Catena 145 (2016) 227–238

Contents lists available at ScienceDirect

Catena

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

Temporal changes of streamflow and its causes in the Liao River Basin over the period of 1953–2011, northeastern China

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ARTICLE INFO

Article history:
Received 6 January 2016
Received in revised form 22 May 2016
Accepted 12 June 2016
Available online 16 June 2016

Keywords:
Streamflow change
Climate change
Human activities
Attribution
Liao River Basin (LRB), China

ABSTRACT

Under the impacts of climate change and human activities, violent fluctuations of streamflow are observed in large river basins in China. Therefore, comparative assessment of the climatic and anthropogenic influence is crucial for better water resources planning and management. This study investigates the streamflow change in the Liao River Basin (LRB), one of the largest basins in northeast China, using long-term hydrological and meteorological data for the period of 1953–2011. The nonparametric Mann–Kendall test, Pettitt test, and cumulative anomaly curve are used to identify trends and change points of the hydro-meteorological variables. In the past 59 years, the annual and seasonal mean streamflow exhibited significant downward trend. The monthly mean streamflow presented upward trends in January, February, and May, while a downward trend was observed in other seasons. Turning points in the streamflow occurred in the years 1964, 1984, and 1998, which divide the long-term runoff series into a natural (baseline) and three human-induced periods. The high (Q_5), low (Q_{95}), and median (Q_{50}) flow during the natural period (1953–1964) was higher than that in two human-induced periods (1965–1984 and 1999–2011). The hydrologic sensitivity method was employed to evaluate the effects of climate change and human activities on the annual runoff during the human-induced periods. The results revealed that anthropogenic influence had a far greater contribution (>56.6%) to the streamflow variability than that by climate change (<43.4%). Thus, human activities are considered as the most important factor controlling streamflow changes in the LRB.

1. Introduction

The hydrological cycle of a basin is a complex process influenced by climate, physical characteristics of the basin, and human activities. Owing to the worsening of the water shortage problems and the global increase of water-related disasters, the effects of climate change and human activities on water resources have long been a focus of hydrological research (IPCC, 2007; Liu et al., 2015; Liu et al., 2016; Miao et al., 2011; Nilsson et al., 2005; Qiu et al., 2016; Ren et al., 2002; Scanlon et al., 2007). The annual runoff of many rivers decreased remarkably in the last decades (e.g., Miao et al., 2011; Tian et al., 2009; G. Wang et al., 2012; S. Wang et al., 2012), causing a number of water resources problems, particularly in arid and semi-arid regions (e.g., Ma et al., 2008; Miao et al., 2011; Vörösmarty et al., 2000). In semi-humid and semi-arid regions, the river runoff has been strongly affected by both climate variability and human activities, causing significant changes in water yield (Brown et al., 2005; Jiang et al., 2015a, 2016b; Jiang et al., 2016a, 2016b; Ma et al., 2008).

Drivers of the river runoff variability differ from river to river and vary through time (Wu et al., 2012; Jiang et al., 2016b). To manage water resources more efficiently, it is necessary to understand the runoff generation and variation under changing environments (Drogue et al., 2004; Xu, 2011). Furthermore, quantitative assessment of the relative impacts of different factors on the runoff is important for regional water resource assessment and exploitation. The main driving factors of the runoff change are climate, including precipitation, temperature, and evapotranspiration, and human activities. The effects of human activities on the runoff in northern China have been conventionally estimated by computing their impact on each component of the water balance equation (Ren et al., 2002), which in fact represents a challenging task owing to the complex and rapidly changing water supply and utilization conditions. New attempts, including regression analysis (Huo et al., 2008; Tian et al., 2009), sensitivity analysis (Jiang et al.,

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http://dx.doi.org/10.1016/j.catena.2016.06.015
0341-8162/

2011; Ma et al., 2008), and hydrologic model simulation methods (Liu et al., 2010; G. Wang et al., 2008; S. Wang et al., 2008) have been recently used to address this problem. Sensitivity is a widely used framework to estimate the response of annual runoff to changes in precipitation and evapotranspiration (Milly et al., 2005). Jiang et al. (2011); Li et al. (2007), and Ma et al. (2008) have used the sensitivity analysis to separate the effects of climate change and human activities on the runoff in the Wuding River Basin, Shiyang River Basin, and Laohahe River Basin, respectively, and showed that the impacts of these factors on streamflow were more significant in arid and semi-arid areas than in humid regions.

As a large river in northeast China in terms of the basin area, the Liao River provides freshwater for >100 million people. In particular, the population of Liaoning Province within the Liao River Basin (LRB) exceeds 50 million, and thus Liao River is called the mother river of Liaoning Province. The economics and agriculture in the LRB are relatively developed, and it is known as a Chinese national production base for agriculture and forestry because of the fertility of the black soils (He et al., 2015). The shortage of water resources in the LRB, like in the many other river basins in northern China, accompanied with rapid growth of population, urbanization, and economy during the last decades, has become a severe problem (Mao et al., 2014; Tu et al., 2012). Although few studies have focused on the runoff changes at certain hydrological gauge stations, tributaries, and even the whole basin of the Liao River (e.g., Guo and Guo, 2010; Mao et al., 2014; Tu et al., 2012; G. Wang et al., 2012; Yang et al., 2012; Zhang et al., 2014; Zhao and Liu, 2015), relative impacts of the integrated climatic and anthropogenic factors on the LRB runoff has seldom been investigated. These studies showed that anthropogenic impacts represent a dominant factor in affecting the drainage runoff variation in the LRB and neighboring areas. However, they focused only on the trend of runoff change, while the relative importance and contribution of different factors (e.g., human activities and climate change) on the runoff change have not been explicitly evaluated owing to difficulties in the separation of their relative impacts. Furthermore, current studies on the runoff changes in the LRB simply analyze changes in the trend of annual runoff in tributaries and the whole basin. Very few studies have investigated the seasonal and monthly runoff changes and other characteristics of the streamflow such as high flow (Q_5), low flow (Q_{95}), and median flow (Q_{50}). Therefore, given the accelerated magnitude of anthropogenic influence within the river basin, it is highly necessary to quantify the relative impacts of climate change and human activities on the runoff change for better water resources management.

This study focuses on the runoff variations and attributed factors in the LRB during the period of 1953–2011. The major objectives are: (1) to investigate the streamflow variability on the annual, seasonal, and monthly scales; (2) to identify the turning years in the runoff variability, which will be used to divide the whole period into the reference baseline period (natural period) and human-induced periods; (3) to quantify the relative impacts of precipitation, evapotranspiration, and human activities on the runoff change using the hydrologic sensitivity method by comparing the results obtained in the human-induced periods with that in the natural period; and (4) to discuss the main influencing modes of human activities on the runoff change. This work provides important insights into future sustainable water resources management, which could be applicable to other rivers affected by similar anthropogenic and natural impacts.

2. Research area

The LRB is located in the southwestern part of northeast China (116.30–125.47°E, 38.43–45.00°N) and borders the Songhua River Basin to the north, the Inner Mongolia Plateau to the west, and the Bohai Gulf to the south (Fig. 1). There is a floodplain in the central and lower reaches of the river. The basin also includes the Dongliao River, Xiliao River, Laoha River, Xilamulun River, Huntai River, Yalu River,

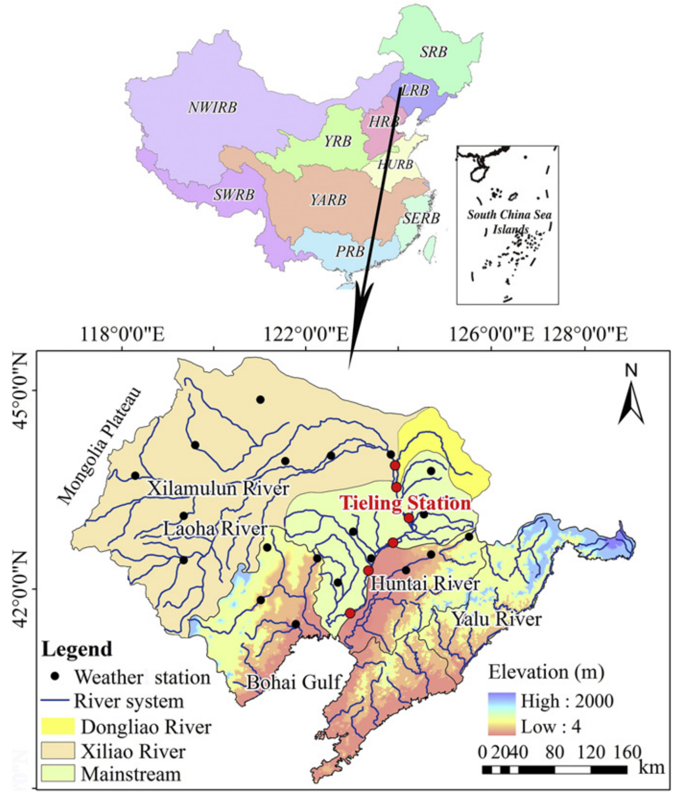

Fig. 1. Location of research area within the Liao River Basin (LRB), northeastern China, with the hydrological stations (red dots) and meteorological stations (black dots) used in this study.

and others. The study area covers the Xiliao River, Dongliao River, and mainstream, accounting for the drainage area above the Tieling station. The LRB has a temperate monsoon climate that is semi-arid or semi-humid depending on the season. A large proportion of the annual precipitation usually occurs from July to September. The average annual precipitation in the study area ranges from 200 mm in the west to 600 mm in the east. The type of soil is highly variable across the basin, with brown forest soil in the Liaodong Peninsula, moister soil in the lower stream floodplain of the Liao River, eolian sandy soil and meadow soil in the Horqin Sandy Land, and Chernozem and calcic soil in the Gongger Grassland (Mao et al., 2014; Tu et al., 2012; G. Wang et al., 2012). The main land use/cover types from east to west are forest, cropland, and grassland. Most of the grasslands are situated in the central area (the Horqin Sandy Land) and in the western portion (the Gongger Grassland and Otindag Sandy Land) of the basin. More specifically, *Setaria viridis* and *Pennisetum flaccidum* communities are widely distributed in and dominate the central area, where land is used for both agriculture and livestock husbandry, whereas the Gongger Grassland is covered primarily by zones of *Stipa grandis* and *Stipa klemenzii* (Li et al., 2011).

3. Data and methods

3.1. Data collection and quality control

Twenty meteorological stations and six hydrological stations were selected in the LRB. These gauging stations are spatially well-distributed, providing more accurate characteristics of climate and hydrology for different controlled catchments. Daily precipitation data series (1953–2011) from the China Meteorological Administration (CMA) were prescreened and underwent primary quality control by removing data with excessive departures from climatology, historical records, or