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Review

Remote sensing for lake research and monitoring – Recent advances

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ABSTRACT

Lakes are important ecosystems providing various ecosystem services. Stressors such as eutrophication or climate change, however, threaten their ecological functions. National and international legislations address these threats and claim consistent, long-term monitoring schemes. Remote sensing data and products provide synoptic, spatio-temporal views and their integration can lead to a better understanding of lake ecology and water quality. Remote sensing therefore gains increasing awareness for analysing water bodies. Various empirical and semi-analytical algorithms exist to derive remote sensing indicators as proxies for climate change or ecological response variables. Nevertheless, most monitoring networks lack an integration of remote sensing data. This review article therefore provides a comprehensive overview how remote sensing can support lake research and monitoring. We focus on remote sensing indicators of lake properties, i.e. water transparency (suspended particulate matter, coloured dissolved organic matter, Secchi disc depth, diffuse attenuation coefficient, turbidity), biota (phytoplankton, cyanobacteria, submerged and emerged aquatic vegetation), bathymetry, water temperature (surface temperature) and ice phenology (ice cover, ice-on, ice-out). After a brief background introducing principles of lake remote sensing we give a review on available sensors and methods. We categorise case studies on remote sensing indicators with respect to lake properties and processes. We discuss existing challenges and benefits of integrating remote sensing into lake monitoring and ecological research including data availability, ready-to-use tools and accuracies.

Contents

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1. Introduction

Inland waters, and especially lakes, have important functions in the environment. They provide habitat for a wide range of species and form essential components in hydrological, nutrient and carbon cycles (Moss, 2012). Humans benefit from various ecosystem services offered by inland waters, i.e. water bodies that are not directly connected to the sea (Carpenter et al., 2011). Water extraction serves for drinking water and irrigation; other usages encompass energy production, transportation, fishery and recreational purposes (Stendera et al., 2012; Carvalho et al., 2013a). Anthropogenic exploitation and multiple interacting stressors, however, threaten ecological functions of inland waters over the entire globe (Adrian et al., 2009). Prominent stressors include eutrophication, inorganic and organic contaminants, morphological alterations and climate change effects such as acidification or increasing water temperatures (Brönmark and Hansson, 2002; Dudgeon et al., 2006).

Several national and international directives address these problems and aim to improve the ecological state of inland waters. Examples are the US Clean Water Act (U.S. Senate, 2002), South African National Water Act (Government of South Africa, 1998), National Water Management Strategy of Australia and New Zealand (Australian Government, 2000), the Canada Water Act (Government of Canada, 1985), and the Water Framework Directive in Europe (European Commission, 2000). A common target of these directives is to improve water quality by identifying stressors and by implementing sustainable management strategies supported by a more or less frequent monitoring (e.g. Gray and Shimshack, 2011; Birk et al., 2012; Warne et al., 2014). Currently, most monitoring programmes are field based even if sampling and analysis are labour, cost and time intensive (Schaeffer et al., 2013). Although providing information on species level, single measurements or unevenly distributed sampling points are problematic and may result in erroneous water quality classifications (Bresciani et al., 2011c; van Puijenbroek et al., 2015). Moreover, in situ measurements hardly capture the temporal and spatial variability of phenomena such as short-living cyanobacterial or phytoplankton blooms (Reyjol et al., 2014).

For a comprehensive understanding of lake ecology and the role of lakes “as sentinels, integrators and regulators of climate change” (Williamson et al., 2009) integrative, frequent and consistent long-term monitoring approaches are required globally (Hestir et al., 2015; van Puijenbroek et al., 2015). Ecologists repeatedly proposed to integrate remote sensing into water quality research and monitoring to benefit from earth observation via satellite sensors (Chen et al., 2004; Williamson et al., 2009; Birk and Ecke, 2014; Reyjol et al., 2014). Remote sensing techniques have already been successfully integrated in terrestrial ecosystem service assessments (e.g. Andrew et al., 2014; Kandziora et al., 2014; de Araujo Barbosa et al., 2015), for assessing indicators of terrestrial habitat quality (e.g. Spanhove et al., 2012) and for supporting management of marine and coastal protected areas (e.g. Kachelriess et al., 2014; Walshe et al., 2014). Until recently, remote sensing based studies of lake ecology and water quality were mainly carried out with airborne data or limited to large water bodies where ocean colour sensors with coarse spatial resolution such as MERIS or MODIS (spatial resolution represents the area on ground covered by an image element, which in the case of MERIS and MODIS is ≥300 m) have been used (e.g. Bresciani et al., 2011a). Maybe therefore the number of publications applying remote sensing in lake ecology or water quality lags far behind those without using remote sensing (Fig. 1) although various methods exist to derive proxies for water quality (e.g. Matthews, 2011; Odermatt et al., 2012).

Since 2010, the number of studies slightly increased (Fig. 1), which may also be due to several large projects funded by national authorities (e.g. Australia’s water for a healthy country flagship, Great Britain’s GloboLakes, North American Great Lakes Restoration Initiative, USA’s Harmful Algal Bloom early warning system project), space agencies (e.g. Diversity II, A Wealth of Water) and the European Commission (e.g. GLaSS, INFORM). Furthermore, recently launched sensors, such as NASA’s Landsat 8 and ESA’s Sentinel-2, offer spatial and radiometric resolutions which suit for inland water applications (Drusch et al., 2012; Pahlevan et al., 2014; Palmer et al., 2015b). The radiometric resolution defines how many brightness levels a sensor can perceive. A recently published special issue on inland water remote sensing of “*Remote Sensing of Environment*” (Palmer et al., 2015b) supports the observation that remote sensing based lake monitoring is gaining importance.

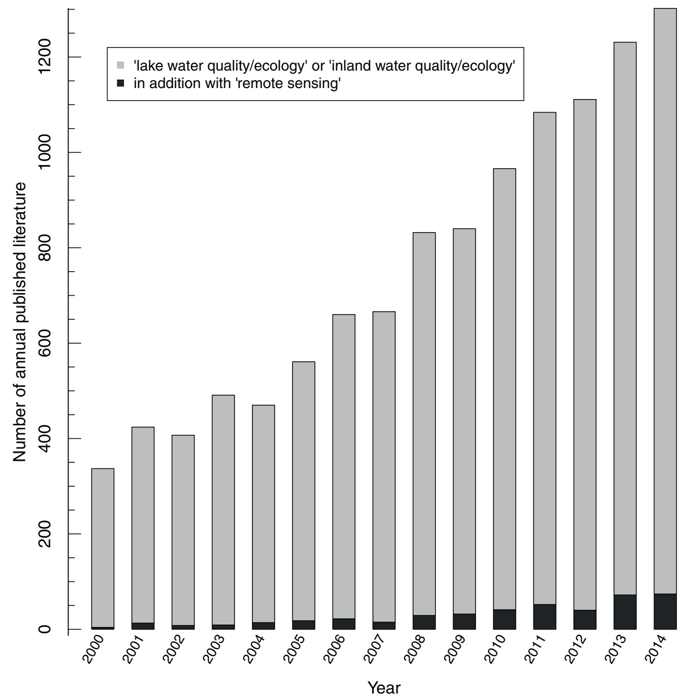

Fig. 1. Number of published literature (2000–2014) listed in Web of Knowledge containing the terms “lake water quality/ecology” or “inland water quality/ecology” (light grey) and the former in addition with “remote sensing” (dark grey).

To further encourage integration of remote sensing for lake monitoring and research this review article gives an overview of methods currently available that provide a better understanding and a foundation for future innovation in this field. To this end, a brief background of inland water remote sensing is given, followed by a section reviewing studies on retrieving remote sensing indicators for lake ecology, in particular, water transparency, biota, hydrology, ice cover and surface water temperature. The last section discusses potential and limitations of remote sensing based methods to promote integrated lake research.

2. Remote sensing indicators of lake ecology

Climate change poses an increasingly apparent stressor for lakes (Hering et al., 2010) and influences lake water quality and ecology (Moss, 2012). In a comprehensive review Adrian et al. (2009) summarised lake properties and their key response variables to climate change. These response variables are related to both trophic states of lakes and catchment processes (Adrian et al., 2009) and therefore may be used as response variables of lake ecosystem health (Zhang et al., 2013) and ecology (Poikane et al., 2015). Based on these response variables we selected indicators feasible to be achieved by