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Present and future of urban water balance in the rapidly urbanizing Heihe River Basin, Northwest China

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ABSTRACT

Urbanization impacts water availability by increasing water demand due to economic development and population growth; in turn, the availability of water affects the growth rate of urbanization. In addition, urbanization alters the hydrologic, or flow, regime of rivers by increasing impervious surface cover. Utilizing an integrated modeling framework linking urban-land expansion, water-allocation, and hydrological processes, this study examines the combined impacts of the changes in land use–land cover and economic activity due to urbanization and in climatic conditions on water resources in the Heihe River Basin in northwest China over the period of 2010–2050. The redistribution of limited water supplies and the increase in water consumption are identified as to pose the highest pressures on water resources resulting from rapid urbanization. The findings of the study indicate that total water consumption is expected to increase from 21.74×10^8 m^3 in 2010 to 24.35×10^8 m^3 in 2050. In addition, the runoff in the downstream reach of the basin is forecasted to increase by 9.14% due to combined effects of urban expansion and climatic changes. This indicates that more water can be withdrawn from the Heihe River to meet the increasing water demand due to urbanization in the middle reach if water demand for ecological sustainability and functioning of the downstream reach remains unchanged. The integrated framework developed here can serve as a useful tool to examine the impact of various development scenarios with the aim of successfully allocating water resources and maximizing water use efficiency in the Heihei River Basin as well as other basins elsewhere with similar characteristics.

1. Introduction

Urbanization has an impact on water availability by changing land use and land cover, which affects hydrological processes in a watershed, and by increasing water demand. Urban water demand depends on the functioning of urban setting and its economic capacity (Collins et al., 2000). Ensuring sustainable water supply for urban environments has been a grand challenge globally (Chen et al., 2014). Water scarcity, which emerges when demand exceeds supply, poses unprecedented challenges to human and ecological security (Cheng and Zhao, 2006). Water scarcity may result from natural processes, but it may also be induced by human activities (Cai, 2008; Fang et al., 2007). Water scarcity can potentially become a serious problem in the future in response to changes in climate, population, and environment.

The impacts of climate and environmental changes on water resources availability have caused sustainability concerns around the world (Kundzewicz et al., 2007; Piao et al., 2010). Water scarcity resulting from climatic and environmental changes leads to a decrease in both agricultural production and food security (Yang et al., 2003). It can also impede socioeconomic development and diminish the health of urban environments (Piao et al., 2010). Either physical or economic, water scarcity experienced in some regions is an artificially created scarcity such that access and availability is restricted in spite of an apparent abundance of water (IWMI, 2006).

Despite agriculture is still the largest consumer of water – accounting for an estimated 72% of the water withdrawals worldwide and over 90% of those in low-income, developing countries (Hoekstra and Mekonnen, 2012), water demand by municipal and industrial sectors is growing at a much faster rate (Rosegrant and Ringler, 2000). Urbanization and industrialization are the engines of economic growth (Bertinelli and Black, 2004); nevertheless, they present big challenges to water sustainability in both developed and developing world (Grimm et al., 2008; McDonald, 2008).

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China has been experiencing rapid urbanization and economic development, which have led to the fast growth of urban water demands as well as increases in river runoffs (Fang et al., 2007). Increase in urban water demand arises from increasing population growth and economic activity in cities. Furthermore, urbanization alters the hydrologic, or flow, regime of rivers by increasing impervious surface cover. Increase in impervious surface cover causes a decrease in infiltration rates, resulting in an increase in the amount of surface water and a decrease in its quality. In turn, the changes in hydrologic regime can have significant implications for allocating water for use in different parts of a river basin (e.g., upstream versus downstream) to keep a balance between water supply and demand within the basin (Liu et al., 2013).

The Heihe River Basin of northwest China is located within arid and semi-arid climatic regions, where potential evapotranspiration exceeds precipitation (Fig. 1). Water supply in the region is provided by the runoff of the Heihe River. Nevertheless, in the Heihe River Basin, the utilization of water resources has already approached or exceeded its threshold (Wang et al., 2009). Transferring water from irrigated agriculture to urban sectors is a growing phenomenon despite of its negative effects (Celio et al., 2010; Levine and Huang, 2007). Thus, facing water scarcity issues, an appropriate allocation of water resources in the Heihe River Basin is necessary in order to meet the water demand within the entire river basin. At any rate, improving water use efficiency and enhancing water security have become the key issues to local, regional, and global economies. Previous research has widely examined the trends in temperature, precipitation (Li et al., 2010), and potential evapotranspiration (Wang et al., 2009) and the spatial and temporal patterns of both green and blue water flows (Zang et al., 2012) in the Heihe River Basin or its subbasins. However, to the knowledge of the authors, there have been no studies to date on the effect of urbanization and industrial transformation on water balance between water supply and demand in the basin.

This study examined the combined impacts of changes in land use land cover and economic activity due to urbanization and in climatic conditions on water resources in the Heihe River Basin over the period of 2010–2050. With the aim of successfully allocating water resources and maximizing water use efficiency in the river basin, it utilized an integrated modeling framework linking urban-land expansion, water-allocation, and hydrological processes. The hydrological effects of changes in land use land cover and climatic conditions were modeled using a basin-scale hydrological model, commonly used in the assessments of water quantity and quality. Forecasts of urban growth and urban land expansion at 2050 were performed using ordered weighted harmonic averaging (IOWHA) operator combination model and dynamics of land system (DLS) model, respectively. Future water demand for the forecasted urbanization was determined and water allocation was optimized and assessed using a computable general equilibrium (CGE) model. The findings of the study provide insights on how to improve water resource management to sustain urban environments in the Heihe River Basin, and other basins elsewhere with similar characteristics.

2. Study area

The Heihe River Basin is located in arid/semi-arid region and has been suffering from serious water scarcity (Li et al., 2009). The total basin area is 0.24 million km^2 and the average altitude of the basin is over 1200 m. The major river of the basin is the Heihe River with a total length of 821 km and composed of three major reaches: upstream, middle, and downstream. The basin is characterized by various geographies and ecosystems, ranging from alpine ecosystems in the southern Qilian Mountains to the oasis towns in the Hexi Corridor of midstream basin, to deserts in the northern downstream basin (Li et al., 2001).

Our study area includes the upstream and middle reaches of the Heihe River (Fig. 1). The upstream reach, which is the water source area, is located at southern Qilian Mountains. This region is characterized by remarkable vertical zonality; the elevation ranges from 5290 m in the high-mountain zone to 2000 m in the low-mountain or hill zone. This results in a steep gradient in mean annual precipitation, which decreases from about 500 mm to 250 mm as elevation decreases. The middle reach is located between the Qilian Mountains and the deserts. The elevation in this portion of the basin ranges from 2000 m to 1340 m and the mean annual precipitation decreases from 250 mm to <100 mm, respectively. Water scarcity is, therefore, mainly created by topographic characteristics of the Heihe River Basin.

In the Heihe River Basin, water supply hardly meets the demand as a whole. The extensive exploitation of water resources in the middle reach of the Heihe River has led to ecological damages in the downstream reach (Cheng and Zhao, 2006). The water supply is mainly from the upstream runoff, local precipitation, and groundwater; and it is principally used for ecological, domestic, industrial, and agricultural purposes (Li et al., 2010). At present, water from the upstream and middle reaches is allocated to restore the ecological environment in the downstream reach. According to the water distribution plan imposed by the State Council of China in 1997, if the discharge of upper reach is equal to or larger than 15.8×10^8 m^3, the middle reach should transfer 9.5×10^8 m^3 water to the downstream reach.

The water consumption per GDP has had a decreasing trend over the period of 2000–2010 (Fig. 2). Among different sectors, agriculture is still the largest water consuming sector in the basin, accounting for more than 90% of total water withdrawals (Fig. 3). Also, prior to 2002, the water consumption per GDP was merely larger than the water consumption per industrial added value; however, the gap between them has widened after 2002. The water consumption per GDP is about 30 m^3/10^3 \$, which is twice as much as that per industrial added value, indicating a very high amount of agricultural water consumption. In addition, urbanization and the other anthropogenic activities have been increasing in the river basin, aggravating water insecurity.

Seven counties are located in the middle reach of the Heihe River Basin, two of which are county-level cities (Suzhou and Ganzhou) and five of which are counties of Zhangye city (Shandan, Minle, Lingze, Gaotai, and Sunan). All are examples of typical oasis counties/cities. The total area of these counties is about 42,000 km^2, and the total population in 2010 was at 1.26 million, with the rural and urban populations accounting for 72.3% and 27.7% of the total, respectively (Wang et al., 2009). In 2010, the urbanization rate in the middle reach region was just below 30%. Overall, the total water use of the region is 2.46×10^9 m^3, 81.7% of which is supplied by the Heihe River and the rest, 18.3%, is supplied by the Liyuanhe River (Li et al., 2001). Since 2001, when the integrated management and allocation strategy of water resources in the entire Heihe River Basin was implemented, the sources of water supply have been changed with a 13.0% decrease in the supply from Heihe River and a 157.6% increase in the supply from groundwater (Wang et al., 2009). However, with the anticipated increase in urbanization and economic development, the need for freshwater is anticipated to exacerbate in the future (Fang et al., 2007).

3. Materials and methods

3.1. Modeling urbanization

The study determined the growth in urbanization in the middle reach based on the trends in population and economic growth and water resource availability, which are the main determinants

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