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Changes in river water temperature between 1980 and 2012 in Yongan watershed, eastern China: Magnitude, drivers and models

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SUMMARY

Climate warming is expected to have major impacts on river water quality, water column/hyporheic zone biogeochemistry and aquatic ecosystems. A quantitative understanding of spatio-temporal air (T_a) and water (T_w) temperature dynamics is required to guide river management and to facilitate adaptations to climate change. This study determined the magnitude, drivers and models for increasing T_w in three river segments of the Yongan watershed in eastern China. Over the 1980–2012 period, T_w in the watershed increased by 0.029–0.046 °C yr^{-1} due to a ~0.050 °C yr^{-1} increase of T_a and changes in local human activities (e.g., increasing developed land and population density and decreasing forest area). A standardized multiple regression model was developed for predicting annual T_w (R^2 = 0.88–0.91) and identifying/partitioning the impact of the principal drivers on increasing T_w:T_a (76 ± 1%), local human activities (14 ± 2%), and water discharge (10 ± 1%). After normalizing water discharge, climate warming and local human activities were estimated to contribute 81–95% and 5–19% of the observed rising T_w, respectively. Models forecast a 0.32–1.76 °C increase in T_w by 2050 compared with the 2000–2012 baseline condition based on four future scenarios. Heterogeneity of warming rates existed across seasons and river segments, with the lower flow river and dry season demonstrating a more pronounced response to climate warming and human activities. Rising T_w due to changes in climate, local human activities and hydrology has a considerable potential to aggravate river water quality degradation and coastal water eutrophication in summer. Thus it should be carefully considered in developing watershed management strategies in response to climate change.

1. Introduction

Water temperature is an important river physical property with a crucial impact on aquatic ecosystem health, as most river biogeochemical processes are functions of temperature (Webb and Nobilis, 2007; Webb et al., 2008; Kaushal et al., 2010; evan Vliet et al., 2012; Xin and Kinouchi, 2013; Luce et al., 2014; Rice and Jastram, 2015). Higher water temperature can impair the habitat of a wide range of aquatic organisms from invertebrates to salmonids (Langan et al., 2001; Caissie, 2006; Isaak et al., 2012; Markovic et al., 2013; Null et al., 2013a,b), as well as degrade water quality such as decreased oxygen-holding capacity, increased oxygen consumption, and enhanced formation of potentially toxic NH_3 (Webb and Nobilis, 2007; Pekárová et al., 2011; El-Jabi et al., 2014). Furthermore, increasing riverine heat flux has a great potential to aggravate eutrophication (including harmful algal blooms) and hypoxia in downstream lakes, estuaries and coastal waters (Liu et al., 2005; Ozaki et al., 2008; Ye et al., 2011; Rice and Jastram, 2015), as well as to impair their biological communities (Seekell and Pace, 2011).

Various studies have shown that rising water temperature is strongly related to climate warming across a range of river types (e.g., watershed size) and time scales (e.g., daily, weekly, monthly, and annual), because air temperature is a major component in calculating net heat fluxes at the air–water interface (Webb et al., 2003, 2008; Caissie, 2006). For example, Seekell and Pace (2011) indicated that a 0.945 °C increase of water temperature in the Hudson River during the period 1946–2008 was primarily related to air temperature increasing. Depending on the river type and time scale, the air–water temperature dynamics can be effectively

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expressed by a linear or logistic function (Mohseni and Stefan, 1999; Webb et al., 2003; Pekárová et al., 2011; van Vliet et al., 2012; Gu et al., 2014). For example, the slopes of the regression lines between water and air temperature generally increase with increasing time scales (daily, weekly, monthly and annually), while the slope decreases from small upstream to large downstream river reaches (Webb et al., 2003; Caissie, 2006). For some groundwater-dominated rivers, due to the influence of groundwater inputs at low air temperature and evaporative cooling at high air temperature, weekly or daily air–water temperature relationships often departure from a linear relationship and are better expressed by a logistic regression (Caissie, 2006; Webb et al., 2003, 2008).

Although the relationship between air and water temperature is generally strong, the strength of such a relationship varies regionally and temporally, and can be highly site specific due to additional influences from local hydrology and human activities, such as changes in land-use and population density (Arismendi et al., 2012; Orr et al., 2015; DeWeber and Wagner, 2014). It is commonly observed that water temperature is inversely related to river discharge, reflecting a reduced thermal buffering capacity due to decreasing flow volumes, increasing travel time, and diminished dilution capacity for inputs of thermal effluents (Gu and Li, 2002; Webb et al., 2003; Moatar and Gailhard, 2006; Albek and Albek, 2009). A global assessment indicated that a decrease in river discharge by 20% and 40% would exacerbate water temperature increases by 0.3 °C and 0.8 °C on average, respectively, in addition to a 2–6 °C increase due to rising air temperature (van Vliet et al., 2011). Furthermore, rivers with low groundwater inputs are generally more sensitive to changes in air temperature compared with groundwater-dominated rivers (Caissie, 2006).

Regarding land-use change, many studies suggest that decreasing forest area (or decreasing vegetation shading (Moore et al., 2005; Ozaki et al., 2008; Pekárová et al., 2011; Simmons et al., 2014) and increasing urban area (or increasing human density and increasing thermal effluent) within a catchment can significantly increase river water temperature in addition to climate warming (Langan et al., 2001; Caissie, 2006; Albek and Albek, 2009; Xin and Kinouchi, 2013; Gu et al., 2014; Lepori et al., 2014; Orr et al., 2015). For example, the observed water temperature increases of 0.11–0.21 $°C\,yr^{-1}$ in winter and spring for some stream segments in central Tokyo and its suburbs between 1978 and 1998 were ascribed to increases in anthropogenic heat input from urban wastewater (Kinouchi, 2007). Other human activities, such as river diversion, channelization and impoundments, can also alter the thermal dynamics of downstream reaches (Liu et al., 2005; Žganec, 2012; Null et al., 2013a,b).

While it has been recognized that increasing river water temperature is a complex function of the interaction of changes in climate, hydrology, and human activities, there is a distinct paucity of studies that address their integrated influence on spatio-temporal river water temperature dynamics due to a lack of long-term data sets (Caissie, 2006). Importantly, little quantitative knowledge is available concerning what contribution of the river warming rate is attributable to climate warming versus local human activities. Such quantitative information is critical for developing effective watershed management plans and water quality standards to protect aquatic species (Moatar and Gailhard, 2006; Caissie, 2006; Kaushal et al., 2010).

Although long-term trend analyses of river water temperature have been widely examined in American and European watersheds, little knowledge is available for rivers in China. Examining long-term river water temperature trends is especially important for watersheds in eastern China that have experienced rapid economic development, human population expansion, and urbanization, as well as significant climate change since the 1980s (Huang et al., 2014; Chen et al., 2014). For coastal waters along the East China Sea, serious algal blooms and persistent hypoxia have been widely reported in recent decades (Li et al., 2007; Gao and Zhang, 2010). From the perspective of future global warming and increased human activities, higher temperature of water from upstream rivers has the potential to greatly aggravate eutrophication (including harmful algal blooms) and hypoxia of downstream coastal waters. These effects are exacerbated by increasing inputs of oxygen-demanding substances and excessive nutrients in many rivers in eastern China (Huang et al., 2014). Accordingly, it is urgent to gain a comprehensive and quantitative understanding of long-term water temperature trends in response to changes in air temperature, hydrology, and human activities for rivers in eastern China.

This study provides the first historical analysis of river water temperature changes in response to changes in climate, hydrology, and human activities for a rapidly developing watershed (i.e., Yongan watershed) in eastern China over the 1980–2012 period. Human activities in this study are defined as increasing developed land, decreasing forest land, and increasing population. Three river segments located in headwater, mid-watershed, and lowland portions of the Yongan watershed were selected for analysis to provide a range in levels of human disturbance and water discharge conditions. This study advances our understanding of river water temperature dynamics by (i) examining the long-term warming rates of annual and monthly river water temperature as well as their spatial heterogeneities, (ii) addressing the drivers of the observed rising river water temperature, (iii) developing a standardized multiple regression model for predicting river water temperature, (iv) identifying individual contributions of climate warming and human activities to rising water temperature, and (v) forecasting trends in river water temperature based on scenarios for future (2013–2050) changes in climate and human activities expected for this watershed. Besides being the first analysis of river water temperature dynamics in China, novel aspects of this study include demonstrating the integrated influence of air temperature, hydrology, and human activities on the spatio-temporal river water temperature dynamics and providing a simple methodology for quantifying the contributions of the identified drivers to variations of river water temperature. The results of this study improve our quantitative understanding of long-term annual, seasonal, and spatial air and water temperature dynamics for improving watershed management and facilitating adaptation to these climate change effects.

2. Materials and methods

2.1. Study watershed

The Yongan watershed (120.2295°–121.0146°E and 28.4695°–29.0395°N; elevation ~15–1000 m) is located in the rapidly developing Taizhou region of Zhejiang Province, China (Fig. 1). The Yongan River is the third largest river of Zhejiang Province and flows into Taizhou Estuary and the East China Sea, a coastal area that commonly experiences hypoxia (Li et al., 2007; Gao and Zhang, 2010). The river drains 2474 km^2 and has an average water depth of 5.42 m and discharge of 72.9 $m^3\,s^{-1}$ at the downstream BZA sampling site (Fig. 1). The climate is subtropical monsoon having an average annual temperature of 17.2 °C (16.3–18.6 °C) and average annual precipitation of 1395 mm (1064–1813 mm). Rainfall mainly occurs in May–September (67% of total annual precipitation) with a typhoon season in July–September, while winter (December, January and February) is a major dry season receiving only 15% of the annual precipitation. There are no major dams/reservoirs or water withdrawals/transfers in the watershed.