Remote Sensing of Environment xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Editorial

Remote sensing of inland waters: Challenges, progress and future directions

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ARTICLE INFO

Article history:
Received 9 September 2014
Received in revised form 12 September 2014
Accepted 13 September 2014
Available online xxxx

Keywords:
Inland waters
Freshwater
Optical
Multispectral
Hyperspectral
Inherent optical properties
Habitat
Ecosystem
Monitoring
Lake
Reservoir
River
Earth observation
Remote sensing

ABSTRACT

Monitoring and understanding the physical, chemical and biological status of global inland waters are immensely important to scientists and policy makers alike. Whereas conventional monitoring approaches tend to be limited in terms of spatial coverage and temporal frequency, remote sensing has the potential to provide an invaluable complementary source of data at local to global scales. Furthermore, as sensors, methodologies, data availability and the network of researchers and engaged stakeholders in this field develop, increasingly widespread use of remote sensing for operational monitoring of inland waters can be envisaged. This special issue on Remote Sensing of Inland Waters comprises 16 articles on freshwater ecosystems around the world ranging from lakes and reservoirs to river systems using optical data from a range of in situ instruments as well as airborne and satellite platforms. The papers variably focus on the retrieval of in-water optical and biogeochemical parameters as well as information on the biophysical properties of shoreline and benthic vegetation. Methodological advances include refined approaches to adjacency correction, inversion-based retrieval models and in situ inherent optical property measurements in highly turbid waters. Remote sensing data are used to evaluate models and theories of environmental drivers of change in a number of different aquatic ecosystems. The range of contributions to the special issue highlights not only the sophistication of methods and the diversity of applications currently being developed, but also the growing international community active in this field. In this introductory paper we briefly highlight the progress that the community has made over recent decades as well as the challenges that remain. It is argued that the operational use of remote sensing for inland water monitoring is a realistic ambition if we can continue to build on these recent achievements.

1. Introduction

In addition to providing water resources for various human uses (Postel, 2000), inland waters provide important and diverse habitat and ecosystem services, supporting high levels of biodiversity (Brönmark & Hansson, 2002; Duker & Bore, 2001). They are important components of global carbon and nutrient cycles (Bastviken, Tranvik, Downing, Crill, & Enrich-Prast, 2011; Tranvik et al., 2009). However, like many other ecosystems, lakes and rivers are threatened by the synergistic effects of multiple, co-occurring environmental pressures, notably nutrient enrichment and other organic and inorganic pollution, climate change, acidification, the establishment and spread of invasive species, and the diversion or extraction of upstream source waters (Brönmark & Hansson, 2002; Dudgeon et al., 2006). Their importance, as well as their sensitivity to and capacity to reflect climate, land use and other environmental change, has garnered inland waters increasing attention over recent years. The assessment and monitoring of lakes and rivers are crucial to our ability to understand and disentangle the effects of environmental change on freshwater ecosystems and to model future change. There is also an increasing regulatory need to increase the coverage and frequency of freshwater monitoring, arising from legislation such as the European Union's Water Framework Directive for example. There are, however, more than 117 million lakes on Earth (Verpoorter, Kutser, Seekel, & Tranvik, 2014) and only a very small proportion of these are regularly and consistently monitored. Conventionally, in situ monitoring is limited in terms of spatial coverage and representativeness, as well as frequency for many sites, and is simply non-existent in a great many others.

Remote sensing has long been recognised as having the potential to complement conventional approaches to lake monitoring (Bukata, 2013 and references therein). Indeed, research on the remote sensing of inland waters has been undertaken for almost as many years as that in ocean colour science, but whereas satellite observations are used operationally to measure ocean colour, their use for monitoring inland waters has made less progress. Inland water remote sensing has faced, and continues to face, many challenges not only in terms of the science underpinning the retrieval of physical and biogeochemical properties

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http://dx.doi.org/10.1016/j.rse.2014.09.021
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over what are typically highly optically complex waters, but it has also suffered from the lack of funding, infrastructure and the mechanisms needed to coordinate research efforts across what has been historically a rather fragmented community.

1.1. Challenges: past and present

The ocean colour sensors that have supported much of the research and development in marine remote sensing have or had coarse spatial resolutions that make them unsuitable for remote sensing applications over most rivers, lakes and reservoirs. This has meant that the inland water community has often had to make use of data from satellite sensors with higher spatial resolutions designed primarily for land applications, such as the Landsat series. However, while these sensors have adequate spatial resolutions for many lakes, their spectral coverage and resolution, as well as their radiometric sensitivity, are not optimal for many applications over inland waters (e.g., phytoplankton pigment or coloured dissolved organic matter (CDOM) retrieval).

The optical complexity of inland waters, atmospheric correction issues, adjacency effects and some other unresolved problems add additional challenges to inland water remote sensing compared to ocean colour remote sensing. The optical complexity of inland waters stems from the fact that these waters are typically characterised by high concentrations of phytoplankton biomass (typically on the order of between 1 and 100 mg m^{-3} chlorophyll-a (chl-a), and up to 350 mg m^{-3} (Gitelson et al., 1993) or higher, especially under "algal scum" conditions (Quibell, 1992)), mineral particles, detritus and CDOM that typically do not co-vary over space and time. Moreover, their optical properties are highly variable between and even within water bodies. These issues have complicated the development of algorithms for inland waters and typically limit their applicability between different water bodies. The continentality of the atmosphere over inland waters and their proximity to the land surface also introduce additional difficulties for atmospheric and adjacency correction procedures and this further impacts the performance of in-water algorithms.

Marine remote sensing research has benefitted from significant investment from space agencies and international funding organisations (e.g., the European Commission (EC)). This funding has supported large, multinational projects on the development and validation of satellite ocean colour products. In contrast, inland water remote sensing has historically been considered mainly a local, national or perhaps regional concern and as such has often fallen between the gaps between funding agencies. The inland water community is smaller in number, more fragmented and less well funded than the ocean colour community, particularly when one considers the number and complexity of the challenges currently faced. Most inland water remote sensing groups are comprised of a small number of scientists and students and historically there has been a lack of coordination and collaboration among these groups at the national or international level. In marine remote sensing, organisations such as the International Ocean-Colour Coordinating Group (IOCCG) fulfil a strategic role in establishing research agendas and coordinating community-wide activities, but until recently the inland water community has had limited representation within such organisations.

The fragmented nature of the inland water remote sensing community and funding has consequently impeded the exchange of skills and expertise across the community and made it more challenging to facilitate shared use of in situ data and other resources necessary to address some of the key challenges and push the science forward. The development and validation of atmospheric and in-water models for optically-complex waters can only be properly advanced through rigorous testing and refinement of candidate algorithms across the full spectrum of optical water types. However, many groups currently only have access to in situ data from a limited range of lakes, and thus validation studies are often biased towards certain optical water types. More comprehensive validation studies can only realistically be achieved through close collaboration and the open exchange of data between international research groups. This argument can be extended to include access to infrastructure, such as fixed moorings for in situ radiometers (e.g., the AERONET-ocean colour (-OC) stations) to support the vicarious calibration and atmospheric correction of satellite data. Currently, there is only a single AERONET-OC station on a lake (Lake Vanern, Sweden), an obvious constraint for atmospheric correction studies over inland waters.

Downing (2014) highlights the isolationism that has existed between limnologists and oceanographers. This extends to the Earth observation community (Bukata, 2013) where historically there has been a notable lack of collaboration between ocean colour and inland water remote sensing scientists. This is, at least in part, a consequence of the nature of research funding, but has limited the exchange of skills and expertise between the two communities. In the last decade or so, some ocean colour scientists have extended their interests from the oceans through the coastal zone to the more optically-complex waters found inland, and in doing so have discovered some methods relatively new to ocean remote sensing which were actually used in inland water remote sensing decades ago (detailed in Bukata, 2013). Unfortunately, a large amount of valuable inland water remote sensing research has also been rather overlooked because it was published in the pre-digital era, and many interesting studies were only published in the grey literature (conference proceedings, PhD theses, etc.) or in electronically inaccessible journals.

More generally, the wider scientific community has been slow to fully recognise the importance of freshwater ecosystems to global-scale processes (e.g., biogeochemical cycling, climate change, maintenance of biodiversity) and the provision of ecosystem services upon which human society relies. Inland waters only comprise a tiny fraction of the Earth's surface water, but it is becoming increasingly clear that they are of disproportionate importance to the global biosphere (Tranvik et al., 2009; Downing, 2014). However, our knowledge of the global status of lakes and their responses to environmental change remains incomplete and there is an urgent need to increase our understanding of the role of lakes in regional- and global-scale processes. The wider adoption of remote sensing observations alongside existing in situ approaches will be crucial to furthering our understanding of the global status and role of inland waters.

1.2. Progress to date

Several recent works have reviewed water constituent retrieval algorithms applied to inland waters using various sensors (Kutser, 2009; Matthews, 2011; Odermatt, Gitelson, Brando, & Schaepman, 2012), an ongoing and major challenge in such optically-complex systems. In this introductory paper, our aim was not to provide an exhaustive review of issues and previous work, but to highlight a few examples from the past to show the particular challenge that inland water remote sensing scientists face and how these challenges have been and are currently being tackled.

In spite of their somewhat limited capabilities, satellite sensors have been used extensively in lake remote sensing for several decades now. Many studies have and continue to exploit the relatively high spatial resolution of sensors intended primarily for land applications. Verdin (1985), for example, used Landsat to retrieve chl-a and Secchi depth in US lakes. Dekker and Peters (1993) assessed Landsat TM capabilities in retrieving various Dutch lake water characteristics (seston dry weight, sum of chl-a and phaeopigments and Secchi depth), although accuracy of the results was found to be limited. Dekker, Vos, and Peters (2001, 2002) obtained reliable total suspended matter (TSM; dry seston weight) retrievals from Landsat and from the Satellite Pour l'Observation de la Terre (SPOT) sensor of the French Centre National d'études Spatiales (CNES). Olmanson, Bauer, and Brezonik (2008) used the Landsat archive for mapping lake water clarity of over 10,000 Minnesota lakes. Tebbs, Remedios, and Harper (2013) mapped high-biomass cyanobacteria blooms in Lake Bogoria using Landsat-derived