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Assessment of trophic state and water quality of coastal-inland lakes based on Fuzzy Inference System

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ABSTRACT

Accurate assessment and monitoring of coastal and inland water quality by satellite optical remote sensing is challenging due to improper atmospheric correction algorithm, inaccurate quantification of in-water constituents' concentration and a lack of efficient models to predict the water quality status. The present study aims to address the latter two parts in conjugation with an appropriate atmospheric correction algorithm to assess trophic status and water quality conditions of two coastal lagoons using Landsat-8 OLI data. Three vital underwater light attenuating factors, directly related to water quality, are considered namely, turbidity, chlorophyll and colored dissolved organic matter (a_{CDOM}). These water quality parameters are quantified based on certain sensitive normalised water-leaving radiance band ratios and threshold values. To assess the accuracy of the derived products, these algorithms were applied to independent in-situ data and statistical evaluation of the results showed good agreement between the estimated and measured values with the errors within desirable limits. Being a primary nutrient indicator, the chlorophyll concentration was used to evaluate Trophic State Index. The Water Quality Index was derived from three parameters namely, chlorophyll concentration, turbidity and $a_{CDOM}(443)$ which were expressed in terms of Trophic State Index, Turbidity Index and Humic-Fulvic Index, respectively. The Water Quality Index maps, derived using a Fuzzy Inference System based on the Centre of Gravity method, provided insights into spatial structures and temporal variability of water quality conditions of the coastal lagoons which are influenced by anthropogenic factors, hydrographic changes and land-ocean-atmospheric interaction processes.

Introduction

Many coastal and inland water systems have been increasingly polluted due to the influence of domestic and industrial waste discharges, high quantity of agro-materials in agricultural runoff, proliferation and rapid growth of algal blooms (including harmful algal blooms), sediment discharge from floods and rivers, and increased human settlement and encroachment (Zuazo et al., 2009). Despite a number of conventional field methods established for monitoring and assessing ecological quality of these water bodies, it is often difficult to implement such methods across a number of discrete water bodies or spatially extensive water systems. These methods are labour intensive, expensive, and time consuming while being difficult to be employed under harsh environmental conditions. Over recent years, space-borne remote sensing techniques have been identified as an important and alternative tool for monitoring and assessing coastal and inland water quality in different spatio-temporal scales. However, its success depends on accurate removal of the atmospheric contribution and quantification of the in-water constituents' concentration and appropriate models for detecting and describing the water quality status.

Water quality models that utilize remote sensing data are based on some important optical parameters such as chlorophyll, suspended sediments, turbidity, Secchi depth, and colored dissolved organic matter (*CDOM*). Over the past decades, a number of studies have developed retrieval algorithms that take advantage of the good relationships between these constituents or parameters and remote sensing reflectance (R_{rs}) at certain wavelengths in the visible-NIR region (Tassan, 1994; Shanmugam, 2011; Barale and Gade, 2014; Beltrán-Abaunza et al., 2014; Nasiha and Shanmugam, 2015; Shanmugam et al., 2016; Giardino et al., 2017; Kulshreshtha and Shanmugam, 2017; Kutser et al., 2017; Manoppo and Budhiman, 2017; Matthews, 2017; Ogashawara et al., 2017). Due to the complexity of the optical conditions in turbid and productive waters within coastal and inland environments (Menken et al., 2006; Matthews, 2011; Wu et al., 2014; Xian, 2015; Mishra et al., 2017), satellite retrieval algorithms often produce significantly large errors because of the unusually high contents of suspended sediments, phytoplankton, detrital and dissolved organic matters in these water bodies. For instance, estimation of the chlorophyll concentration is often impacted because of the increasingly high overlapping absorption features of *CDOM* and detrital contents with

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phytoplankton signal in the blue region. Thus, it is essential to develop reasonably good algorithms for the water quality parameters which are used to derive the trophic and water quality indices (*TSI* and *WQI*). Atmospheric correction of satellite data is another important problem, especially for turbid and productive inland waters. It has been reported in many recent studies that global atmospheric correction algorithms produce improbable negative or highly biased water-leaving radiance values in turbid productive waters. While the atmospheric correction (particularly aerosol estimation) was successfully applied to satellite data over the coastal and oceanic waters using the NIR or SWIR schemes (Shi and Wang, 2009, 2014; Bailey et al., 2010), accurate retrieval of the water-leaving radiances in highly productive and algal bloom waters remains a difficult problem. Moreover, these algorithms are not directly applicable for high resolution sensors like OLI8 that have very few broad spectral bands posing limitations for aerosol (atmospheric) correction over the coastal-inland regions. Recently, a novel aerosol correction technique was developed by Singh and Shanmugam (2014) and successfully tested on several MODIS-Aqua data from coastal and open ocean waters and HICO data from coastal and inland waters (Singh and Shanmugam, 2014; Singh and Shanmugam, 2016; Varunan and Shanmugam, 2017). Because the algorithm does not require any ancillary parameters, it can be easily adopted for retrieving the water-leaving radiance products from satellite data.

Over the past decades, several *WQI* models have been developed that use a single parametric index or multi-dimensional criteria to investigate the inland and coastal water quality status. The *WQI* assessment based on a single parameter essentially depends upon numerical modelling techniques that are simpler to implement due to the absence of inter-dependency on other water quality variables (Norris and Morris, 1995; Kallidaikurichi and Rao, 2010; Dosskey and Qiu, 2011; Bedri et al., 2013, 2015). A single parametric approach used a single bacterial modelling function to estimate the water quality status in coastal waters (Bedri et al., 2013) or an eutrophication index as a potential surrogate indicator to assess the water quality status in estuarine and inland water systems (Cloern, 2001; de Jonge et al., 2002; Atkins and Burdon, 2006; Ferreira et al., 2007; Bricker et al., 2008). The *WQI* solely based on either a bacterial model or eutrophication index neglects the in-water constituents' concentrations and associated physico-chemical factors that adversely affect the water quality status. Consequently, the *WQI* predicted by a single parameter is potentially susceptible to large errors. In contrast, the multi-parametric models employ nitrogen parameters (such as total organic nitrogen, dissolved inorganic nitrogen, ammonia concentrations, nitrates and nitrites) and nitrogen to phosphate ratios to evaluate the *WQI* status in river and lake waters (Twilley et al., 2001; Caccia and Boyer, 2005; Gavio et al., 2010; Mohanraj et al., 2013). Other studies used dissolved oxygen, turbidity, pH levels, temperature, salinity and water clarity as surrogate indicators for assessing the water quality conditions for inland waterways, rivers and estuaries (Simeonov et al., 2003; Cox et al., 2005; Schaffelke et al., 2005; Behera et al., 2013; Al-Mutairi et al., 2014; Naik et al., 2014; De La Mora-Orozco et al., 2017). The single and multi-parametric models largely depend on nutrient concentrations and physico-chemical parameters which are difficult to deduce from the satellite data owing to the lack of optical signatures in the visible and NIR regions. Such models may provide useful water quality information when applied to discrete water sample data collected from the limited geographic area, which will restrict our ability to assess water quality on different spatio-temporal scales.

The chlorophyll concentration is used as a standard water quality parameter to assess the trophic state of inland and marine waters (Carlson, 1977; Lillesand et al., 1983; Baban, 1996; Gurlin et al., 2011; Barale and Gade, 2014). The increased levels of chlorophyll concentration and phytoplankton abundance are considered as an immediate biological response to nutrient enrichment that leads to the elevated primary productivity, commonly referred to as eutrophication. The eutrophication state can be inferred based on a Trophic State Index (*TSI*) level (Carlson, 1977). Consequently, the chlorophyll concentration serves as a proxy of nutrient loading and forms a major link-pin to assess the trophic state in various water environments (Andersen et al., 2009; Nixon, 2009; Ferreira et al., 2011; Borja et al., 2012). Carlson (1977) developed the functional relationships between Secchi depth versus chlorophyll concentration and total phosphorus to determine the trophic state of inland lakes. Other studies have reported similar correlations between these parameters for an improved assessment of the trophic status of inland waters (Lillesand et al., 1983; Baban, 1996; Vollenweider et al., 1998; Ferreira et al., 2010). It should be noted that these *TSI* algorithms (solely depending on Secchi transparency) could yield large errors in turbid productive inland waters and clear oceanic waters due to the saturation of Secchi values or poor sensitivity of the applied models. Few other studies used enhanced phytoplankton growth, average chlorophyll concentration, Biological Oxygen Demand (*BOD*), dissolved inorganic nitrogen and phosphorus tracers as pertinent criteria to develop their *TSI* models (Swanson, 1998; Bricker et al., 1999; Cloern, 2001; Hailin and Baoyin, 2006), but the applicability of these methods to remote sensing data remained unaddressed. The monitoring of estuarine water using Moderate Resolution Imaging Spectroradiometer (MODIS) data for the region of Tampa Bay, Florida has been reported wherein chlorophyll concentration, total suspended sediment and CDOM were considered as key parameters to assess the water quality conditions (Hu et al., 2004). However, the accuracy of retrieving water quality products for Type 2 waters was warranted under the condition that improvement in the sensor calibration and characterization must be carried out to provide higher applicability of MODIS data. A more recent study employed MODIS/Aqua data to assess water quality conditions in three regions of Tampa Bay (Old, Middle and Low) (Chen et al., 2007). Time series analysis showed that retrieval of turbidity based on R_{rs} (645) can be a valuable tool for investigating the seasonal trends in water quality conditions of estuarine and coastal domains.

A greater challenge lies in interpreting and evaluating the single valued output for the derived parameter which lacks sharp distinct boundaries in the information system due to the influence of multiple input parameters. One such real-world application is the water quality modelling which involves large-scale uncertainties due to the complex decision-making process for certain governing input parameters and is often resolved using the concept of a Fuzzy Inference System (*FIS*) algorithm (Genther and Glesner, 1997; Chang et al., 2001). The preliminary five-layer *FIS* architecture was introduced by Lofti Zadeh in 1965 and has potential applications in the field of physical/environment modelling (Zadeh, 1965; Mamdani and Assilian, 1975; Mamdani et al., 1984; Saade and Diab, 2004; Bai and Wang, 2006). Mamdani et al. (1984) Type *FIS* has high interpretability as it combines the fuzzy set theory and performs the automatic computation to resolve the ambiguity in the physical modelling process. Therefore, for the first time, Mamdani Type *FIS* technique was chosen and implemented in the present study to evaluate water quality conditions.

Several water quality algorithms have been developed based on the fuzzy logic tool, however, their application to satellite data for optical remote sensing of water quality conditions is greatly limited due to the complexity of implementing both neural network and fuzzy decision system into single mainframe structure which is considered as an integral component of Adaptive Network-based Fuzzy Inference System (ANFIS) (Sii et al., 1993; Delgado et al., 1998; Ishibuchi et al., 1999; Lu et al., 1999; Chang et al., 2001). The present study reveals an effective approach of coupling the mainframe concept of Fuzzy Inference System (Mamdani Type *FIS*) with the principle of optical remote sensing to demonstrate the possible application of a fuzzy logic tool in determining the water quality conditions for estuarine, coastal and inland waters.

In the present study, we develop *TSI* and *WQI* models for the remote assessment of water quality in two important coastal inland lakes (Muttukadu and Chilika Lakes) on the east coast of India. The *TSI* is derived as a function of the chlorophyll concentration from the normalised

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