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Application of time series of remotely sensed normalized difference water, vegetation and moisture indices in characterizing flood dynamics of large-scale arid zone floodplains

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ABSTRACT

Floodplains are a key ecological feature of arid and semi-arid regions and flooding is the main source of vegetation productivity. Characterizing the spatiotemporal flood dynamics, such as surface water and changes in subsequent vegetation growth vigour and biomass, is essential in better understanding of ecology and hydrology of these regions. Recent remotely sensed flooding studies of arid zone floodplains have concentrated on improving classification of surface water, particularly in mixed water-vegetation areas; less is known about the effect of surface water flooding pattern on emergent vegetation dynamics. We use an integrated framework for mapping both flood extents and the persistence of floodplain response changes of water, vegetation and moisture in Cooper Creek, Australia. We analysed pixel-based time series of multiple indices generated by daily MODIS data for 14 highly variable flow flood events between 2000 and 2012. Results indicate that for the extremely flat Cooper Creek floodplain, mapping inundation area by changes in vegetation growth vigour and biomass was significantly larger than surface water mapping area (16.2% for the 2004 flood event) and the difference in inundation mapping mainly occurs around the inundated edges. In addition, by studying surface water and subsequent vegetation response together, it is possible to generate new information, such as the lag time between flooding and peak vegetation growth vigour and biomass, and persistence time of surface water and green vegetation, which provide important insights to arid zone floodplain behaviour. The large extent and high frequency of MODIS images provide advantages in characterizing inundation dynamics for large-scale floodplains where instantaneous (daily) inundation extent is considerably smaller than total cumulative inundation extent, compared with sensors with higher spatial resolution but lower temporal resolution; however, the coarse resolution of MODIS (500 m) limits its performance for small flood events. Globally, this approach is suitable for other large, low-gradient floodplains in arid zones that show similar, long duration vegetation responses as observed in Cooper Creek.

1. Introduction

Floodplains are a key ecological feature of arid and semi-arid regions, providing intermittent water availability in dry areas, and flooding patterns are often complex in time and space. Flood water stimulates fish breeding, water bird migration and breeding, increases vegetation productivity and the availability of soil nutrients (Balcombe and Arthington, 2009; Baldwin et al., 2013; Capon, 2003; Colloff and Baldwin, 2010; Roshier et al., 2002). Examples of dryland floodplains are the Tarim River of China (Zhao et al., 2009), the Okavango Delta (Milzow et al., 2009) and mid to lower reaches of Lake Eyre Basin (LEB) rivers in Australia (Knighton and Nanson, 1994b; McMahon et al., 2008b). Remote sensing can often provide the only suitable spatial and temporal estimates of flood dynamics (Haas et al., 2009; Ogilvie et al., 2015; Sakamoto et al., 2007), an essential element of successful hydrological and ecological management of arid zone rivers (Costelloe et al., 2003; Jarihani et al., 2013; Powell et al., 2014), particularly for rivers with limited ground monitoring infrastructure and complex flow paths (Alsdorf et al., 2007; Costelloe et al., 2006). Flood detection is a classical theme in remote sensing and inundation mapping methods largely rely on detecting surface water (Sakamoto et al., 2007). In addition to mapping flood extents, remote sensing also provides the potential for measuring floodplain ecosystem responses that are of value to ecological and hydrological studies.

One of the substantial ecosystem responses to flooding in arid zones is the subsequent vegetation response. Vegetation responds quickly in

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the form of annual grasses and forbs, and these may be maintained for months by soil moisture availability arising from floodplain infiltration (Capon, 2005; Thoms, 2003). Vegetation growth vigour and biomass respond to a flood pulse firstly by increasing rapidly to a high peak (maturity phase), then its vigour is lost (senescence) and finally reaches dormancy during the inter-flood dry period (Powell et al., 2014). The vegetation cycle can last for months; thus, remote sensing imagery can capture changes in vegetation growth vigour and biomass and it has been used to map inundation extent in arid regions (Fu and Burgher, 2015; Landmann et al., 2010; Parsons and Thoms, 2013; Sims and Colloff, 2012; Thapa et al., 2015; Thomas et al., 2011; Wen and Saintilan, 2015). Vegetation dynamics also influence streamflow transmission losses, the percentage of upstream water that is lost in the floodplain and results in diminishing downstream discharge. These transmission losses exert a significant impact on the ecohydrology of large-scale arid zone floodplains (Costelloe et al., 2003; Knighton and Nanson, 1994a; Morin et al., 2009). Evapotranspiration is one of the dominant processes of transmission loss and evapotranspiration rates can significantly differ between areas covered by vegetation, moist soil and free water (McMahon et al., 2013). Therefore, errors in detection of floodplain response to inundation can produce significant errors in estimating evapotranspiration (Mohammadi et al., 2015; Ronglin et al., 2015; Trambauer et al., 2014) and the accurate quantification of evapotranspiration in flood events requires a thorough analysis of land cover type (e.g. vegetation, moist soil and free water), duration (retention time) and intensity.

Optical sensing has been successfully used in arid regions due to the low proportion of cloudy days, and minimal tree canopies (Capon, 2005; Makkeasorn et al., 2009). Remotely sensed indices which are sensitive to moisture (as open water, moist soil or vegetation water) and vegetation have been effectively used to map flood extents (Boschetti et al., 2014; Deus and Gloaguen, 2013; Tateishi, 2006; Powell et al., 2014; Shilapkar, 2013). These indices have been applied singly or in conjunction in flood mapping of arid regions (Campos et al., 2012; Soti et al., 2009; Thomas et al., 2015) and can discriminate between water in inundated areas, vegetation and dry bare soils. Much of the recent research has concentrated on improving classification accuracy of surface water from mixed pixels containing vegetation and soil (Haas et al., 2009; Kaptué et al., 2013; Li et al., 2015; Ogilvie et al., 2015; Thomas et al., 2015). The indices have also been used in hydrological modelling to estimate evapotranspiration from diverse land covers (Guerschman et al., 2009), to identify inundated paddy rice fields (Sakamoto et al., 2007; Teluguntla et al., 2015) and flood mapping in estuarine wetlands (Jeong et al., 2012) where land cover in the inundated areas is likely mixed.

The choice of optical remote sensing platform for arid zone flood mapping is determined by considerations of scale, revisit frequency and length of record. In very large scale floodplains where inundation travels downstream over periods of weeks, the total cumulative inundation extent during the flooding period is greater than the instantaneous inundation extent on any given day (Knighton and Nanson, 2001, 2002; McMahon et al., 2005). One of the main benefits of flooding in these systems is providing a period of increased vegetation growth vigour and biomass during and after flood recession. The spatial and temporal dynamics of vegetation growth vigour and biomass to flooding is therefore a better indicator of the region of the impact of flood waters on the floodplain ecosystem (Capon, 2005; Sims and Colloff, 2012).

Readily available Landsat imagery with a long record provides sufficient spatial resolution to show complex inundation patterns at the landscape scale but its 16-day frequency and interference of clouds makes acquisition of a detailed time-series of flood images over a single flood event unlikely (Haas et al., 2009). MODIS (Moderate Resolution Imaging Spectroradiometer) images are collected more frequently and can encapsulate the changes in flood extent during a flood event, but their coarse spatial resolution provides a sub-optimal representation of the instantaneous distribution of flooding, especially in flat landscapes with complex channel networks (Aires et al., 2014; Huang et al., 2013; Justice et al., 1998; Ogilvie et al., 2015; Sakamoto et al., 2007). Many surface water mapping products and methods in different temporal and spatial resolutions have been developed for the purpose of flood mapping and detection of water bodies. These include the Global Lake and Wetland Database (GLWD) (Lehner and Döll, 2004), the Moderate Resolution Imaging Spectroradiometer (MODIS) 250 m land–water mask (MOD44W) (Carroll et al., 2009), Global Inundation Extent from Multi-Satellite (GIEMS and GIEMS-D15) (Fluet-Chouinard et al., 2015; Papa et al., 2010), Global 3 arc-second Water Body Map (G3WBM) (Yamazaki et al., 2015) and Water Observation from Space (WOfS) (Mueller et al., 2016). However, the methods for these products focus mainly on the spectral features of water and do not utilize post-flood vegetation indices that can provide additional information of inundation characteristics.

The objective of this research is to improve understanding of spatio-temporal floodplain response dynamics to floods in large-scale arid regions by utilizing pixel-based time-series of remotely sensed water, vegetation and moisture indices that capture the immediate and subsequent response to inundation. We analyse complex inundation patterns of flood events by using normalized difference indices of key dynamic floodplain response states; open water extent, vegetation growth vigour and biomass and surface moisture level, from daily images of MODIS reflectance data in a large arid zone river system (Cooper Creek, Australia) over a 13-year period (2000 − 2012). This approach is not limited to water mapping of inundation area, but it investigates changes in vegetation and moisture responses through the innovative combined analysis of normalized difference indices in characterizing dynamics of multiple floodplain response states induced by flooding. We contend that the proposed approach will assist arid zone ecologists in understanding ecosystem responses to highly variable flood events, and hydrologists to better estimate water balance dynamics.

2. Materials and methods

2.1. Study area

The study reach is on Cooper Creek, the largest catchment of the Lake Eyre Basin and is defined upstream by the confluence of upstream tributaries (Thompson and Barcoo Rivers) and Cullyamurra gauging station as the downstream limit (Fig. 1). The study reach floodplain (area delineated by a purple polygon in Fig. 1) has an area of 22,510 km^2, reaches length of 480 km and occurs over an average floodplain slope of only 1.7×10^{-4} m/m (McMahon et al., 2008b). The width of the floodplain varies between 10 and 60 km and narrows down to a few hundred metres at Cullyamurra Station. It is an example of semi-arid, mud-dominated, anastomosing rivers (Nanson, 2013) and is characterized by extremely complex, anastomosing flow paths over the broad floodplain.

Annual inflow to the study reach is intermittent and highly seasonal occurring mainly in the summer with high inter-annual variability (Knighton and Nanson, 1997). Combined mean annual streamflow from Thompson and Barcoo Rivers is 3150 GL ranging from a <100 GL to the maximum recorded flow of 23,500 GL in the 1974 flood event (McMahon et al., 2008b). Spatial and temporal patterns of rainfall are also highly variable with mean annual rainfall ranging from 300 mm (upstream) to approximately 200 mm (downstream) (McMahon et al., 2008a). Based on gauged upstream and downstream streamflow, transmission losses of 75–80% occur on average through evapotranspiration and infiltration/percolation (Knighton and Nanson, 1994a) but vary non-linearly with the inflow volume. The characteristics of flood events during the study period (2000–2012) are shown in Table 1.

The study reach is covered with a thick (2–7 m) impermeable alluvial mud which prohibits recharging unconfined groundwater under the floodplain and recharge only takes place through the base of waterholes at times of flood scour in the high magnitude flood events (Cendón et