Data temporal autocorrelation problems were also solved. Most importantly, we have shown that GAMM can separate the influence of environmental water on vegetation from that of natural floods and is suitable for applications in lake-connected floodplains. The work illustrates the complexity of the spatial distribution of vegetation response to environmental water. It is also based on a 30-year satellite data set, thus making full use of historical data and giving greater confidence in the long-term results. The different lag times and spatial influences will be the foundation of further analysis, such as the effects of specific environmental water regimes.

Vegetation condition was represented by NDVI based on the 30-year Landsat dataset, which solved the problem of discontinuous and incomplete field data. Some errors existed due to image quality, including gap pixels and missing images. Moreover, the condition of trees and understory vegetation have not been separated in this research. A more specific vegetation response, such as River Red Gum condition, would be needed to model individual priority species in the floodplain.

A lag time on the influence of climatic factors could be added to the model to increase biophysical accuracy. In semi-arid areas, vegetation shows a time-lagged response to rainfall pulses [18]. Therefore, in future modelling, different lag times of climate factors could help improve model fit.

In future research, we would like to consider the influence of groundwater and human activities. Increasing groundwater extraction has been shown to lead to decrease in floodplain productivity, including in the EVC *semi-arid floodplain woodland* [17,48]. Although distance to water was used in the model, the relative influences of surface water and groundwater need to be further explored. Our model tests the effect of environmental water and natural floods regardless how far that pixel is from surface water. To further explore how environmental water aids vegetation health, it would be worth including a physical model considering flow path, flow volume and release timing. Improved understanding from such an approach may offer an opportunity to improve the efficiency of environmental water use, making full use of precious water resources.

5. Conclusions

In this paper, we modelled vegetation response to environmental water using GAMM based on 30-year Landsat data, combining with climate factors and natural floods. We found that the influences of environmental water and natural floods are different in lag time and spatial distribution. In most area of Hattah Lakes, environmental water can help vegetation growth in 1 to 3 months and different patterns between EVCs have been found. To better support environmental water delivery strategy and management, further studies such as combining with water balance model are needed. Overall, this work can help management better understand and manage environmental water to restore and maintain vegetation health under climate change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs14030708/s1, Figure S1: VIF results for predictor variables.

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