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Research papers

Estimating river accommodation capacity for organic pollutants in data-scarce areas

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ABSTRACT

Globally, water quality degradation severely threatens the security of water resources. Understanding a river's capacity to accommodate pollutants (or water environmental capacity: WEC) can help efficiently protect rivers. However, the requirement for comprehensive ground-observed hydrological and water quality data in previous methods makes it difficult to estimate WEC in areas with limited ground observations. This paper proposes a new framework for WEC estimation in data-scarce areas based on remotely sensed skin water temperature and limited ground observations. Two new models were developed to calculate the two critical parameters for WEC estimation: water temperature, and integrated pollutant degradation coefficients (k). Images of ASTER Surface Kinetic Temperature (AST_08) 90 m grid product were used to retrieve water temperatures. The above results were subsequently used to calculate a river's capacity to accommodate pollutants, or WEC, in agriculturally dominated areas. The use of remote sensing techniques enables the methods to be applied over large spatial scales and to areas with limited ground observations. The application and testing of the framework in four rivers, including two Chinese rivers (the Huai and the Wei Rivers) and two Australian rivers (the Ovens and the Gwydir Rivers), suggest that the models performed well to calculate the real-time water temperature and the coefficient k based on limited ground-observations. Uncertainty analysis on water temperature calculated from remotely sensed land surface temperature and ground-observed meteorological air temperature suggests that remotely sensed water temperature had high concurrence with ground observations (RMSE = 3.08 °C with $R^2 = 0.88$), while the sparse-spatially distributed meteorological stations reduced the accuracy in estimating water temperature (RMSE = 4.39 °C with $R^2 = 0.91$). We found that the coefficient (k) increased with water temperature over different seasons in an exponential form but in a logarithmical form with streamflow velocity. Comparison with previous research and other models with abundant data revealed the practicability and effectiveness of our models, which can be easily applied to rivers with insufficient ground observations across the globe.

1. Introduction

Rapid socio-economic development in developing countries has resulted in many quality problems in rivers (Levashova et al., 2004; Liu et al., 2011). Pollution discharged from upstream watersheds and excessive upstream water abstraction has dramatically changed the hydrological regimes and reduce the dilution capacity of a river and may significantly degrade water quality at downstream reaches (Yoon et al., 2015). This deterioration of water quality negatively affects socio-economic development and damages the water ecosystem (Joniak and Kuczyńska-Kippen, 2010; Rui et al. 2015).

The rapid deterioration of river water quality urgently requires effective water quality management strategies to reduce the resulting environmental pressures (Li and Zou, 2015). The most common approach for water quality protection is the use of water quality standards, allowing for the selection of protection levels (Han et al., 2010; Li et al., 2010). Water quality standards, or boundary values for water quality indicators, are then used to calculate the water environmental

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capacity (WEC), or the capacity of a water body to accommodate a certain amount of pollutants, and subsequently to reduce the amount of pollutants discharging into rivers. The WEC has a similar role in water quality protection with the terms "Assimilative Capacity" (Payandeh et al., 2015), "Total Maximum Daily Loads" (Bachmann et al., 2003; Cooter et al., 2010; Kim et al., 2014), etc. (Wang et al., 2015).

Management of the WEC is a key factor to control pollution in rivers (Keller and Cavallaro, 2008). Based on the estimation of the WEC, the total allowable amount of pollutants discharged into rivers can be obtained and allocated appropriately among different industries and areas to ensure that the emission quantities are within the WEC (Chen et al., 2014). A number of methods has emerged for determining the WEC with either simple or complicated mathematical/statistical models (Antonellini et al, 2014; Cuadra and Björklund, 2007; Gong and Jin, 2009; Liu and Borthwick, 2011; Pandey et al, 2011; Zhang et al, 2014b; Wang et al, 2014; Yang et al., 2015). Water quality models with one, two and three dimensions have been used widely and significant progress has been achieved (Imteaz and Asaeda, 2000; Wan et al., 2001; Park et al., 2005; Testa et al., 2013; Li et al., 2015). In general, the models have a high demand for ground observations of hydrology and water quality, as well as for scientific expertise. Several models require extensive field measurement campaigns and also may rely on expert panels, which can lack transparency in making recommendations or are influenced by expert bias (Hughes et al., 2014) that can be very costly (Alcazar et al., 2008). In addition, in many real-world situations, neither the financial capacity nor the necessary scientific expertise is available. Consequently, a lack of effective hydrological and water quality monitoring creates difficulties in river water quality protection (Yu et al., 2015). This significantly restricts the wide application of traditional WEC models in situations with insufficient ground monitoring of hydrological and water quality parameters. Therefore, significantly limited data availability appeals less data-intensive or parsimonious methods, which can be applied in many different situations with limited ground observations (Hughes et al., 2014).

In the WEC models, the rate of pollutant degradation in rivers can be determined by using the integrated degradation coefficient (CAEP, 2003; Dang et al., 2009). The most critical factors influencing the integrated degradation coefficient are water temperature and river discharge (Chen et al., 2007; Gomes and Wai, 2014). For organic pollutants, water temperature is the principal factor influencing the integrated degradation coefficient (Wright and Mcdonell, 1979; Brown and Barnwell, 1987; Li and Liao, 2002; Yang et al., 2014). Therefore, the integrated degradation coefficient for organic pollutants in rivers can be estimated via the water-temperature-dependent function. This greatly facilitates estimation of the WEC in areas with insufficient ground observations for water quality due to the easy access to water temperature estimated via meteorological air-temperature or remotely sensed land surface temperature. This significantly extends the potential to rapidly estimate the WEC in data limited areas. Remote sensing techniques are very convenient in obtaining geo-information from the earth's surface at multiple temporal-spatial scales (Gassman et al., 2007; Nesme et al., 2012), e.g., land-use and vegetation (Leuning et al., 2008; Li et al., 2009; Nesme et al., 2012; Duan et al., 2014), land surface temperature and evapotranspiration (Zhang et al., 2010; Tang et al, 2010, 2011; Duan et al., 2012, 2014), soil moisture (McVicar et al, 2002), catchment drought and runoff (McVicar et al, 2001; Li et al., 2009; Zhang et al., 2009). Moreover, the great advantage for remote sensing in extrapolating land (LST) temperature makes it easy to estimate the WEC in data limited areas. Among all remotely sensed LST, the ASTER Surface Kinetic Temperature (AST_08) product, generated using the five Thermal Infrared (TIR) bands (acquired either during the day or night time), contains LST at 90 m spatial resolution for the land areas and is widely used for studies of volcanism, thermal inertia, surface energy, and high-resolution mapping of fires (refer to https://lpdaac.usgs.gov).

Water surface temperature (WST), including skin (or radiant) WST and bulk WST (Li et al., 2013; Teggi et al., 2014; Zhang et al, 2014a; Wan et al., 2017), is often derived from the methods for land surface temperature (LST). LST and WST are the most commonly remotely-sensed data available for restoration of freshwater ecosystems because water temperature controls the biogeochemical and hydrological processes and plays crucial roles in energy and heat exchanges between water and atmosphere (Alcântara et al., 2010; Thiemann and Schiller, 2003). But the skin WST (e.g., within the upper 0.1 mm of the water surface) can merely reflect the thermal radiation status within a very thin depth under the water surface. Thus it cannot be directly used to replace the bulk WST (e.g., within 10 cm or 4 m below the water surface) (Torgersen et al., 2001) – a key parameter for WEC estimation. In the river ecosystem the photosynthetic rate of phytoplankton, controlling the degeneration rate of organic pollutants and influencing the magnitude of WEC, often occurs in the upper 4 m water layer, e.g., for Lake Constance around noon (Thiemann and Schiller, 2003). A conversion between skin and bulk WSTs has to be made to avoid unexpected uncertainties in the applications (Li et al., 2013). A regional algorithm for bulk temperature was presented for Lake Constance but had high data requirement, e.g., data of air temperature from a weather station within the last three days, which are often hard to get in data-limited regions, restricted its application in other regions across the world (Thiemann and Schiller, 2003). Therefore, it is urgently necessary to develop a new algorithm to convert the remotely-sensed skin WST to bulk WST, or water temperature used for WEC calculation in ground data-limited regions.

Our primary goal was to set up a WEC framework for rivers with limited ground observations, based on the advantages of remote sensing techniques in obtaining data of water surface temperature. Our specific objectives were:

1. To retrieve water temperature by converting remotely sensed skin WST to bulk WST in rivers with limited ground observations;
2. To calculate the integrated degradation coefficient (k) for organic pollutants at any level of temperature; and
3. To estimate the corresponding WEC based on the coefficient (k) for ground-observation limited areas.

This paper is structured around the three objectives in Methods (Section 3), Results and Discussion (Section 4), and Conclusion (Section 5). The data sets used are described in Section 2.

2. Study area and materials

2.1. Study area

The Wei River basin, situated between 103.5 and 110.5°E and 33.5–37.5°N, is located in a continental monsoon climatic zone; the mean temperature ranges from 6 to 14 °C with a mean rainfall of 450–700 mm, and the mean pan evaporation ranges from 1000 to 2000 mm (Li et al., 2014). In recent decades, the entire basin has encountered many serious droughts with long durations and high severity (Huang et al., 2014). The basin is the primary region for agriculture, industry and commerce in Northwestern China (Song et al., 2007). Intensive human activities have resulted in substantial negative impacts on the Wei River, which are characterized by decreasing annual runoff and heavy pollution (Zuo et al., 2014). As a result, 69.2% of the water quality observations exceeded the national water protection standards (e.g., in 2009) and resulted in serious degradation of ecosystem function (Wu et al., 2014b). The two principal issues in terms of pollution in this region are chemical oxygen demand (COD) and ammonia nitrogen (NH_3-N) levels (Zhang et al., 2012), which deserve special attention in future water-resource protection strategies.

Linjiacun (LJC) and Xianyang (XY) are two important hydrological and water quality monitoring stations along the river. The water surface width of this reach ranges from 27 to 500 m and the water depth varies