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Detecting gradual and abrupt changes in water quality time series in response to regional payment programs for watershed services in an agricultural area

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SUMMARY

Market-based watershed protection instruments can effectively improve water quality at various catchment scales. Two payments for watershed services (PWS) programs for water quality improvement have been successively implemented in the Huai River catchment and its sub-watershed, the Shaying River catchment, in Henan Province since 2009. To detect changes in water quality in response to PWS schemes, nonparametric statistical approaches were used to analyze gradual and abrupt trends in water quality, focusing on chemical oxygen demand (COD) and ammonia-nitrogen (NH_3-N) at 26 monitoring stations in the Huai River watershed during 2006–2013. The nonparametric Mann–Kendall test and the Theil–Sen estimator were used to identify trends and their magnitudes in weekly water quality observations and the Pettitt test was applied to change-point analysis of water quality time series. We found decreasing concentration trends in the weekly water quality data set in this catchment, with water quality at most stations affected by the PWS schemes. The COD and NH_3-N concentrations decreased at 26 stations by an average of 0.05 mg/L wk and 0.01 mg/L wk, respectively, from 2006 to 2013. Meanwhile, the mean concentrations of COD and NH_3-N decreased at the 26 stations by an average of 18.03 mg/L and 4.82 mg/L, respectively, after the abrupt change points of the time-series trends of these two pollutants. We also estimated annual reductions in COD and NH_3-N for each station based on average flow observations using the Theil–Sen approach along with the resulting economic benefits from 2009 to 2010. The COD and NH_3-N reductions were 14604.50 and 6213.25 t/y, respectively, in the Huai River catchment in Henan Province. The total economic benefits of reductions in these two pollutants were 769.71 million ¥ in 2009 and 2010, accounting for 0.08% and 0.06%, respectively, of the GDP in the entire Huai River watershed of Henan Province. These results provide new insights into the linkages between PWS programs and water quality improvements at regional and local scales for effective management of water resources.

1. Introduction

With rapid population and economic growth at a global scale, increasing attention is being paid to water services supplied to humans and ecosystems (Brauman et al., 2007; Seckler et al., 1998). Surface water quality is a critical factor determining the water services supplied by a watershed to humans and is of great concern to the public and decision-makers at all levels. Variations in water quality and quantity within a regional or local watershed can be attributed directly or indirectly to anthropogenic activities, e.g., climate change (Delpla et al., 2009; Piao et al., 2010; Solheim et al., 2010; Whitehead et al., 2009), land use (Tong and Chen, 2002; Wan et al., 2014), and industrial and agricultural activities (Carr and Neary, 2006; Dabrowski et al., 2009).

Much of the research on surface water quality has evaluated temporal and spatial variations at different catchments using multivariate statistics and trend analysis (Antonopoulos et al., 2001; Luo et al., 2011; Pejman et al., 2009; Singh et al., 2004) and has investigated major contributing factors to water quality changes such as land use and cover and climate change (Chang, 2008; Mimikou et al., 2000; Tong and Chen, 2002). Studies of the spatial and seasonal variability of water quality have demonstrated that water quality degradation, e.g., increases in nitrogen (N), phosphorus (P), and organic pollutants, is strongly related to agricultural activities and urban sprawl (Bu et al., 2010; Carpenter et al., 1998). To improve surface water quality, various

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environmental measures and legislation targeting water pollution have been implemented in trans-boundary watersheds to tackle trans-boundary water quality issues, e.g., the European Union Water Framework Directive (European Parliament, 2000) and payments for water services (PWS) programs (Bennett, 2009; Scherr et al., 2006; Wunder, 2005). Payment for water-related services or PWS is widely used as a mechanism to some extent to translate external, non-market values associated with aquatic environment into financial incentives (Engel et al., 2008). PWS can also serve as an effective means of funding water services providers and an incentive for landowners to implement land management practices that improve water services (Daily, 1997; Landell-Mills and Porras, 2002; Porras et al., 2013). These market-based environmental protection and sustainable development initiatives have played an important role in water quality improvements and alleviation of rural poverty (Hering et al., 2010; Liu et al., 2007; Lu and He, 2014; Miranda et al., 2003; Scheur and Naus, 2010; Zheng et al., 2013).

However, there has been relatively little research on concomitant changes in water quality, such as dissolved oxygen (DO), temperature, chemical oxygen demand (COD), ammonia-nitrogen (NH_3-N), in catchments at regional scales before and after implementation of incentive-based environmental tools such as PWS projects and other policies targeting pollutant reduction. Collection of long-term water quality and hydrological observations at the same monitoring stations has been, and still is, a major challenge, particularly in developing countries, which have few environmental data sets that can be effectively shared (Porras et al., 2013; Van House et al., 1998; Wunder et al., 2008). However, data on trends in water quality are in increasing demand both for understanding human impacts on watershed systems and for assessing the effectiveness of water quality policies or interventions. Spatiotemporal analysis of water quality can also provide important information on water quality conditions to the public and various levels of government.

The Huai River watershed has witnessed rapid improvements in water quality, but is still a focus of attention for its negative impacts on human health due to transboundary pollution, most notably between Henan and Anhui Provinces (Economy, 2010; Ma, 2006; Ou, 2005; Qi et al., 2012; Zhou et al., 2013). The primary pollutants of greatest concern were heavy metals, persistent organic pollutants (POPs), pesticides, and other hazardous contaminants. These pollutants have chronically accumulated in surface sediments of the Huai River in Henan Province and pose human health risks through drinking water and the food chain, directly or indirectly (Fu et al., 2014; Gao, 2008; Liu, 2010; Schwarzenbach et al., 2010; Zhang et al., 2009).

Most importantly, increasing COD and NH_3-N discharges from industrial and agricultural activities and household sewage have exceeded the assimilation capacity of the aquatic environment in this catchment, and have become the greatest priority for water pollution control due to the negative effects of these oxygen-consuming substances on aquatic organisms (Wu and Yu, 2010). Two PWS programs were carried out successively in 2009 and 2010 aimed at improving water quality in the Shaying River and all of the Huai River watersheds in Henan Province. Previous studies have assessed water quality changes in these catchments using multivariate statistical methods (Jiang et al., 2011; Yang et al., 2012), and have also evaluated the effectiveness of water funds in controlling water pollution in these two watersheds (Ma, 2006; Lu and He, 2014). Ma (2006) evaluated the 10th Five-Year (2001–2005) Water Pollution Control Plan for the Huai River Watershed in Henan Province and found that this plan did not achieve its expected goals, e.g., water pollution in the river and total COD and NH_3-N exceeded the planning objectives, even with targeted investments of 5.61 billion RMB. Lu and He (2014) analyzed the impacts of PWS on water quality in the Shaying River watershed and found that economic incentives had played an important role in water quality improvements and pollutant reduction. However, few studies have been conducted on spatiotemporal variations in water quality and resulting economic benefits in these two watersheds using weekly monitoring data sets in response to implementation of these PWS programs.

The main purpose of this research was to detect spatiotemporal trends in water quality in the Huai River watershed in Henan Province before and after implementation of the PWS programs in 2009 and 2010. The Mann–Kendall test, Pettitt test, and other statistical methods were used to assess spatial and temporal variations in water quality. The goal of the study was to obtain information on the response of water quality to PWS programs that may be useful for both policymakers and researchers.

2. Methodology

2.1. The Huai River catchment and water quality data sets

The Huai River study area (Fig. 1) originates in the Tongbai Mountains in Henan Province and flows directly into adjacent downstream Anhui Province. The river has a mainstream length of 417 km and a total drainage area of 87683.1 km^2, about 52.5% of the total area of Henan Province. It is divided into four sub-catchments based on the geographic characteristics of the local river systems and topography: the mainstream and southern tributaries of the Huai River, the Hong River, the Shaying River, and rivers on the Yudong Plain, with corresponding areas of 18300.6, 15468.2, 35082.5, and 18831.8 km^2, respectively. We located 30 monitoring stations in river systems in this catchment from west to east through the mountains and rolling hills (generally 500–1500 m and 200–500 m above sea level, respectively) to the plains (<200 m above sea level), with various average flows (Table 1).

The studied catchment is situated in a transitional region from the northern subtropical zone to the warm temperate zone with a marked continental monsoon climate, along the geographic divide of the Qin Mountains between north China and south China. The area had an average annual temperature of 13–15 °C and a mean annual precipitation of 634–1200 mm during 1969–2004, with a distinct decrease from south to north and notable seasonality in which >50% of the annual rainfall occurred during June and September (Cheng et al., 2011).

Approximately 59% of the land is arable in this catchment. The primary soils are paddy soils, fluvo-aquic soils, lime concretion black soils, cinnamon soils, yellow–brown earths, and yellow–cinnamon soils, which are favorable for growing crops such as wheat, maize, and rice with plentiful sunshine and warmth. Consequently, the arable land in the Shaying River watershed and the Yudong Plain has historically been and remains one of China's major grain-growing regions, without a change in land use.

The catchment includes 11 cities: Zhengzhou, Kaifeng, Xuchang, Shangqiu, Pingdingshan, Xuchang, Luohe, Zhumadian, and Xinyang, as well as Ruyang County in Luoyang and Tongbai County in Nanyang. It was largely rural and highly populated with an average population density of 723.97 cap/km^2, more than five times the national average of 141.74 cap/km^2 in 2013. In contrast, the gross domestic product (GDP) per capita in this catchment was 28889.68 RMB, only 68.94% of the national average of 41907.59 RMB in 2013. The catchment was poorly developed with clear regional differences. The maximum GDP per capita was 82581.23 RMB in Zhengzhou, followed by 39243.51 RMB in Xuchang and 31215.22 RMB in Luohe, and the minimum GDP was 15832.45 RMB in Zhoukou in 2013.

Water pollutants such as COD and NH_3-N originated mainly from household sewage and industrial wastewater (Department