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Water scarcity assessment index from the realistic perspective of human basic water requirements

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ABSTRACT

Significant population growth with rapid economic development have led to water scarcity problems around the world. Currently, most of the simple water scarcity assessment methods only refer to per capita water use, failing to take into account actual water availability and actual human domestic water use. Therefore, we have developed a simple and practical method to assess water scarcity, incorporating total water resources, water use efficiency, and the proportion of domestic water. In this approach, a new water scarcity index is employed to describe different levels of water scarcity using various thresholds based on the basic daily human water use per person. This may help to visualize the extent of water scarcity in a region while focusing on human interests. To illustrate this approach, we take China–the world's largest developing country–as an example, analysing its nationwide water scarcity in 2021 while validating it with the results of other scholars on China's water scarcity. The results show that our water scarcity assessment index is very accurate, revealing that in 2021, the disparity in water resources between the northern and southern regions of China remains substantial, with severe water scarcity still widely concentrated in northern China.

1. Introduction

Continuous water supply plays a vital role in daily life and social development (Ethaib et al., 2022). However, increasing water consumption is due to the significant population growth and rapid economic development, resulting in extremely high water resource pressures, which cause water scarcity in numerous places around the world (Liu et al., 2017). For instance, in regions such as Greater London with high population density, intense irrigation present in areas like the High Plains of the United States, and nations like India that exhibit both traits, there is a prevalent issue of water scarcity (Mekonnen and Hoekstra, 2016). Nevertheless, in addition to direct water supply shortages caused by the forces of nature, human factors, as well as socio-political factors, are often overlooked, leading to the masking of the causes of scarcity. This complexity of water scarcity is labelled by Mehta as 'real' scarcity (related to socially and ecologically relevant physical phenomena like grass cover, fodder, distance to water for disadvantaged groups, cycles of natural resource abundance and scarcity, agro-meteorological hydrology, etc.) and 'manufactured' scarcity (constructing water scarcity as a perpetual and pervasive natural phenomenon, the industry of disaster relief and drought relief, and perverse benefits) (Mehta, 2003). Moreover, there are also sudden and uncontrolled factors affecting water resources, such as the outbreak of the COVID-19 pandemic crisis, which has put many additional pressures on water resources, including the increase in local agricultural irrigation brought about by the localised production of food, and the parallel alteration of the virtual water trade caused by the changes that have taken place in the food trade (Al-Saidi and Hussein, 2021).

Currently, water scarcity is still a conceptual definition. Hussam's study found that the two narratives of water mismanagement and water insufficiency made up the dominant discourse on water scarcity, where the water mismanagement narrative is not dominant as it does not significantly influence policy, while the water insufficiency narrative, which represents the relationship between supply and demand, is the dominant and prevailing narrative (Hussein, 2016). Significantly, the narrative of water insufficiency is not absolute and monolithic, but rather has different sub-narratives within the social structures and political contexts of different countries. An example of this is in Jordan, where the sub-narrative of water scarcity can be mapped to a pattern of inequitable sharing with neighbouring countries (some Jordanian narrators argue that Israel and Syria are responsible for Jordan's water scarcity in violation of the treaty); scarcity caused by a reduction in the availability of surface and groundwater due to climate change, such as droughts and high temperatures; scarcity caused by the low level of

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precipitation due to Jordan's geographic location in an arid and semi-arid region; and scarcity caused by the rapid growth of the population due to the influx of immigrants and refugees (Hussein, 2018). Against this background, the Jordanian government, through its water awareness programme, has attempted to link the water scarcity with related discourses of civic insecurity and national insecurity to the population, in order to change their daily life water use habits towards water conservation and thereby alleviate the demand for water (Benedict and Hussein, 2019). In addition, there are other critical interpretations of water scarcity within the social framework, for instance Mehta argues that water scarcity is a 'crisis of unequal power relations' in controlling water resources, where the key is who can compete for a sufficient quantity of water (Mehta, 2005).

In general, determine whether an area is short of water depending on the people's natural demand for water, the proportion of resources available to meet these demands, and the water scarcity on temporal and spatial scales (Rijsberman, 2006). From the perspective of physical water scarcity, it is mainly a shortage of blue water (fresh water available for human use) and green water (water available for plant uptake) (Rosa et al., 2020). Various studies have taken different approaches to defining water scarcity. There are classical indicators for blue water; for instance, Falkenmark et al. developed the Falkenmark indicator, which is the most widely used measure. They defined the water conditions in each area based on annual per capita water availability into four classifications: no stress (>1700 m^3), stress (1000–1700 m^3), scarcity (500–1000 m^3), and absolute scarcity (<500 m^3) (Falkenmark, 1989). Raskin et al. developed the percentage of total annual withdrawals to available water resources as the Water Resources Vulnerability Index. In their opinion, a country is considered to be experiencing water scarcity when yearly withdrawals are between 20 and 40% of the yearly supply, and severely water scarce when these withdrawals exceed 40% (Raskin et al., 1997). By contrast, given that green water resources are extremely limited and crucial for food security and environmental safety, assessing their scarcity is also important (Schyns et al., 2015). Rockstrom et al. proposed a composite green-blue water scarcity index to measure green water congestion, which establishes thresholds based on the food criterion of a global average requirement of 1300 m^2 per capita per day for both green and blue water resources, and indicates water scarcity in the study area when green and blue water availability falls below the thresholds (Rockström et al., 2009). Similarly, Gerten et al. improved on the Rockstrom et al. indicator by calculating the green and blue water required to maintain dietary standards in each country based on local crop water productivity, replacing the inherent 1300 m^2 per capita per day threshold (Gerten et al., 2011). Furthermore, there are yet more sophisticated but also more comprehensive approaches, such as the Water Poverty Index, which evaluates water stress from five aspects: resources, access, capacity, use, and environment (Sullivan et al., 2003). However, there are few simple water scarcity assessment indicators from the perspective of both water use efficiency and human domestic water use, therefore, it is necessary to review the simple water scarcity assessment indicators to date to identify this research gap, as summarised in Table 1 below.

In addition, it is noteworthy that economic and institutional elements are also significant determinants of water scarcity (Rosa et al., 2020). This economic water scarcity was previously used to describe countries where freshwater resources were sufficient to meet even projected future water demands, but significant improvements in the efficiency of current water use were necessary to accomplish this (Seckler et al., 1999). In fact, many countries are not suffering from water scarcity, if only in terms of hydrological data, but rather experience physical water scarcity due to underinvestment in water infrastructure and institutions, as well as incomplete water treatment processes that prevent them from obtaining sufficient quantity and quality water, which may also result in inefficient water use in agriculture and hence an overly high water footprint (Vallino et al., 2020). On the other hand, Mehta argues that water scarcity is not simply the result of natural processes, but rather of socio-political processes, and therefore Mehta believes that socio-political and institutional considerations need to be taken into account when assessing water scarcity (Mehta, 2007). In this paper, in support of a simple assessment of water scarcity, the complexity of these 'anthropogenic' factors behind scarcity can be abstracted to water use efficiency, which to some extent reflects the social, political and economic factors behind water management. Therefore, this paper analyses from the perspective of human interest in

Table 1
Simple water scarcity assessment indicators review.

Name	Methodology	Advantage	Disadvantage	Water use efficiency	human domestic water use	Ref
Falkenmark indicator	Annual per capita water availability	Convenient calculations	Without consideration of other constraints that lead to water scarcity	×	×	Falkenmark (1989)
Water Resources Vulnerability Index	the percentage of total annual withdrawals to available water resources	straightforward	Ignoring the complexity and diversity of water resources	×	×	Raskin et al. (1997)
IWMI indicator	The ratio of primary water supply to utilisable water supply	Distinguishes between physical and economic water scarcity	Difficulty in data collection and processing	✓	×	Seckler (1998)
SDG6 water stress indicator	Ratio of total freshwater abstraction to total renewable water resources minus environmental flow requirements	Well reflected in blue water indicator	Difficulty in monitoring data	✓	×	Vanham et al. (2018)
Quantity-Quality Indicator	Sum of blue water scarcity index and grey water scarcity index	Simple data application	Incomplete consideration of water resources in this perspective does not include green water	✓	×	Zeng et al. (2013)
Water footprint indicator	Ratio of external water footprint to national water footprint	Reflects virtual water trade	Difficulties in data collection and processing	×	×	Hoekstra et al. (2012)
Green-blue indicator	Average daily food requirement per person standard	Comprehensive consideration of water resources	Not representative of food water requirements for all countries	✓	×	Rockström et al. (2009)
Availability and scarcity of green and blue water	Ratio of blue-green water demand based on local crop productivity to blue-green water availability	Consideration of differences in food requirements in various countries	Inaccurate water requirements for livestock products	✓	×	Gerten et al. (2011)

creating a water scarcity index that incorporates both water use efficiency and the proportion of human domestic water use. The accuracy of the index is evaluated by taking China as a case study as well as comparing the results with other researchers. This paper has the following structure: Section 2 presents the details of the water scarcity index developed here. In Section 3 and Section 4, results and discussion are presented in terms of the analysis and evaluation of our water scarcity index.

2. Methodology

2.1. Case study

As the largest developing country in the world, China is also the second-largest economy and possesses the sixth-largest total freshwater resources, while remaining one of the thirteen nations most severely affected by water scarcity (Long and Pijanowski, 2017). In general, China faces many water shortage issues that are likely to rise in the future because of the impact of several challenges, including urbanization, industrialization, climate change, environmental degradation, and the high rate of agricultural demand growth (Varis and Vakkilainen, 2001). One of the biggest problems is the spatial inconsistency between freshwater demand and freshwater resource availability, as the south has abundant water and the north is dry (Zhao et al., 2015). Therefore, accurately evaluating the water shortage status in each region is essential for sustainable development in China and will provide a reference for specific water resource management problems.

Based on the significant differences in the total amount of available water resources prevalent in the northern and southern regions of China, we chose the Chinese region for our study to accurately assess the water scarcity index we developed. The map below shows the division of China's provincial administrative regions to provide a better understanding of the areas in China where water scarcity may exist (Fig. 1).

2.2. Data collection and processing

Data used to calculate the water scarcity index were gathered from the China Statistical Yearbook. We chose the 2021 water resources and population statistics for the provincial administrative regions due to the completeness and representativeness of the data. In order to reflect the degree of water scarcity in different regions of China more intuitively, the statistical data were modelled and imported into ArcGIS Pro to complete the zoning.

2.3. Water scarcity index (WSI)

The fundamental issue of water scarcity lies in the spatial and temporal inconsistency of freshwater demand and supply, which can be assessed either from a physical perspective or by considering the impact of social and economic adaptations (Mekonnen and Hoekstra, 2016). Therefore, this study tries to develop a straightforward approach to measuring water scarcity based on total water resources, water use efficiency, and human basic demand for water. It was also incorporated into ArcGIS Pro for spatial analysis. The specific methodology is as follows:

Fig. 1. The map of administrative regions in China.

$$WSI = \frac{TWR \times WUE \times PDW}{Number\ of\ Days\ per\ Year \times Population} \quad (1)$$

The parameters are defined as follows:

(1) Total water resources (TWR): Total water resources refers to all the water available for use in a given area at a given time.
(2) Water use efficiency (WUE): Water use efficiency is the ratio of actual water supply to available water.
(3) Proportion of domestic water (PDW): The proportion of domestic water consumption reflects the proportion of domestic water use in total water use.

This methodology provides a comprehensive indicator to quantify regional water scarcity in terms of the amount of water used per capita per day for domestic purposes by considering the total water resources, the water use efficiency, and the proportion of domestic water, combined with population and time factors. Furthermore, the water scarcity index is categorized into no stress (>0.2 m^3), stress (0.1–0.2 m^3), scarcity (0.05–0.1 m^3), and absolute scarcity (<0.05 m^3) based on the definition of minimum water requirements to meet 50 L (0.05 m^3) per capita per day for human basic life (Gleick, 1996).

3. Results

3.1. Statistical analysis of the results

A comparison of the water scarcity index calculated using Eq. (1) for each region of China, with a threshold of 0.2 (no stress), is shown in Fig. 2. The results show that most regions in China are still suffering from water problems, including some economically developed cities with heavy water problems, such as Beijing (0.01), Tianjin (0.008), and Shanghai (0.02). In contrast, Qinghai (1.43) and Xizang (10.56) have abundant water resources, which are significantly higher than in other regions.

3.2. Spatial analysis of the results

In this study, ArcGIS Pro software was used to raster water resource data from various provinces in China in order to comprehensively and visually assess water scarcity across the country. As can be seen in Fig. 3, the water scarcity index shows obvious spatial distribution differences, mainly between the northern and southern regions of China. Overall, the water scarcity index shows absolute scarcity in the north and no stress in the south. Specifically, a wide range of areas in northern China, including Inner Mongolia, Liaoning, and Shaanxi, exhibit water scarcity and some pressure on water resources. It is worth noting that some areas in the north also show absolute water scarcity, especially in Beijing, Tianjin, Hebei and Shanxi, indicating that the available water resources in these regions do not meet the minimum basic human needs of the region.

4. Discussion and conclusion

As a country with a vast total amount of freshwater resources, China has a large number of rivers and extensive watersheds, while showing significant water scarcity as shown in Fig. 3. There are numerous factors that contribute to the apparent shortage of water resources in some parts of China, which could be reflected in the cyclical cycles of abundance and scarcity of water resources on a temporal scale, as well as in the spatial scale of direct supply constraints caused by climate change, which are in contradiction with socio-economic demand for water. This often intensifies with economic development, population growth, lack of water management and weak social institutions, resulting in further water scarcity.

The scores on the water scarcity index for each region of China reveal

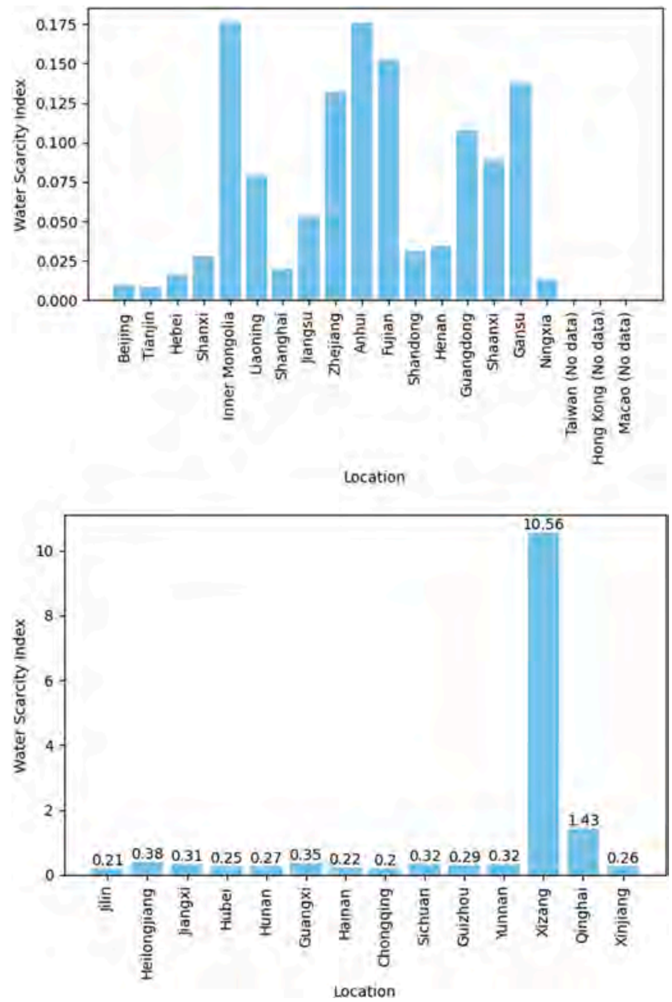

Fig. 2. The water shortage situation in different regions of China: water shortage (above), no water shortage (below).

an interesting pattern of water scarcity that potentially supports the narrative of water scarcity due to increasing population and rapid economic development. Major economically developed cities such as Beijing, Tianjin and Shanghai report absolute water scarcity (WSI of 0.01, 0.008 and 0.02 respectively). This paradox can be attributed to their high population densities and high levels of industrial activity, leading to exponential increases in water demand. In contrast, regions with more moderate economic development, such as Qinghai and Xizang, enjoy an abundance of water resources (WSI 1.43 and 10.56, respectively), mainly due to their low population densities. However, it is essentially due to the uneven distribution of water resources in the river basins as well as the uneven distribution of precipitation due to climate influence. In this context, effective water management policies play a key role in alleviating water scarcity. Especially in economically developed but water-stressed regions, there is a need to emphasise the sustainability of water use and water security. There are a number of very broad management approaches to the sustainability of water resources, whereas for a particular country or region, such as the case study in this paper, it is important to consider the linkages between hydrological and environmental and socio-economic conditions, as well as managing the environment and improving the socio-economic development of the region in accordance with sustainability standards (Salamé et al., 2021). At this level, hydro-economic modelling (Harou et al., 2009), which integrates engineering, economic and hydrological considerations, combined with the water sustainability calculation index (Sandoval-Solis et al., 2011), which incorporates the perspectives

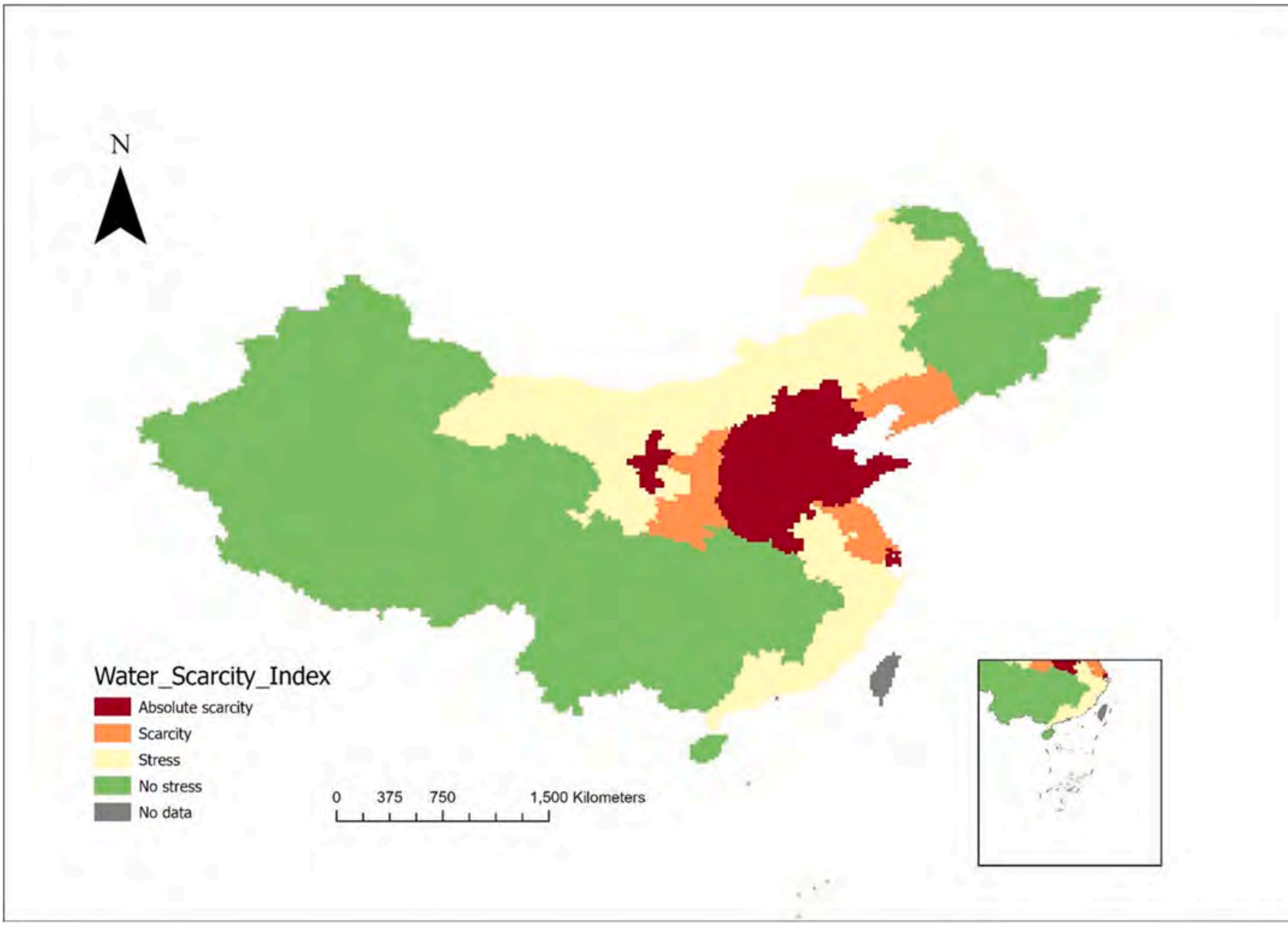

Fig. 3. The water scarcity index in China.

of water users, the environment and the river basin, could facilitate the management of water resource sustainability. In addition, water security places greater emphasis on ensuring the availability and quality of water resources, the management of risks associated with water pollution, and the protection of ecosystems in a peaceful environment (Grey and Sadoff, 2007; Escap, 2013). Additionally, infrastructure development should not be underestimated in addressing water scarcity. Apart from Qinghai and Tibet, much of southern China, such as Sichuan (WSI 0.32), Guangxi (WSI 0.35), and Yunnan (WSI 0.32), is also rich in water resources, and a series of water transfer projects, such as the South-to-North Water Transfer, have been set up to capture the potential benefits (Fang et al., 2015). However, this is a massive undertaking that requires strict control of the water transfer and water use infrastructure along the route. In addition to investments in benefit-related water conveyance infrastructure, investments in infrastructure for adaptation to climate change-induced disasters, such as floods and droughts, should not be overlooked in order to reduce the impacts of disasters on the quality of water resources and enhance social stability.

Many studies have assessed China's water resource situation using coarser resolutions and models developed on the basis of traditional methods of calculating the water scarcity index. For example, Long et al. (Long and Pijanowski, 2017) developed a composite score of the water scarcity index by combining the water resources available index, use-to-resource ratio index, and precipitation index to spatially assess the water scarcity situation in China. Their results are generally similar to ours, revealing a generalized north-south disparity in China, and some of the absolute water scarcity regions are assessed identically (Ningxia, Beijing, Tianjin, Shanxi, Shandong, Hebei, Henan, and Shanghai). In contrast, our water scarcity index is simpler, the data required is easier to collect, and our index focuses more on the intuitive measure of people's domestic water use, which provides a more realistic perspective of regional water scarcity. Moreover, Zeng et al. (2013) developed a simple water scarcity assessment method by combining water quantity and quality, and although they applied it only to the example of Beijing, China, the results are consistent with ours in that Beijing is an absolute water scarcity area. By contrast, the PDW needed in our water scarcity index also reflects water quality indicators to some extent. Also, our water scarcity index provides a better understanding than the more complex assessment of green water scarcity.

However, there are some limitations to the water scarcity index we developed. We have only assessed the water resources dimension, and more comprehensive factors such as social, political, and economic factors have not been taken into account. These factors play an important role in exploring the reasons behind water scarcity, which, as Mehta has been emphasising, the crucial issue of water scarcity is not so much the availability of the resource, but rather who has access to sufficient quantities of the resource through a kind of political process of grappling, which is the result of decisions of inclusion and exclusion, possibly related to the price of water, the lack of infrastructure, or social exclusion (Mehta, 2013). A more comprehensive and complex index would provide a more accurate picture of regional water scarcity. For example, the study by Wang et al. (2018) assessed water scarcity in China's Yunnan Province using socio-economic and engineering-control indicators and found that the central part of the province has a serious water scarcity problem, which is not captured by our index calculations. This is due to this study's greater focus on water scarcity at the national level, at administrative district resolution, however, the application of the index may be limited by data availability and data quality. Although our index supports applications at a variety of scales, in some cases data limitations may affect the accuracy and general applicability of the index. Especially in higher resolution applications, the completeness and accuracy of the data available in some areas may be difficult to ensure. Overall, our water scarcity index is relatively simple and accurate, and is more suitable for use in a national or larger-scale region.

In conclusion, this study develops a simple method for assessing water scarcity by integrating total water resources, water use efficiency, and proportion of domestic water, which effectively takes into account the realistic perspective of basic water consumption for human life. It is easy to apply because the requirement for data is straightforward. The water scarcity index reflects the average daily amount of water available for domestic use by humans themselves and is close to reality. Using China as an example, the accuracy of the index is evaluated, and the results are consistent with the basic scenario that water scarcity varies significantly between the northern and southern regions of China.

CRediT authorship contribution statement

Rundong Liao: Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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