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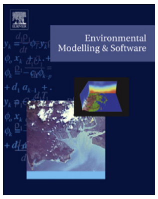

Seasonally-managed wetland footprint delineation using Landsat ETM+ satellite imagery

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ABSTRACT

One major challenge in water resource management is the estimation of evapotranspiration losses from seasonally managed wetlands. Quantifying these losses is complicated by the dynamic nature of the wetlands' areal footprint during the periods of flood-up and drawdown. We present a data-lean solution to this problem using an example application in the San Joaquin Basin, California. Through analysis of high-resolution Landsat Enhanced Thematic Mapper Plus (ETM+) satellite imagery, we develop a metric to better capture the extent of total flooded wetland area. The procedure is validated using year-long, continuously-logged field datasets for two wetlands within the study area. The proposed classification which uses a Landsat ETM + Band 5 (mid-IR wavelength) to Band 2 (visible green wavelength) ratio improves estimates by 30–50% relative to previous wetland delineation studies. Requiring modest ancillary data, the study results provide a practical and efficient option for wetland management in data-sparse regions or un-gauged watersheds.

1. Introduction

Seasonally managed wetlands are man-made impoundments that undergo a complex hydrologic cycle of inundation and drainage designed to mimic natural ecohydrologic function. In seasonally managed wetlands, changes associated with standing water inundation and vegetation response also play a role in energy cycling, by influencing solar radiation partitioning into latent heat by plant transpiration and thermal energy storage in the water column. Prevailing climate and temperature conditions determine the timing of the annual progression of wetland flooding, holding, and draw down. The areal extent of the wetland during this cycle is known as the "wetland footprint." At any point in time, direct evaporation, transpiration, and seepage (soil infiltration) losses from the wetlands are a function of their footprint.

During flood-up, the footprint gradually expands as water is diverted into each impoundment until the pond is filled to an elevation set by weir boards at the pond outlet. As the pond begins to fill, the clay-rich soils which had become desiccated during the dewatering period provide a dense network of preferential flow paths. This results in significant losses to soil infiltration. As wetland sediments become fully saturated, the clay soils swell and "seal". In response to increased soil water availability, plant community composition shifts; macrophytes begin to displace terrestrial grasses; emergent wetland vegetation grows to pond shooting depth, and transpiration increases. Similarly, during wetland drawdown, pond sediments become exposed to the atmosphere as water elevation recedes until there is no further outflow from the pond. Infiltration, direct water and soil evaporation, and plant transpiration rates undergo another shift.

The temporal and spatial dynamics of these losses are resource-intensive to measure in the field and difficult to accurately quantify through indirect methods. Yet despite the challenge, these dynamics are crucial for informed, science-based wetland management – both from a water resource allocation and an ecosystem function perspective. This paper examines the potential for satellite imagery and image processing thermal algorithms to provide a signal consistently differentiating open water, bare soil, emergent wetland vegetation, and terrestrial vegetation. A successful methodology would result in improved estimates of the dynamic "wetland footprint."

1.1. Applications of remote sensing to wetland and land–water interface delineation

Remote sensing offers the potential to track temporal changes in wetland hydrology, chemistry, and vegetation dynamics, thereby accounting for fluxes in water and constituent cycling.

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Multispectral imagery has been successfully used in the past for year-round open water delineation, as well as for vegetation classification and change detection in a variety of ecosystems. Mapping studies by Lunetta and Balogh (1999), Berberoglu et al. (2004), Klemas (2005), Phillips et al. (2005), Frohn et al. (2009), and Klemas (2011), have demonstrated the potential of applying remote sensing methods to wetland identification. None of these, however, were concerned with the wetland footprint as a direct foundation for water management decision-making based on modeled simulations of water quality. Whereas delineation of open water and general vegetation characterization is sufficient for wetland identification, the objectives of our study required capturing the wetland footprint transparently and consistently enough to aid in decision-support.

The feedbacks between vegetation characteristics and environmental function of wetland ecosystems were studied by Kokaly et al. (2003) and Lin and Liquan (2006). These studies illustrate how vegetation characteristics such as density, vitality, and spatial extent may serve as important ecohydrologic indicators. Remote sensing-based vegetation mapping by Macleod and Congalton (1998), Phinn et al. (1999), Harvey and Hill (2001), and Schmidt et al. (2004) has been successful at a number of spatial scales. While we can base the legitimacy of remote sensing-based approaches for wetland analysis on these and more recent studies, they have been particularly effective in permanent wetlands in which vegetation composition and extent of flooded area remain relatively static throughout the year. Though permanent wetlands are subject to water losses to infiltration, evaporation, and plant transpiration, they are rarely – if ever - completely dewatered. Conversely, in seasonal wetlands inundation and dewatering occur with regularity and represent a key boundary condition regulating both the ecologic and hydrologic response of the system. This hydrologic seasonality exerts an important control on plant community composition, transpiration, and spectral characteristics. However, time-lags between the recession of water and the vegetation community's response create additional complexity. We aimed to address these important limitations by developing methods appropriate to seasonal wetlands.

Though coastal and wetland systems are not identical, there is some overlap, particularly in the delineation of the land–water interface. Klemas (2013) provides an overview of the latest airborne remote sensing methods applied to the analysis of coastal features and processes. Many techniques, such as close-range aerial photography, airborne LiDAR surveys, kinematic differential GPS post-processing, and airborne hyperspectral imagery, are compatible with wetland delineation. However, the accuracy of many land–water interface delineation methods in wetland systems is limited by the spatial resolution of the satellite imagery, spectral signature overlap between wetland vegetation species, and by the high ecological complexity and spatial irregularity of the wetlands (Ozesmi and Bauer, 2002).

Since Ozesmi and Bauer's review, image processing techniques have improved. The efforts driving these developments can be grouped into two main camps. The first is concerned with computational methods and signal processing. Baker et al. (2006) and Wright and Gallant (2007) used classification trees, a computational technique which originated in computational biology but has since spread to other fields as well, to combine Landsat imagery with field-based observations. The authors found that while ancillary environmental data improved classification accuracies, hard classification remained problematic. Wright and Gallant concluded that probability landscapes, rather than hard classification, may be the more practical approach to classifying wetlands. Similarly, pixel classification using artificial neural networks is quite promising for deciphering the spatial and temporal dynamics of wetland ecosystems. However, based on the work of Bagan et al. (2005), Ĉerná and Chytrý (2005), and Xie et al. (2008), neural network analysis becomes very computationally expensive for all but the smallest datasets.

Approaching the problem from a function, rather than process, perspective, others have sought to inform remote sensing by drawing on methods from landscape ecology in careful reviews of the published literature (Maier, 2013). Cushman et al. (2008) and Kelly et al. (2011) looked at using landscape metrics as proxies for ecologic characterization to aid in wetland delineation. Such approaches are well-suited for analysis over broad spatial scales, yet have an important limitation. The authors conclude that due to the variability of both structural and functional landscape characteristics, the identification of appropriate matrices for a given study area may well form a separate study in itself. As such, pattern metrics are not readily generalizable across geographic regions.

Alongside advances in image processing, higher resolution imagery has become more readily available both from commercial vendors and through further advances in airborne, rather than satellite, sensors. Maxa and Bolstad (2009) employed high resolution IKONOS satellite imagery merged with 1-m resolution LiDAR data to map and classify wetlands in the Wisconsin Wetland Inventory. LiDAR data was also used by Cook et al. (2009) in conjunction with ultra-fine precision commercial QuickBird imagery to estimate wetland plant productivity. Adam et al. (2010) review recent multispectral and hyperspectral remote sensing wetland studies, noting in particular the advantages of remote sensing data acquisition via hand-held sensors. These improvements, driven in part by advances in mechanical and optical engineering, are valuable contributions to the field. Nevertheless, the cost of commercial imagery or airborne sensor deployment remains an obstacle and hinders the application of higher-resolution imagery in studies requiring multi-temporal analysis for monitoring and evaluation of highly dynamic systems. Cost is of particular concern for studies at large spatial scales, such as river basins, and when regulatory pressures and an increasingly constrained water management environment provide the motivation, but not the resources, to execute the analysis.

1.2. Study area

To better understand the feedbacks between energy and water fluxes as they relate to mapping the dynamic wetland "footprint," and to demonstrate how a better understanding could improve response to environmental regulation, a region of the Sacramento–San Joaquin River Delta of California was chosen as a case study. The Sacramento–San Joaquin Delta covers 840,000 acres of floodplain estuary lying at the confluence of the Sacramento and San Joaquin River basins. Suisun Marsh forms the largest continuous brackish water marsh in the western United States and contains more than 10 percent of California's remaining natural wetlands (DWR, 2008). Both marsh and delta lie along key migration paths of anadromous fish and wildfowl on the Pacific Flyway. Peat soils, abundant water supplies, and a moderate marine climate contribute to high agricultural productivity. In addition to being a vital ecological and agricultural resource, the Delta serves California's two largest water systems – the federal Central Valley Project and the State Water Project. Its water exports maintain managed wetlands and riparian corridors both within and upstream of the Delta, support two-thirds of the state's urban population, and irrigate 3-million acres of agricultural land state-wide (DWR, 2008).

Within the San Joaquin River Basin portion of the greater Delta area, the Grasslands Ecological Area (GEA) forms a contiguous mixture of 77,000 ha of seasonal and permanent wetlands (Fig. 1, right-most inset). Once part of a much larger wetland complex, the