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Measuring freshwater aquatic ecosystems: The need for a hyperspectral global mapping satellite mission

Erin Lee Hestir [a,b,*], Vittorio E. Brando [a,c], Mariano Bresciani [c], Claudia Giardino [c], Erica Matta [c], Paolo Villa [c], Arnold G. Dekker [a]

[a] Commonwealth Scientific & Industrial Research Organization (CSIRO), Canberra, Australia
[b] Department of Marine, Earth & Atmospheric Sciences, NC State University, Raleigh, USA
[c] Institute for Electromagnetic Sensing of the Environment (CNR-IREA), Milano, Italy

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ABSTRACT

Freshwater ecosystems underpin global water and food security, yet are some of the most endangered ecosystems in the world because they are particularly vulnerable to land management change and climate variability. The US National Research Council's guidance to NASA regarding missions for the coming decade includes a polar orbiting, global mapping hyperspectral satellite remote sensing mission, the Hyperspectral Infrared Imager (HyspIRI), to make quantitative measurements of ecosystem change. Traditionally, freshwater ecosystems have been challenging to measure with satellite remote sensing because they are small and spatially complex, require high fidelity spectroradiometry, and are best described with biophysical variables derived from high spectral resolution data. In this study, we evaluate the contribution of a hyperspectral global mapping satellite mission to measuring freshwater ecosystems. We demonstrate the need for such a mission, and evaluate the suitability and gaps, through an examination of the measurement resolution issues impacting freshwater ecosystem measurements (spatial, temporal, spectral and radiometric). These are exemplified through three case studies that use remote sensing to characterize a component of freshwater ecosystems that drive primary productivity. The high radiometric quality proposed for the HyspIRI mission makes it uniquely well designed for measuring freshwater ecosystems accurately at moderate to high spatial resolutions. The spatial and spectral resolutions of the HyspIRI mission are well suited for the retrieval of multiple biophysical variables, such as phycocyanin and chlorophyll-a. The effective temporal resolution is suitable for characterizing growing season wetland phenology in temperate regions, but may not be appropriate for tracking algal bloom dynamics, or ecosystem responses to extreme events in monsoonal regions. Global mapping missions provide the systematic, repeated measurements necessary to measure the drivers of freshwater biodiversity change. Archival global mapping missions with open access and free data policies increase end user uptake globally. Overall, an archival, hyperspectral global mapping mission uniquely meets the measurement requirements of multiple end users for freshwater ecosystem science and management.

1. Introduction

1.1. Freshwater ecosystems in the Anthropocene

Increasing pressure for human water, food and energy security make understanding freshwater ecosystem processes and managing sustainable ecosystem services critical. Freshwater is a fundamental resource for human life, and the services provided by surface freshwater ecosystems underpin global water security, food security and economic productivity (Hanjra & Qureshi, 2010). Freshwater ecosystems occur in freshwater systems including lakes, ponds, streams and rivers, and in the wetlands, marshes, swamps and bogs associated with these water bodies. Freshwater systems provide multiple services to both humans and the environment, including 1) provisioning water for consumption, energy, and transportation; 2) cultural amenities such as recreation, tourism and religious significance; 3) maintaining water quality, flood and erosion control; and 4) supporting biodiversity and ecosystem function such as nutrient and carbon cycling and primary production (Aylward et al., 2005).

The intensifying exploitation of freshwater resources to meet the water, energy and food needs of a rapidly growing global population often places biodiversity and other ecosystem functions at risk. The degradation of these services is exacerbated by climate change and variability. Surface freshwaters are among the most anthropogenically modified ecosystems on Earth (Carpenter, Stanley, & Vander Zanden,

* Corresponding author at: Department of Marine, Earth & Atmospheric Sciences, NC State University, Raleigh USA.

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2011), and are exceptionally vulnerable to climate change (Woodward, Perkins, & Brown, 2010). Although freshwater systems occupy a relatively small portion of the Earth's surface (~2–3%; Downing et al., 2006; Raymond et al., 2013), freshwater ecosystems have a disproportionate role in driving global biodiversity and ecological function. Freshwater ecosystems support 10% of the world's animal species, and nearly 35% of all vertebrate species (Stendera et al., 2012). Unfortunately, freshwater ecosystems have the highest rates of biodiversity loss globally, and may be the most endangered ecosystems in the world (Dudgeon et al., 2006).

Freshwater ecosystems are also increasingly recognized as an important factor in the global carbon cycle. Carbon emissions from surface inland waters are estimated to be on the same order of magnitude as carbon emissions from deforestation or carbon uptake from oceans (Tranvik et al., 2009). Yet inland waters are poorly accounted for in global estimates of terrestrial net primary production (Raymond et al., 2013). Wetlands are widely recognized as one of the most important sources of global methane emissions, but also sequester large amounts of carbon dioxide in the soils. The relative role of freshwater ecosystems in the carbon cycle and how that role will change with increasing pressure from human activity and changing climate is poorly understood and requires significant study (e.g., Bridgham, Moore, Richardson, & Roulet, 2014; Mitsch et al., 2013).

1.2. Observation needs

To improve understanding of global freshwater responses to multiple stressors, valid, standardized and accurate data are needed. In collecting data in the field, there are logistical, operational and financial considerations that usually impede freshwater ecosystem measurements. *In situ* measurements and monitoring provide detailed information pertinent to understanding key ecosystem characteristics, forming the basis of long term monitoring records needed to assess status and identify trends. Unfortunately, in situ approaches are limited to point-based representations of complex and dynamic systems. Furthermore, *in situ* measurements in freshwater systems are also limited by logistics such as access, cost and timing, which all restrict systematicity. Satellite remote sensing can complement *in situ* freshwater ecosystem sampling.

The potential of satellite remote sensing for freshwater inventory and monitoring has long been recognized by the scientific community; optical satellite datasets have been used to detect freshwater systems for decades (e.g., Carpenter & Carpenter, 1983; Lulla, 1983; Strong, 1974), as have active remote sensing datasets (Melack, 2004). Stand-alone radar data or radar used in conjunction with optical remote sensing data have been particularly useful for wetland and flood plain detection (Alsdorf et al., 2000; Henderson & Lewis, 2008; Hess, Melack, Novo, Barbosa, & Gastil, 2003; Silva, Costa, & Melack, 2010), lake detection, surface and volume estimates (Crétaux et al., 2011; Strozzi, Wiesmann, Kääb, Joshi, & Mool, 2012). Traditionally, however, satellite remote sensing of freshwater systems has been limited by sensor technology; current and past missions have not provided the measurement resolutions needed to fully resolve freshwater ecosystem properties and processes.

Optical satellite remote sensing of Earth's ecosystems has helped to transform our understanding of ecosystem change (Cohen & Goward, 2004; Wulder, Masek, Cohen, Loveland, & Woodcock, 2012). High spectral resolution (hyperspectral) remote sensing, or imaging spectroscopy, provides measurements across hundreds of discrete bands, forming a contiguous spectrum that enables detection and identification of earth surface materials, which makes quantitative measurements of ecosystem properties and processes surpassing other remote sensing modalities (Bioucas-Dias et al., 2013; Green et al., 1998; Ustin, Roberts, Gamon, Asner, & Green, 2004). Archival, polar orbiting, global mapping satellite missions make systematic measurements over years to decades, providing a time series of consistently measured data to assess system condition, identify change, and understand process for a limited, but important suite of biophysical variables.

Freshwater systems may be small and spatially complex, requiring moderate to small pixel sizes. Discriminating wetland vegetation requires moderate to high spatial and spectral resolutions in both visible and shortwave infrared regions (Hestir et al., 2008). Inferring ecosystem process such as watershed runoff, environmental flows, lake currents and stratification, and inundation processes that drive habitat connectivity, sediment and nutrient discharge, algal blooms, and wetland greenhouse gas emissions from space requires both high spatial and temporal resolutions (Kutser, Metsamaa, Strömbeck, & Vahtmäe, 2006; Song, Xu, Tian, & Wang, 2009). Measuring water column conditions requires satellite measurements to have high spectral resolution and the sensitivity to resolve small changes in water-leaving radiance relative to the noise of the sensor and the atmosphere (i.e., high radiometric resolution and high signal to noise ratio; Hu et al., 2012). Several reviews published over the past decades have summarized the applications, potential and limitations of satellite remote sensing for freshwater systems based on these resolution limitations (Adam, Mutanga, & Rugege, 2010; Carbonneau & Piegay, 2012; Dekker & Hestir, 2012; Heumann, 2011; Klemas, 2013a,b, 2014; Matthews, 2011; Mertes, 2002; Odermatt, Gitelson, Brando, & Schaepman, 2012; Ozesmi & Bauer, 2002).

1.3. The Hyperspectral Infrared Imager (HyspIRI) mission

The United States National Research Council (US NRC) highlights the need for a global mapping satellite mission that deploys an imaging spectrometer to make much needed global observations of ecosystem change (National Research Council, 2007). The US NRC's guidance to NASA recommends the development of the Hyperspectral Infrared Imager (HyspIRI) to address this need. The proposed mission will make optical measurements in over 200 bands in the visible, near and shortwave infrared, and will have multiple thermal infrared bands. HyspIRI is planned to have an equatorial revisit time of ~19 days, with a 60 m pixel resolution (Devred et al., 2013). To the best of our knowledge, there is no other current or planned mission that could deliver archival, regularly repeated measurements with the high spectral and spatial resolutions needed to address freshwater ecosystem science and management challenges. In this study, we evaluate the potential contribution of a hyperspectral global mapping satellite mission to measuring freshwater ecosystems, focusing on passive optical remote sensing in the visible, near and shortwave infrared regions. We demonstrate the need for such a mission, and evaluate the suitability and gaps of such a mission through an examination of the measurement resolution (spatial, temporal, spectral and radiometric), exemplified through three case studies that use remote sensing to characterize a component of freshwater ecosystem primary production.

2. Observing freshwater systems from space

2.1. Freshwater ecology in remote sensing literature

As sensor technologies have improved both in measurement fidelity and spatial and spectral resolutions, the application of remote sensing to freshwater systems has also increased. Since 2000, the portion of aquatic applications in remote sensing publications has shown a significant increasing trend of 4% of the mean portion of remote sensing publications per year (Mann–Kendall test for trend: $\tau = 0.58$, $p = 0.004$; Fig. 1).

2.2. Freshwater resource management and satellite remote sensing products

Based on a survey of US Environmental Protection Agency personnel, Schaeffer et al. (2013) described the primary barriers to water quality managers adopting satellite products. These include 1) actual and perceived cost, both in terms of cost of data and cost for accessing

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