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Research article

Empirical estimation of suspended solids concentration in the Indus Delta Region using Landsat-7 ETM+ imagery

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ABSTRACT

Suspended Solids Concentration (SSC) in water is related to its quality and transparency. Satellite remote sensing has proven to be an efficient means of monitoring water quality in large deltas because in situ sampling methods are costly, laborious, time consuming, and spatially constrained. In this study, the potential of Landsat's Enhanced Thematic Mapper Plus (ETM+) sensor was explored to develop a model for remote sensing-based quantification of SSC within the large, turbid Indus Delta Region (IDR, south of Pakistan). Six scenes were atmospherically corrected using the Dark Object Subtraction (DOS) method, to formulate a model for monitoring water quality of the IDR. An empirical model was developed and validated using in situ SSC measurements (9.4–761.4 mg/L) from several data collection campaigns coinciding (within an 11-day window) with satellite overpasses. It was found that using Band 1 (blue: 450–520 nm), Band 2 (green: 520–600 nm), Band 3 (red: 630–690 nm), and Band 5 (shortwave infrared: 1550–1750 nm) of Landsat-7 ETM + along with the Normalized Difference Suspended Sediment Index (NDSSI) can help in precise and accurate estimation of SSC, resulting in a relatively small Root Mean Square Error of 67.24 mg/L, Mean Absolute Error of 54.75 mg/L, and coefficient of determination of 0.88. Further, it was also evident that residuals do not increase with an increasing time window (0–11 days) between the satellite overpass and in situ data collection. Therefore, the established algorithm can potentially be used for frequent (after 8 days) synoptic mapping of SSC in the IDR and other similar estuarine environments.

1. Introduction

Estuarine water systems are one of the most sensitive and productive aquatic environments in the world (Lansing et al., 1998), and are often under pressure because of anthropogenic activities such as land reclamation and dredging. Thus, there is an increase in the Suspended Solids Concentration (SSC) in deltas and their neighboring waters, which ultimately affects marine ecosystems. Besides anthropogenic activities, rivers are the main source of sediment deposition along estuarine plains (Syvitski et al., 2013). About 18 × 10^9 tons per annum of total suspended sediments are deposited globally by rivers, and 80% of this sediment load is attributed to Southern Asia alone (Chakrapani, 2005). Furthermore, sediments are necessary for the development of aquatic ecosystems as they introduce a variety of minerals, nutrients, and organic matter. Therefore, a decrease in the amount of suspended sediments may lead to degradation of an ecosystem (Bian et al., 2010). However, it should be noted that while sediment input is important for aquatic habitat growth, it can cause environmental issues (e.g., closure of a harbor) if the deposition rates are too high (Grashorn et al., 2015). Therefore, monitoring of SSC in deltas and their adjacent coastal waters is of importance for a variety of applications dedicated to coastal management, which are often linked to an economic interest (Brommer and Bochev-van der Burgh, 2009). This includes studies aiming to evaluate the impact of human activities on sediment transport (e.g., dam construction, installation of offshore wind farms, and sand extraction; Panagopoulos et al., 2008), downstream sedimentation (O'Flynn et al., 2013), and coastal geomorphological processes (e.g., accretion and erosion occurring in a coastal region; (Baker et al., 2011). Monitoring the

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dynamics of SSC in response to natural (river discharges, tidal currents, and waves) and/or anthropogenic forces is very important for optimizing human efforts to increase ecosystem sustainability of an estuarine region (Morton, 2003).

In situ monitoring of SSC is challenging, as concentration values are spatially heterogeneous in a large estuarine region (Guang et al., 2006). Satellite remote sensing has played a significant role in accomplishing efficient monitoring of SSC, by helping researchers to estimate these concentrations in different geographical locations around the globe (Binding et al., 2005; Butt and Nazeer, 2015; Gao et al., 2015; Han et al., 2016; Lyu et al., 2015; Nazeer et al., 2017b; Nazeer and Nichol, 2015; Wang and Lu, 2010; Wang and Jiang, 2008).

Remote sensing of water quality variables involves the analysis of the inherent optical components of the water-leaving reflectance following removal of environmental effects. The spectral shape and magnitude of the corrected water-leaving reflectance are of interest. The observed signal consists of the signal from the optically active components of the water and surface reflected glint, as well as bottom reflectance in shallow waters. Using the classical optical oceanography approach of water body classification, in Case 1 waters (open ocean), chlorophyll-a (Chl-a) and water are the major components contributing to the observed signal. In Case 2 (inland waters), the corresponding elements are Chl-a, SSC, colored dissolved organic matter (CDOM), and the water itself. Case 2 waters are considered optically complex waters because of the presence of these other components that make it challenging to develop algorithms for predicting water quality variables (Nazeer et al., 2017a). The absorption by water in Case 1 is higher than in Case 2 in the near-infrared (NIR) and short-wavelength infrared (SWIR) spectra due to the presence of scattering particulate material (IOCCG, 2000; Mobley et al., 2004; Morel and Prieur, 1977).

Consequently, different wavebands have been suggested for the estimation of SSC in several studies (Table 1). A study on different concentrations of suspended solids by Chen et al. (2004) found a logarithmic relationship between SSC and wavebands in the range of 450–700 nm, and a linear relationship from 700 to 1015 nm. Hence, it is advantageous to use remote sensing as a tool for the estimation of coastal/estuarine water quality monitoring in areas where data are scarce, such as developing countries such as Pakistan. So far, no study has devised a remote sensing-based model for the estimation and monitoring of the SSC in the Indus Delta Region (IDR). Therefore, this study aims to develop a remote sensing-based empirical model for the quantification of SSC in the IDR, using the relatively higher spatial resolution (30 m) Landsat-7 (L7) Enhanced Thematic Mapper Plus (ETM+) imagery as opposed to other sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS, 250 m).

2. Study area and data used

2.1. Study area

IDR is an economic hub for Pakistan, with the Indus River being the major river flowing through the territory (Zia et al., 2017) (Fig. 1). The Indus River has an approximate length of 3180 km. It starts from the west of Tibet and flows to the Arabian Sea (south of Pakistan) where it forms the IDR, covering an area of about 17,000 km^2 (Syvitski et al., 2013). The IDR receives 22 creeks, including the Phitti, Waddi Khuddi, Dabbo, Hajambro, Khobar, Wari, Khar, Keti Bunder, and Chann Creeks. Among all these creeks, Khobar is the main creek that connects the Indus River to the Arabian Sea/Indian Ocean. After the construction of dams and barrages, the amount of sediment delivered to the IDR region has significantly decreased, resulting in environmental imbalances such as pollution, soil erosion, change of river direction, and deforestation (Giosan et al., 2006).

2.2. In situ Suspended Solids Concentration (SSC) data

The in situ SSC data used in this study (Fig. 1) were provided by the National Institute of Oceanography (NIO) of Pakistan. In situ data were collected during different data collection campaigns in 2001, 2002, 2005, and 2016 (Table 2). At each sampling location, surface water was sampled in clean, plastic gallon-sized containers from various locations in the IDR, and were later filtered for estimation of SSC using the gravimetric method to measure the concentration of total suspended solids (Pavanelli and Bigi, 2005). First, the weight of a dried Whatman GF/F glass microfiber 47 mm filter was noted. Next, sampled water was passed through the weighed dried filter attached to a water vacuum pump apparatus until the filter got clogged. The volume of the filtered water was recorded, and the choked filter was again weighed after autoclaving it overnight at temperatures of 103–105 °C in an oven. The weight of the suspended solids was calculated as the difference between the initial and final weights of the dried filters. This value was then divided by the volume of filtered water to obtain SSC in mg/L. A separate glass microfiber filter was used to calculate the SSC for each sampling location.

2.3. Satellite data

Since its launch in February 2013, Landsat 8 (L8) has proven to have many advantages over L7 for the monitoring of coastal/inland waters, such as utilization of the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) onboard instruments, and the absence of Scan Line Corrector (SLC) failure (Chander et al., 2009).

Table 1
Previous studies for the estimation of SSC using satellite remote sensing over different regions.

Reference	Wavelength(s) used (nm)	Sensor used	Region
Binding et al. (2005)	665	AVHRR	Irish Sea
D'Sa et al. (2007)	555 and 670	SeaWiFS	Gulf of Mexico
Ma and Dai (2005)	485 and 835	L7 ETM+	Taihu Lake, China
Aquino da Silva et al. (2015)	560 and 660	CBERS 2B and L5 TM	Parnaíba River, Brazil
Asadpour et al. (2012)	485, 565 and 655 nm	THEOS	Penang Island, Malaysia
Qiu (2013)	551, 555, 560, 678, 680 and 705	MODIS, MERIS and GOCI	Yellow River Estuary, China
Zhou et al. (2006)	660	L5 TM	Taihu Lake, China

AVHRR (Advanced Very High-Resolution Radiometer), SeaWiFS (Sea-Viewing Wide Field-of-View Sensor), L7 ETM+ (Landsat 7 Enhanced Thematic Mapper Plus), CBERS (China–Brazil Earth Resources Satellite), L5 TM (Landsat 5 Thematic Mapper), THEOS (Thailand Earth Observation Satellite), MODIS (Moderate Resolution Imaging Spectroradiometer), MERIS (Medium Resolution Imaging Spectrometer), GOCI (Geostationary Ocean Color Imager).