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Is there a relationship between water scarcity and water use efficiency in China? A national decadal assessment across spatial scales

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ABSTRACT

The relationship between water scarcity and water use efficiency is widely disputed, and despite considerable work on the topic, little attention has been paid to their spatial relationships. Using a host of spatial analyses, a variety of spatial correlations between water scarcity and water use efficiency from 2003 to 2013 in China are examined at local to national scales. The bivariate Global Spatial Autocorrelation indicates significant ($p < 0.001$) positive spatial correlation between water scarcity and water use efficiency across all regions with bivariate Moran's $I > 0$. The bivariate Local Indicators of Spatial Association (LISA) analysis shows significant ($p < 0.05$) high water scarcity and high water use efficiency correlations with regional clustering in northern China, centering on Beijing, and low water scarcity and low water use efficiency regional clustering in southern China, centering on Hunan. The coefficients of our Spatial Lag Model show that both water scarcity and water use efficiency have significant inherent spatial dependence ($p < 0.01$), but no significant causal mechanisms ($p > 0.1$) between them were found. We discuss the implications of influencing factors including (1) the geographical agglomeration in economics, population and freshwater supplies, (2) physical and virtual water transfer, and (3) technology and water resources management to such strong spatial patterns of water use and efficiency. This study affirms the need to pay attention to water use management and efficiency improvements together in scarce environments and especially within a geographic context.

1. Introduction

Water covers nearly 70% of the Earth's surface but only 3% is fresh water. Currently, humans are experiencing water shortages worse than ever before as population and economic growth, urbanization and industrialization, climate change, water pollution, poor water management, and so on, all diminish the quantity and quality of water resources from local to global scales (UN-Water, 2007; WRG, 2013; WWAP, 2012, 2015). Based on a recent study (Mekonnen and Hoekstra, 2016), two-thirds of the global population lives under severe water scarcity at least one month of the year and half a billion people face severe water scarcity all year round. The increasing magnitude and extent of water scarcity is undoubtedly undermining global sustainable development, food security, ecosystem services, job creation and other aspects of human well-being (UNEP, 2007; Alexandratos and Bruinsma, 2012; WWAP, 2012, 2015, 2016). Improving water use efficiency of associated sectors such as agriculture, industry and residential consumption is considered to be one potential solution to the water scarcity problem (FAO, 2012; Alexandratos and Bruinsma, 2012; Wada et al., 2014; WWAP, 2016). However, some scholars have argued that this solution is overly simplistic as there is a complex "nexus" between resource scarcity and efficiency of use (Varghese et al., 2013). Indeed, scarcity and efficiency are two fundamental themes of economics; scarce resources should be used with an "eye" toward efficiency (Luptáčik, 2010). Although it is often believed that resource scarcity will lead to a more prudent use of a resource (Ostromet al., 1999; Molden et al., 2010; Berg et al., 2016), some scholars have noted that less efficient use of resources under scarcity is common, as exemplified by studies on fishery, mineral, energy, and forest resource consumption (e.g., Maldonado and Moreno-Sanchez, 2009; Varghese et al., 2013; Harmsenet al., 2013). For the case of scarce water resources, some researchers have argued that scarcity has improved use efficiency (Garrido, 2011; Merli et al., 2016), but others have demonstrated that it has done just the opposite (Ercin and Hoekstra, 2012; Varghese et al., 2013; WWAP, 2015). The overarching objective of our paper is to quantify the linkages between water scarcity and water use efficiency, within a spatial-temporal context, measured for regional to national scales in China over a 10-year period, with the aim of improving our

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understanding of this complex "scarcity-use" nexus.

With the agriculture sector being the main source of fresh water consumption globally (CAWMA, 2007), water scarcity and water use efficiency are widely discussed in the literature based on the recognition that improving efficiency of water use by farmers will help ensure sustained water supply when water resources become scarce (WWAP, 2012). Yet some researchers focus almost entirely on water use efficiency as a component of their assessment to characterize water scarcity (or poverty) at local to global scales. They often use a single index such as ratio of water use to available water (Raskin et al., 1997; Zhouet al., 2016) or a combined score with some composite index to determine relationships between use and scarcity (Lawrence et al., 2002; Zhang et al., 2012; Vyver, 2013; Pan et al., 2016). Others consider water use efficiency as a sole means to address water scarcity proposing solutions that focus on improving water resource management, water consumption, suggesting technical solutions that support efficiency of use (Jiang, 2009; Walter et al., 2011; Guan et al., 2014; Zhao et al., 2015). These studies imply that efficient water use would relieve water stress; however, it is clear that efficiency and productivity gains cannot alter global resource supply patterns alone (WWAP, 2012) or address water scarcities at local scales or during unusually dry periods in arid areas (Alexandratos and Bruinsma, 2012; Mubako et al., 2013; Mekonnen and Hoekstra, 2016). Even in water-abundant countries, water resources are unevenly distributed spatially and temporally (Duncan et al., 2013). Connolly and Hagelman (2015) showed for example that water consumption patterns and drivers were spatiotemporal non-stationary. Dissecting the geographical coupling mechanisms between efficiency and scarcity is critical for us to address fully water scarcity issues. Currently, water scarcity, and water use efficiency are widely discussed at a variety of spatial and temporal scales (Gain and Wada, 2014; Tzoraki et al., 2015; Ren et al., 2016; Zhang et al., 2016), quantitative and causal relationship between water scarcity and water use efficiency have been explored (Varghese et al., 2013; Mubako et al., 2013; Osman et al., 2016), and the direct effects of water stress on water use efficiency have been assessed (Boutraa et al., 2010; Ruttanaprasert et al., 2016), but few spatially explicit studies have been conducted on the spatial patterns and interactions of use and scarcity. Obviously, scarcity and use of water resources are characterized by geographical differences at local, regional and national extents. This study attempts to examine their association from a geographical perspective using a series of spatial analyses that quantify the relationships between water scarcity and water use efficiency.

According to the WHO (2014), the majority of people affected by water scarcity and sanitation issues live in developing countries. In fact, one in five developing countries will face water scarcity by 2030 (FAO, 2003). China is the largest developing country, the second largest economy in the world and ranks as the sixth largest country globally for total available freshwater resources. Unfortunately, China was listed by the UN as one of the 13 countries most affected by severe water scarcity and faces a geographic mismatch between freshwater demand and available freshwater resources, as it is characterized by a rainy south and arid north regions (Varis and Vakkilainen, 2001; Jiang, 2009; Zhao et al., 2015; Guan et al., 2014; Liu et al., 2015b). Over the past several decades, a series of policy measures were implemented to reduce water use in scarce environments in China (Jiang, 2009; WRG, 2013); the water use efficiency gains, however, were largely offset by the water demand increase created by continued economic growth (Zhao et al., 2015). In the meantime, farmland and urban expansion both have negative effects on water environmental quality as China's rapid urban–rural transformation continues at unprecedented rates (Liu et al., 2015a). In addition, as China is a large country with extreme climatic variability between regions, virtual water flows can apply as international trade could potentially offset local supply imbalances (FAO, 2012; Zhao et al., 2015). Virtual water flow (in sensu Oki and Kanae, 2004) is that quantity of water that is used to produce a product that is transported by trade from one location to another. Consequentially, China's societal and environmental vulnerability of river systems could affect neighboring countries as well (Varis et al., 2014) and virtual water flow could be substantial. Therefore, examining China's pattern of water use and scarcity together can provide insights that are more general to the complex nexus between water scarcity and water use efficiency at local to potentially global scales.

To gain a better understanding of the spatial relationships between water scarcity and water use efficiency, this study addresses the following research questions: what are the spatial distribution patterns between water scarcity and water use efficiency in China? Does water scarcity affect water use efficiency, or vice versa? To answer these questions, we conduct several spatial analyses and report this work as follows. Section 2 presents our water scarcity index and water use efficiency index and describes the details of several spatial analysis methods used here. Section 3 presents the results of our spatial analyses designed to answer our questions. Section 4 discusses the spatial association patterns with some further explanations about causes of water scarcity. Section 5 summarizes our conclusions while providing implications to policy and water management practices.

2. Methods and data

For exploring spatial correlations between water scarcity and water use efficiency in China, a water scarcity index (*WSI*) and a water use efficiency index (*WUEI*) were developed following Raskin et al. (1997), Feitelson and Chenoweth (2002) and others, and then they were introduced into spatial analysis tools such as ArcGIS 9.3 and GeoDa 1.6.7. Our *WSI*, *WUEI*, and spatial analysis methods are presented below.

2.1. *Water scarcity index (WSI)*

In essence, water scarcity is the spatial and temporal mismatch of freshwater demand and availability (Savenije, 2000; Mekonnen and Hoekstra, 2016). Previously, there have been numerous methodologies and indices presented to quantify water scarcity, including simple neo-Malthusian per capita totals and ratios of demand to supply that can be classified as weighted with or without some socio-political-economic indicators (Rijsberman, 2006; Chenoweth, 2008; Brown and Matlock, 2011; Pedro-Monzonís et al., 2015). Other researchers have created quantity–quality–environmental flow requirement (QQE) approaches (Liu et al., 2016), and System Dynamics Model (SDM) that simulate spatial-temporal changes in water scarcity (Sušnik et al., 2012) and so on. Indices based on human or environmental water demands, vulnerability, or other measures expressed as indices have also widely employed (Rijsberman, 2006; Brown and Matlock, 2011). What is clear, however, is that there is no universal standard for water scarcity assessment (Padowski and Jawitz, 2009). Complicating assessments of water supply and scarcity are the complex nature of quantifying a nation's water sanitation systems on supply (Raskin et al., 1997) and the socio-political and institutional dependencies of scarcity (Mehta, 2007). This study attempts to establish broad, simple, and intuitive approach to measure water scarcity based on human water requirements, water use, and rainfall which are incorporated into a GIS and analyzed using spatial statistical approaches. The details of our approach are as follows:

(1) *Water resources available index (WRI)*. Total water resources available per capita, per year, and by region is categorized here into no stress (> 1700 m^3/capita/year), stress (1000–1700 m^3/capita/year), scarcity (500–1000 m^3/capita/year), and absolute scarcity (< 500 m^3/capita/year) following the definition of Falkenmark (1989) and coded as 0–3 as no stress, stress, scarcity, and absolute scarcity, respectively. More specifically, *WRI* measures a lack of water due to per capita usage and to corresponding population growth rates (Chenoweth, 2008; Brown and Matlock, 2011).

(2) *Use-to-resource ratio index (URI)*.The ratio of annual water withdrawals to annual renewable water resources by region is