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Integration of Palmer Drought Severity Index and remote sensing data to simulate wetland water surface from 1910 to 2009 in Cottonwood Lake area, North Dakota

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ABSTRACT

Spatiotemporal variations of wetland water in the Prairie Pothole Region are controlled by many factors; two of them are temperature and precipitation that form the basis of the Palmer Drought Severity Index (PDSI). Taking the 196 km^2 Cottonwood Lake area in North Dakota as our pilot study site, we integrated PDSI, Landsat images, and aerial photography records to simulate monthly water surface. First, we developed a new Wetland Water Area Index (WWAI) from PDSI to predict water surface area. Second, we developed a water allocation model to simulate the spatial distribution of water bodies at a resolution of 30 m. Third, we used an additional procedure to model the small wetlands (less than 0.8 ha) that could not be detected by Landsat. Our results showed that i) WWAI was highly correlated with water area with an R^2 of 0.90, resulting in a simple regression prediction of monthly water area to capture the intra- and inter-annual water change from 1910 to 2009; ii) the spatial distribution of water bodies modeled from our approach agreed well with the water locations visually identified from the aerial photography records; and iii) the R^2 between our modeled water bodies (including both large and small wetlands) and those from aerial photography records could be up to 0.83 with a mean average error of 0.64 km^2 within the study area where the modeled wetland water areas ranged from about 2 to 14 km^2. These results indicate that our approach holds great potential to simulate major changes in wetland water surface for ecosystem service; however, our products could capture neither the short-term water change caused by intensive rainstorm events nor the wetland change caused by human activities.

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1. Introduction

1.1. Prairie Pothole Region and the wetlands

The Prairie Pothole Region (PPR) of North America extends from north-central Iowa to central Alberta and covers an area of 715,000 km^2 (Fig. 1), where there are millions of topographic depressional wetlands created by the last glacial retreat approximately 12,000 years ago (Fenneman, 1931). These wetlands are relatively small, lie within small isolated depressions, are generally underlain by glacial till of low permeability, and are embedded in a landscape matrix of natural grassland and agriculture (Winter & Rosenberry, 1995). These wetlands vary from shallow and temporary to deep and permanent, depending on topography and the water balance (Fang & Pomeroy, 2008; van der Kamp & Hayashi, 2009). Most wetlands are shallow with depths generally less than 1 m and are small with an estimated median of 0.16 ha, 70% are 0.4 ha or smaller, and 83% are 0.8 ha or smaller (Sethre et al., 2005; Zhang et al., 2009). Wetlands in the PPR can contain water over time varying from days to years, but temporary and seasonal wetlands maintain surface water less than three months (Stewart & Kantrud, 1971). The natural landscape of the PPR has been substantially filled, leveled, drained, and converted to agriculture since European settlement in the late 1800s, resulting in the loss of over half of the original 8 million ha of wetlands (Dahl & Johnson, 1991; Euliss & Mushet, 1996).

Spatiotemporal climate variation and the corresponding drought/deluge cycle are common in the PPR and they affect the dynamics of PPR wetlands. The PPR is characterized by a dynamic continental climate and is well-known for its extreme and variable climate with high annual and regional variation in precipitation (Bragg, 1995; Woodhouse & Overpeck, 1998). Variations in temperature and moisture content of competing air masses lead to great seasonal and annual differences in precipitation and evaporation rates, and strong north–south temperature and east–west precipitation gradients produce distinct regional climates. Climatic fluctuations drive hydrology, with atmospheric deposition, evaporation, and transpiration being the major components of the water balance of the wetlands and

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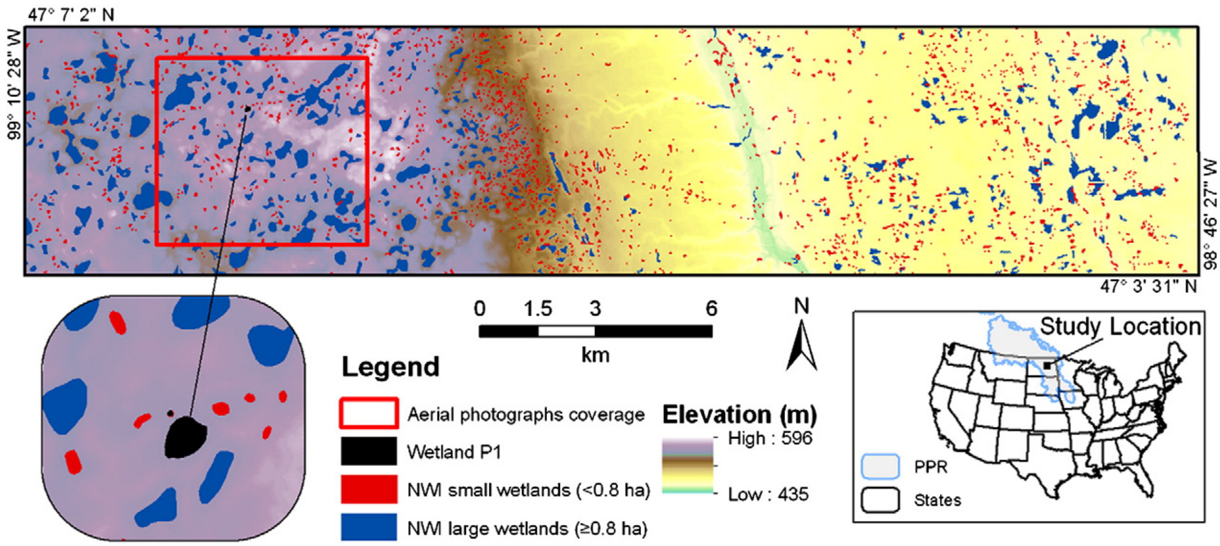

Fig. 1. The study area (LiDAR digital elevation as background) is located in the Prairie Pothole Region (PPR). Aerial photographs were collected and processed for an area marked by the red rectangle.

accounting for more than 60% of the variation in the number of wet basins (LaBaugh et al., 1998; Larson, 1995). Long-term cycles between periods of drought (Woodhouse & Overpeck, 1998) and deluge (Winter & Rosenberry, 1998) can persist for several years or even decades and determine the return time of the hydrological cycle (Diaz, 1983, 1986; Duvick & Blasing, 1981; Johnson et al., 2005; Karl & Koscielny, 1982; Karl & Riebsame, 1984). Prairie wetlands are often dry during drought and fill to depths beyond the tolerance limits of most emergent vegetation during deluge (Winter & Rosenberry, 1998).

Under a variable climate, water level fluctuation of the PPR wetlands is comprehensively determined by snowmelt, storm runoff, direct precipitation, evapotranspiration, seepage inflow, and outflow (Johnson et al., 2005; Millar, 1971). In spring, these basins receive extensive and rapidly melting water contributions from the in situ melt of accumulated snow, as well as an overland flow from precipitation upon the surrounding saturated uplands. During summer, the water balance of prairie wetlands is controlled by direct precipitation, lake evaporation, and wetland vegetation transpiration (Carroll et al., 2005; LaBaugh et al., 1998; Parkhurst et al., 1998; Winter & Rosenberry, 1995), with evapotranspiration representing the single largest loss of water from most prairie wetlands (Rosenberry et al., 2004). When snowmelt or a rainstorm is significant, many usually-isolated (in terms of surface-water) wetlands may connect to one another through the “fill and spill” mechanism (van der Kamp & Hayashi, 2009; Winter & LaBaugh, 2003). Deep groundwater flow in low conductivity till is very slow and has negligible effects on water balance for the PPR wetlands (van der Kamp & Hayashi, 2009). Shallow ground water through shoreline seepage loss, however, accounts for a considerable portion of the water loss for small wetlands (Eisenlohr, 1966; Millar, 1971; van der Kamp & Hayashi, 2009).

Along with water level fluctuation, inter- and intra-annual water surface change is a key factor in regulating many ecosystem services, including flood abatement, water quality improvement, biodiversity enhancement, carbon management, and aquifer recharge (Gleason et al., 2008). For wildlife conservation, the PPR is renowned for harboring large proportions of North American continental waterfowl populations (e.g., Batt et al., 1989). For floodwater mitigation, the antecedent water volume that already occupies the wetlands immediately prior to a flood event must be considered, which requires the continuous monitoring of wetland water dynamics (Gleason & Tangen, 2008; Huang et al., 2011). For the emissions of major greenhouse gases (i.e., carbon dioxide, methane, and nitrous oxide) from wetland ecosystems, the soil water-filled pore space is the major factor for determining the anaerobic and aerobic condition (Gleason et al., 2009).

1.2. Monitoring program issues and research objectives

Due to the importance of the wetland water surface area in so many fields, the water dynamics of the PPR wetlands have been studied by many researchers. One approach measures water levels in wetlands and their surrounding catchments. This approach enables us to better understand the hydrological process and mechanism of water level fluctuations of individual wetlands, but it limits the number of wetlands that can be assessed; this reduces our ability to characterize wetland dynamics over broad spatial extents and under a variety of conditions (Niemuth et al., 2010; Rosenberry et al., 2004).

The second approach is to use satellite images, especially from Landsat, to map lake areas. Landsat time series allow for wetland change detection with different image processing methods such as density slice, maximum likelihood, and sub-pixel unmixing (Frazier & Page, 2000; Ozesmi & Bauer, 2002; Sethre et al., 2005; Work et al., 1974). For example, Beeri and Phillips (2007) used Landsat images from 1997 to 2005 to develop a model for detecting the seasonal advance and retreat of surface waters. However, several limitations exist when using Landsat data to create a Landsat-based monitoring program. First, Landsat images have a spatial resolution of 30–60 m, making it difficult to detect wetlands smaller than 0.4–0.8 ha (Ozesmi & Bauer, 2002; Sethre et al., 2005; Work et al., 1974). Second, satellite records are only available since the 1970s, making interpretation of earlier history difficult. Third, satellite images are most desired in spring when prairie ponds generally reach their maximum water surface soon after snowmelt; however, during this same period cloud cover tends to be frequent, reducing the probability of a cloud-free day during the satellite overpass (Sethre et al., 2005). Short observational records, limited resolution, and a need for cloud-free images are three limitations of satellite observations (Liu & Schwartz, 2011). Satellite-based monitoring approaches, like those of Zhang et al. (2009), could not quantitatively describe water transfers; therefore, the need for more quantitative approaches was emphasized by Liu and Schwartz (2011).

The third approach is to use aerial photographs to provide historical data on the occurrence of pothole lakes. With aerial photography at a scale of 1:24,000–1:25,000 from 1979 to 1994, the National Wetlands Inventory (NWI) datasets were created. The NWI datasets include wetland boundaries along with wetland regimes, but