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The impacts of climate change and land cover/use transition on the hydrology in the upper Yellow River Basin, China

Lan Cuo [a,*], Yongxin Zhang [b], Yanhong Gao [c], Zhenchun Hao [d], Luosang Cairang [e]

[a] Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China
[b] Research Applications Laboratory, National Center for Atmospheric Research, Boulder, CO, United States
[c] Key Laboratory of Land Surface Process and Climate Change in Cold and Arid Regions, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, Gansu Province, China
[d] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, Jiangsu Province, China
[e] Qinghai Agriculture and Forestry Administration, Xining, Qinghai Province, China

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SUMMARY

Observed streamflow over the past decades in the upper Yellow River Basin (UYRB) was examined for changes in hydrological regime. The modified Variable Infiltration Capacity (VIC) model was employed to better understand climate change impact and long-term and recent land cover/use change impact as it relates to the "Grain for Green Project" and "Three Rivers Source Region Reserve" on water resources by examining mechanisms behind observed streamflow changes.

UYRB hydrological regimes have undergone changes over the past decades as reflected by a decrease in wet and warm season streamflow, and annual streamflow. Progressively more streamflow has been generated in the early part of the year compared to the latter part, consequently leading to the earlier occurrence of the day representing the midpoint of yearly mass flow. VIC simulations suggest that these changes in observed streamflow were due to the combined effects of changes in precipitation, evapotranspiration, rainfall runoff, and baseflow and were caused primarily by climate change above Tang Nai Hai (TNH) hydrometric station. Below TNH where human activity is relative intense, land cover/use change and reservoir release impacts became important. Changes in snowmelt runoff were negligible over the past decades. Owing to this, snowmelt runoff appeared to play only a modest role in the changing hydrology of the region. The conservation programs were shown to start to exhibit some positive impacts on water resources in the UYRB.

1. Introduction

The Yellow River, considered the cradle of Chinese civilization, originates in northern Tibetan Plateau (TP), flows through the Loess Plateau and the North China Plain, eventually empties into the Bohai Sea to the east of China. It supports 30% of China's population (Huang et al., 2009) and 13% of China's total cultivated area (Cai and Rosegrant, 2004). The Yellow River's headwater is situated in the Bayan Har mountain range in southern Qinghai Province of northern Tibetan Plateau (Fig. 1). The upper Yellow River Basin (UYRB) above the Tang Nai Hai (TNH) hydrometric station contributes approximately 35% of the total annual discharge in disproportion to its 15% area of the entire Yellow River Basin (Hu et al., 2011). Fragile and unique temperate, alpine, and wetland ecosystems within the UYRB rely on its available water resources. Understanding UYRB hydrological processes, especially in the context of global climate change and increased human activity, is necessary for informed current and future sustainable management of its water resources. Streamflow, being an integrated component of hydrology in a basin, and changes in streamflow reflect the combined effects of climate, vegetation, and soil (Rodriguez-Iturbe et al., 2001). It is important to understand how climate, land cover/use change will impact streamflow and, hence, available water resources on a basin scale.

A number of observational studies have shown that streamflow measured at TNH decreased over the past decades (Cao et al., 2006; Tang et al., 2008; Hu et al., 2011). Cao et al. (2006) found that TNH annual discharge exhibited a statistically non-significant decreasing trend between 1956 and 2000. Seasonally, except for increases detected for April, May, and June, all other months exhibited decreases in discharge. Hu et al. (2011), who analyzed TNH streamflow for a prolonged period of time (1959–2008), found that decreasing TNH streamflow was associated with decreasing wet season (from May to September) precipitation and rising temperatures. The same authors speculated that the source region

* Corresponding author. Address: Building 3, Courtyard 16, Lincui Road, Chaoyang District, Beijing 100101, China. Tel.: +86 010 84097091; fax: +86 010 84097079.
E-mail address: lancuo@itpcas.ac.cn (L. Cuo).

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catchment was largely undisturbed by human activity, which led the authors to conclude that decreasing streamflow was predominantly caused by climate change. Most of these studies focused on the revelation of the changes based on the correlation analysis between streamflow and temperature/precipitation, whereas the mechanisms that link climate change to streamflow change were rarely explored. Also, few studies examined streamflow changes at hydrometric stations other than TNH in the UYRB and it is unclear whether or not their findings are applicable to the entire UYRB.

Like elsewhere on Earth, climate change is taking place in the Yellow River Basin as reported by Wang et al. (2001), Fu et al. (2004), Yang et al. (2004), Xu et al. (2007), Zhao et al. (2007), Tang et al. (2008), Zhang et al. (2008) and Hu et al. (2011). These studies consistently describe basin-wide temperature increases, tempo-spatial variations in precipitation changes, and decreases in water resources in the Yellow River Basin. Based primarily on statistical trend analyses of observed climatology, many of these studies speculated that changes in water resources have resulted from climate change, especially changes in precipitation and temperature. What are lacking in these studies are in-depth analyses and the quantification of the changes in water balance terms related to climate change.

Snow has been widely recognized as an important component of water resources in cold regions. As suggested by Barnett et al. (2005) and Stewart (2009), snowpack changes in a warming climate were altering hydrological cycles and water availability. Clearly, the validity of this assertion relies on several factors, such as the proportion of snow to total precipitation, seasonal cycles of storm occurrences, elevation, and air temperature. As an example, in the Pacific Northwest (PNW) of the United States of America where major storm systems occur in winter and where winter average air temperature is around 0.5 °C (Mote and Salathe, 2010; Gao et al., 2011), rising temperatures in the past have greatly affected winter snow–rain partitioning (Hamlet et al., 2005), resulting in a transition from nival to pluvial hydrological regimes for low to midrange elevation basins (Cuo et al., 2009). Similar transitions are also projected for PNW highland basins in the mid-21st century as global warming progresses (Cuo et al., 2011).

To date, there has been limited research but with mixed reports concerning the role of snow in UYRB hydrology as well as the impacts of snow change on UYRB streamflow. Lan et al. (1999) reported on the importance of snowmelt in the UYRB, especially during springtime when snowmelt accounts for nearly 40% of total runoff. However, Immerzeel et al. (2010) found that during 2000–2007 meltwater derived from snow and ice played only a modest role in mean annual streamflow across the upstream region of the Yellow River Basin (elevation greater than 2000 m). To what degree snowmelt contributes to UYRB water resources certainly merits further investigation.

Besides climate change, human activity (e.g., agriculture, industrialization, urbanization, ecosystem conservation and reservoir operation) induced land cover/use change also influences UYRB water resources and hydrology. This appears to be especially true considering that human intrusion within this particularly harsh but pristine environment has increased in recent decades. As an example, Li and Liu (2004) and Dong et al. (2005) reported widespread grassland degradation in the UYRB during the 1980s and the 1990s and attributed the degradation to intensification of human activity such as overgrazing and digging caterpillar fungus. The recognition of human disturbance to the local ecosystem led to the implementation of the "Grain for Green Project" (GGP) ecosystem restoration initiative in 2000. The GGP was aimed at turning the previously cultivated and grazed land back into forests and pastures by providing subsidies to farmers and nomads in the form of grain and cash. Later, in 2005, Qinghai provincial and China central governments also launched an eco-environmental protection project and established the Three Rivers Source Region Reserve (TRSRR), comprised of the headwaters of the Yellow River, the Yangtze River, and the Mekong River that lie side by side in southern Qinghai Province. These efforts represent intensive human intervention aimed to ameliorate ecosystem degradation. However, it is unknown to what extent the intensive intervention has influenced water resources in the region and whether or not the intervention has been effective.

A few studies have examined the impacts of both climate change and land cover/use change on UYRB hydrology. For example, Zhao et al. (2009) used sensitivity-based analysis and a dynamic water balance model to study the impacts of climate change as manifested by precipitation and potential evapotranspiration (ET) change and the impacts of vegetation change, respectively, on streamflow at the Jimai, Tang Nai Hai, and Lan Zhou hydrometric stations in the UYRB in 1956–2000. Their results showed that vegetation change played a secondary role in affecting changes in streamflow at Tang Nai Hai while both climate change and vegetation change were important factors at Lan Zhou. On the other hand, Zheng et al. (2009) applied the concept of climate elasticity to assess the impacts of climate and land surface changes on UYRB streamflow from 1960 to 2000, and showed that land use changes played a more important role in reducing streamflow during the 1990s. Apparently, the inconsistencies between these studies stem from the different methods, time periods, and base scenarios used. None of these studies examined the influence of the recent large-scale human intervention on streamflow in the region.

This study, by applying a rigorously calibrated and validated physically-based macroscale hydrological model over the UYRB, aims to identify changes in observed streamflow at several locations and to explore the causes of streamflow changes by examining climate change impacts on water balance terms, and land cover/use change (both long term and recent human intervention) impacts on streamflow. Furthermore, this study tries to reveal the importance of snowmelt contribution to streamflow. The ultimate objective of this study is to identify the mechanisms that are responsible for streamflow changes in the UYRB.

2. Study area

The UYRB, situated above Jingyuan County, Gansu Province (JYR, 36°45′N, 104°45′E, 1400 m above mean sea level), is the area investigated in this study (Fig. 1). Previous studies focused mainly on the Yellow River Basin above TNH (headwater region) where population density is low (6/km^2 based on the 2003 census data). This study also includes areas below TNH and above JYR where two economic centers, Xining City and Lanzhou (LZH) City are located. In total, about 5.8 million people live in the Xining and Lanzhou corridor.

According to a 90-m elevation map, UYRB elevation ranges between 1400 m and 6300 m and drops off from the southwest to the northeast. TNH hydrometric station (35°30′N, 100°9′E, 2700 m) is located just above the Longyang Gorge Reservoir (247×10^8 m^3 water storage capacity) in Qinghai Province. Ji Mai (JMA, 33°46′N, 99°39′E, 3955 m), Tang Ke (TAK, 33°25′N, 102°28′E, 3435 m), and Ma Qu (MAQ, 33°58′N, 102°5′E, 3435 m) hydrometric stations are located upstream of TNH. Streamflow measured at and above TNH had not been affected by large dams or major irrigation diversions and as a result largely reflected the natural conditions. Near JYR, LZH gauge (36°04′N, 103°49′E, 1600 m) is located, and right above LZH, there is another large reservoir, the Liujia Gorge Reservoir (64×10^8 m^3 water storage capacity). Both reservoirs could be expected to affect streamflow at LZH. Also, below the