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Landsat 8: Providing continuity and increased precision for measuring multi-decadal time series of total suspended matter

Leo Lymburner [a,*], Elizabeth Botha [b], Erin Hestir [c], Janet Anstee [b], Stephen Sagar [a], Arnold Dekker [d], Tim Malthus [e]

[a] National Earth and Marine Observation Group, Geoscience Australia, Canberra 2609, Australia
[b] CSIRO Oceans and Atmosphere Flagship, Acton, Canberra, 2601, Australia
[c] Center for Geospatial Analytics, Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC, USA
[d] CSIRO Land and Water Flagship, Acton, Canberra, 2601, Australia
[e] CSIRO Oceans and Atmosphere Flagship, Dutton Park, Brisbane, 4102, Australia

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The water clarity of many inland water bodies is under threat due to intensifying land use pressures in conjunction with changes in water levels that result from increasing demand and climate variability. The recent launch of Landsat 8 coupled with Geoscience Australia's recent reprocessing of the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) archives over the whole of Australia to a consistent surface reflectance product enables sub continental scale spatio-temporal analysis of freshwater optical water quality in support of monitoring and decision making for water management agencies. In this research, we present an objective assessment of the potential of Landsat 5 TM, Landsat 7 ETM+ and Landsat 8 Operational Land Imager (OLI) data for monitoring inland water quality dynamics over a number of lakes and reservoirs with a range of optical water types in New South Wales and Queensland, Australia. We used bio-optical modelling to develop sensor-specific total suspended matter (TSM) retrieval algorithms that account for the difference in relative spectral response between Landsat 7 ETM+ and Landsat 8 OLI. We were able to compare the suitability of the different sensors for optical water quality measurements using water bodies that fell within Landsat path overlaps where Landsat images of surface reflectance were acquired within 24 h between Landsat 5 TM and Landsat 7 ETM+ or Landsat 7 ETM+ and Landsat 8 OLI. These water bodies represent a range of hydrological and limnological conditions, and enabled us to assess: 1) the comparability of TSM measurements retrieved from each sensor, and 2) the surface reflectance to image noise characteristics of Landsat 7 ETM+ and Landsat 8 OLI. Comparisons of lake surface reflectance and noise equivalent reflectance difference show that the improved radiometric resolution and increased quantization of Landsat 8 OLI relative to Landsat 7 ETM+ significantly reduce image noise and spectral heterogeneity, indicating that Landsat 8 OLI data are expected to provide more precise water quality retrievals relative to Landsat 7 ETM+. We found that: 1) the TSM retrievals from the different sensors are highly comparable; 2) Landsat 5 TM overestimated TSM relative to Landsat 7 ETM+ by 6.4%; and 3) Landsat 7 ETM+ overestimated TSM relative to Landsat 8 OLI by only 1.4%. Retrieved TSM values were highly correlated with independent *in situ* data acquired within 24 h of satellite overpass ($r = 0.99$) with a mean average error of 14 mg/L. The results demonstrate that time series analysis of TSM retrievals can be conducted across a wide range of lakes at the sub-continental scale to characterise the multi-decadal TSM dynamics.

1. Introduction

Land use intensification and watershed disturbance often lead to an increase in both sediment and nutrient fluxes to rivers and other inland water bodies, and a large portion of these increased fluxes are retained in inland waters, including both lakes (Olmanson, Bauer, & Brezonik, 2008) and constructed reservoirs (Harrison, Bouwman, Mayorga, & Seitzinger, 2010; Harrison et al., 2005). Sediments and nutrients of anthropogenic origin are among the most important pollutant stressors threatening water security for human consumption and freshwater biodiversity (Davies-Colley & Smith, 2001; Foley et al., 2005; Vorosmarty et al., 2010) and affect the aesthetic value and ecological and biogeochemical function of a water body. Total suspended matter (TSM), the mass or concentration of inorganic and organic matter held in suspension, is a well recognised indicator of water quality (Bilotta & Brazier, 2008). Increased TSM in aquatic ecosystems reduce water clarity and the depth of the euphotic zone (Bilotta & Brazier, 2008; Davies-Colley

* Corresponding author.
E-mail address: leo.lymburner@ga.gov.au (L. Lymburner).

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& Smith, 2001), impacting primary producers including phytoplankton and aquatic macrophytes, and eventually leading to an impoverished ecological status (Dennison et al., 1993; Jeppesen et al., 2009).

The Landsat series of sensors, and specifically the Landsat 5 TM, Landsat 7 ETM + and Landsat 8 OLI sensors have acquired data systematically according to a long term acquisition plan (Arvidson, Gasch, & Goward, 2001). This in combination with their 30 m spatial resolution means that the Landsat series of satellites provide a unique, freely available dataset to identify both historical baselines and current changes in TSM in relatively small water bodies across large geographic areas. Previous studies have mapped TSM using Landsat (Carpenter & Carpenter, 1983; Dekker, Vos, & Peters, 2002; Heege, Kiselev, Wettle, & Hung, 2014; Kong et al., 2015; Lulla, 1983; Mertes, Smith, & Adams, 1993). These studies, however, typically focus on a specific location, a single Landsat sensor, or a small number of scenes.

One of the greatest challenges to developing a systematic time series of TSM across large geographic regions is ensuring that the TSM estimates are not varying due to changes in sensors Barnes et al. (2014). This includes changes in spectral response functions (Fleming, 2006; Flood, 2014) as well as radiometric quality, which impacts the accuracy of the retrieval as well as the effective spatial resolution of the data (Hu et al., 2012; Hestir, Brando, Bresciani, et al., 2015). Although Landsat 8 OLI has been demonstrated to have sufficient radiometric capability to measure TSM in turbid coastal waters (*e.g.*, Vanhellemont & Ruddick, 2014), the comparability of TSM retrievals across different Landsat sensors needs to be evaluated. For example, in a simulation study for turbid coastal waters, Pahlevan and Schott (2013) showed higher spatial variability and lower accuracy in TSM retrievals from Landsat 7 ETM + compared to Landsat 8 OLI due to the lower quantization of the sensor (8 bits for ETM + and 12 bits for OLI). However, they also conclude that overall the TSM products derived from the two simulated sensors were generally comparable and should be sufficient for long-term monitoring of coastal waters. Vanhellemont and Ruddick (2014) retrieved total suspended matter (TSM) from actual Landsat 8 observations of a turbid coastal environment. For Landsat 7 ETM +, however, they found it necessary to bin data to 11×11 pixels to overcome the limited quantization. This reduced the effective spatial resolution of Landsat 7 ETM + to 330 m, which would significantly limit the utility of Landsat for TSM time series analyses in smaller inland waterbodies.

To develop sufficiently reliable TSM time series for inland water bodies, a consistent, systematic and standardized methodology must be successfully implemented across the Landsat archive, which is comprised of multiple scenes and sensors and well characterised but variable radiometric quality (Dekker & Hestir, 2012; Malthus, Hestir, Dekker, & Brando, 2012; Markham & Helder, 2012). The development of the Australian Geoscience Data Cube (Purss et al., 2015) provides access to Landsat observations of the entire Australian continent that have all been processed using the same atmospheric correction, view angle and BRDF correction technique (Li et al., 2010) and pixel quality flagging methods (Irish, Barker, Goward, & Arvidson, 2006; Sixsmith, Oliver, & Lymburner, 2013; Zhu & Woodcock, 2012). This makes it possible to retrieve a multi-sensor time series of surface reflectance observations that have had the cloud and cloud shadows removed. The availability of this consistently processed surface reflectance dataset across Australia allows for the first time the development of a systematic, standardized methodology to estimate lake and reservoir TSM. This can now be done across large geographic areas and enables the comparison of inland water TSM retrievals across different sensors to support long-term monitoring of water bodies to identify both short term changes and long term trends in water quality.

Systematic TSM retrieval algorithm for time series of inland water bodies requires being able to apply an algorithm to Landsat data at full (30 m) resolution while accounting for the differing spectral response functions of the sensors (Flood, 2014). It also requires the automated removal of sun glint and small white cap affected observations (Devred et al., 2013; Kutser, 2012). Furthermore, retrieving TSM from many different waterbodies over a large geographic area will include lakes that span a range of optical conditions due to a variety of hydro-limnological settings. In many parts of the world, including Australia, *in situ TSM* optical water quality characterisation data are only available for a limited number of lakes. This necessitates that the systematic TSM retrieval algorithm cannot be dependent on the availability of TSM measurements necessary for an empirical approach (*e.g.* Olmanson et al., 2008) or on the inherent optical properties for each water body necessary for a full physics-based approach (*e.g.* Heege et al., 2014).

The objectives of this study are to: 1) develop a method for generating time series of TSM measurements at the multi-decadal scale using multiple Landsat sensors; 2) apply this technique to quantify the temporal dynamics of TSM of lakes distributed through a region with high variability in rainfall and climatic zones ranging from mid-latitude temperate, alpine, and semi-arid to sub-tropical; 3) evaluate the performance of the different Landsat sensors for inland water TSM retrievals across large regions to support long-term monitoring activities.

2. Method

2.1. Site description

Australia provides an excellent case study for the development of a systematic TSM retrieval approach. The continent is under high water stress due to low annual precipitation, the highest rates of surface water loss due to evapotranspiration and increasing anthropogenic water demand. It is ranked among the worst of developed countries for the way in which water resource management affects ecosystems (Emerson et al., 2012). Surface water quality in Australia is declining (Emerson et al., 2012), recurring harmful and nuisance algal blooms are widespread (Davis & Koop, 2006), nutrient fluxes and dynamics are poorly resolved (Davis & Koop, 2006), and sediment erosion and transport to freshwater ecosystems and the coastal zone remain as critical concerns (McCulloch et al., 2003; Prosser et al., 2001). Under the *Water Act 2007* and *Water Regulations 2008*, the Australia Bureau of Meteorology is responsible for reporting on Australian inland water quality. However, water quality information in Australia is sparse, difficult to obtain, and variable in content and accuracy due to the fact that it has been collected by different agencies using different sampling techniques and is constrained by different licensing conditions (Dekker & Hestir, 2012). In Australia, the states of New South Wales and Queensland have a large number of lakes and reservoirs which are measurable with Landsat pixel resolutions (Dekker & Hestir, 2012), and have some TSM measurements available. The states also span a large gradient of hydro-climatic conditions. Thus, we selected lakes and reservoirs from within the state of New South Wales and Queensland for application of systematic TSM retrieval (Fig. 1).

2.2. Water body identification

Although the spatial resolution of Landsat makes it ideal for measuring a variety of inland water bodies (Hestir, Brando, Campbell, et al., 2015), smaller water bodies are subjected to adjacency effects (Giardino, Brando, Dekker, Strömbeck, & Candiani, 2007). To ensure that only pure water reflectance was analysed in this study, only water bodies that were larger than 3×3 Landsat pixels were used (Table 1, Fig. 1). Subsequent to this screening, the location for the time series of surface reflectance observations for each water body was selected using the following criteria:

- Located in the deepest part of the water body (to ensure optical depth and permanent inundation in the case of water bodies with highly variable inundation regimes)
- Located as far from the shore as possible while still meeting the criterion above (to minimise the impact of adjacency effects)