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Spectral similarity approach for mapping turbidity of an inland waterbody

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ABSTRACT

Turbidity is an important quality parameter of water from its optical property point of view. It varies spatio-temporally over large waterbodies and its well distributed measurement on field is tedious and time consuming. Generally, normalized difference turbidity index (NDTI), or band ratio, or regression analysis between turbidity concentration and band reflectance, approaches have been adapted to retrieve turbidity using multispectral remote sensing data. These techniques usually provide qualitative rather than quantitative estimates of turbidity. However, in the present study, spectral similarity analysis, between the spectral characteristics of spaceborne hyperspectral remote sensing data and spectral library generated on field, was carried out to quantify turbidity in the part of Chilika Lake, Odisha, India. Spatial spectral contextual image analysis, spectral angle mapper (SAM) technique was evaluated for the same. The SAM spectral matching technique has been widely used in geological application (mineral mapping), however, the application of this kind of techniques is limited in water quality studies due to non-availability of reference spectral libraries. A spectral library was generated on field for the different concentrations of turbidity using well calibrated instruments like field spectro-radiometer, turbidity meter and hand held global positioning system. The field spectra were classified into 7 classes of turbidity concentration as <5, 5–10, 10–15, 15–25, 25–45, 45–100 and >100 NTU for analysis. Analysis reveal that at each location in the lake under consideration, the field spectra matched with the image spectra with SAM score of 0.8 and more. The observed turbidity at each location was also very much falling in the estimated turbidity class range. It was observed that the spectral similarity approach provides more quantitative estimate of turbidity as compared to NDTI.

1. Introduction

The streams and rivers bring large amount of sediments along with them to inland surface or coastal waters, which in turn indicates erosion and related problems in the upstream river basin, worldwide (Amos and Mosher, 1985; Ritchie et al., 1987; Ritchie and Cooper, 1988; Choubey and Subramanian, 1992; Schiebe et al., 1992). More sediments and their deposition in waterbody may damage instruments installed in the hydraulic structures, reduce the useful life of the reservoir, increase the cost of water treatment (Bhargava and Mariam, 1990). Most importantly, the presence of sediments alter the inherent optical properties (IOPs) of the entire water column such as absorption, backscattering, downwelling irradiance and the angular distribution. This may affect the quantity and spectral quality of energy/light reflected from/absorbed by the water surface (Jerlov, 1976; Kirk, 1983; Ritchie et al., 2003; Cannizzaro and Carder, 2006; Wu et al., 2014). Moreover, the change in light attenuation by water column may deteriorate aquatic life and primary productivity, as well as the growth of aquatic vegetation (Ritchie et al., 2003; Wang et al., 2007; Birtwell et al., 2008; Zhang et al., 2010; Wu et al., 2014). Therefore, regular monitoring of surface waters is critical for maintaining and improving its quality. Hitherto, the water quality is being assessed by in-situ measurements and laboratory analysis of samples collected. These point measurements may be accurate for particular location at particular time, but, they do not provide spatio-temporal information needed for better assessment of water quality from management point of view. As remote sensing can easily detect the changes in the backscattering characteristics of the surface water and provide synoptic coverage, it has received widespread attention in the field of water quality

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monitoring (Quibell, 1991; Gitelson et al., 1993; Han and Rundquist, 1996; Ritchie et al., 2003; Zhang et al., 2010). The most common and optically sensitive water constituents namely turbidity and total suspended solids (TSS) have been usually estimated using remote sensing data (Hinton, 1991; Millie et al., 1995; Aguirre-Gomez, 2000; Kratzer et al., 2000; Doxaran et al., 2002; Tyler et al., 2006; Teodoro et al., 2008; Olmanson et al., 2013; Papoutsa et al., 2014).

Numerous studies have been carried out on water quality assessment and monitoring using remotely sensed data. These studies may be categorized into three types of models (i) the most simple empirical models, developed based on relationship between the backscattering characteristics of water surface and concentration of particular water quality parameter (Tassan, 1993; O'Reilly et al., 1998; Yuan et al., 2001; Deng and Li, 2003; Miller and McKee, 2004; Han et al., 2006; Zhou et al., 2006; Chen et al., 2007; Pavelsky and Smith, 2009; Chawira et al., 2013). For the development of these models, simple regression analysis to complex data driven models (Artificial Neural Networks) are being used. These models are easy to implement, but, they lack physics of the underlying process. Moreover, these developed models do not have general applicability as they are site specific in nature. (ii) another similar class of model belongs to band ratio technique, in this approach, the most sensitive bands, with respect to particular water component, are identified and then ratio between the bands are being taken to enhance the satellite image for that particular component concentration. Normalized Difference Turbidity Index (NDTI) for example, has been used for qualitative estimates of turbidity in inland waterbodies around the globe (Lacaux et al., 2007; Gardelle et al., 2010). (iii) Another technique called the semi-analytical models, uses the IOPs of water are being assessed through radiative transfer theory or more sophisticated instruments and later, empirical relationships are being established between these IOPs and water component using simple regression or soft computing techniques (Doerffer and Fischer, 1994; Carder et al., 1999; Dekker et al., 2001; Warrick et al., 2004; Cannizzaro and Carder, 2006; Morel et al., 2007; Wang et al., 2007; Zhang et al., 2010). These techniques have extensively been used for coastal/marine waters, however, their application to inland surface waters is limited due to non-availability of high spatial and spectral resolution remote sensing data. Mostly, multispectral remote sensing data have been utilized in these models which results in reasonable accuracy. However, with the advancement in sensor technology and emergence of imaging spectroscopy (hyperspectral remote sensing), the results of these techniques improved, as the imaging spectro-radiometers acquire image data in many narrow contiguous spectral bands (Plaza et al., 2009). The technique enables the mapping of surface constituents having diagnostic absorption features of even 20–40 nm width (Van der Meer, 2006).

However, in the present study, an image classification technique, based on spectral similarity between continuous spectra of hyperspectral remote sensing image and field spectral library generated for different concentrations of turbidity using field spectroradiometer, has been adopted for spatial quantification of the turbidity concentration in Chilika Lake, Odisha, India. This technique has been usually used to map minerals using hyperspectral remote sensing data (Van der Meer and de Jong, 2000; Van der Meer, 2006). Its application in the field of water quality studies is constrained by the availability of reference spectral library of different components with varying concentration (Mannheim et al., 2004; Osin'ska-Skotak et al., 2007; Santini et al., 2010; Yu et al., 2010; Zhu and Yu, 2013; Zhu et al., 2013; Wu et al., 2014; Kar et al., 2016). Here, an attempt has been made to develop a spectral library and its application on hyperspectral remote sensing data to classify water with regards to different concentrations of turbidity. The results of turbidity mapping are very encouraging as compared to NDTI band ratio approach. It was also realized that the developed spectral library may also be utilized for mapping the water quality of inland waterbody using hyperspectral remote sensing data of any date.

2. Study area

The coastal lagoons, located at the interface of rivers and sea, are one of the most productive, complex and dynamic ecosystems (Srichandan et al., 2015). Such ecosystems experience steep change in their bio-physical and chemical properties due to the mixing of fresh river water flow from one side and sea water intrusion from other (Srichandan et al., 2015). Chilika Lake, the largest coastal lagoon in India and the second largest lagoon in the world with width of 20 km and length of around 64 km has been selected as study site. It is a brackish water lagoon, spread over the Puri, Khurda and Ganjam districts of Odisha state on the east coast of India, covering an area of over 1,100 km^2 as shown in Fig. 1.

The frequent change in physico–chemical properties and their interaction with each other in Chilika Lake makes it a unique experimental site (Muduli et al., 2012, 2013). In 1981, Chilika Lake was designated as the first Indian wetland of international importance under the Ramsar Convention. At the northern end, tributaries of the Mahanadi River, such as Daya, Nuna and Bhargavi join the lagoon and are responsible for the large fresh water and sediment flux to the lagoon. The lagoon is separated from the Bay of Bengal by sand bar of 60 km length. The lagoon is connected to the Bay of Bengal through three inlet mouths, these are (i) the artificially dredged mouth near Sippakuda (Satapara), (ii) naturally opened mouth just 2 km north of dredged mouth at Gabbakunda during August 2008 and (iii) through Palur canal in southern sector.

The climate of the region is tropical, with two dominant seasons defined in terms of wind patterns i.e., Southwest monsoon from June to September and Northeast monsoon from November to February; with an average annual rainfall of 1239 mm and 72 rainy days. The water quality of the lagoon changes widely with onset of different seasons and exhibits different ecological characteristics in localized pockets. The water of Daya, Bhargavi, Luna and Makara rivers contributes major portion (66%) of fresh water discharge (Muduli et al., 2013). The Chilika Development Authority's (CDA) physico–chemical investigations indicate highly turbid water due to strong mixing of overlying water with sediments, the transparency values ranging between 8 and 117 cm (Mahapatro et al., 2012). It has been also reported that the total sediment load discharged into the lagoon has increased from 1.8 M tones in 1998 to 2.94 M tones in 2001 (Panigrahi et al., 2007). This highly productive ecosystem with its rich fishery resources sustains the livelihood of around 1.5 million fishermen who live in 132 villages on the shore and islands in the Lagoon (Ramesh et al., 2011).

3. Methodology

Considering the importance of the Chilika Lake, an attempt has been made to map its water quality with regard to turbidity using high spatial and spectral resolution hyperspectral remote sensing data. In the present analysis, to understand the capabilities of spectral similarity approach in the field of water quality studies, the Earth Observing – 1 (EO-1) Hyperion (Path: 140, Row: 46) hyperspectral remote sensing data of March 08, 2016 has been utilized. The Hyperion image consists of 220 spectral bands ranging from 400 to 2500 nm wavelength with a high spatial resolution of 30 m. A Hyperion image covers an area of 7.5 $\times$ 100 km, and provide detailed spectral mapping across all 220 channels at