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Multiple Optimal Depth Predictors Analysis (MODPA) for river bathymetry: Findings from spectroradiometry, simulations, and satellite imagery

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ABSTRACT

Remote mapping of bathymetry can play a key role in gaining spatial and temporal insight into fluvial processes, ranging from hydraulics and morphodynamics to habitat conditions. This research introduces Multiple Optimal Depth Predictors Analysis (MODPA), which combines previously developed depth predictors along with additional predictors derived from the intensity component of the HSI color space transformation. MODPA empirically selects a set of optimal predictors among all candidates utilizing partial least squares (PLS), stepwise, or principal component (PC) regression models. The primary focus of this study was on shallow (< 1 m deep) and clearly flowing streams where substrate variability could have a pronounced effect on depth retrieval. Spectroscopic experiments were performed under controlled conditions in a hydraulic laboratory to examine the robustness of bathymetry models with respect to changes in bottom type. Further, simulations from radiative transfer modeling were used to extend the analysis by isolating the effect of inherent optical properties (IOPs) and by investigating the performance of bathymetry models in optically complex and deeper streams. The bathymetry of the Sarca River, a shallow river in the Italian Alps, was mapped using a WorldView-2 (WV-2) image, for which we evaluated the atmospheric compensation (AComp) product. Results indicated the greater robustness of multiple-predictor models particularly MODPA rather than single-predictor models, such as Optimal Band Ratio Analysis (OBRA), with respect to heterogeneity of bottom types, IOPs, and atmospheric effects. The HSI intensity component enhanced the accuracy of depth retrieval, particularly in optically-complex waters and also for low spectral resolution imagery (e.g., GeoEye). Further, the enhanced spectral resolution of WV-2 imagery improved bathymetry retrieval compared to 4-band GeoEye data.

1. Introduction

Remote sensing techniques provide an alternative to traditional field-based measurements and have the potential to enhance our understanding of fluvial systems by providing spatially and temporally explicit information (Marcus and Fonstad, 2008; Carbonneau et al., 2012; Legleiter and Overstreet, 2012; Niroumand-Jadidi and Vitti, 2016; Shintani and Fonstad, 2017; Niroumand-Jadidi and Vitti, 2017a). The recent integration of remote sensing and river sciences has emerged as a growing research field termed “fluvial remote sensing” (Marcus and Fonstad, 2010; Carbonneau et al., 2012). Advancements in sensors, such as water-penetrating, green-wavelength light detection and ranging (LiDAR), or platforms, such as unmanned aerial vehicles (UAVs), have recently provided new tools for characterizing fluvial systems (Kinzel et al., 2013; Flener et al., 2013; Shintani and Fonstad, 2017). However, green LiDAR observations are mainly feasible by means of low-altitude platforms (e.g., manned aircrafts), which leads to a lower spatial and temporal coverage compared to optical sensing by means of satellites. Furthermore, the application of green LiDAR in riverine environments is hindered by low point density of observations and also the confusion among laser returns from the water surface, water column, and riverbed (Legleiter and Overstreet, 2012; Kinzel et al., 2013). UAVs offer the potential for higher spatial and temporal resolution, but at the cost of spatial coverage. In this context, passive optical remote sensing aboard airborne and spaceborne platforms remains a broadly applicable means of characterizing a wide range of attributes in fluvial systems, including bathymetry (Legleiter and Overstreet, 2012; Niroumand-Jadidi and Vitti, 2016), substrate type

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and composition (Legleiter et al., 2016b), grain size (Carbonneau et al., 2004; Niroumand-Jadidi and Vitti, 2017b), and hydromorphological units (Legleiter et al., 2004).

Bathymetry is one of the key applications of remote sensing to fluvial systems that facilitates understanding river form, process, and function (Shintani and Fonstad, 2017). Information on water depth can play a valuable role in mapping in-stream habitats (Carbonneau et al., 2012; Hugue et al., 2016), parameterization and analysis of hydromorphological processes (Bryant and Gilvear, 1999; Flener et al., 2012), and river management (Fonstad and Marcus, 2005; Legleiter and Overstreet, 2012). Optical sensors onboard aerial and satellite platforms have long been used for studying shallow coastal environments (Lyzenga, 1978; Lyzenga, 1981; Philpot, 1989; Dierssen et al., 2003; Louchard et al., 2003; Lesser and Mobley, 2007). Because of their smaller spatial scales, fluvial systems have mostly utilized aerial imagery to derive bathymetric data (Winterbottom and Gilvear, 1997; Jordan and Fonstad, 2005; Walther et al., 2011; Legleiter, 2013). With recent enhancements in spatial resolution of satellite imagery, mapping river bathymetry from space is receiving more interest due to larger spatial coverage and higher temporal resolution of satellite sensors than those onboard aerial platforms. Legleiter and Overstreet (2012) performed a feasibility assessment of mapping the bathymetry of gravel-bed rivers from space using WorldView-2 (WV-2) imagery.

The theoretical basis for optical remote sensing of bathymetry in riverine environments is built upon research conducted in optically shallow coastal environments (Legleiter et al., 2004; Legleiter et al., 2009). Bathymetric techniques fall into two main approaches: through-water photogrammetry (Fryer, 1983; Westaway et al., 2001) and spectrally based analysis (Lyzenga, 1978; Lee et al., 1998). Through-water photogrammetry utilizes stereo imagery to produce a digital elevation model by accounting for refraction of light at the air-water interface (Westaway et al., 2001; Lane et al., 2010). One particular type of photogrammetric approach known as Structure from Motion (SfM) has received growing interest for measuring bathymetry and characterizing riverbed topography (Woodget et al., 2015; Dietrich, 2017). SfM is capable of reconstructing three-dimensional geometry using multiple overlapping images taken from a wide range of angles (Shintani and Fonstad, 2017). Spectrally based approaches to deriving bathymetric data can be divided into physics-based and empirical models (Brando et al., 2009; Dekker et al., 2011). The first rely on inversion of radiative transfer models and account for the physics of how light interacts with the water surface, water-column, and bottom (Lee et al., 1998; Lee et al., 1999; Lesser and Mobley, 2007; Brando et al., 2009), while the latter provide regression-based predictions of bathymetry (Lyzenga, 1978; Philpot, 1989).

The seminal work of Lyzenga (1978, 1981) provides a basis for empirical retrieval of water depths from optical imagery, which was the focus of this research. Lyzenga's model assumes a linear relation between an image-derived quantity (X) and the water depth (d), where X is a predictor obtained from log-transformation of image values in a given spectral band. Multiple regression (Lyzenga, 1985; Lyzenga et al., 2006) and ratio methods (Stumpf et al., 2003) have been demonstrated to enhance the robustness of bathymetry retrieval with respect to substrate variability and water quality heterogeneity. The first employs multiple spectral bands to perform a multiple linear regression between image-derived predictors (X) and water depths (d) while the latter model considers a log-transformed band ratio as a single predictor of water depth. More recently, Optimal Band Ratio Analysis (OBRA) was introduced to identify the pair of bands, among all possible pairs, for which the ratio model yields the strongest correlation with water depth (Legleiter et al., 2009). Each of these types of predictors has been reported as optimal in different case studies (Legleiter and Overstreet, 2012; Bramante et al., 2013; Jawak and Luis, 2016).

Further development of new techniques is required to systematically select and combine a set of predictors that provide robust retrievals in the presence of all the complicating factors that might impact depth retrieval (e.g., variations in bottom types, IOPs and water-surface roughness). We pursued five main objectives in this study:

(1) Developing a new approach called Multiple Optimal Depth Predictors Analysis (MODPA) for bathymetry retrieval. This method seeks to identify and incorporate optimal depth predictors among all the possible Lyzenga and ratio predictors as well as additional predictors from color space transformation. The selection of optimal predictors was performed using several feature selection methods including stepwise, partial least square (PLS), and principal component (PC) regressions;
(2) Assessing the robustness of the proposed MODPA compared to existing models with respect to heterogeneity in substrate types, IOPs, and atmospheric effects. Bathymetry models were comprehensively examined using spectroscopic experiments, radiative transfer simulations, and WV-2 imagery. The spectroscopic experiments were conducted under controlled conditions in a hydraulic laboratory and involved collecting a set of spectra in a range of water depths with variable substrates. The effects of IOPs, as influenced by chlorophyll-a (Chl-a), suspended sediment concentration (SSC), and colored dissolved organic matter (CDOM), were isolated using the simulated data. Moreover, we considered an optically complex testing scenario where bottom type and IOPs were both allowed to vary;
(3) Examining the performance of the proposed MODPA method for bathymetry mapping of the Sarca River, a shallow and narrow alpine river in Italy, using WV-2 imagery. This analysis quantified the effectiveness of MODPA compared to other models in the spectrally complex environment of a real case study. Different strategies were considered for the validation of results including an approach built upon comparison of image-derived depths with the estimates based on principles of river hydraulics;
(4) Assessing the effect of atmospheric correction on bathymetry retrieval of the Sarca River, which is an important consideration due to the low reflectivity of water bodies and accordingly sizable contribution of the atmosphere to the total at sensor radiance (Gitelson and Kondratyev, 1991; Mouw et al., 2015). The newly released surface reflectance product of DigitalGlobe (2016), called atmospheric compensation (AComp), was assessed to understand the robustness of bathymetric models with respect to atmospheric effects;
(5) Assessing the efficacy of WV-2 sensor's additional spectral bands compared to traditional high resolution satellite imagery (HRSI, < 5 m pixel size) with only four bands such as GeoEye.

2. Bathymetry from optical imagery

In the context of optical remote sensing of water bodies, the total radiance reaching the sensor at a given wavelength λ, $L_T(\lambda)$, consists of four main components: upwelling radiances from the bottom, $L_b(\lambda)$, water column, $L_c(\lambda)$, and surface of the water body, $L_s(\lambda)$, as well as the atmospheric path radiance, $L_p(\lambda)$. These components are summarized in the following equation (Legleiter et al., 2004; Legleiter et al., 2009):

$$L_T(\lambda) = L_b(\lambda) + L_c(\lambda) + L_s(\lambda) + L_p(\lambda) \tag{1}$$

Aside from $L_p(\lambda)$, each of these radiance components can be associated with a specific property of the water body. For instance, the surface-reflected component of the radiance can be linked to the roughness of the water surface, which in turn is a function of local hydraulics in riverine environments and can potentially reveal information about flow velocity (Overstreet and Legleiter, 2017; Legleiter et al., 2017). Information on bathymetry is embedded in the bottom-reflected radiance component, which is affected not only by water depth but also by bottom type and indirectly by water column optical properties (Lee et al., 1998; Stumpf et al., 2003; Legleiter et al., 2009). Thus, it is essential to isolate the radiance component of interest or to