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Assessment of trends in inundation extent in the Barotse Floodplain, upper Zambezi River Basin: A remote sensing-based approach

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ABSTRACT

Study region: The annually flooded Barotse Floodplain in the upper Zambezi River Basin in the Western Province of Zambia, Southern Africa.
Study focus: Discharge variability plays a significant role in inundation extent and thus it controls habitat conditions of river channels and the linked wetlands. The linkage between discharge and inundation extent in the Barotse Floodplain allowed us to analyse the trends in extent overtime using optical satellite imagery MODIS. The Desert Flood Index, a surface water extraction algorithm, was used to generate time series of inundation extent. For validation of the inundation extent we used a flood mask extracted from a supervised classification land cover map using Landsat imagery. The land cover map was validated using the error matrix method with ground truthed data. The estimated inundation extent time series enabled us to test the inundation correlation with discharge and water level using Pearson r correlation, a parametric statistical test. Based on the established correlation we used the Mann–Kendall, a non-parametric test, to analyse trends in the inundation extent and discharge and water level time series from which we made inferences on the direction of the historical trend in inundation extent.
New hydrological insights for the region: The results revealed that there is observable inter-annual variability in inundation extent in the Barotse Floodplain with prominent differences demonstrated in both the flood ascending/peak and receding period. For the period 2003–2013 the results indicated a rising trend in inundation extent with a Mann–Kendall Z statistic of 1.71 and increase in magnitude of 33.1 km^2 at significance level alpha of 0.05. Strong correlations between inundation extent and water level and between inundation extent and discharge with correlation coefficients of determination of 0.86 and 0.89 respectively were observed. For the period 2000–2011 water level time series showed a rising trend with the Mann–Kendall Z statistic of 2.97 and increase in magnitude of 0.1 m at significance level alpha of 0.05. Overall, during the period 1952–2004 discharge in the floodplain showed a declining trend with Mann–Kendall Z statistics of −2.88 and −3.38 at the inlet and outlet of the floodplain respectively. By correlation inference, the overall inundation extent trend in the floodplain was in a downward movement. Rainfall and discharge variability, high evapotranspiration and the changes in the land cover-use in the catchment of the floodplain are largely the factors affecting the observed variability and trends in inundation extent in the floodplain. The presented remote sensing based approach significantly reduces the need for the expensive and time limiting traditional physical field based

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wetland inundation mapping methods that form a limitation for achieving progress in wetland monitoring especially in open and sparsely gauged floodplains such as the Barotse.

1. Introduction

Ecosystem functions and associated services in wetlands are determined by inundation dynamics (DeGroot et al., 2006). Thus, implications of wetland inundation on water, wetland policies and management are immense. Changes in temporal and spatial dynamics of wetland inundation may be an important indicator of the modifications in the functioning of wetland ecosystem (Erwin, 2009; Clare and Creed, 2014; Kingsford et al., 2016). There is a recognition of the significance of wetlands at regional level as it concerns nutrient export to surface waters, greenhouse gas emissions and biodiversity (Foster et al., 2012). Therefore, monitoring of wetlands has taken on a heightened relevance (Erwin, 2009). However, the complexities in assessing the spatial and temporal regimes make it extremely challenging to make the necessary observations for deepened understanding of the inundation dynamics and the potential implications on wetland ecosystems of the various flow components (Stisen et al., 2008; Erwin, 2009). In the Zambezi Basin, this challenge is compounded by inadequate and dilapidated hydro-meteorological stations (Cohen et al., 2014) including time and financial resource limitations associated with traditional field survey wetland mapping methods. In many cases, this problem is so severe that even the application of conventional prediction tools is severely limited in this part of Africa (Cohen et al., 2014).

The application of satellite based remote sensing techniques in inundation extent assessments provides an important and expanded avenue for data collection on the dynamic state of inundation, especially for vast wetlands where ground based methods are virtually impractical (Schumann et al., 2007; Ticehurst et al., 2014). With the advantage of area coverage (spatial resolution), regular revisit time (temporal resolution) and acquisition of data in a wide range of the electromagnetic spectrum (spectral resolution), the remote sensing approach is best suited for study of inundation dynamics as compared to conventional mapping methods (Ticehurst et al., 2013; Ticehurst et al., 2014). A host of satellite sensors are currently generating enormous amounts of data at various resolutions that form the core for both historical and continued monitoring of inundation regimes and other landforms. Among the vast spectrum of uses, earth observation based data has increasingly become an important source of information for water use planning, monitoring and management at various levels of management such as field, catchment and regional scale (Mu et al., 2007).

Though some studies related to floodplain inundation mapping using satellite imagery have previously been conducted in Zambia (e.g Tiger Initiative, 2008; Aduah and Mantey, 2012, Meire, 2012; Cai et al., 2015), only one publication (Cai et al., 2015) in public domain was done in the Barotse Floodplain. However, the Landsat imagery used by Cai et al. (2015) imposed a limitation on the number of time series they could generate and compare which affected their analysis of the variations in inundation extent. Furthermore, none of the studies attempted to statistically analyse trends in floodplain inundation extent and the correlation with flow and water level. The need to further understand the within season and inter-annual variations in inundation and how it relates to discharge/water-level motivated this study to use a different and simple satellite remote sensing and statistical analysis approach to add to the existing knowledge on the inundation dynamics in the Barotse Floodplain.

For inundation extent mapping the Moderate-resolution Imaging Spectrometer (MODIS) data presents a better option for large wetland inundation mapping (Ticehurst et al., 2013; Ticehurst et al., 2014). Despite the inherent limitation of cloud cover MODIS is seen as a better option because all historical data from 2000 to the present are readily available for free, it has near-global spatial coverage (250 m–1 km), a better temporal scale (1–2 times/day) and can easily be processed with most available satellite imagery data processing computer software (Ticehurst et al., 2013; Ticehurst et al., 2014). For mapping of open water features with optical satellite imagery the use of indices is the most common practice (Baig et al., 2013; Ticehurst et al., 2014). Various spectral based water features extraction indices have been developed and include the Normalised Difference Vegetation Index (NDVI) (Rouse et al., 1973), Normalised Difference Water Index (NDWI) (McFeeters, 1996), Modified Normalised Difference Water Index (MNDWI) (Xu, 2006), Automated Water Extraction Index (AWEI) (Feyisa et al., 2014), and the Desert Flood Index (DFI) developed by Baig et al. (2013). The NDWI developed by McFeeters (1996) and the MNDWI by Xu (2006) are the most utilised water feature extraction indices (Baig et al., 2013). However, Baig et al. (2013) discovered that under all the experimental conditions they subjected the DFI and MNDWI, the DFI performed better. The performance assessment of the two indices was carried out on MODIS and Landsat images in a flooding season of the Indus River in Pakistan. The DFI focuses on more precision in the calculation of water proportion at sub pixel level and the increasing of the contrast between water and non-water features. The other multi-band based indices such as the NDWI and the MNDWI are focused on differentiating the water body from the non-water-body information by using pixel scales instead of the proportion of the water area, which critically affects precision in water information extraction (Wang, 2007; Baig et al., 2013). Based on the nature of the study area and the focus of our study, MODIS imagery and the DFI were seen as better options and that the MODIS imagery were readily available.

Furthermore, the statistical approach sought to augment our understanding of the interaction between inundation, discharge and water level. However, climate and hydrological data such as discharge and water level are known to be non-normal hence statistical characterisation is normally done using non-parametric statistical tests (Hirsch and Helsel, 2002). To detect change point(s) and trends in hydrological data the Pettit and the Mann–Kendall are commonly used non-parametric tests (Hirsch and Helsel, 2002). The Pettit (1979) Homogeneity test approach is a common non-parametric application in change point detection studies involving hydrological or climate series (Pohlert, 2014; Hirsch and Helsel, 2002). The Mann–Kendall Test possesses advantage over other tests because it does not need the data to be normally distributed and has low sensitivity to abrupt changes due to inhomogeneity in time