Journal of Hydrology 519 (2014) 69–79

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Drivers of drying on the Yongding River in Beijing

Bo Jiang [a], Christina P. Wong [b], Fei Lu [a], Zhiyun Ouyang [a,*], Yajuan Wang [c]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[b] School of Sustainability, Arizona State University, PO Box 875502, Tempe, AZ 85287-5502, USA
[c] Beijing Hydrologic Center, Beijing 100089, China

ARTICLE INFO

Article history:
Received 3 January 2013
Received in revised form 30 April 2014
Accepted 22 June 2014
Available online 11 July 2014
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Ezio Todini, Associate Editor

Keywords:
Human activities
Precipitation
Streamflow
Monotonic trend
Abrupt change
Regression analysis

SUMMARY

In recent decades, the Yongding River in Beijing has ceased to flow due to the impact of climate and anthropogenic factors, which has led to severe environmental degradation. The Beijing government is constructing new freshwater ecosystems on the Yongding River to improve environmental conditions for ecosystem services. Clarification is needed on the influence of precipitation and anthropogenic factors on streamflow decline in Beijing. A hydrological time-series analysis was conducted on recorded streamflow at Guanting Reservoir, Yanchi, and Sanjiadian to estimate the influence of precipitation variability on the drying of the Yongding River in Beijing. From 1980 to 2010, the mean annual rates of streamflow decline were 0.44 $m^3\ s^{-1}\ yr^{-1}$ (Guanting), 0.42 $m^3\ s^{-1}\ yr^{-1}$ (Yanchi), and 0.03 $m^3\ s^{-1}\ yr^{-1}$ (Sanjiadian). The most probable abrupt change-point for annual streamflow was 1999 at Guanting Reservoir and Yanchi, and was 2000 at Sanjiadian. Between the pre-change (1980–1999) and post-change (2000–2010) periods, mean annual streamflow decreased by 68.56% (Guanting), 66.92% (Yanchi), and 96.78% (Sanjiadian). A multiple regression analysis using annual precipitation and streamflow at Guanting, Yanchi, and Sanjiadian showed an insignificant relationship between local precipitation and streamflow in both periods. Next we assessed the potential impact of upstream human activities on downstream flow using: (1) correlation statistics between upstream flow and downstream flow, (2) water abstracted above Sanjiadian, and (3) upstream socioeconomic data. The results suggest upstream human activities are important drivers on downstream flow decline, which could possibly explain the weak relationship between precipitation and streamflow. Further analysis is needed to clarify the influence of upstream water consumption on Guanting Reservoir to advise management on the new freshwater ecosystems along the Yongding River.

1. Introduction

The Yongding River is Beijing's largest river, commonly known as the city's "Mother River". Humans have impacted the Yongding River for centuries by deforestation, flood control, and water diversions. The headwaters of the Yongding River were historically wooded with large tracts of primary forests, however deforestation from the 13th to 20th centuries caused massive, dangerous floods in Beijing (Li, 2005). Dams were constructed on the Yongding River for flood mitigation, such as the famous Guanting Reservoir built in 1954. In the past 30 years, increased damming and water abstraction have dramatically altered the hydrology of the Yongding River, which experts believe made the Yongding River perennially dry, in particular the lower reaches in Beijing (Yu et al., 2011). Since the late 1970s, the climate regime on the Yongding River has transitioned towards increased drought prevalence (Wang et al., 2011). In the last decade, mean annual precipitation in Beijing was 30% lower than the long-term historical mean of 585 mm (Probe, 2010). Streamflow reduction has led to the loss of freshwater ecosystems on the Yongding River, resulting in bare sandy channels, which are considered key contributors to Beijing's dust events (Yue et al., 2006). In Beijing, the channels became gravel mines and dumping grounds for sewage and trash (Dong, 2002). Beijing officials attribute the Yongding River's poor environmental quality to slow economic development in the region. In 2009, the Beijing Water Authority (BWA) approved the construction of the Yongding River Green Ecological Corridor to "ensure water ecosystem services to advance socioeconomic conditions to improve urban livability". The Yongding Corridor seeks to address environmental damages with the construction of six lakes and three functional wetlands, which will bring 130 million m^3 of water to the Yongding River. The management targets are: (1) wetland water purification, (2) groundwater recharge and subsidence prevention, (3) elimination of seasonal blowing dust, (4) urban temperature reductions, and (5) aesthetics and recreation. The

* Corresponding author. Tel.: +86 10 6284 9191; fax: +86 10 6284 9816.
E-mail address: zyouyang@rcees.ac.cn (Z. Ouyang).

http://dx.doi.org/10.1016/j.jhydrol.2014.06.033
0022-1694/

water sources will be reclaimed water from wastewater treatment plants (128 million m^3), upstream water from Guanting Reservoir (10–30 million m^3), and local runoff (2 million m^3) (BWA, 2009). Determining where increasing and decreasing streamflow trends occur, and quantifying the factors driving trends can help authorities manage the Yongding Corridor for the long-term provision of ecosystem services. To prepare for future water allocations, we studied past influences of precipitation and evaluated possible human drivers on streamflow decline in the Yongding River in Beijing.

Concern on the implications of climate change and direct human activities on water resources is growing worldwide. Hydrological processes are increasingly being altered by water infrastructure (Rosenberg et al., 2000), landscape alterations (Gao et al., 2011), and human-induced climate changes from greenhouse gases and aerosols (Barnett et al., 2008). The separation and quantification of climate variation and human impacts on streamflow can be challenging due to the complex interactions between climate, human activities, and hydrological processes. A range of statistical and modeling techniques have been developed to estimate streamflow changes from climate change and human activities (Li et al., 2007; Barnett et al., 2008; Yang and Tian, 2009; Gautam et al., 2010; Ma et al., 2010; Gao et al., 2011). The impacts of climate variability on hydrologic time-series can be estimated using trend analysis (Lettenmaier et al., 1994; Whitfield and Cannon, 2000).

Trend analysis helps to identify the presence of a trend in a hydrologic time-series at different temporal and spatial scales (Lettenmaier et al., 1994; Douglas et al., 2000; Burn and Hag Elnur, 2002; Yue et al., 2003; Birsan et al., 2005, 2012; Hamed, 2008). The most common statistical technique is the non-parametric Mann–Kendall test (Mann, 1945; Kendall, 1975), which is used to identify the existence of monotonic trends in a time-series. The main weakness of the Mann–Kendall statistic is it is designed to detect the monotonic trend, however hydrologic changes can occur both gradually (trend) and abruptly (step-change) (Kundzewicz and Robson, 2004; Mazvimavi and Wolski, 2006). A gradual change is typically slow and constant over time while an abrupt change occurs quickly due to a sudden alteration within a watershed (e.g., reservoir construction, water diversions) (Kundzewicz and Robson, 2000; Smyth et al., 2008). For highly altered watersheds, like the Yongding River, the streamflow record may have periods of abrupt change due to anthropogenic or drought disturbances. An important statistical technique for analyzing climate variability and human activities is calculating change-points, which are commonly determined using the Pettitt test (Pettitt, 1979). Monotonic trend and abrupt change point analyses are often used in combination to characterize a time-series.

After identifying the change-points, three methods can be used to estimate the impact of human activities and climate variability on streamflow, which are hydrologic model simulation, sensitivity analysis, and regression analysis. Hydrologic models can simulate runoff under altered precipitation regimes, land cover alterations, and/or impoundments (Christensen and Lettenmaier, 2006; Guo et al., 2008; Ma et al., 2010). However, simulating runoff using hydrologic models often requires extensive datasets and tedious operations. Hydrologic sensitivity analysis calculates the percent change in mean annual runoff due to changes in mean annual precipitation and potential evapotranspiration (PET) (Dooge et al., 1999; Milly and Dunne, 2002). Jones et al. (2006) estimated the percent change in mean annual runoff under different climate scenarios for 22 Australian catchments by calculating the hydrologic sensitivity of rainfall–runoff models. Chen et al. (2013) used hydrological sensitivity to quantify the effects of climate variability and human activities on runoff in the Kaidu River Basin in northwest China. Regression analysis can determine the correlation between runoff and climate variables (Jiang et al., 2011). Du et al. (2011) used linear regression analysis to separate the impact of human activities and precipitation on streamflow. Zhang et al. (2012) used a runoff model driven by precipitation and evapotranspiration to establish the non-linear relationship between runoff and climate. Jiang et al. (2011) compared all three methods in estimating climate and human activities on runoff from the Laohahe Basin. They found all three methods created consistent estimates of percent change in mean annual runoff from climate variability and human activities. Lastly, the estimates of human activities on streamflow have been evaluated using land use and land cover (Yang and Tian, 2009; Ma et al., 2010) and general historical information (Gao et al., 2011). In this paper, the influences of precipitation on streamflow were estimated at Guanting Reservoir, Yanchi, and Sanjiadian. Precipitation and streamflow trends were characterized using the Mann–Kendall test at all stations. The Pettitt test was used to identify the most probable abrupt change-point in annual runoff from 1980 to 2010 by dividing the runoff time-series into pre- and post-change periods. The statistical influences of precipitation were estimated using the multiple regression analysis method. Subsequently, possible human drivers on streamflow decline were evaluated in three ways by comparing: (1) correlation statistics between upstream flow and downstream flow, (2) Yanchi runoff to water abstracted through the Yongding River Diversion Canal, and (3) upstream socioeconomic trends to inflow and outflow at Guanting Reservoir.

This paper evaluates the influence of precipitation and possible human drivers on streamflow decline of the Yongding River in Beijing from 1980 to 2010. The main research questions are: what is the influence of local precipitation variability on streamflow decline along the Yongding River in Beijing, and what are the potential human drivers of streamflow decline? The paper objectives are: (1) determine the temporal trends in the precipitation and streamflow time-series; (2) identify the abrupt change-points in streamflow; (3) identify the impact of precipitation changes on streamflow; (4) evaluate potential human drivers using historical information, water abstracted through the Yongding River Diversion Canal, and upstream socioeconomic data.

2. Materials and methods

2.1. Study area

The Yongding River is 747 km long with a watershed area of 47,016 km^2, and is a major tributary of the Hai River Basin. The Yongding River starts in Shanxi Province flows through Inner Mongolia Autonomous Region and Hebei Province and terminates at Bohai Bay. The headwaters of the Yongding River, located in northern Shanxi Province and northern Hebei Province, are referred to as the Sanggan River, and the headwaters located in the Inner Mongolia Autonomous Region are known as the Yang River. Our study area extends from Guanting Reservoir in Hebei Province to Sanjiadian in Beijing Municipality, stretching between longitudes 115°36′–116°13′E and latitudes 40°14′–39°52′N (Fig. 1). The study site covers three hydrological stations: (1) Guanting Reservoir, (2) Yanchi, and (3) Sanjiadian. The study area is defined as the Beijing section of the Yongding River, including the Guanting Reservoir, but excluding Yanqing since the majority of hydrologic stations are in Beijing Municipality.

Beijing has a seasonal temperate and semiarid continental monsoonal climate. The average annual precipitation spans 550–660 mm in which roughly 85% of the rainfall occurs from June to September. The major land use types in the Yongding River Basin are forest, grassland, cropland, urban, and industrial.

For each section we conceptualized the water balance to identify the main drivers in the system. Fig. 2 outlines our hypothesis