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Research Paper

Spatio-temporal water quality mapping from satellite images using geographically and temporally weighted regression

Hone-Jay Chu[a,*], Shish-Jeng Kong[b], Chih-Hua Chang[c]

[a] *Department of Geomatics, National Cheng Kung University, Tainan, Taiwan*
[b] *Department of Geomatics, National Cheng Kung University, Tainan, Taiwan*
[c] *Department of Environmental Engineering, National Cheng Kung University, Tainan, Taiwan*

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ABSTRACT

The turbidity (TB) of a water body varies with time and space. Water quality is traditionally estimated via linear regression based on satellite images. However, estimating and mapping water quality require a spatio-temporal nonstationary model, while TB mapping necessitates the use of geographically and temporally weighted regression (GTWR) and geographically weighted regression (GWR) models, both of which are more precise than linear regression. Given the temporal nonstationary models for mapping water quality, GTWR offers the best option for estimating regional water quality. Compared with GWR, GTWR provides highly reliable information for water quality mapping, boasts a relatively high goodness of fit, improves the explanation of variance from 44% to 87%, and shows a sufficient space–time explanatory power. The seasonal patterns of TB and the main spatial patterns of TB variability can be identified using the estimated TB maps from GTWR and by conducting an empirical orthogonal function (EOF) analysis.

1. Introduction

Optical remote sensing is a powerful, unique tool for understanding the influence of water constituents on the underwater optical field and bio-optical properties of surface waters. Satellite optical sensors measure the amount of solar radiation upwelled from water bodies at various wavelengths, which can be correlated to the levels of important water quality parameters, such as chlorophyll-a, turbidity (TB), suspended matter, and colored dissolved organic matter (Hellweger et al., 2004). Compared with traditional point water-sampling methods, satellite remote sensing is a highly practical and cost-effective approach for determining the spatio-temporal variation in the water quality parameters of seas and large inland waters (Devlin et al., 2015), such as lakes and reservoirs. Understanding the temporal trends and spatial distributions of water quality are essential for maintaining the health of aquatic ecosystems and ensuring the safety of water.

The existing algorithms for estimating water quality parameters from satellite images are often based on linear regressions between ground-based and remote sensing data (Hellweger et al., 2004). This finding is particularly true for lakes and reservoirs (Kloiber et al., 2002; Miller and McKee, 2004; Matthews, 2011; Dalu et al., 2015) as most satellite sensors with appropriate spatial resolutions are not specifically designed for studying surface water quality. For example, the sensors onboard land observation satellites, such as SPOT and Landsat, are not equipped with water-constituent-specific channels similar to ocean color sensors. Traditional regression approaches usually consider the spectral information as independent variables that are provided by two or three optical channels in land application sensors. Compared with ocean color algorithms for mapping chlorophyll-a concentrations across the ocean, a regression-based algorithm developed in an inland water body can rarely be used elsewhere; even worse, some season-specific algorithms are only reliable for a short period (Danson et al., 1995).

Traditional regression models transform measured spectral image data to water quality information without the consideration of spatio-temporal variation in model coefficients. The waters nearby lakes tend to demonstrate similar physico-chemical characteristics because they share common environmental factors. For example, high levels of suspended matter are usually observed in areas upstream of a lake or in areas that receive direct runoff, while high concentrations of phytoplankton are often observed in lake embayments because of the lack of hydraulic exchange amid the wide availability of nutrients in these areas (Yurista et al., 2004). Moreover, the relationships between water quality parameters and remote sensing are physically dependent on the bio-optical relation of a lake, which does not remain constant for a year. Seasonal thermal stratification is often identified as the most important factor that influences the temporal variations of nutrients available to

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[*] Corresponding author.
E-mail address: honejaychu@gmail.com (H.-J. Chu).

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phytoplankton. The levels of eroded particles are often reported to reduce water clarity during rainy seasons. The degradation of vegetation and aquatic plants during winter releases natural organic matters that discolor the receiving water to yellow or brown. Therefore, the time of an observation has an important role in determining the relationships between water quality parameters and satellite images.

The spatio-temporal variability of water quality parameters can also be observed in different bio-optical relations and atmospheric conditions. This study explicitly considers the spatio-temporal dependence models for overcoming spatio-temporal variability. The relationship between remote sensing and ground-based observations varies with time and space, and the traditional regression model cannot explain the spatio-temporal variations in water quality. Accordingly, this study proposes a highly reliable method for water quality assessment in the general space and time domains. A regression model that considers the spatio-temporal coefficient can sufficiently explain the spatial and temporal variations in the quality of water from a target area.

This research aims to improve the water quality estimation based on regressions between remote sensing and ground-based observation and to address the limitations of the traditional regression method that transfers a point dataset to a regional water quality map. The water quality monitoring network is generally sparse, and remote sensing images can cover an entire area. In this case, remote sensing images provide useful water quality information if a spatio-temporal relationship between remote sensing and ground-based observation is available. This study employs various regression models to assess the retrospective estimation of the spatio-temporal distribution of water quality. Spatio-temporal water quality mapping is quantified using linear regression (LR), geographically weighted regression (GWR), and geographically and temporally weighted regression (GTWR) models.

2. Study area and materials

The Taiwan Environmental Protection Administration (TWEPA) and Water Resource Agency (WRA) regularly monitor the water quality throughout Taiwan. A seasonal time series of the quality of water in the Tseng-Wen Reservoir were collected from these agencies, respectively. Fig. 1 shows the sampling sites. The TB, which refers to the haziness of fluid caused by suspended solids that are transported by flowing water, of the whole reservoir was recorded by eleven stations of TWEPA and WRA. The recorded TB data from 2005 to 2013 were collected from these stations with a three-month data sampling frequency.

Formosat-2 offers a 24 km × 24 km scene coverage with 2 m resolution in panchromatic and 8 m resolution in four multispectral bands from visible to near-infrared. These four bands are centered at 485, 560, 660, and 830 nm. Formosat-2 is the first satellite equipped a high spatial resolution sensor for a daily revisit orbit and for taking images of any accessible area in the world at any given day. Twenty-eight Formosat-2 satellite images of the Tseng-Wen Reservoir that were captured from 2005 to 2013 were collected for this study. The Tseng-Wen Reservoir is the largest reservoir at the Chiayi County in Taiwan. The ground-based and remote sensing data have similar sampling dates, and any date difference was limited to less than seven days. Water quality data and satellite images used in this study are mostly collected on cloudless days when retention time of the reservoir is longer than the average (120–180 days). Therefore, the seven-day differences in water quality are considered as a minor problem in this study. The date of Formosat-2 image collection was matched to the date of ground observation as closely as possible.

The annual rainfall in the Tseng-Wen Reservoir is concentrated in summer (the second season, which takes place between May and August), thereby generating high TB levels during dry seasons because of the erosion of fine particles. Although the rainfall in autumn (the third season, which takes place between September and November) is several times higher than that in spring and winter, this period has relatively low TB levels. The seasonal temperature changes in the reservoir are indistinct, and the water temperature remains warm (> 15 °C) during winter to support the growth of most phytoplankton species. Fig. 2 shows the seasonal distribution of TB in the reservoir from 2005 to 2013. The TB in dry seasons, including spring (the first season, which takes place between February and April) and winter (the fourth season, which takes place between December and January), may originate from phytoplankton. Compared with temporal variety, no significant changes were observed in the levels of TB from upstream to downstream. The TB in the upstream, which receives direct watershed inflow, was slightly higher and showed more fluctuations than that in the midstream and downstream. The ground-based data identify rainfall pattern as the primary driver of the temporal variation of TB in the reservoir. Fig. 1 shows the stations of TWEPA (stations 1–6) and WRA (stations 7–11).

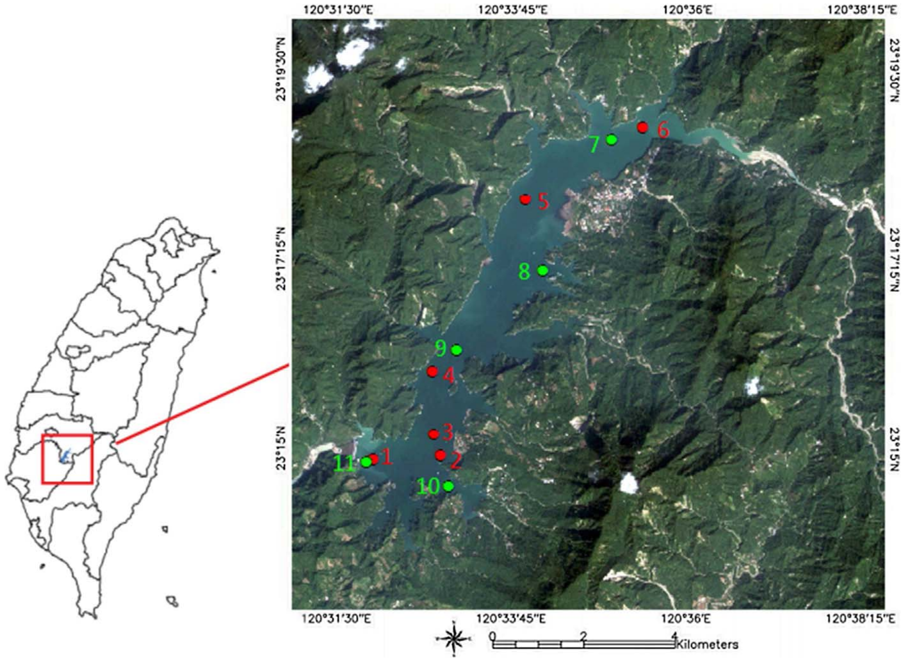

Fig. 1. Study area and 11 water-quality sampling points in Tseng-Wen reservoir.