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Research article

A novel framework for the use of remote sensing for monitoring catchments at continental scales

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ABSTRACT

Historical ecology can teach us valuable lessons on the processes and drivers of environmental change that can inform future monitoring priorities and management strategies. Environmental data to study environmental history, however, is often absent or of low quality. Even when studying changes occurring during the last few decades, monitoring efforts are scarce due to logistical and cost limitations, leaving large areas unassessed. The aim of this study is to evaluate the use of estuarine water colour as an indicator of historical environmental change in catchments. Water colour change was assessed in estuaries in Australia from 1987 to 2015 using satellite remote sensing. Random points were selected for each estuary and applied to the Australian Geoscience Data Cube (based on Landsat images) to obtain reflectance data through time. We propose a framework where (i) water colour is used to detect historical changes in catchments using generalised additive models, (ii) possible stressors and pressures driving those changes are evaluated using other available historical data, and (iii) lessons learned inform appropriate monitoring and management actions. This framework represents a novel approach to generate historical data for large-scale assessments of environmental change at catchment level, even in poorly studied areas.

1. Introduction

At least three quarters of the global habitable land has been impacted by human activities (Hannah et al., 1994), with habitat modification and destruction the driving forces of biodiversity and ecosystem services loss (Barbier et al., 2011; Sala et al., 2000; Zedler and Kercher, 2005). Some of the most dramatic changes occurred at landscape level due to policies and management strategies developed at local and regional scales (O'Neill et al., 1997). These large-scale impacts have resulted in marked reductions in physico-chemical water quality in inland and coastal waters worldwide (e.g. Capuzzo et al., 2015; O'Neill et al., 1997; Rothenberger et al., 2009; Wang et al., 2015), making water bodies "sentinels of environmental change" (Williamson et al., 2008). Physical and chemical water quality can change as a result of acute pressures, such as dredging or intense storms, or gradually, as a consequence of chronic pressures (e.g. land use change). We use the term pressure to indicate the fundamental change to a landscape (e.g. mining, land-use intensification) which results in stressors (e.g. sediment loads/turbidity, nutrient loads) that lead to changes in ecological condition (e.g. chlorophyll). Reduced water quality can, in turn, produce ecosystem changes (e.g. Gallegos and Kenworthy, 1996; Wenger et al., 2015), inducing further biodiversity and services loss.

While some of the most dramatic ecosystem changes on land occurred during the 19th and 20th centuries (Hannah et al., 1994), there is an increasingly recognised need to study the historical ecology to understand the drivers of ecosystem change and design future management strategies (e.g. Engelhard et al., 2016; Swetnam et al., 1999; Thurstan et al., 2015). In addition, management strategies informed only by studies lasting a few years fail to encompass the role of processes occurring at larger temporal scales, such as weather and climatic shifts and ecological responses of long-lived organisms (Jackson et al., 2001; Swetnam et al., 1999; Thurstan et al., 2015). The study of historical ecology is, however, challenged by data availability due to high-quality data from long-term monitoring efforts (10 years+) being rare and usually biased by cultural factors in the collection and storage of data, leaving large areas understudied (Robarts et al., 2008; Swetnam et al., 1999).

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Therefore, historical ecology assessments rely on techniques that can “look back in time”, such as data obtained using paleo-environmental approaches, cores to assess historical water condition (Kemp et al., 2005; Van Metre et al., 1997) and diversity composition (Edgar et al., 1999; Harris and Weisler, 2017; Pandolfi and Jackson, 2006), as well as in historical records of human activities, such as fisheries catch (Alleway and Connell, 2015). At smaller temporal scales (decades), remote sensing techniques have also been used to assess historical land-use (e.g. Griffiths et al., 2012; Huang and Klemas, 2012), vegetation (e.g. Asbridge et al., 2016; Hais et al., 2009) and water quality change (e.g. Binding et al., 2015; Le et al., 2013).

Satellites can measure the electromagnetic energy reflected by the Earth across a wide range of wavelengths, according to the specific sensors on the satellite. They can, therefore, detect a combination of spectral reflectance in different wavelengths, referred here as ‘colour’. As water colour is affected by a range of variables (phytoplankton, non-chlorophyllous suspended particles and coloured dissolved organic matter, Prieur and Sathyendranath, 1981), understanding the causes of the water colour change is a highly complex task. To translate water colour changes into changes in physico-chemical characteristics of the water, past studies have used both analytical and empirical methods, along with in-situ data, for both training and validation procedures (e.g. Barnes et al., 2013; Dekker et al., 2002; Olmanson et al., 2008). The relationships between in-situ and remotely sensed data, however, vary in space and time in optically complex waters such as estuaries (Brando and Dekker, 2003), limiting the application of this technique to areas and times when in-situ data is available. Here, we propose the direct use of water colour measured with remote sensing as an indicator of historical environmental change that can be modelled in combination with other historical data to understand the drivers of those changes at catchment to continental scales. The data produced here are not spatially or temporally confounded by cultural factors (as in the case of historical records, Swetnam et al., 1999), as satellites use systematic sampling in space and time. In addition, satellite data have high spatial and temporal resolution when compared with historical records of in-situ data. With pioneering projects such as the Australian Geosciences Data Cube (Lewis et al., 2016; Purss et al., 2015) and the Google Earth Engine making remote sensing accessible to non-experts, the development of new opportunities for the use of satellite image time-series is timely.

The aim of this study was to use water colour measured by remote sensing to detect historical environmental change in catchments, triggering targeted historical data collection on the stressors and pressures causing those changes. Lessons learned using this approach will inform future monitoring priorities and management decisions. The following framework is proposed:

1. Identify estuaries that show net changes in water colour measured using remote sensing;
2. Assess the stressors and pressures that have led to the observed changes in water colour using other types of historical data available for the area;
3. If stressors and pressures evaluated could not explain the changes in water colour, this opens an opportunity for further investigations to understand the behaviour;
4. If changes in stressors and/or pressures can explain changes in water colour, monitoring or management actions should be considered based on the historical lessons learned.

This study explored the methodologies and procedures to apply in steps 1 to 3. Step 4 involves monitoring and management decisions that have been extensively discussed before (e.g. Atkinson et al., 2004; Field et al., 2007; Nichols and Williams, 2006) and are outside the scope of this study.

We tested this framework using Australian estuaries as a model system. The coast of Australia has just under 1000 moderate to large estuaries, ranging from tropical to temperate environments and spanning different levels of habitat and catchment modification (Geoscience Australia, 2015b). It includes estuaries with a wide range of influences from terrestrial and coastal forces and catchment sizes, making Australia a good model for testing methodologies for large scale monitoring.

2. Methods

2.1. Mapping Australian estuaries and their catchments

Location and extent of each of the 947 Australian estuaries were obtained from Geoscience Australia (2015b), with each estuary divided in different functional zones (e.g. main channel, central basin, fluvial delta, intertidal flats, mangroves). The main channel and central basin zones were the focus of this study, all other zones were excluded. For each estuary, catchments were mapped by creating drainage basin polygons derived from a 90 m DEM (Bureau of Meteorology, 2015a), developed by Environmental Resources Information Network (ERIN), Department of Environment and Energy, Australian Government.

2.2. Remote sensing data

A maximum of 500 random points were selected within the relevant zone(s) of each estuary using ArcGIS 10.3, with a minimum distance of 70 m between each point and using a buffer of 120 m from the outline of the estuary (Fig. 1). For each random point, we extracted the time series of every available Landsat satellite image date, including data from both the TM and ETM+ sensors. Landsat sensors measure reflectance in the 450–520 nm (blue), 520–600 nm (green) and 630–690 nm (red) wavelength ranges, respectively. We chose the Landsat family of satellites primarily due to its historical coverage (1987 onwards) and relatively high spatial resolution (30 m pixels), which makes it suitable for monitoring water colour change in medium-sized and larger water bodies. Additionally, Landsat has previously been successfully used for water quality analysis in Australian water bodies (e.g. Dekker and Hestir, 2012; Lymburner et al., 2016; Phinn et al., 2005). Time series of pixel data from across the temporal range of the Australian Landsat archive were extracted from the Australian Geoscience Data Cube (Lewis et al., 2016; Purss et al., 2015). The Australian Geoscience Data Cube restructures 30 years of continuously acquired Landsat imagery in an innovative high-performance computing – high performance data environment. Data processing includes spectral calibration, geometric and atmospheric correction to produce a standardised measure of optical surface reflectance across the full range of the data according to the Australian Reference Grid 25 product (Geoscience Australia, 2015a). Data within each satellite image are spatially segmented into 1° x 1° tiles forming a grid that covers the Australian continent so that the geographic location of each pixel is constant through the time series, and the same geometric and atmospheric corrections and quality flags methods were performed on each image scene, including the removal of clouds and cloud shadows (Irish et al., 2006; Li et al., 2010; Sixsmith et al., 2013). Therefore, we extracted reflectance information from the Landsat time-series at the pixel under each random point (Fig. 1).