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Monitoring of wetland inundation dynamics in the Delmarva Peninsula using Landsat time-series imagery from 1985 to 2011

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ABSTRACT

Wetlands provide important ecosystem services, the provision of which is largely controlled by fluctuations in inundation and soil saturation. Inundation is highly dynamic and can vary substantially through time in response to multiple drivers, including precipitation and evapotranspiration. This research focused on developing a practical and effective framework for regional, long-term monitoring of wetland inundation dynamics using airborne LiDAR intensity data (Lang et al., 2013) and Landsat time-series imagery. Subpixel water fraction (SWF) maps indicating the percent of surface water within each 30-m pixel were generated on an annual basis over the entire Delmarva Peninsula on the East Coast of the United States from 1985 to 2011. Comprehensive accuracy assessments of the SWF maps were conducted using historical high-resolution aerial photography to determine the reference condition. The assessment resulted in an estimated root mean square error (RMSE) of 7.78% for the sample of open water areas (mean SWF was ~40% for this region of the map). Moreover, a separate accuracy assessment targeting inundation in wetlands (i.e. presence or absence of water) yielded an overall accuracy of 93%. Accuracies derived indicated that Landsat data can be calibrated to accurately extract long-term water information at the regional scale. Characteristics of inundation were examined with respect to different wetland types defined by water regime and dominant vegetation types, as well as different physical drivers. Results showed that tidal wetlands typically exhibited more intensive inundation than nontidal wetlands, and a higher degree of inundation was associated with emergent wetlands compared to wetland areas dominated by woody vegetation. Analysis of change drivers revealed that tide exerted a statistically significant influence on coastal inundation with r^2 values of 32–36% and $p < 0.01$, whereas inundation changes in inland wetland areas were in part driven by precipitation with r^2 values of 25–34% and $p < 0.08$. Because an up-to-date archive of Landsat imagery is globally available and LiDAR data are becoming increasingly more affordable, the developed framework can be easily implemented to generate a continuous inundation record in many regions of the globe to assist in ongoing and future studies focused on wetland hydrology and wetland management.

1. Introduction

Wetlands are unique ecosystems where terrestrial and aquatic habitats intermix (Mitsch and Gosselink, 2007). The wet to dry transition along wetland ecotones supports a diverse biological community that is often not present elsewhere in the landscape (Carter et al., 1994; Chapman et al., 1996). Wetlands are tremendously productive, providing a variety of ecosystem services, such as water purification, flood regulation, erosion control, coastline protection, and sediment and nutrient transport (Gosselink and Turner, 1978; Keddy, 2000; de Groot et al., 2006). With the importance of wetlands as a natural resource being increasingly recognized, reliable information on wetland condition and functioning is required to help promote effective management decisions that will improve the resilience and sustainability of human-environment systems.

A key factor controlling the functioning of a wetland area is its inundation extent (Nestler and Long, 1997). Inundated areas can change rapidly in response to tide, precipitation, snow melt, human alteration, and other factors (Millar, 1971; Johnson et al., 2005). Recent studies show that inundated areas play critical roles in many Earth system processes, including land-atmosphere energy balance (Krinner, 2003), carbon and nitrogen cycling (Shindell et al., 2005; Fox et al., 2014), and surface- and groundwater interchange (Winter, 1999; Becker, 2006).

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Despite their broad impact, wetlands are among the least well characterized in current land cover products (e.g. Wickham et al., 2010, 2013). Long-term, routine monitoring of inundation dynamics is needed to improve understanding of the health and functioning of wetland ecosystems.

Remotely sensed data can provide a spatially continuous and highly consistent map-like representation of the Earth's surface (Foody, 2002), and therefore, it has been recognized as an important data source for monitoring wetland inundation dynamics (Huang et al., 2014). Satellite imagery in particular has the potential to capture large-scale, up-to-date wetland information in a repetitive manner, making it possible to obtain temporal trends at regional to global scales. Optical images from a variety of satellite sensors have been applied extensively to study wetlands (Lang et al., 2015), including Landsat MSS/TM/ETM + (e.g. Jensen et al., 1986; Lunetta and Balogh, 1999; Huang et al., 2011; Tulbure et al., 2016), SPOT (e.g. Davranche et al., 2010), and AVHRR (e.g. Ramsey et al., 1997). The utility of Synthetic Aperture Radar (SAR) imagery has also been explored in many wetland studies (e.g. Townsend, 2001; Kasischke et al., 2003; Lang et al., 2008), taking advantage of its day-and-night, all-weather observation capability and its sensitivity to soil moisture (Fung, 1994; Ulaby et al., 1986). Recently, there has been increasing interest in the use of airborne Light Detection and Ranging (LiDAR) intensity data to detect inundation beneath the forest canopy (e.g. Lang and McCarty, 2009). Despite the demonstrated use of LiDAR intensity data to produce highly accurate inundation maps, LiDAR inundation monitoring over large areas or at fine temporal scales is greatly constrained by limited data availability.

Much effort has been devoted to generating regional or global scale inundation maps at coarse to moderate spatial resolutions, ranging from 1° longitude by 0.5° latitude (e.g. Brakenridge et al., 2013), 25 km (e.g. Prigent et al., 2007; Papa et al., 2010), 1 km (e.g. Friedl et al., 2010), to 250 m (e.g. Carroll et al., 2009). Because the majority of individual inundated areas are smaller than 0.01 km^2 (Downing et al., 2006; Verpoorter et al., 2014), these maps cannot provide the spatial details necessary to fully characterize inundation status. Some recent studies used Landsat imagery to map water bodies at a finer spatial resolution (e.g. Liao et al., 2014; Verpoorter et al., 2014; Carroll et al., 2016; Feng et al., 2016). However, these studies were mainly focused on open water areas such as lakes and rivers, and little emphasis has been placed on woody wetlands (swamps) with intermittent inundation. Moreover, most inundation maps at the 30-m pixel scale lack subpixel information, and therefore, may be of limited use over wetlands and other shallow and periodically inundated areas where partial inundation is common. An additional concern associated with nearly all existing Landsat-derived regional to global inundation products is their extremely limited temporal resolution, as they were created only once (e.g. Verpoorter et al., 2014; Feng et al., 2016) or every ten years (e.g. Liao et al., 2014; Carroll et al., 2016), which makes the monitoring of inundation dynamics unrealistic even on an annual basis.

The value of a map constructed from remotely sensed data is largely a function of its quality (Foody, 2002). Compared to the validation of other land cover products, assessing the accuracy of inundation maps is a more challenging task due to the highly dynamic nature of inundation extent in most wetland areas. Because of the dynamics, it is best to collect reference data at or close to the time of image acquisition. For example, Hess et al. (2003) primarily used digital videography acquired simultaneously with SAR mosaic scenes for locating validation sites to assess map accuracy of wetland inundation and vegetation over the central Amazon basin. Nonetheless, little investigation has focused on accuracy assessment of long-term inundation products created at the regional scale. Neither has the use of archived historical high-resolution data to extract reference information on wetland inundation been intensively explored.

The diversity among different wetland types is significant from the perspective of land surface process modeling (Lafleur, 1990). Wetlands represented as a single category can introduce considerable uncertainty into climate models (Comer et al., 2000), as their carbon storage capacity varies with soil and vegetation type and coverage. Differences in energy exchange among wetland types can be greater than differences between wetland and non-wetland surfaces (Desjardins et al., 1994; Roulet et al., 1997). Because inundation is crucial to wetland functioning including carbon storage, understanding how it varies among major wetland types is necessary to support management and policy decisions.

Dramatic changes have occurred in the inundated area of many of the world's aquatic ecosystems during the past several decades. These changes are driven by a wide range of biophysical, socioeconomic and political factors (Millennium Ecosystem Assessment, 2005). However, most existing studies on the assessment of inundation dynamics were performed over relatively easy to map and less dynamic aquatic ecosystems (e.g. lakes), and irrespective of wetland type or the characteristics of the study site. Because the role of a specific factor may differ substantially by the location and type of wetland, it is important to investigate possible drivers of local inundation change with respect to different wetland types.

The main objective of this study was to develop a practical and effective framework for regional, long-term monitoring of wetland inundation dynamics. The study was conducted over the Delmarva Peninsula, which is adjacent to the Chesapeake Bay along the East Coast of the United States. This region is recognized for its rich network of wetlands, and the important ecosystem services that they provide. The approach proposed by Huang et al. (2014) to map localized inundation in forested wetland areas using LiDAR intensity and Landsat data was refined and adapted for use over a long time period and a much larger area with a rich array of wetland types. Landsat time-series images were acquired over the entire study area during the leaf-off season in early spring from 1985 to 2011. The refined approach was applied to these data to generate a set of temporally consecutive maps of subpixel water fraction (SWF), indicating the percent of surface water within every 30-m Landsat pixel at each time step. A comprehensive accuracy assessment evaluated the quality of the SWF maps. A key focus of this research was the examination of wetland inundation patterns and long-term dynamics with respect to different wetland types as well as the factors that may cause inundation changes. The large area and long temporal period investigated allows for better understanding of wetland dynamics than can be accomplished by examining only a small wetland area for a short period of time.

2. Study area

The study area is the Delmarva Peninsula on the East Coast of the United States, occupied by most of the State of Delaware and portions of Maryland and Virginia (Fig. 1). The area of the peninsula is 14,230 km^2. The peninsula is bounded by the Chesapeake Bay to the west, Delaware Bay and the Atlantic Ocean to the east, and the Elk River and its isthmus to the north. This area is distinguished by flat topography with a maximum elevation of 31 m above sea level. Temperature ranges from an average of about 2 °C in January and February to 25 °C in July and August (Shedlock et al., 1999). Rain and snow are two major forms of precipitation on the peninsula. Average precipitation is about 112 cm per year (Hamilton et al., 1993). Approximately 50% of annual precipitation is lost to the atmosphere due to evapotranspiration. The remaining precipitation recharges groundwater or enters streams via surface flow (Ator et al., 2005). According to National Land Cover Database (NLCD) 2011 (Homer et al., 2015), land cover of this area is dominated by agriculture (~42%), followed by wetlands (~31%) and forest (~11%). Agriculture plays an important role in the Delmarva's economy. Most of the area is rural, except for a few large population centers such as Dover, Delaware and Salisbury, Maryland.

Fig. 2 illustrates the spatial distribution of different wetland types depicted by the U.S. Fish and Wildlife Service (FWS) National Wetlands Inventory (NWI, see more details in Section 3.4). A large area of tidal wetlands has formed close to the estuaries that line the coast of the