Remote Sensing of Environment 178 (2016) 142–157

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Surface water extent dynamics from three decades of seasonally continuous Landsat time series at subcontinental scale in a semi-arid region

Mirela G. Tulbure [a,*], Mark Broich [a], Stephen V. Stehman [b], Anil Kommareddy [c]

[a] School of Biological, Earth and Environmental Science, University of New South Wales, Sydney, NSW, Australia
[b] Department of Forest and Natural Resources Management, State University of New York, Syracuse, NY, USA
[c] Department of Geographical Sciences, University of Maryland, 4321 Hartwick Bld., Suite 400, College Park, MD 20742, USA

ARTICLE INFO

Article history:
Received 18 September 2015
Received in revised form 5 February 2016
Accepted 13 February 2016
Available online 23 March 2016

Keywords:
Landsat time series
Seasonally continuous
Surface water dynamics
Flooding dynamics
Accuracy assessment
Probability sampling design
Murray–Darling Basin
Australia
Competing water demands
Drought
Random forest
Long term trends
Water
River basin
Water management

ABSTRACT

Seasonally continuous long-term information on surface water and flooding extent over subcontinental scales is critical for quantifying spatiotemporal changes in surface water dynamics. We used seasonally continuous Landsat TM/ETM+ data and generic random forest-based models to synoptically map the extent and dynamics of surface water and flooding (1986–2011) over the Murray–Darling Basin (MDB). The MDB is a large semi-arid basin with competing demands for water that has recently experienced one of the most severe droughts in the southeast of Australia. We used a stratified random probability sampling design with 500 sample pixels each observed across time to assess the accuracy of the surface water maps. We further developed models to map flooded forest at a riparian site that experienced severe tree dieback. Water indices and bands 5 and 6 were among the top 10 explanatory variables most important for mapping surface water. Surface water extent per season per year showed high inter-annual and seasonal variability, with low extent and variability during the Millennium Drought (1999–2009). Accuracy assessment yielded an overall classification accuracy of 99.9% (±0.02% standard error) with 87% (±3%) and 96% (±2%) producer's and user's accuracy of water, respectively. User's and producer's accuracies of water were higher for Landsat 7 than Landsat 5 data. Both producer's and user's accuracies of water were lower in wet years compared to dry years. The approach presented here can be further developed for global application and is relevant to areas with competing water demands. Quantifying the uncertainty of the accuracy assessment and providing an unbiased accuracy estimate are imperative steps when remotely sensed products are intended to be used for follow on applications.

1. Introduction

Surface water is a critical resource in semi-arid areas (Hughes, Kingston, & Todd, 2011), which together with arid areas cover one third of the globe (FAO, 1989). Surface water bodies and seasonally inundated floodplains in semi-arid areas play major roles in water availability, hydrological and biogeochemical cycles (Pricope, 2013). Surface water bodies in semi-arid areas have been impacted dramatically due to large scale land cover and land use changes, climate change and variability, and increasing water demands from agricultural, industrial and domestic water uses (Leblanc, Tweed, Van Dijk, & Timbal, 2012). In water scarce regions, understanding the spatiotemporal patterns of surface water extent and flooding dynamics (hereafter surface water dynamics) is important as changes in surface water can lead to flooding or drought, and water shortages (Feyisa, Meilby, Fensholt, & Proud, 2014), with significant consequences to human life, agricultural systems, global water, and food security (Hanjra & Qureshi, 2010).

Australia's surface water bodies in arid and semi-arid regions are characterized by 'boom and bust' ecological dynamics with extreme flow variability (Arthington & Balcombe, 2011). Australia is also subject to El Niño Southern-Oscillation (ENSO) induced climatic variability, with a recent example being the transition from the droughts of the past decade to the La Niña rains that caused flooding across large areas of Eastern Australia in 2010 (Heberger, 2011). To understand these dynamics, spatially explicit and temporally dynamic, statistically validated, seasonally continuous high resolution surface water and flooding maps developed in a synoptic yet detailed way are needed.

Satellite remote sensing has been widely used for mapping surface water extent, with Landsat data being one of the most common types of data employed for mapping surface water. The infrared and visible bands on the Thematic Mapper (TM) and Enhanced Thematic Mapper

* Corresponding author.
E-mail address: Mirela.Tulbure@unsw.edu.au (M.G. Tulbure).

http://dx.doi.org/10.1016/j.rse.2016.02.034
0034-4257/

Plus (ETM+) sensors on Landsat 5 and 7, respectively, allow separation of surface water from the land surface (Baker, Lawrence, Montagne, & Patten, 2006, 2007; Bwangoy, Hansen, Roy, De Grandi, & Justice, 2010; Feng, Sexton, Channan, & Townshend, 2015; Margono, Bwangoy, Potapov, & Hansen, 2014; Ozesmi & Bauer, 2002; Tulbure & Broich, 2013; Verpoorter, Kutser, Seekell, & Tranvik, 2014; Ward et al., 2014; Wright & Gallant, 2007; Yamazaki, Trigg, & Ikeshima, 2015).

Previous methods mapping surface water used water indices based on single spectral band thresholding, two spectral bands such as the Normalized Difference Water Index (NDWI, (McFeeters, 1996) and the Modified Normalized Difference Water Index (MNDWI, (Xu, 2006) or multi-band indices followed by thresholding. However, water as a spectral target is variable in space and time. Consequently, identifying a single threshold yielding the highest accuracy can be time consuming and may not be feasible as the spectral signature of water varies as a function of sediment load, algal content, depth and bottom reflectance signal (Jensen, 2007). In previous studies using optical data (Feng et al., 2015; Frazier & Page, 2000; Kingsford, Brandis, Thomas, Crighton, Knowles & Gale, 2004; Verpoorter, Kutser, Seekell & Tranvik, 2014; Verpoorter, Kutser, & Tranvik, 2012; Yamazaki et al., 2015), flood extent mapping over large areas has been compromised by turbidity or the spectral response of bottom sediments increasing the diversity of occuring water signatures. Hence, manual editing has often been necessary (Danaher & Collett, 2006). More recent methods used a threshold of the Automated Water Extraction Index (AWEI) for improved classification in areas affected by shadow and dark surfaces such as mountainous areas (Feyisa et al., 2014). Another approach is to use a combination of spectral bands and other variables and classification trees to develop models based on a range of predictor variables rather than selected indices (Tulbure & Broich, 2013; Wright & Gallant, 2007) thus modelling and thereby accounting for regional differences in threshold values when mapping surface water. Classification trees are widely used in land cover classifications (Friedl & Brodley, 1997; Pal & Mather, 2003) and have the ability to accurately map surface water for relatively small areas with homogenous classes (Tulbure & Broich, 2013). However, previous work has shown that ensemble classifiers such as random forest are superior to a single classification tree, especially when targets are spectrally variable (Pal, 2005; Rodriguez-Galiano, Ghimire, Rogan, Chica-Olmo, & Rigol-Sanchez, 2012), such as surface water bodies and flooded areas of the MDB.

Previous work mapping surface water and wetland dynamics has estimated the accuracy of the classification without providing the uncertainty (i.e., standard errors of the accuracy estimates) of the estimate (Mueller et al., 2016; Tulbure & Broich, 2013; Wright & Gallant, 2007). Quantifying the uncertainty of the accuracy assessment and providing an unbiased estimate of the accuracy of SWD products are imperative steps when remotely sensed products are intended to be used for follow on applications, as outlined in this work. These steps are only possible when using a probability sampling design, which is a critical part of a statistically rigorous and unbiased accuracy assessment (Stehman & Czaplewski, 1998). For the entire MDB specifically, there is no validated surface water dynamics and flooding layer using a statistically rigorous and unbiased accuracy assessment that includes uncertainty estimates, based on the entire Landsat archive but recent work has shown a surface water map aggregated over time (Mueller et al., 2016). Moreover, for the entire MDB there is no quantification of seasonally continuous dynamics of surface water and flooding extent from 1986 to 2011 in the context of the major hydroclimatic events of the SE of Australia.

This study used almost three decades of seasonally continuous time series of Landsat and ancillary data to automatically generate a comprehensive historical record of validated surface water dynamics (1986–2011) for the entire MDB, one of the largest river basins of Australia. The objectives of this research were to: (1) Synoptically map the extent and dynamics of surface water with internally consistent algorithms using the seasonally continuous Landsat data (TM and ETM+) over 26 years. This time period encompassed the longest and most severe drought on record, the Millennium Drought (1999–2009) and the 2010–2011 La Niña flood years; (2) Implement a statistically rigorous accuracy assessment that includes unbiased accuracy estimates, including accuracy of the surface water dynamics product using Landsat 5 and Landsat 7 separately, accuracy across time, and accuracy contrasting 'wet' and 'dry' years; and (3) use the same method described and developed for objective (1) for a new application to map flooded forest areas in the largest river red gum forest in the world, a riparian site that sustained tree dieback.

2. Methods

2.1. Study area

2.1.1. Murray–Darling Basin

The MDB is a large semi-arid region (14% of Australia's area) with scarce water resources, high natural hydroclimatic variability and competing water demands. The MDB contains one of Australia's largest river systems (more than 1 million km^2) and important groundwater systems. The basin drains one seventh of the Australian land mass, spans four states, New South Wales, Victoria, Queensland and South Australia and the Australian Capital territory and harbours the three largest rivers of Australia: the Darling River (2740 km), the Murray River (2520 km) and the Murrumbidgee River (1575 km). The basin has been termed Australia's agricultural heartland producing one third of Australia's food supply. Almost three quarters of Australia's irrigated crops and pastures are grown in the basin with 84% of land used for agricultural production, and only 10% for conservation and natural environments (Murray–Darling Basin Authority, 2012). The different land cover and land use types, including multiple crops with different phenologies create a wide variability of spectral signatures in the basin (Fig. 1)

There are nearly 30,000 wetlands in the MDB, 16 Ramsar listed, including the world's largest river red gum forest (Barmah–Millewa, Fig. 1), and 200 wetlands of national significance (Australian Government, 2012). The majority of these wetlands are reliant on intermittent river flows and vary in response to water availability. The majority of the runoff in the Murray–Darling river system originates from a small percentage of the basin area along the southern and eastern rim. Almost 86% of the catchment area contributes only irregular run-off to rivers (Australian Government, 2012).

2.1.2. Barmah–Millewa Forest (BMF)

We focused on the largest *Eucalyptus camaldulensis* (Dehnh.) river red gum forest in the world (approximately 700 km^2), the BMF (Fig. 1), an area currently experiencing decline in health of river red gum, as a test case for investigating dynamics of flooded forest. The site provides a dramatic example of floodplain forest dieback (Cunningham, Mac Nally, Read, Baker, White, Thomson & Griffioen, 2009; Palmer, Reidy Liermann, Nilsson, Flörke, Alcamo, Lake & Bond, 2008). Further, BMF is a key site for management of environmental flows (environmental water added to the system to mimic natural flooding patterns and maintain ecological condition). Recently, the site experienced the largest environmental water release in Australia's history (McGinness, Arthur, Ward, & Ward, 2014). The BMF is located on the Murray River at the border between the Australian states of New South Wales and Victoria (Fig. 1) and has a semi-arid climate with predominantly winter rainfall (BoM, 2013). Previous disturbances to the site include river regulation, water extraction, burning, timber harvesting and grazing (Mac Nally & Parkinson, 2005). The BMF consists of nearly 70% open canopy river red gum forest, river red gum woodland (23%) and mixed box eucalypt woodland (6%) (MDBA, 2010). River red gum tree densities range from more than 700 trees/ha in open canopy forests to less than 50 trees/ha in open woodlands (kerle, 2005; OEH, 2012).