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A global assessment of climate–water quality relationships in large rivers: An elasticity perspective

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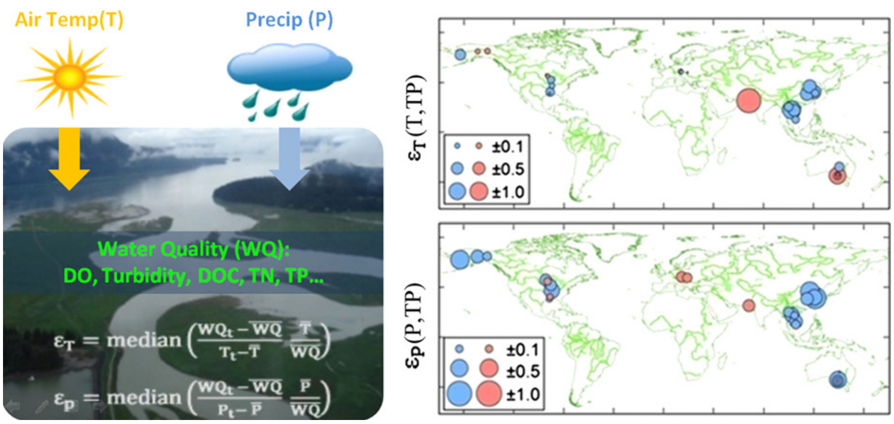
HIGHLIGHTS

- The first comprehensive global study on climate–river water quality relationship
- Common characteristics of climate elasticity of water quality (CEWQ) were revealed.
- CEWQ is robust and overweighs statistical correlations for providing intensity info.
- Impacts of CEWQ determinants, e.g. population and geographic location, were reported.
- CEWQ can help understand climate change impacts on rivers, e.g. nutrient changes.

GRAPHICAL ABSTRACT



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ABSTRACT

To uncover climate–water quality relationships in large rivers on a global scale, the present study investigates the climate elasticity of river water quality (CEWQ) using long-term monthly records observed at 14 large rivers. Temperature and precipitation elasticities of 12 water quality parameters, highlighted by N- and P-nutrients, are assessed. General observations on elasticity values show the usefulness of this approach to describe the magnitude of stream water quality responses to climate change, which improves that of simple statistical correlation. Sensitivity type, intensity and variability rank of CEWQ are reported and specific characteristics and mechanism of elasticity of nutrient parameters are also revealed. Among them, the performance of ammonia, total phosphorus–air temperature models, and nitrite, orthophosphorus-precipitation models are the best. Spatial and temporal assessment shows that precipitation elasticity is more variable in space than temperature elasticity and that seasonal variation is more evident for precipitation elasticity than for temperature elasticity. Moreover, both anthropogenic activities and environmental factors are found to impact CEWQ for select variables. The major relationships that can be inferred include: (1) human population has a strong linear correlation with temperature elasticity of turbidity and total phosphorus; and (2) latitude has a strong linear correlation with precipitation elasticity of turbidity and N nutrients. As this work improves our understanding of the relation between climate factors and surface water quality, it is potentially helpful for investigating the effect of climate change on water quality in large rivers, such as on the long-term change of nutrient concentrations.

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1. Introduction

Climate change impacts on water availability and hydrologic risks have been extensively studied over the past few decades (Kundzewicz et al., 2007; Milly et al., 2008, 2005). However, it is only in recent years that climate-related river water quality issues have started to receive attention (Kundzewicz et al., 2007; Whitehead et al., 2009; Delpla et al., 2009). Among the climatic variables and associated factors, air temperature, precipitation, evaporative demand, and water-related extreme events (e.g. floods, droughts) have been identified as the major drivers influencing the water quality (Delpla et al., 2009; Kundzewicz and Krysanova, 2010). However, there still exist large information gaps regarding the climate–water quality nexus and the sensitivity of water quality response to climatic factors (Whitehead et al., 2009). Studies on this topic so far have largely focused on a regional scale or on limited water quality parameters (Whitehead et al., 2006; Prathumratana et al., 2008; Tibby and Tiller, 2007). Therefore, broader-scale conclusions regarding the sensitivity of all the key water quality parameters to major climatic drivers have not been possible. This provides the motivation for the present study, where the climate–water quality relationship is examined through analyzing the sensitivity of various water quality parameters to climate variables in many large rivers across the world.

Generally speaking, the climate sensitivity of water quality is assessed either using a long series of observations or deriving estimates from process-based water quality models. The majority of publications on this topic adopt a process-based approach, such as the contributions by Cox and Whitehead (2009) and Whitehead et al. (2006). While these help us in understanding how the climate drives water quality, they are restricted by the need to focus on a local area or a single river due to the complexity and diversity in the aquatic environment. On the other hand, empirical statistical approaches are more preferred for an elementary analysis of the climate–water quality relationship (Fukushima et al., 2000; Prathumratana et al., 2008), especially for a preliminary investigation at large scales. This is the alternative adopted in the current study.

The empirical statistical approach directly analyzes the dependence between climatic factors and water quality parameters by considering them as two groups of random variables (Milly et al., 2008; Watmough et al., 2004; Webb et al., 2008). One classical example is the regression of the stream water–air temperature relationship (Rehana and Mujumdar, 2011; Ozaki et al., 2003), with dependence being characterized using the Pearson's correlation (Prathumratana et al., 2008; Tibby and Tiller, 2007) or modeled using nonlinear regression alternatives. While statistical approaches are easier and quicker to use for an elementary but large-scale analysis, they also have an important limitation in that they require substantial observational data for both water quality and meteorological variables.

The present study performs a global investigation of the sensitivity of river water quality parameters (DO, turbidity, C, N, P nutrients) to air temperature and precipitation using sample-based estimates of climate elasticity for each of the water quality variables considered. Monthly hydrologic and water quality data representing a 20-year segment of the record from 14 large rivers across the world are used for the analysis. The rest of the paper is organized as follows. In Section 2, we present the basis for the elasticity approach for estimation of the climate sensitivity of water quality to selected climatic drivers. In Section 3, we report the estimated relationship for the locations and variables assessed, in reference to its variation across the regions the analysis is performed for. A comparison is also made between the elasticity method and the statistical correlation method. Following this, we present elasticity results and interpret their variations by taking their physical attributes into account. We discuss the seasonal variation observed in the elasticity analysis across disjointed time segments of the data analyzed, and assess the difference in results when using continuous or discrete formulations for estimating the elasticity.

2. Datasets and methods

As this study is data intensive and representative of a global scale, we use as many water quality records as possible to perform the assessment. Besides the elasticity approach to study climate–water quality relationship, traditional correlation analysis is also used for comparison.

2.1. Rivers and datasets

2.1.1. Study area

Based on the water quality monitoring records from UNEP/GEMS (United Nations Environment Programme/Global Environment Monitoring System), we consider, for the present analysis, a total of 51 monitoring stations in the mainstream of 14 large rivers, covering 5 continents, 15 countries, and 10 climate types (Rubel and Kottek, 2010) (Fig. 1 and Table 1). Due to their extent of spread across the world, we assume that these rivers are representative of large rivers and thus able to cover their typical water quality characteristics. For some of these rivers, the data measurements are intensive and extensive; for instance, reliable data are available for 18 stations in the Mekong River basin.

2.1.2. Water quality data

All the water quality records, except those for Australia, are obtained from UNEP/GEMS/Water (www.gemstat.org). The number of stations and the number/type of water quality parameters vary from country to country. An assessment of the impact of the changing frequency of data submission by the respective countries/organizations managing the rivers, with some countries providing data every month or season while others providing data only once a year or every other year, is also conducted. For the present study, we investigate a total of 51 stations (from 14 rivers) and 20 water quality parameters (the 12 main parameters reported in Table 2) with long-term (20.7 yrs on average) monthly or even weekly observations as the basis for forming a monthly time series for all these stations. For details of the analytical methods used for formulating the water quality variables, please refer to the Analytical Methods for Environmental Water Quality by GEMS/Water (http://www.unep.org/gemswater/TechnicalResources/AnalyticalMethodsforEnvironmentalWaterQuality/tabid/78547/Default.aspx) or the National Environmental Methods Index by USGS (US Geological Survey) and USEPA (www.nemi.gov), especially for the stations located in the United States.

Water quality data for the Murray–Darling River in Australia and the Cooper Creek in South Australia (ranked among the top 100 in terms of river length) are obtained from the South Australia EPA websites (http://www.epa.sa.gov.au). These cover 12 parameters with more than 36 yrs of monthly monitoring history.

2.1.3. Climate data

For 50 out of the 51 stations considered in this study, climate data (monthly average temperature and precipitation) are reconstructed gridded records available at a 0.5° × 0.5° latitude/longitude grid resolution (NOAA/OAR/ESRL PSD, 2013; Willmott, 2013; Matsuura and Willmott, 2013a, 2013b). The temperature gridded fields are derived from monthly weather-station averages using a combination of spatial interpolation methods and climatologically-aided interpolation (CAI), while the precipitation grids are produced just from CAI (Matsuura and Willmott, 2013a, 2013b). Station data, monthly total precipitation (P, mm), and monthly-mean air temperature (T, °C) are gathered from several updated sources, with the Global Historical Climatology Network (GHCN) serving as the main source (Matsuura and Willmott, 2013a, 2013b).

Due to the lack of available gridded data for one of the stations in the Yangtze River, we use the closest weather stations and original records in the GHCN-Monthly temperature dataset (GHCN-M) v3 for temperature (2013) and GHCN-M v2 for precipitation (2013).