The temporal–spatial assessment of water scarcity with the Water Poverty Index: a study in the middle basin of the Heihe River, northwest China

Xia Tang and Qi Feng

ABSTRACT

This paper details an application of the Water Poverty Index (WPI) to evaluate the state of water resources in an inland river basin using a case study of the Heihe River Basin (HRB) located in northwest China. The WPI includes five components (resources, access, capacity, use, and environment) and has 13 indicators; each indicator is assigned an equal weighting. The selected set of components and indicators was used to discuss the spatial and temporal variation of the water scarcity situation in the middle of the HRB for a 10-year assessment period. The results show that the water scarcity situation of the HRB is generally evolving in a positive way from 2001 to 2010. However, the WPI varied widely (from 24.6 to 66.5) at a spatial scale. The water situation was best maintained in Jiayuguan City, and it was most severe in Jiuquan City. These variations suggest that different cities require different policy intervention to improve the overall water situation. Overall, the WPI appears to be a reasonable approach to examine the water scarcity situation and help decision makers to better devise local policy.

Key words | Heihe River Basin, temporal–spatial, Water Poverty Index, water scarcity

INTRODUCTION

There are several ways to define water scarcity. According to UN Water (UN-Water 2007), water scarcity is defined as the point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully. Water scarcity is a global threat to sustainable development and political stability, resulting in the availability of clean, affordable, reliable, and sustainable water as a central issue to national sustainable development objectives. Recently, global climate change has resulted in a negative effect on water availability and the health of freshwater ecosystems in many regions (Kundzewicz et al. 2008), especially arid and ecologically fragile regions where water scarcities have become increasingly serious.

Monitoring and assessing water scarcity is therefore an issue. However, due to the complexity of the concept of water scarcity itself, no consolidated approach or standard is available. Water scarcity can be measured in different ways: i.e. the ‘Falkenmark’ Water Stress Index, Criticality Ratio, Water Poverty Index (WPI) and so on. Different measurements capture different aspects of the pressures on water resources. The ‘Falkenmark’ Water Stress Index focuses on two factors: population and total freshwater resources in a region, measuring scarcity as the average per capita water availability per year (Falkenmark & Widstrand 1989). The Criticality Ratio measures water scarcity as the proportion of annual water withdrawal relative to the total annual available water resources (Alcamo et al. 1997; Perveen & James 2011). By contrast, the WPI is a new and holistic tool, which can effectively measure a population’s relationship with available water resources, including multiple indicators designed to reflect the role of human well-being and infrastructure in water availability.
The WPI concept was first proposed by Sullivan (2001, 2002) and was intended to enable decision makers to target crosscutting issues in an integrated way by tracking the physical, economic, and social drivers. It has been widely applied as a powerful tool in evaluation at various scales, for example, international (Lawrence et al. 2002), national (Sullivan et al. 2006; Komnenic et al. 2009), regional (Sullivan & Meigh 2005; Heidecke 2006; Van Ty et al. 2010; Garriga & Foguet 2011; Manandhar et al. 2012; Jemmali & Sullivan 2014), and community levels (Sullivan et al. 2005; Cullis & O’Regan 2004; Sullivan 2005). The WPI is an interdisciplinary index that integrates five components related to water resources, i.e., hydrological, physical, social, economic, and environmental information, and their underlying components provide a true reflection of the situation in a study area. Therefore, the WPI may be the most useful approach to analyze the water scarcity situation and provide water policy priorities for inland river basins.

In this paper, we selected the Heihe River Basin (HRB) as a case study (Figure 1). The Heihe River is the second-largest inland river in northwestern China. The basin is in a typical arid region that is suffering from a serious shortage of water. The HRB is an important and strategic region due to its middle reaches linking the inland Xinjiang Province to the rest of northern China (Cheng 2002). Recently, the identification of water scarcity in this basin (Deng & Zhao 2015) and water stress of a certain city in this basin (Zhang et al. 2015) have been studied. However, to the best of our knowledge, quantification of the spatial and temporal dynamics of water scarcity in the middle reaches of the HRB is limited.

Based on the consideration above, the WPI was structured to geographically and temporally explore the

Figure 1 | Location of the study area: three cities in the middle of the Heihe River Basin.
patterns of water scarcity, and a 10-year integrated evaluation of the HRB was obtained. The objectives of this study were: (1) to analyze the water stress at two spatial scales: the middle of the river basin and three cities (Zhangye City, Jiuquan City and Jiayuguan City); (2) to identify the underlying factors that affect water stress; and (3) to provide decision makers of water poverty reduction initiatives for the specific cities within the study area.

**METHODOLOGY**

**Study area**

The HRB is an important snow-fed river basin in China, originating from the northeastern edge of the Tibetan Plateau (Figure 1). It encompasses nearly 0.23 million km² and lies between 96°05' to 104°E and 37°43' to 42°40'N. The average altitude exceeds 1,200 m (Zang et al. 2012). The river basin covers 11 counties/districts of northwestern China. It is home to nearly 1.8 million people, most of whom are concentrated in the middle plains and depend on agriculture-based livelihoods. The land cover of the basin is broadly classified into three different types: desert, mountains, and oases, which together cover 98.6% of the total area (Cheng & Zhao 2006).

The middle of HRB is located in Hexi Corridor, northwestern China, and includes Zhangye City, Jiuquan City and Jiayuguan City (Figure 1). The elevation ranges from 1,234 to 3,633 m, and its climate is characterized as arid. The mean annual precipitation varies in an easterly to westerly direction from 250 to 50 mm, and the mean annual evaporation ranges from 2,000 to 3,500 mm. The middle reaches of the HRB account for 95% of the HRB population and produce over 80% of the gross domestic product (GDP) for the whole region. However, irrigation agriculture in the midstream region consumes approximately 65% of river runoff while over 90% of the irrigation water in the downstream region originates from groundwater (Xiao et al. 2011).

In addition to global warming, continued urbanization, industrialization, and an enlargement of irrigated areas are continually increasing water demands for social and economic development (Mondal et al. 2010). Since the 1980s, water consumption has increased sharply, leading to intense competition between midstream agricultural development and downstream ecological protection in the HRB. The area is also suffering from increasing water-related problems due to climatic variability, expanding population and agriculture. Therefore, assessing the water resource situation for the basis of developing policy intervention is a pressing need.

**Basic concept of WPI**

The WPI is an integrated water management tool that is mainly relevant at the community or district level (Lawrence et al. 2002). This is a holistic approach to water resource evaluation, in keeping with the Sustainable Livelihood Approach used by many donor organizations to evaluate developmental progress (Sullivan 2001, 2002; Sullivan et al. 2003; Adger et al. 2004; Korc & Ford 2013). This approach attempts to provide a multi-dimensional picture of human welfare in relation to water resource availability by measuring: (1) access to water; (2) water availability; (3) water used for domestic, agricultural, and productive purposes; (4) the capacity for sustaining access; and (5) environmental aspects.

**Resources**

The physical availability of water takes into account the variability of the resource as well as the total amount of water. This is a measure of groundwater and surface water availability adjusted for quality and reliability. Here, we used a proxy, i.e. the annual amount of available surface water and groundwater, expressed on a per capita basis plus precipitation.

**Access**

Population access to safe water and clean sanitation accounts not only for the time and effort required to collect domestic water, but also irrigation water and its impact on food production. In this study, there were three variables for this index: (1) water supply per capita; (2) wastewater discharge per year; and (3) water-saving irrigation area.

**Capacity**

This index reveals the people’s ability to manage the water supply and their ability to purchase water. The capacity
component consists of: (1) the GDP per capita income; and (2) the government investment in water infrastructure.

Use

This index measures how water is used by different sectors of the economy, particularly the industrial and agricultural sectors. It is expressed as the proportion of water used for different purposes relative to the total water demand. Four components constitute this index: (1) domestic water use (%); (2) industrial water use (%); (3) agricultural water use (%); and (4) forest, livestock, and fisheries water use (%).

Environment

The index represents the environmental impact of water management to ensure long-term ecological integrity and sustainable development. This component investigates two aspects: (1) annual average groundwater table level; and (2) ecological water consumption. This index includes an evaluation of the environmental integrity related to water and ecosystem goods and services from aquatic habitats in the area.

Application of the WPI

This paper assessed the water poverty situation in three cities of the middle HRB using a multiple indicator-based WPI framework. The research is a preliminary attempt to select 15 variables and five components to visualize water stress considering the relevance and availability of data in the study areas. Based on the WPI results, we clearly know how water scarcity situation varies in the basins with respect to different WPI components. By relating WPI components to social, economic and environmental information, the underlying factors has been obtained and guidance on how to improve can be prioritized and targeted.

The WPI approach is complex because this index is determined by comparing the actual current empirical situation (as identified from data), with this pre-set standard (Sullivan 2001). It is more suited for analyses at a local scale to ensure that it is responsive to specific socio-economic and physical situations. Therefore, we adapted the approach to represent a location-specific WPI for the case study area of the middle HRB. The WPI components and indicators used in this research are presented in Table 1. The index ranges from 0–100 and is generated as a weighted additive value of five major components, which are resources, access, capacity, use and environment. Each dimension includes two to four sub-dimensions. The data were collected over 10 years (2001 to 2010) to illustrate the water stress changes over time. The observed values of each indicator were obtained from Gansu Statistics Yearbook (2001–2010) and Gansu Water Bulletin (2001–2010). The basic values of sub-components for middle basin of the Heihe River for 2001–2011 are presented in Table 2.

Calculation procedure

Because the basic values for each sub-component were collected from various sources and defined and recorded in different ways, normalization of the data was necessary before making definitive comparisons. Minimum–maximum (abbreviated as min–max) method is a simple and mostly used in many WPI studies (Sullivan & Meigh 2003; Sullivan 2005; Van Ty et al. 2010). Therefore, this method was applied in this study. The calculation procedure is described as follows.

First, each sub-component was standardized to a comparable range of 0 to 1 using the min–max approach
shown in Equation (1):

$$
\begin{align*}
    x_i^* &= \frac{x_i - x_{\min}}{x_{\max} - x_{\min} / 1.05} & \text{(if } x_i \text{ is a positive indicator)} \\
    x_i^* &= \frac{x_{\max} - x_i}{x_{\max} - x_{\min} / 1.05} & \text{(if } x_i \text{ is a negative indicator)}
\end{align*}
$$

(1)

where $x_i^*$ is the standardized value of an indicator for location $i$; $x_i$, $x_{\min}$, and $x_{\max}$ are the original values for location $i$, and the lowest and highest values of all the study basins considered, respectively. It should be noted that we calculate $x_i^*$ for each year of 2001–2010. Because $x_i$ includes a huge amount of data, only a summary of all the original data was given in Table 2. The mean $x_i$ values in Table 2 show an overall understanding for each sub-component, and these were not used in the calculation.

The sub-components were classified into two types of indicators: positive and negative. For the positive indicators, the higher the original value of an index, the better the water management situation, such as water supply per capita, government investment in the water infrastructure and so on. For the negative indicators, the lower the primary value of a factor, the higher the level of water poverty, for example, the wastewater discharge per year, and the groundwater level. However, there are some shortages about this calculate methodology. For example, there is 0 or 1 borderline value. The maximum and minimum values are usually adjusted so as to avoid values of 0 and 1. Following the approach used by Heidecke (2006), 5% was added to the highest observed values and deducted from the lowest observed values. So the values were still only relative to each other using this approach and cannot really be used for different periods.

Second, the sub-components of the various WPI aspects were then added and multiplied by 100; and within each of the five components, the values of the sub-component indices were averaged to obtain the component index as shown in Equation (2):

$$
WPI = \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i} = \frac{w_i R + w_a A + w_c C + w_u U + w_e E}{w_i + w_a + w_c + w_u + w_e}
$$

(2)
where $R$, $A$, $C$, $U$, and $E$ denote indexes of the five components Resources, Access, Capacity, Use, and Environment, respectively.

Heidecke (2006) highlighted the importance of transparency with respect to the assigned weights to avoid misinterpretation or manipulation of results. Garriga & Foguet (2011) used the principal component analysis method to assign the weights for sub-indices. Jemmali & Sullivan (2014) argued that weights should be maintained neutral at a value of one, leaving the possibility that different weights could be determined by stakeholder consultation rather than by science or mathematics. Accordingly, the issue of weights is an interesting theme that should be addressed in future research. In this research, due to the difficulty for getting the importance of data, and for the sake of simplicity, equal weights for the five components and various sub-components were considered for the aggregate (Sullivan et al. 2003; Pandey et al. 2012; Zhang et al. 2012). Finally, equal weights were given to the variables of the indicators, and the five components were added together to produce a combined WPI range from 0 to 100. The highest value of the WPI (100) represents the best situation where there is the lowest possible level of water poverty, while 0 is the worst situation. Therefore, Equation (2) can be rewritten as:

$$WPI = \frac{R + A + C + U + E}{5} \quad (3)$$

RESULTS AND DISCUSSION

Temporal status of water scarcity in the middle of HRB

Over the entire study period 2001–2010, there were significant variations in the values calculated for WPI and its Resources, Access, Capacity, Use and Environmental components (Figure 2). The WPI increased from 2001 until 2007, decreased in 2008 and 2009 and then increased again in 2010. The average WPI in the middle of HRB was 43.0. The WPI score of 29 in 2003 indicated the worst water scarcity situation. In contrast, 2007 had the best situation with a WPI score of 58.3. Generally, it can be concluded that: (1) the water scarcity situation in the middle of HRB is evolving in a positive way; and (2) relatively long time-series data (2001–2010) are more helpful for identifying and interpreting the dynamics of water scarcity and stress compared with short-term data.

The capacity component increased steadily, which suggested economic development accelerated in the middle of HRB during this period. The Capacity results can also reflect that the area has invested in water management. In contrast to the Capacity component, the Use component is volatile, e.g. two low values in 2003 and 2007 (Figure 2). Water resources in the HRB were highly exploited during these periods. After 2002, the government promoted water-saving and adjusted the plantation patterns, which was beneficial for agricultural water saving as well as

![Figure 2](https://iwaponline.com/ws/article-pdf/16/5/1266/411779/ws016051266.pdf)
industry production and other sectors. Therefore, the Use was relatively low and increased at a slower rate after 2002.

The Resources and Environmental components fluctuated in some years. This may be attributed to the fluctuation of annual precipitation (Table 2) and glaciers supply melt water to the Heihe River. Access component was either enhanced or slightly weakened in the middle of HRB over the study period, indicating that the overall trend of Access was getting better. The investment by local government to water access is effective.

Spatial status of water scarcity in the middle of HRB

All WPI components (average value during 2001–2010) for three cities in the study basin were shown in a radar map (Figure 3), by which the spatial distribution of WPI can be presented in a visible way. Although the radar maps of three cities are quite close, we can still identify Jiuquan City as the region of the most urgent attention, where three lowest scores are found on Environment, Access and Capacity. Jiayuguan City shows the much higher scores on Environment and Access than two other cities, and therefore has the biggest enclosed pentagram area (Figure 3), which indicates the best situation regarding water access and management (Zhang et al. 2015).

In order to give decision makers a visual instrument for displaying information to examine data (Henninger & Snel 2002), we combined temporal and spatial analysis of WPI distribution and reveal clearly the change trends of water scarcity in study area (Figure 4). Since it is a long-term analysis, a spatial and temporal distribution of the WPI was created at intervals of 5 years: 2001, 2005, and 2010. Among these years, no consistent trend was observed temporally and spatially. For Zhangye City, the highest value of the WPI (2005) was nearly triple the amount of the lowest value (2001). Comparing 2001 with 2005, the WPI for the three cities increased, whereas comparing 2005 with 2010, it decreased for Jiuquan and Zhangye in 2005. The scores for Jiayuguan City maintained a relatively steady growth, and the WPI showed a 35% increase from 35.3 to 54.3 from 2001 to 2010. These results suggested that the requirement of policy intervention for water situation is different in different cities, and it also changed annually.
The underlying factors that affect water scarcity

Figure 5 details temporally and spatially the variation of all WPI components. The longer the bars in Figure 5, the higher are the values of the WPI and the less severe the water scarcity situation for a particular city. Based on these results, we investigate the underlying factors that affect water stress, and consequently provide policy priorities for each city within the study area.

Overall, three cities improved their capacities during the study period (Figure 5), which can be attributed to the GDP growth, i.e. economic development. The Zhangye City has the highest average capacity in three cities. Although the total GDP per capita of Zhangye City showed relatively lower (Table 2), the standardized GDP per capita of Zhangye City continued to rise significantly during 2001–2010 because the differential in the GDP per capita between Zhangye City and the other cities became lower over time. In other words, economic development in Zhangye City quickened pace to catch up with other cities.

The development policy from government is also an important factor. Since 2000, Zhangye City had begun its economic structural adjustment through two initiatives: replacing crops that have high water use with water efficient crops and adjusting the primary, secondary, and tertiary sector ratios (Huang 2015). This was supported by a water reallocation scheme in 2000 and a Water-Saving Society project in 2002 by which the midstream area
should discharge 950 million m$^3$ of water in normal years to downstream areas when the upstream area discharges 1,580 million m$^3$ of water (Lu et al. 2015). The Water-Saving Society project makes the Access increased. Initially, water reallocation scheme benefits Ecological water consumption, the sub-component of Environment. Increasing Access, Environment and Capacity led the overall WPI trend of Zhangye City increased from 2001 to 2005 (Figures 4 and 5). However, implementation of the water reallocation program has a negative effect on the aquatic environment. The replenishment of groundwater has increased (Cheng et al. 2014). Continuous water reallocation caused the gradual decline of groundwater level, another sub-component of Environment. So the Environment decreased significantly, which plays an important role for the WPI decrease of Zhangye City from 2005 to 2010.

Some natural factors (e.g. resource availability and variability) are out of control. Annual precipitation is one of such factors, which brings directly/indirectly positive impact to the components of WPI. Therefore, annual precipitation is an important reason why the WPI scores for three cities are volatile over the period 2001–2010.

Based on the analysis above, policy priorities for each city are provided on the aspects which are controllable by policy interventions. For Zhangye City, planting water efficient crops should be insisted on in the future. Besides, as indicated above, the reallocation policies should be optimized to improve the imbalance between irrigation and ecological water consumption. The statuses of water scarcity for Jiuquan City and Zhangye City are quite similar (Figure 5), except the Capacity component. Therefore, the Water-Saving Society policy implemented in Zhangye City is also important for Jiuquan City. Considering Jiuquan City has even higher GDP per capita than Zhangye City, local government should pay more attention in increasing the investment in water infrastructure. Jiayuguan City has the best water situation than two other cities, the average WPI of which (44.1) is highest. Furthermore, it has low score on the Use index. Given the more limited amount of available water, achievement of a balanced water use structure makes more sense for Jiayuguan City.

### Accuracy of WPI in this study

The WPI is dependent on the sub-components selected as well as the weights expressing the relative importance of these indicators. When selecting the variables, two aspects should be considered: the study relevance, and the availability of data. In this study, we calculated the WPI at a city/basin scale by collecting existing data as much as we could. The aspects related to measures of governance were cautiously chosen and refined, such as groundwater governance and significant infrastructure investments. Since it was difficult to evaluate the data accuracy and its importance, all the sub-components were assigned an equal weighting. The WPI method developed in this study could be applied in arid inland river basin, yet its applicability in other regions was in doubt. It should be noted that WPI value and sub-components value are useful only for comparison among the different regions with same sub-components. More accurate WPI values may be obtained in the future when more appropriate indicators and better data quality become available.

Climate change can affect the WPI, because climate change has profound effects on water resources (Griffin et al. 2013). Most studies indicated that variation of water resources in the upstream (mountain) area of the HRB is mainly dependent on climate change (Liu et al. 2011; Li et al. 2012; Xiong & Yan 2013). The zones of alpine tundra, snow and glaciers are major water production areas of the Heihe River, accounting for 80.2% of the total runoff out of the Qilian Mountains (Cheng et al. 2014). According to the relationship established between the air temperature and the meltwater discharge from Song et al. (2010), the annual mean Qiyi glacier meltwater discharge changed from $1.52 \times 10^8$ m$^3$ to $1.93 \times 10^8$ m$^3$ when the annual mean temperature increased from 7.72 °C (1960–1995) to 8.58 °C (1996–2004) in Qilian mountains. In addition, a water scarcity assessment at a finer temporal resolution (season or month) revealed that annual assessments fail to capture water scarcity that may be prevalent during the dry season (Gain & Wada 2014). Consideration of climate change and seasonal variation can provide a more accurate assessment of water scarcity at different spatial and temporal scales in the future.
CONCLUSIONS

As discussed above, a number of different variables clearly influence the measurement water scarcity, such as natural, political, economic and demographic conditions. Adequately reflecting all of these variables in indicators is critical for providing an integrated overview of the water sector (Heidecke 2006). By incorporating five components into a framework, the WPI provides such a simple and easy-to-use indicator for reflecting the situation of a specific region. It should be noted that the WPI is not intended to show unexpected or new results, and it aims to provide a straightforward and transparent tool to express information in a much more effective way than previously. However, if a general assessment of water stress at an extensive scale is conducted over only a short time period or using a snapshot survey, the incomplete information could mislead decision makers. To provide more reliable information, this study analyzed the changes in water stress across the middle HRB geographically and temporally with WPI. Policy priorities had been provided for three specific cities of the studied region using the simple results obtained from single and/or comparable values. The WPI method could be improved by incorporating more appropriate data. Future research should consider developing the available WPI indicators comprehensively covering human health and meteorological conditions related to water supply.

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