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Improving river water quality monitoring using satellite data products and a genetic algorithm processing approach

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A B S T R A C T

Adequate river quality monitoring is of major importance for riverine environmental sustainability. This study develops a methodology for real-time water quality measurement in a river at 30 m spatial and 1 day temporal scales using the satellite remote sensing technique to support daily water quality monitoring usually done at gauges. Considering the limited spatio-temporal resolutions of all the current satellite products, this study integrates the corrected band-specific Landsat and Moderate-resolution Imaging Spectroradiometer (MODIS) surface reflectance values, identified by a physically-based approach, with the observed pollutant concentrations. A combination of regression analysis and genetic algorithm (GA) based multivariate nonlinear formulations among the Landsat *versus* MODIS surface reflectances and Landsat surface reflectance *versus in-situ* pollutant concentration is used to estimate eight water quality parameters. All the possible combinations of the Landsat and MODIS satellite bands containing the spectral signature of pollutants are selected as independent variables. Linear and nonlinear regression analysis is carried out for these combinations using the SPSS software to get the best (significant) correlated relations which are, further, enhanced using the GA. This formulation is applied and tested in the Brahmani River located in eastern India's Odisha state for its real-time application; and water quality mapping is carried out for a typical river reach of the Brahmani River. A Monte-Carlo simulation based uncertainty and sensitivity analysis of the used algorithms reveal that the methods have the potential to be used in ungauged river reaches.

1. Introduction

For environmental pollution control and policy planning for contaminated site management, there is a need of river water quality data at various spatio-temporal scales. Human activities and uses, such as, settling, industrialization, agriculture etc. cause point and nonpoint source pollution and deteriorate the water quality ecosystems (Reinhardt et al., 2010; Vignolo et al., 2006). Hence, for operational management of wastewater facilities and sectoral water supply from riverine sources, measurement of the physical, chemical and biological conditions of river water at finer spatio-temporal scales is of paramount importance (Vignolo et al., 2006). Generally, for water quality measurement, different environmental and government agencies use gauges, laboratory analysis, digital in-situ sensing, and remote sensing based methods. However, the number stations are reducing world-wide (Ullrich and Volk, 2010; Volk et al., 2009; BendeMichl et al., 2011) because the

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water quality networks are too expensive to maintain. The usual conventional sampling techniques often fail to characterize the solute dynamics at finer temporal and spatial scales due to human activities of storm water disposal in the water body (Reinhardt et al., 2010).

During the last two decades, remote sensing methods are used for water quality study, since it can cover larger area of water body (Ritchie et al., 2003). In principle, remote sensing method approaches use different optical/thermal sensors to gather information, which are extracted by processing the acquired images. The pollutants influence the thermal and optical properties of surface water by changing the reflected energy spectra or by emitting thermal radiation from it (Ritchie et al., 2003). The distribution of heavy metal concentration in water is controlled by suspended sediments, phytoplankton and dissolved organic matters which change the optical properties of water. Hence, the heavy metal concentration is well correlated with the spectral properties of water (Chen et al., 2010). Initially, the Nimbus-7 satellite based Coastal Zone Color Scanner (CZCS) was developed to measure the chlorophyll concentration in oceans (Gons et al., 2002). However, the coarse spatial, temporal and spectral resolutions and data accessibility limits the use of remote sensing in monitoring water quality parameters to lakes or inland waters (Miller et al., 2005; Doxaran et al., 2002). Similarly, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellites have a spatial resolution of 1 km which is being used to monitor water quality in large water bodies (Hooker and McClain, 2000); and cannot be used to monitor river water quality.

In recent years, the spatial and temporal resolution and number of satellites has increased, and hence, these satellites can now also be used for the water quality study in the lakes and wide rivers to estimate the pollutant concentration of Chlorophyll, vegetation fluorescence, weed growth, total suspended solids, Secchi disk depth, turbidity, absorption by colored dissolved organic matter and phycocyanin (e.g., Odermatt et al., 2012; Matthews, 2011; Guanter et al., 2010; Swenson and Wahr, 2009; Cavalli et al., 2009; Chavula et al., 2009; Gons et al., 2008). Conversely, the coarse resolution and high-cost of the European Medium Resolution Imaging Spectrometer (MERIS) satellite products restricts their extensive use in many developing and developed countries. In contrast, due to daily revisit period and free-availability of the MODerate-resolution Imaging Spectroradiometer (MODIS), it is widely used to measure water quality parameters. Both the 'Terra' and 'Aqua' spacecraft of MODIS satellite are sun-synchronous and collect emitted and reflected energy in 36 spectral bands, of which, the first and second bands have a minimum spatial resolution of 250 m. Hence, these two bands can be used in small to medium rivers. The MODIS-aqua 645 nm band of 250 m spatial resolution provides the feasibility for monitoring water quality and biological elements (Chen et al., 2007; Wong et al., 2007; Dall'Olmo et al., 2005; Hu et al., 2004; Miller and Mckee, 2004), which is extensively applied in developing models for the estimation of concentration of total suspended matter (TSM), turbidity and Chlorophyll (Feng et al., 2014; Petus et al., 2014; Son and Wang, 2012; Wang et al., 2011; Shi and Wang, 2010; Werdell et al., 2009; Chavula et al., 2009; Chen et al., 2007). The study by Chen et al. (2010) reveals that the heavy metals like Cu, Pb and Zn have the highest correlation with the bands of central wavelength 711 nm, 671 nm and 771 nm, respectively. Subsequently, Chen et al. (2012) derived logarithmic relations between the Landsat TM satellite's surface reflectance (bands 1–4) and heavy metal concentrations in the Pearl River Estuary. Liu et al. (2013a,b) used the MERIS satellite reflectance data to study Zn in this estuary. Cheng et al. (2015) also studied lake-scale heavy metals (Cu, Zn, Pb and Cd) using the surface reflectance of MODIS bands of 1000 m spatial resolution through regression analysis.

The Landsat satellite image is widely used due to its medium spatial resolution (30 m), temporal resolution (16 days) and free-availability. Landsat is used for water quality monitoring of lakes and large water bodies to estimate the concentrations of chlorophyll-a (chl-a), sechhi-disk-depth (SDD), total phosphorous, turbidity, and dissolved solids (Guan et al., 2011; Olmanson et al., 2008; Peckham and Lillesand, 2006). However, the 16 days revisit period of this satellite restricts the daily monitoring of river water quality which is a great challenge now-a-days. Hence, it is evident that the remote sensing-based Landsat products are rarely used for water quality monitoring in rivers and small-width streams due to their coarser spatial resolutions and longer revisit periods.

To address the above limitations, in this study, an approach is advocated by coupling the spectral reflectance of low-spatial (250 m) and high-temporal (1 day) MODIS satellite with the high-spatial (30 m) and low-temporal (16 days) Landsat satellite to obtain the solute concentrations which could be applied at a 1 day temporal and 250 m spatial scales in the river. To achieve this, genetic algorithm (GA) based relations between the reflectance values of Landsat and MODIS satellites; between the reflectance values of Landsat and observed pollutant concentrations; and between the reflectance values of MODIS and observed pollutant concentrations are established. These formulations are evaluated through the sensitivity and uncertainty analysis of inputs, outputs and GA-based daily-scale water quality models. The developed models between Landsat surface reflectance and pollutant concentrations are validated using the 2250 number of laboratory-based water quality datasets at 25 gauging stations of the Brahamani River in the eastern India, which is one of the most polluted rivers, caused due to rapid industrial, mining, urban and agricultural development.

The paper is organized as follows. Section 2 describes the methodology details adopted in this study; Section 3 presents the study area and data processing; Section 4 describes the results and discussion; Section 5 proposes the environment sustainability issues for addressing heavy metal water pollution; and Section 6 concludes the study.

2. Methodology

This section describes the methodologies in details with four Sections in which Section 2.1 develops a physics-based approach to identify the Landsat spectral bands which carry the spectral signature of the heavy metals. Section 2.2 mentions

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