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Improving water quality in China: Environmental investment pays dividends

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A B S T R A C T

This study highlights how Chinese economic development detrimentally impacted water quality in recent decades and how this has been improved by enormous investment in environmental remediation funded by the Chinese government. To our knowledge, this study is the first to describe the variability of surface water quality in inland waters in China, the affecting drivers behind the changes, and how the government-financed conservation actions have impacted water quality. Water quality was found to be poorest in the North and the Northeast China Plain where there is greater coverage of developed land (cities + cropland), a higher gross domestic product (GDP), and higher population density. There are significant positive relationships between the concentration of the annual mean chemical oxygen demand (COD) and the percentage of developed land use (cities + cropland), GDP, and population density in the individual watersheds ($p < 0.001$). During the past decade, following Chinese government-financed investments in environmental restoration and reforestation, the water quality of Chinese inland waters has improved markedly, which is particularly evident from the significant and exponentially decreasing GDP-normalized COD and ammonium (NH_4^+-N) concentrations. It is evident that the increasing GDP in China over the past decade did not occur at the continued expense of its inland water ecosystems. This offers hope for the future, also for other industrializing countries, that with appropriate environmental investments a high GDP can be reached and maintained, while simultaneously preserving inland aquatic ecosystems, particularly through management of sewage discharge.

1. Introduction

Inland waters such as lakes, reservoirs, streams, rivers, etc, provide a wide variety of ecosystem services ranging from potable water, to sources of food, through to transportation and sites for recreation (Downing et al., 2006). However, these inland water ecosystems are threatened across the planet by the dual pressure of anthropogenic activities and climate change (Bragazza et al., 2012; Feng et al., 2008; Williamson et al., 2014). Land use intensification and urbanization have resulted in increased discharge of wastewater from households, agriculture, and industry, resulting in an elevated risk of point and non-point source pollution (Foley et al., 2005; Zhou et al., 2016). Eutrophication is a common

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consequence of deteriorating water quality and is a state characterized by high nutrient levels, low water transparency, and excessive growth of algal cells (Paerl et al., 2011a, 2011b; Qin et al., 2015). Blooms of toxic and hypoxia-generating cyanobacteria are an indicator of advanced eutrophication and represent a serious threat to potable water supplies and the ecological sustainability of inland water ecosystems (Paerl and Huisman, 2008; Paerl and Otten, 2013). Therefore, protection of inland waters is required to safeguard the quality and safety of the myriad of ecosystem services that these waters provided to consumers (Guo, 2007; Paerl and Huisman, 2008). Furthermore, primary production and land use practices within a watershed impact greenhouse gas emissions from inland waters, as for example organic carbon is metabolized to carbon dioxide (CO_2) and/or methane (CH_4) and nitrogenous compounds are transformed to nitrous oxides (N_2O) (Butman and Raymond, 2011; Davidson et al., 2015; Maberly et al., 2012; Weyhenmeyer et al., 2015). Knowledge of impacts on water quality in inland waters, and the associated drivers, are therefore of great importance to obtain a better understanding of their role in the global carbon cycle (Bianchi, 2011; Li et al., 2016; Maberly et al., 2012; Piao et al., 2009) and to allow for implementation of measures to protect inland freshwater resources (Williamson et al., 2008, 2009).

The water quality of inland waters is determined by numerous factors such as land use, hydrologic conditions, and anthropogenic activities (Kellerman et al., 2014; Kothawala et al., 2014). The effects of the morphological features of a lake, including depth, surface area, and water retention time, on trophic levels have been widely investigated (Nõges et al., 2003; Nõges, 2009), and many studies have been undertaken to elucidate the relationships between water quality and watershed land use (Carney, 2009; Kothawala et al., 2014; Liu et al., 2011; Müller et al., 1998; Maberly et al., 2003; Stedmon and Markager, 2005; Taranu and Gregory-Eaves, 2008). However, most studies to date have been conducted in lakes with similar land use in their watersheds and with comparable lake morphometric characteristics, and typically have limited spatial and temporal resolution. Furthermore, the majority of the studies have focused on direct relationships between water quality and the corresponding flow rate at different time scales (i.e. daily/weekly/monthly) (Chen et al., 2015; Goldman et al., 2014; Guo et al., 2014; Koch et al., 2013; Stedmon and Markager, 2005; Striegl et al., 2005). Generally, population density and industrial development have been considered important driving factors of declining water quality in inland waters (Duan et al., 2009). The gross domestic product (GDP) offers one measure of development that can be analyzed. However, the population density and economic statistical data presented in the limited number of studies linking these metrics to water quality are frequently estimated from information derived from statistical yearbooks published by various administrative units (Duan et al., 2009; Huang et al., 2014). In most cases, though, administrative units do not encompass the whole watershed. Further investigation into the direct relationships between water quality, human population density and GDP of individual watersheds is therefore required to assess the role these metrics may play in determining the health of inland waters.

In China, eutrophication coupled with environmental degradation has been considered as one of the prices paid for the rapid economic development occurring since the “reform and opening up-policy” was introduced in the late 1970s (Liu and Diamond, 2005; Liu et al., 2013). Importantly, in recent years, measures to remedy eutrophication have been introduced such as the Natural Forest Conservation Program (NFCP) and the Grain to Green Program (GTGP, also known as the Sloping Land Conversion Program and the Farm to Forest Program), the world's largest government-financed conservation action programs whose implementation was prompted by severe droughts in 1997 and unprecedented floods in 1998 (Liu et al., 2008; Ouyang et al., 2016). Furthermore, today, billions of RMB Chinese Yuan are dedicated to ecosystem restoration via environmental protection actions (e.g. the establishment of wastewater treatment plants). It is yet to be determined how these actions affect water quality and whether they have effectively reversed anthropogenically induced water quality degradation to any extent.

The objective of this study was to investigate the long-term variations of water quality in Chinese inland waters and to access the factors contributing to changes in water quality. An additional aim was to elucidate how conservation actions introduced by the Chinese government in the past two decades have impacted water quality. To elucidate the dynamics of water quality in Chinese inland waters, weekly data on water quality for the period January 2006 to December 2015 ($n = 499$) were examined for a total of 145 sites spanning the entire country (Fig. 1). These water quality measurements included dissolved oxygen (DO), chemical oxygen demand (COD), and ammonium (NH_4^+-N) at all 145 sites. Data on land use and land cover (LULC), population density, and GDP with 1-km spatial resolution and 5-year intervals during the past two decades were analyzed to assess relationships between water quality and the hypothesized driving factors. Government led investments in areas such as environmental restoration and reforestation were further investigated to determine how these actions have impacted the water quality in Chinese inland waters during the past two decades.

2. Materials and methods

2.1. Gauged datasets

Water quality, including DO, COD, and NH_4^+-N, was determined on a weekly basis for a total of 145 monitoring sites in major rivers and lakes in China from January 2006 to December 2015 (Fig. 1). The data were collected by the China National Environmental Monitoring Center (data available at http://www.cnemc.cn/publish/107/0594/350/newList_1.html). The main indices for chemical indicators of different water quality levels were categorized according to the water quality standards for surface waters in China (GB3838-2002). Level I: COD $\leq$2.0 mg L^{-1}; NH_4^+-N $\leq$ 0.15 mg L^{-1}; DO $\geq$ 7.5 mg L^{-1}. Level II: 2.0 mg L^{-1} < COD $\leq$4.0 mg L^{-1}; 0.15 mg L^{-1} < NH_4^+-N $\leq$ 0.50 mg L^{-1}; 6.0 mg L^{-1} $\leq$ DO < 7.5 mg L^{-1}. Level III: 4.0 mg L^{-1} < COD $\leq$6.0 mg L^{-1}; 0.50 mg L^{-1} < NH_4^+-N $\leq$ 1.00 mg L^{-1}; 5.0 mg L^{-1} $\leq$ DO < 6.0 mg L^{-1}. Level IV: 6.0 mg L^{-1} < COD $\leq$10.0 mg L^{-1}; 1.00 mg L^{-1} < NH_4^+-N $\leq$ 1.50 mg L^{-1}; 3.0 mg L^{-1} $\leq$ DO < 5.0 mg L^{-1}. Level V: 10.0 mg L^{-1} < COD $\leq$15.0 mg L^{-1}; 1.50 mg L^{-1} < NH_4^+-N $\leq$ 2.00 mg L^{-1}; 2.0 mg L^{-1} $\leq$ DO < 3.0 mg L^{-1}. Water belonging to levels I to III is potable after conventional water treatment. The highest level of water quality (i.e. the most polluted) parameters (DO, COD, and NH_4^+-N) set the level for the site.

Data on annual water quality levels for >11×10^4 km rivers from 1999 to 2014 were obtained from the Annual Bulletin of Water Resources published by the Ministry of Water Resources of China (http://www.mwr.gov.cn/zwzc/hygb/szygb/).

2.2. Watershed land use, population density, and GDP data

The watershed boundaries of all the 145 study sites were delineated using a DEM with a resolution of 90 m (available at http://srtm.csi.cgiar.org/index.asp) in Q-GIS software (Version 2.14.3; available at http://www.qgis.org/en/site/). LULC compositions in 1995, 2000, 2005, and 2010 of the individual watersheds located upstream of each water quality monitoring site were