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Reconstructing semi-arid wetland surface water dynamics through spectral mixture analysis of a time series of Landsat satellite images (1984–2011)

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ABSTRACT

Wetlands are valuable ecosystems for maintaining biodiversity, but are vulnerable to climate change and land conversion. Despite their importance, wetland hydrology is poorly understood as few tools exist to monitor their hydrologic regime at a landscape scale. This is especially true when monitoring hydrologic change at scales below 30 m, the resolution of one Landsat pixel. To address this, we used spectral mixture analysis (SMA) of a time series of Landsat satellite imagery to reconstruct surface-water hydrographs for 750 wetlands in Douglas County, Washington State, USA, from 1984 to 2011. SMA estimates the fractional abundance of spectra representing physically meaningful materials, known as spectral endmembers, which comprise a mixed pixel, thus providing sub-pixel estimates of surface water extent. Endmembers for water and sage steppe were selected directly from each image scene in the Landsat time series, whereas endmembers for salt and wetland vegetation were derived from a mean spectral signature of selected dates spanning the 1984–2011 timeframe. This method worked well ($R^2 = 0.99$) for even small wetlands ($<1800\ m^2$) providing a wall-to-wall dataset of reconstructed surface-water hydrographs for wetlands across our study area. We have validated this method only in semi-arid regions. Further research is necessary to extend its validity to other environments. This method can be used to better understand the role of hydrology in wetland ecosystems and as a monitoring tool to identify wetlands undergoing abnormal change.

1. Introduction

Wetlands are among the most biodiverse ecosystems in the world, due largely to their dynamic hydrology (Mitsch & Gosselink, 2007). The hydroperiod, which we define as the pattern of flooding and drying within a wetland, is the most important determinant in the establishment and maintenance of specific wetland habitat types and the species that they support (Babbitt, 2005; Correa-Araneda, Urrutia, Soto-Mora, Figueroa, & Hauenstein, 2012; Mitsch & Gosselink, 2007; Tavernini, Mura, & Rossetti, 2005). Despite the importance of the wetland hydroperiod, it is not well understood (Mitsch & Gosselink, 2007), in part because it is time-consuming and expensive to monitor changes in wetland hydrology using field measurements. Landscape-level hydroperiod data are scarce because tracking changes in wetland water levels over weeks and months requires the installation of expensive monitoring equipment or visiting sites many times a year for several years (Ryan, Palen, Adams, & Rochefort, 2014). However, without broad-scale long-term hydroperiod data it is not possible to adequately monitor changes in the hydrologic regime of wetlands to understand general patterns across different wetland types and to distinguish the difference between natural and abnormal changes to wetland hydrology. Furthermore, without adequate baseline data of the wetland hydroperiod, it is not possible to understand how changes in temperature and precipitation will impact the hydrology, structure and function of wetlands under climate change (Arnell et al., 2001; Poiani, Johnson, Swanson, & Winter, 1996; Ryan et al., 2014; Werner, Johnson, & Guntenspergen, 2013).

1.1. Wetland definition

We define wetlands using the United States Army Corps of Engineer's definition of wetlands as “those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions.” (Environmental Laboratory, 1987) Shallow lakes and lake fringes meet the above definition within our study area, and therefore, this analysis includes both large and small waterbodies.

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1.2. Remote sensing of wetland surface water dynamics

Remote sensing has provided a useful means to study the changes in wetlands through spatially explicit, cost- and time-effective data (Ozesmi & Bauer, 2002). However, mapping the hydroperiod of wetlands offers several challenges to remote-sensing analysts. The core challenge is the trade-off between temporal and spatial resolution of remotely sensed imagery. Currently, no one sensor has both the temporal and spatial resolution to detect the fine-scale patterns of wetland change over time, particularly for small wetlands (Gallant, 2015; Tiner, 2009; Wulder, Hall, Coops, Steven, & Franklin, 2014).

Landsat imagery with moderate spatial and temporal resolution has widely been used for surface water mapping through hard classification methods (sensu Foody, 2000), which classify pixels as either water or non-water. Commonly used classification methods include thematic classification, multi-band indices (e.g. normalized difference water index, NDWI (McFeeters, 1996)), single band thresholding, and spectral mixture analysis (Ozesmi & Bauer, 2002). These methods have been successfully applied to map surface water changes of large lakes and wetlands (Adams & Sada, 2014; Bryant & Rainey, 2002; Castaneda & Herrero, 2005; Hui, Xu, Huang, Yu, & Gong, 2008; Liu et al., 2013; Sener, Davraz, & Sener, 2010). However, wetlands that express changes in surface water extent at fine scales (below 30 m – the resolution of 1 Landsat pixel) and small wetlands, which we define as wetlands smaller than 5 ha, have received considerably less attention (Ryan et al., 2014). This is an issue because in many regions of the world the majority of the landscape is composed of small wetlands (Downing et al., 2014; Gilmer, Work, Colwell, & Rebel, 1980; Halabisky, Moskal, & Hall, 2011).

For high resolution mapping of wetlands analysts typically use high-resolution aerial imagery (<1 m), but repeat coverage is lacking (Tiner, 1990). This has limited high-resolution remote sensing of wetlands to detecting change between a few dates (Adams & Sada, 2014; Dyke & Wasson, 2005; Hui et al., 2008; Liu et al., 2013; Murkin, Murkin & Ball, 1997; Niemuth, Estey, Reynolds, Loesch & Meeks, 2006). Although useful, change detection of wetlands under these limitations does not provide enough detail for understanding patterns and dynamics of annual and inter-annual wetland response, much less to determine if measured changes in the surface water extent represent natural year-to-year variability, or abnormal changes in wetland hydrology. Even several dates of aerial imagery cannot provide enough information to determine the hydrologic regime of a particular wetland necessary for monitoring or future climate modeling.

In order to address this limitation several researchers have used one or more soft classification techniques such as multi-band indices and single band tracking to predict sub-pixel surface water estimates of Landsat imagery (Beeri & Phillips, 2007; Frohn et al., 2012; Gómez-Rodríguez, Bustamante, & Díaz-Paniagua, 2010; Huang, Peng, Lang, Yeo, & McCarty, 2014; Huang, Dahal, Young, Chander, & Liu, 2011; Reschke & Hüttich, 2014; Rover, Wylie, & Ji, 2010b). Soft classification methods do not assign a pixel to one class, but instead provide an estimate of class membership and can be used to measure the sub-pixel surface water area through regression modeling and classification and regression trees (Foody, 2000). However, these methods require a large amount of training data from field data or higher resolution imagery from the same time period and are not directly transferable to other study areas (but see Rover, Wylie, & Ji, 2010a).

Spectral mixture analysis (SMA) is a physically based technique which can be used to estimate the percent cover of surface water without the need for extensive training data. SMA estimates the fractional abundance of spectra representing physically meaningful materials, known as spectral endmembers, which comprise a mixed pixel, thus providing sub-pixel estimates of surface water extent (Adams, Smith, & Johnson, 1986; Adams & Gillespie, 2006). While SMA provides sub-pixel fractions of surface materials, it is commonly used to drive a classification by converting mixed pixels into water or non-water through selection of a threshold value (Shanmugam, Ahn, & Sanjeevi, 2006). Frohn et al. (2012) used SMA to identify wetlands at sub-pixels scales, but did not use it to estimate the percent cover of surface water or track changes to surface water through time.

While sub-pixel methods can identify the percent cover of surface water they do not provide the location of surface water within a pixel, which makes tracking change over time challenging. To remedy this issue, researchers have either tracked changes of individual pixels (Beeri & Phillips, 2007; Collins et al., 2014; Gómez-Rodríguez et al., 2010; Reschke & Hüttich, 2014) or summarized changes for all pixels within an entire landscape (Beeri & Phillips, 2007; Huang et al., 2014; Huang et al., 2011). Table 1 summarizes the key papers that meet one or more of the criteria necessary for high resolution mapping of wetland surface water dynamics.

What is almost entirely missing from the methods summarized in Table 1 is the ability to track changes to individual wetlands and the temporal detail to monitor both seasonal and long-term changes in wetland hydrology. Only one study that achieved this was Gómez-Rodríguez et al. (2010) in which the authors measured changes in the flooding duration of wetlands by examining how pixel reflectance of the near infrared band changed through time for over 800 temporary ponds spanning a 23-year time period in the Doñana National Park, Spain. Because the authors co-registered images to correct for small pixel misalignments between image scenes they could track changes of surface water extent for pixels within an individual wetland showing a significant trend of hydroperiod shortening likely due to groundwater depletion from agricultural irrigation. However, a challenge with tracking single pixels through time is the labor-intensive and imperfect process of pixel-to-pixel registration and atmospheric correction for multi-date analysis (Dai, 1998; Song, Woodcock, Seto, Lenney, & Macomber, 2001; Wyawahare, Patil, & Abhyankar, 2009). For some projects, it is not feasible to perform these pre-processing steps on hundreds of images.

We sought to develop a method that mapped surface water dynamics at temporal and spatial scales similar to Gómez-Rodríguez et al. (2010), but with minimal pre-processing. Additionally, we aimed to use this data to reconstruct individual wetland surface water hydrographs, which chart the pattern of flooding within a wetland over time. Here we use the term hydrograph to refer to temporal changes in surface-water extent (area) within a wetland, rather than temporal changes in water depth. This is due to the difficulty of determining water depth from a pixel composed of multiple surface materials.

The goal of this project was to develop a semi-automated tool to map and monitor wetland dynamics for individual wetlands while still covering a broad landscape. Specific objectives of this research were to:

1.) Develop a method with minimal pre-processing to estimate surface-water extent for wetlands at scales below 30 m.
2.) Reconstruct individual wetland hydrographs from 1984 to 2011.
3.) Determine if hydrographs could be used to classify wetland types and monitor wetland change over time.

2. Study area

We chose Douglas County, Washington (WA), located in the Columbia Plateau ecoregion in the Northwest of the United States as our study area (Fig. 1) as wetlands are abundant and representative of semi-arid ecosystems common to Western North America. Douglas County is 4714 km^2 in size with non-irrigated farming and ranching being the dominant land uses. It is a semi-arid sage steppe ecosystem, receiving an average of 29 cm of precipitation a year. Douglas County is bordered by the Columbia River with a low elevation of 180 m near the river and rising to an elevation of 1220 m at the top of the plateau. In general, the surface topography of the plateau is subtle and free from shadows resolved at the 30-m Landsat scale. Isolated, depressional wetlands are the dominant wetland type. Wetlands are typically shallow and do not