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Spatial Patterns of Irrigation Water Withdrawals in China and Implications for Water Saving

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Abstract: By considering numerical features, spatial variation, and spatial association, the spatial patterns of China's irrigation water withdrawals in 2001 and 2010 were explored at the regional, provincial, and prefectural scales. In addition, an overlay analysis was used to develop specific water-saving guidance for areas under different levels of water stress and with different degrees of irrigation water withdrawals. It was found that at the regional scale, irrigation water withdrawals were highest in the Middle-Lower Yangtze River region in both years, while at the provincial scale, the largest irrigation water withdrawals occurred in Xinjiang. During 2001–2010, the total of irrigation water withdrawals decreased; however, in the Northeast region, especially in Heilongjiang Province, it experienced a dramatic increase. The spatial variation was largest at the prefectural scale, with an apparent effect. The spatial association was globally negative at the provincial scale, and Xinjiang was the only significant high-low outlier. In contrast, the association displayed a significant positive relationship at the prefectural scale, and several clusters and outliers were detected. Finally, it was found that the water stress in the northern part of China worsened and water-saving irrigation techniques urgently need to be applied in the Northeast region, the Huang-Huai-Hai Plain region, and Gansu-Xinjiang region. This study verified that a multi-scale and aspect analysis of the spatial patterns of irrigation water withdrawals were essential and provided water-saving advice for different areas.

Keywords: irrigation water withdrawals; water stress; spatial pattern; China

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1 Introduction

A shortage of water resources is one of the most critical issues currently facing China. With its burgeoning industrialization, rapid urbanization, and population growth, China's demand for water continues to increase. According to the China Water Resources Bulletin, the total water withdrawal of the country was 5.20×10^{11} m^3 in 1993, which increased to 6.02×10^{11}m^3 in 2010. The agricultural sector accounts for the largest water withdrawals, although more water has been allocated to industrial and domestic use than ever before. Irrigation water is a vital component of agricultural water, accounting for about 90% of all water used in agriculture in China. Given the large irrigation water withdrawals in China, saving irrigation water is an efficient way to ease the country's overall water use pressure. Decreasing the irrigation water demand is the most obvious intervention to reduce the vulnerability of water resources (Wu *et al.*, 2013). In addition, ensuring that sufficient irrigation water is supplied guarantees sustainable agricultural production. Nearly 70% of the grain in China is harvested from irrigated land (Shen and He, 1996). The expansion of irrigation has made a significant contribu-

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tion to the dramatic increase in China's grain production over the last 50 years, but whether irrigated agriculture is sustainable depends largely on the continued adequacy of water supplies. China should expand the use of water saving technologies to support agricultural development (Blanke *et al.*, 2007). Therefore, it is important to realize water-saving irrigation to ensure the sustainable use of water and feed the enormous population of China.

The spatial distribution of water resources and agriculture between the north and south of China is extremely uneven, with 81% of the water resources in the south, but 64% of the arable land in the north (Varis and Vakkilainen, 2001). This distribution has a large influence on the spatial pattern of irrigation water withdrawals in China. Understanding the spatial patterns of irrigation water withdrawals can not only help to improve our knowledge of the current water use situation, but also help to understand better the factors that influence the pattern. Scientists and politicians could then develop specific policies to ensure sustainable water use in the future. Currently, extensive efforts have been made to survey and estimate the amount and the distribution of irrigation water withdrawals. For example, global irrigation water withdrawals have been collected or calculated for 167 countries and analyzed by continent and by income-based grouping (Frenken and Gillet, 2012). The United States Geological Survey (USGS) has estimated the irrigation water withdrawals of the states and the district every five years since 1950 (Maupin *et al.*, 2014). In China, irrigation water withdrawals are reported annually in the Water Resources Bulletin (Ministry of Water Resources of the People's Republic of China, 2011) and scientists have focused on estimating the irrigation water requirements and the use efficiency (Liao and Huang, 2004; Shen *et al.*, 2013; Wu *et al.*, 2015). However, other aspects of the spatial pattern of China's irrigation water withdrawals, such as spatial variations and spatial associations, have been less well researched. In addition, scale effects are very common in geographical phenomena and should be considered in spatial analysis, but few studies have taken the different scales into account when analyzing the spatial pattern of irrigation water use. Current studies of the spatial patterns of irrigation water withdrawal have mainly concentrated on the amount and distribution at only one scale. It is still not common to use spatial information regarding water use to inform water-saving policy.

This study investigated the spatial patterns of irrigation water withdrawals by considering different aspects at different scales in China, and it provided guidance on the conservation of water. Regional, provincial, and prefectural scales were considered and detailed information regarding the numerical features, spatial variation, and spatial association of the irrigation water withdrawals were analyzed at these scales. We then divided the country into different water-saving areas based on the level of irrigation water withdrawals and water stress. Finally, we discussed the scale effects of the spatial pattern of the irrigation water withdrawals and developed specific water-saving advice for different areas.

2 Materials and Methods

2.1 Data sources and preprocessing

The data used in this study included irrigation water withdrawals, baseline water stress, and land cover of irrigated land in China for 2001 and 2010 (Taiwan, Hong Kong, and Macao are not included because of the data unavailabilty). Irrigation water withdrawal data covered 344 prefectural units in China and were derived from the Water Resources Bulletin of all provinces in 2001 and 2010. The divisions of prefectural units were based on the administrative divisions in 2010 to avoid the data inconsistency caused by the adjustment of administrative divisions over time. The baseline water stress was calculated for 1140 river basins of China as vector files; the data were acquired from the dataset of *Baseline Water Stress*: *China*, developed by the World Resources Institute (Wang *et al*., 2016b). Baseline water stress measures total annual water withdrawals (agricultural, industrial, and domestic) expressed as a percentage of the total annual available runoff as an indicator of water stress. The water stress can be divided into six categories based on the value of the baseline water stress (Gassert *et al.*, 2014): low (<10%), low to medium (10%–20%), medium to high (20%–40%), high (40%–80%), extremely high (>80%), and arid and low water withdrawals (areas with available water and water withdrawals less than 0.030 m/m^2 and 0.012 m/m^2, respectively). High values indicate a large water stress for a particular area.

Irrigated land data were derived from the National Land Use/Cover Database of China, developed by the

Institute of Remote Sensing and Digital Earth (RADI) Chinese Academy of Sciences. Land cover types were visually interpreted from medium-resolution satellite images and field surveys were conducted to verify the classification results (Zhang *et al.*, 2009; Zhang *et al.*, 2014). The land cover data of China consisted of six first-level types: woodland, grassland, cultivated land, settlements, water bodies, and barren land. Cultivated land consisted of three second-level types: paddy land, irrigable land, and dry land (Zhang *et al.*, 2009). The paddy land and irrigable land data were converted from an interpreted vector format into a 1 km × 1 km raster format, indicating the percentage of each land area in each grid. The paddy land and irrigable land were then summated together and referred to as irrigated land in later analyses.

2.2 Spatial scales

Scale effects are determined as the variation in results when data for one set of areal units are progressively aggregated into fewer and larger units for analysis (Jelinski and Wu, 1996). Such effects exist universally in geographical phenomena and in spatial analyses. To comprehensively analyze the spatial pattern of the irrigation water withdrawals in China, the spatial pattern was explored at three scales: regional, provincial, and prefectural scales (Fig.1).

At the regional scale, China was divided into nine agricultural regions according to *The Comprehensive Agricultural Regionalization of China* (Nationwide Committee of Agricultural Regionalization, 1981). They were: 1) Northeast agriculture and forestry region; 2) Inner Mongolia and along the Great Wall pastoral, agriculture and forestry region; 3) Huang-Huai-Hai Plain agriculture region; 4) Loess Plateau agriculture, forestry, and pastoral region; 5) Middle-Lower Yangtze River agriculture, forestry, and aquaculture region; 6) Southwest agriculture and forestry region; 7) South agriculture, forestry, and tropical crops region; 8) Gansu-Xinjiang agriculture, forestry, and pastoral region; and 9) Qinghai-Tibet Plateau pastoral, agriculture, and forestry region (Fig. 1a). The names of the regions were abbreviated by using the location in the remainder of this paper. The irrigation water withdrawals of the nine agricultural regions were aggregated from 344 prefectural units. When a prefectural unit covered multiple regions, it was allocated to the region with the largest area of irrigated land in the prefectural unit.

At the provincial scale, there were 31 divisions, including 22 provinces (Hebei, Shanxi, Liaoning, Jilin, Heilongjiang, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Hainan, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, and Qinghai), four municipalities (Beijing, Tianjin, Shanghai, and Chongqing), and five autonomous regions (Inner Mongolia, Guangxi, Tibet, Ningxia, and Xinjiang) (Fig. 1b).

At the prefectural scale, based on data availability and the administration divisions of National Bureau of Statistics of China (http://www.stats.gov.cn/tjsj/tjbz/xzqhdm/), 344 units were derived, including 333 prefecture-level administration units, six county-level administration units directly under the provincial government, one aggregated unit of county-level administration units directly under the provincial government, and four municipalities. The prefecture-level administration units included 283 prefecture-level cities, 17 prefectures, 30 autonomous prefectures and three leagues. The six county-level administration units under the provincial government were Jiyuan in Henan; Xiantao, Qianjiang, Tianmen and Shennongjia in Hubei; and Shihezi in Xinjiang. Nineteen county-level administration units under the provincial government in Hainan were aggregated into one unit. To complete the study area, four municipalities were also included at the prefectural scale (Fig. 1c).

2.3 Spatial pattern indicators

At each scale, we described the spatial pattern of irrigation water withdrawals from three aspects: the numerical features, the spatial variation, and the spatial association. The coefficient of variation (*CV*) was used to depict the spatial variation, while the global and local Moran's *I* indexes were used to test the global and local spatial association of irrigation water withdrawals.

2.3.1 Spatial variation indicator

The *CV* was selected to measure the spatial variation of irrigation water withdrawals at different scales. It is often expressed as a percentage, and is defined as the ratio of the standard deviation (*SD*) to the mean (Equ. 1 and Equ. 2) (Lovie, 2005). It was considered to be more reasonable to use the *CV* than the *SD* in this study, because the *SD* must always be understood in the context of the mean of the data, which varied at the different scales used in this study. In contrast, the value of the *CV*

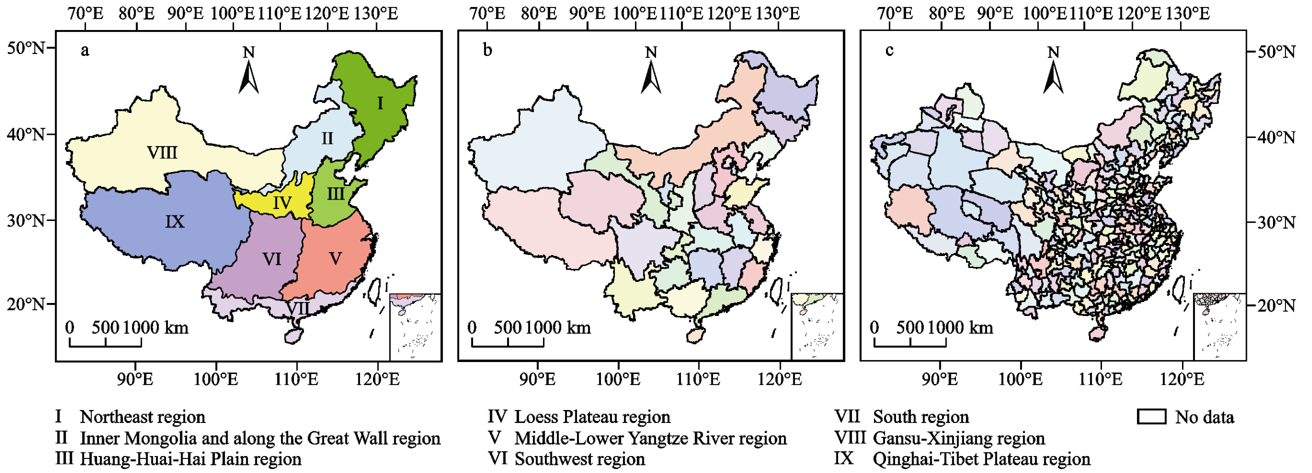

Fig. 1 Study area at the regional scale (a), the provincial scale (b), and the prefectural scale(c). Taiwan, Hong Kong, and Macao are not included

is independent of the unit (or the mean) in which the measurement was made (Lovie, 2005). In this study, using the *CV* allowed for a comparison of the spatial variation of the irrigation water withdrawals between scales, which have widely different means.

$$SD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - \overline{X})^2} \quad (1)$$

$$CV = SD / \overline{X} \quad (2)$$

where the *CV* is the coefficient of variation; *SD* is the standard deviation; n is the number of divisions at a given scale (n = 9, 31, and 344 at the regional, provincial, and prefectural scales, respectively); X_i is the irrigation water withdrawal of the ith division at a given scale (i =1, 2, …, n); and $\overline{X}$ is the mean irrigation water withdrawal of the divisions. The larger the *CV* value is, the more spatial variation in irrigation water withdrawals.

2.3.2 Spatial association indicators

Spatial association statistics are used to measure and analyze the degree of dependency among divisions in a geographic space. In this study, the global Moran's *I* and local Moran's *I* were used to analyze the global and local spatial association of irrigation water withdrawals, respectively. The spatial association statistics require the geographical relationship of the divisions to be modeled. For both analyses, a matrix of spatial weighting is used to conceptualize the spatial relationships and express how strong the influence is between the divisions. We used aspatial weighting matrix that took distance into consideration. It assumed that the effects between nearby regions are large, and the converse. In this matrix, the weightings vary in inverse relation to the distance among divisions:

$$w_{ij} = 1 / d_{ij} \quad (3)$$

where w_{ij} is the elements of weighting matrix; d_{ij} is the distance between the center of gravity of region i and region j. The matrix is standardized in such a way that the rows sum to one by dividing each value by the row sum of the original matrix. The regional scale was omitted from the spatial association analysis because of the small size of its divisions.

(1) Global indicators of spatial association

Global indicators of association measure if, and how much, the dataset is associated throughout the study region. One of the principal global indicators of association is the Moran's *I*. It estimates the overall degree of spatial association for a dataset (Moran, 1948):

$$\text{Global Moran's } I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(X_i - \overline{X})(X_j - \overline{X})}{\sum_{i=1}^{n}(X_i - \overline{X})^2} \quad (4)$$

where n is the number of spatial divisions; X_i and X_j are the irrigation water withdrawals in division i and j ($i \neq j$); $\overline{X}$ is the average value; and w_{ij} is the matrix of spatial weights. The values of the global Moran's *I* range from −1 to +1. Positive values indicate a positive association, i.e., the clustering of similar values across geographic space. In contrast, negative values indicate a negative association. This means that neighboring values are more dissimilar than expected by chance, suggesting a spatial pattern similar to a chess board. Theoretically, if Moran's *I* converges to zero, it indicates a random spatial pattern.

(2) Local indicators of spatial association (LISA)

LISA allows us to locate clustered patterns by comparing the values in each specific location with values in neighboring locations. We used the local Moran's *I* index (Equ. 5) to identify different spatial association patterns, including high-high clusters, low-low clusters, high-low outliers, and low-high outliers (Anselin, 1993). The high-high clusters were areas with high irrigation water withdrawals that were surrounded by neighboring areas also with high irrigation water withdrawal, while low-low clusters were areas with low irrigation water withdrawal that were surrounded by neighboring areas also with low irrigation water withdrawal. These two patterns were apositive spatial associations. In contrast, spatial outliers were identified when a region with high irrigation water withdrawal was surrounded by neighboring regions with low irrigation water withdrawal and vice versa.

$$\text{Local Moran's } I = \frac{X_i - \bar{X}}{S_i^2} \sum_{j=1, j \neq i}^{n} w_{ij}(X_j - \bar{X}) \tag{5}$$

where S_i^2 is the variance of the irrogation water withdrawals, and the other symbols are the same as described above. A high positive local Moran's *I* value implies an area has similarly high or low values as its neighbors, while a high negative local Moran's *I* value means the location is significantly different from the surrounding areas. The local Moran's *I* can be standardized so that its significance level can be tested based on the assumption of a normal distribution (Anselin, 1995; Levine, 2004).

2.4 Overlay analysis

Irrigation water withdrawals were overlaid with the water stress to identify areas where water-saving measures were required. Through the overlay analysis, we attempted to answer two questions. First, where were the most important areas where irrigation water should be saved? Given that the available water resources vary spatially in China, areas of high irrigation water withdrawal do not necessarily face an urgent demand for water saving. By overlaying the irrigation water withdrawals with the water stress in China, we were able to identify areas with high irrigation water withdrawals and serious water stress, where there should be an emphasis on saving irrigation water. Second, where should more attention be given to other sectors to ease the water stress? Areas with serious water stress, but relatively low irrigation water withdrawals, should also save water in the industrial and domestic sectors. Overall, with an overlay analysis, we could provide more specific water-saving advice for different areas.

To ensure reasonable results from the overlay analysis, we transformed the irrigation water withdrawals to the same scale as the river basins of the water stress dataset. First, we assumed that the irrigation water withdrawals per irrigated area were uniform in a prefectural unit and then we discretized the withdrawals into 1 km^2 grids based on land cover data:

$$IW_i = IW_j / A_j \times A_i \tag{6}$$

where IW_i is the irrigation water withdrawal in grid *i*; IW_j is the irrigation water withdrawal of the prefectural unit *j*; A_j is the area of irrigated land in the prefectural unit *j*; and A_i is the area of irrigated land in grid *i*. Then we summed the irrigation water withdrawals of the grids in one river basin to obtain the value of the river basin. We then classified the irrigation water withdrawals into two types, i.e., high and low withdrawals, using 2.5×10^9 m^3 as the cut-off value. The choice of the cut-off value was based on the overall situation of irrigation water withdrawal in China. We also classified the baseline water stress into two types (serious and less serious) using 40% as the cut-off value (Reig*et al.*, 2013). Finally, we overlaid the irrigation water with the baseline water stress of 2001 and 2010 based on their geographical location in the ESRI's ArcView geographic information system (GIS) software.

3 Results

3.1 Spatial patterns of irrigation water withdrawals at regional scale

The amount and the changes of irrigation water withdrawals varied significantly across geographic space. The total irrigation water used in China decreased by 3.03% from 3.47×10^{11} m^3 in 2001 to 3.36×10^{11} m^3 in 2010 (Table 1). At the regional scale, the Middle-Lower

Yangtze River region had the highest irrigation water withdrawals, accounting for more than 30% of the national total in both 2001 and 2010. This was followed by the Huang-Huai-Hai Plain region and the Gansu- Xinjiang region, where the irrigation water withdrawals were about half of those in the Middle-Lower Yangtze River region. The Qinghai-Tibet Plateau region had the lowest irrigation water withdrawals, accounting for only about 0.70% of the national total. During the period studied, only the Northeast and Qinghai-Tibet Plateau regions experienced an increase in irrigation water withdrawals, with a dramatic increase of 28.17% in the Northeast region. The irrigation water withdrawals of the other regions decreased, with the largest decrease in withdrawals (11.88%) occurring in the Huang-Huai-Hai Plain region. During 2001–2010, the *CV* decreased from 78.36% to 76.62%, indicating a decrease in the spatial variation of irrigation water withdrawals at the regional scale (Table 2).

3.2 Spatial patterns of irrigation water withdrawals at provincial scale

The irrigation water withdrawals of 31 provincial units in China of 2001 and 2010 are shown in Fig. 2, and are sorted in descending order of the irrigation water withdrawals for 2001. Xinjiang had the highest irrigation water withdrawals, followed by Jiangsu. In contrast, the four municipalities, Tibet, and Qinghai had the lowest irrigation water withdrawals at the provincial scale. During 2001–2010, there was an increase in irrigation water withdrawals in 13 provincial units. The largest increases in withdrawals occurred in Heilongjiang, Anhui, and Jiangsu. Withdrawals in Heilongjiang increased dramatically by 44.64% and its ranking increased from the seventh to the third largest province in terms of irrigation water withdrawals. On the other hand, there was a decrease in irrigation water withdrawals in the other 18 provincial units. The largest decrease occurred in Hunan and Shandong, while Beijing had the greatest decreasing rate of 52.90%. During the period studied, the *CV* increased from 74.40% to 76.52% (Table 2). This suggests that the spatial variation of the irrigation water withdrawals increased at the provincial scale. In addition, the Moran's *I* was significant at the 0.1 level, with a dispersed distribution at the global level in both years (Table 2). The irrigation water withdrawals of neighboring provinces were more dissimilar than would be expected by random chance; however, the intensity

Table 1 Irrigation water withdrawals in 2001 and 2010 and changes at the regional scale

Agricultural region	2001		2010		2001–2010	
	IW (10^9 m^3)	Percent (%)	IW (10^9 m^3)	Percent (%)	Change (10^9 m^3)	Change rate (%)
Middle-Lower Yangtze River region	108.13	31.17	103.67	30.82	−4.46	−4.12
Huang-Huai-Hai Plain region	55.40	15.97	48.82	14.51	−6.58	−11.88
Gansu-Xinjiang region	54.54	15.72	51.55	15.32	−2.99	−5.48
South region	41.17	11.87	38.27	11.38	−2.90	−7.04
Northeast region	31.27	9.01	40.08	11.91	8.81	28.17
Southwest region	29.42	8.48	28.86	8.58	−0.56	−1.90
Inner Mongolia and along the Great Wall region	12.70	3.66	11.86	3.53	−0.84	−6.61
Loess Plateau region	11.85	3.42	10.69	3.18	−1.16	−9.79
Qinghai-Tibet Plateau region	2.44	0.70	2.59	0.77	0.15	6.15
Total	346.92	100	336.39	100	−10.52	−3.03

Note: IW is irrigation water withdrawals

Table 2 *CV* and Moran's *I* of irrigation water withdrawals at different scales

Indicator	Regional scale		Provincial scale		Prefectural scale	
	2001	2010	2001	2010	2001	2010
CV(%)	78.36	76.62	74.40	76.52	94.55	100.34
Moran's *I*	–	–	−0.1607*	−0.1478*	0.1542**	0.1613**

Notes: * indicates the value is significant at the 0.1 level and ** indicates the value is significant at the 0.01 level

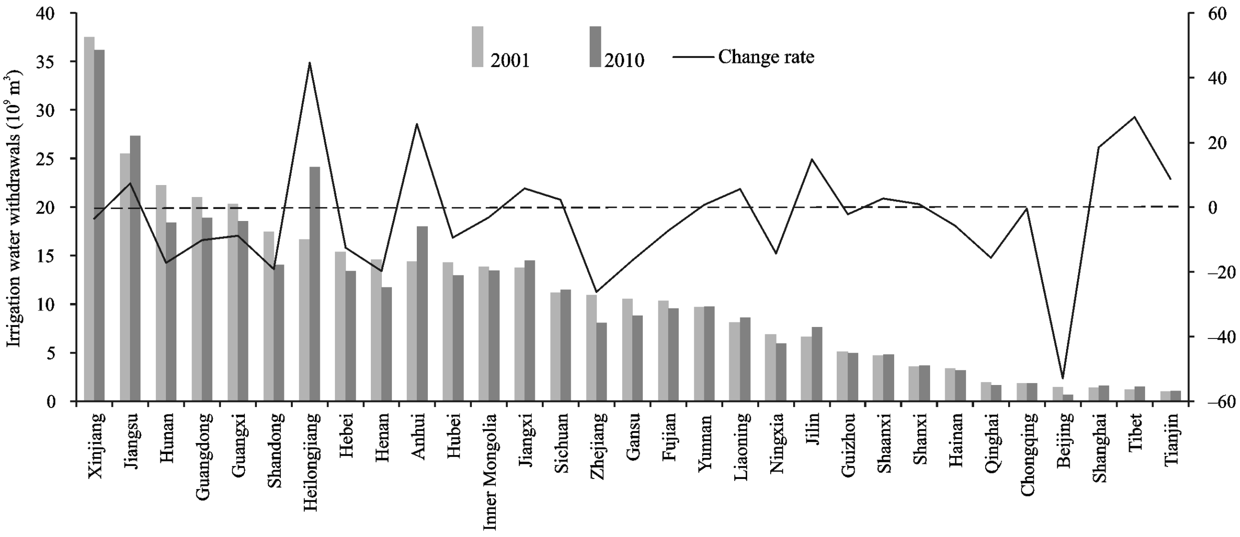

Fig. 2 Irrigation water withdrawals of 2001 and 2010 and rate of change at provincial scale

of the pattern of dispersal decreased in 2010. Correspondingly, the LISA analysis showed that no clusters existed at the provincial scale; however, Xinjiang was the only outlier which had significantly higher irrigation water withdrawals than its neighboring provinces.

3.3 Spatial patterns of irrigation water withdrawals at prefectural scale

The irrigation water withdrawals of 2001 at prefectural scales were classified into five categories using a natural break method (Fig. 3a) and for 2010 were depicted using the same cut-off value as that used for 2001 (Fig. 3b). The area of irrigated land in 2001 and 2010 was also depicted (Fig. 3d and Fig. 3e), to explore factors that influence the spatial patterns of irrigation water withdrawals in later analyses. In both 2001 and 2010, Aksu Prefecture and Kashi City of Xinjiang, and Bayannur City of Inner Mongolia had larger irrigation water withdrawals than any other prefectural units. In contrast, Alxa League in Inner Mongolia and Nagqu Prefecture in Tibet had the lowest irrigation water withdrawals among all the prefectural units. During 2001–2010, Jiamusi City in Heilongjiang, Ili Kazak Autonomous Prefecture in Xinjiang and Yancheng City in Jiangsu experienced a greater increase in irrigation water withdrawals than other prefectural units. In contrast, Guilin City of Guangxi, Changde City of Hunan, and Aksu Prefecture of Xinjiang had the greatest decreases in irrigation water withdrawals among all the prefectural units. The spatial pattern of irrigation water withdrawals showed some spatial consistency with the area of irrigated land; however, the changes were less consistent (Fig. 3c and Fig. 3f). This phenomenon indicated that changes in irrigation water withdrawals may be influenced by a combination of many factors, such as the area of irrigated land, planting pattern, irrigation technologies, and management policies (Pulido-Calvo *et al.*, 2003; Nair *et al.*, 2013).

During 2001–2010, the *CV* value increased from 94.55% to 100.34% and the Moran's *I* was positive and statistically significant at the 0.01 level (Table 2). This suggests that the spatial variation of the irrigation water withdrawals increased at the prefectural scale and the spatial distribution of the irrigation water withdrawals displayed an agglomeration phenomenon. The prefectural units with a similar amount of irrigation water withdrawals were clustered together. In addition, the Moran's *I* increased from 0.1542 to 0.1613 during 2001–2010 (Table 2), which means that the spatial agglomeration phenomenon was strengthened and prefectural units in close proximity to each other might have more interactions and associations in terms of irrigation activities.

Exploring the LISA map of the irrigation water withdrawals, we found evidence of spatial associations (Fig. 4). These spatial associations were mostly positive and were dominated by low-low clusters. In 2001, a cluster of prefectural units with low irrigation water withdrawals, and neighboring prefectures with low water withdrawals, was apparent in the mountain areas of the

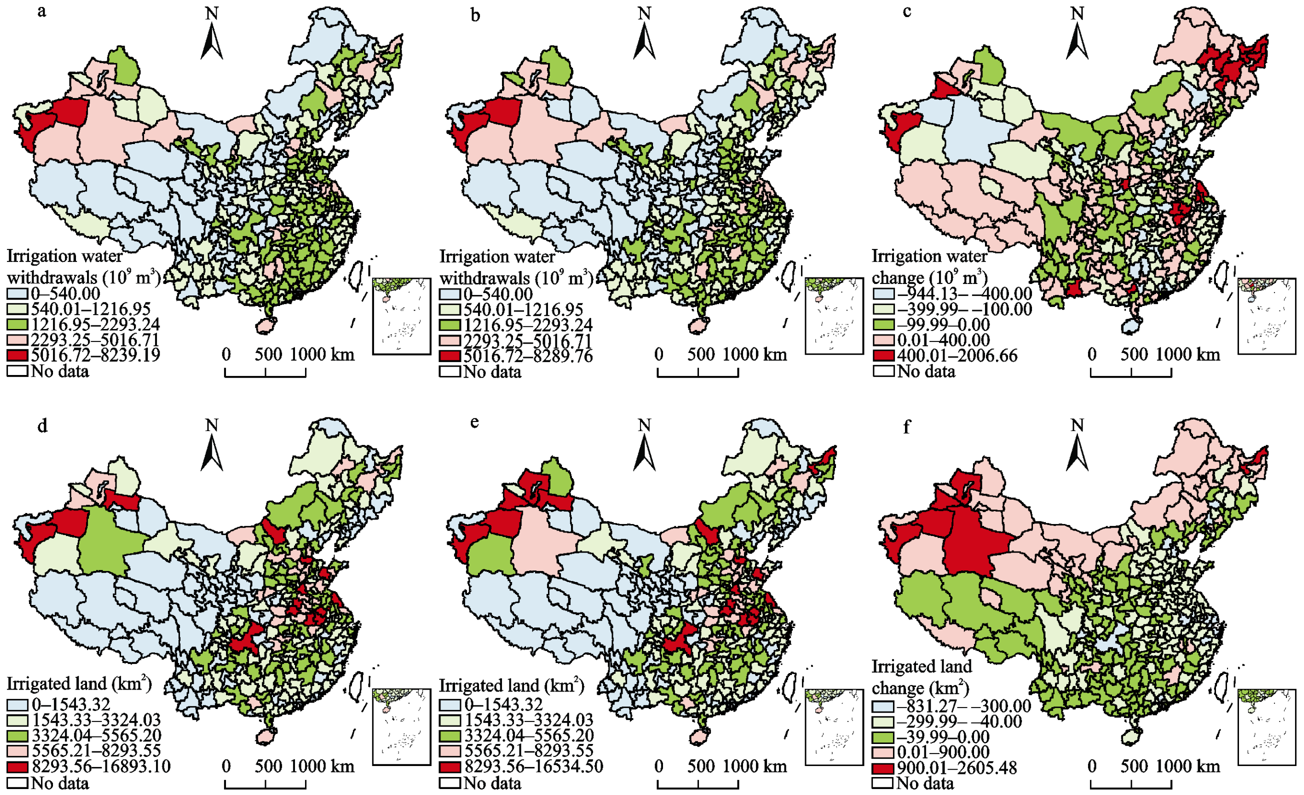

Fig. 3 Irrigation water withdrawals in 2001 (a), 2010 (b), and changes (c) at prefectural scale; the area of irrigated land in 2001 (d), 2010 (e), and changes (f) at prefectural scale

northeastern Qinghai-Tibet Plateau and the south of the Loess Plateau. In addition, three clusters of prefectures with high irrigation water withdrawals, surrounded by other prefectural units with high irrigation water withdrawals, were apparent in the basin areas of Xinjiang, the plain areas of Jiangsu, and the hilly areas around south Hunan. In contrast, some distinct high-value outliers were apparent in Tongliao City, Bayannur City of Inner Mongolia, Wuwei City of Gansu, Yinchuan City of Ningxia, Chongqing Municipality, and Chengdu City of Sichuan, while low-value outliers were detected in areas of Kizilsu Kirgiz Autonomous Prefecture, Karamay City, and Shihezi City of Xingjiang, and Haikou City of Hainan. In 2010, the general profile of spatial clustering was similar to that of 2001. However, one notable change was apparent in the Northeast region. Six cities in Heilongjiang (Harbin, Qiqihar, Jixi, Shuangyashan, Jiamusi, and Suihua) made a transition to a cluster of high irrigation water withdrawals, with their irrigation water withdrawals increasing dramatically (Fig. 3c). In conjunction with the change in these cities, Yichun City, Qitaihe City, and Heihe City of Heilongjiang became low-value outliers. This transition might be partly due to the expansion of irrigated land in the Northeast region (Fig. 3f). However, the area of irrigated land in Harbin City and Qiqihar City decreased during the period studied, indicating a decrease in the irrigation efficiency in terms of irrigation water withdrawals per unit area. This suggests that the irrigation water withdrawals in these locations were affected by other factors, such as planting, irrigation technology, and management policies. Another apparent change was the shrinkage of the high-value clusters in the southern hilly areas as the irrigation water withdrawals decreased in Shaoyang City, Yongzhou City, and Hengyang City in Hunan. In these locations, the area of irrigated land also decreased, indicating a positive effect of the land on water. Only Guilin remained as a significant cluster in 2010. Some transitions of the high-value outliers in the north of China occurred in Tongliao City of Inner Mongolia, Yinchuan City of Ningxia, Wuwei City, and Jiuquan City of Gansu. Overall, the changes in the spatial association pattern were directly caused by changes in the irrigation water withdrawals and their spatial relationships, with the underlying causes likely to include area of irrigated land, irrigation technology, and management policies.

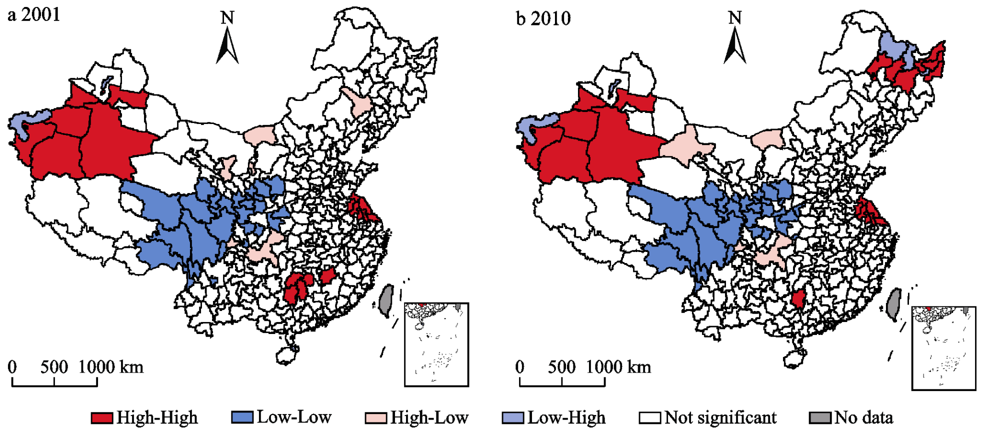

Fig. 4 Local indicators of spatial association (LISA) map of irrigation water withdrawals in China at prefectural scale. High-High and Low-Low represent statistically significant clusters of high and low irrigation water withdrawals, whereas High-Low and Low-High are outliers representing either high irrigation water withdrawals surrounded by low irrigation water withdrawals, or vice versa

3.4 Spatial relationships of irrigation water withdrawals and water stress

The overlay of the irrigation water withdrawals and the baseline water stress for 2001 and 2010 is shown in Fig. 5. The serious water stress areas were mainly located in the north of China and the eastern and southern coastal regions, while less serious water stress areas were mainly located in the southern part of China. In 2001, areas with high irrigation water withdrawal and serious water stress were mainly located in the Huang-Huai-Hai Plain region, the south of the Northeast region, the east of the Loess Plateau region, and the east and the west of Gansu-Xinjiang region. In contrast, areas with high irrigation water withdrawal and less serious water stress were clustered in the Middle-Lower Yangtze River region and the South region. In 2010, the area of high irrigation water withdrawal expanded and its spatial pattern overlaid with water stress also changed. The most notable change occurred in Heilongjiang, where irrigation water withdrawals and the area of irrigated land both increased dramatically in 2010. In the east of Sichuan, one river basin experienced an increase in water stress with increasing irrigation water withdrawal (Fig. 3c). Thus, the increased water stress may be partly caused by water use in the agricultural sector. Another apparent difference was the expansion of areas with high irrigation water withdrawal and less serious water stress in the south of China. This was mainly due to an increase of irrigation water withdrawal in the middle of Guangxi and the south of Jiangxi.

4 Discussion

4.1 Scale effects of spatial patterns of irrigation water withdrawals

The numerical features differed over the different scales

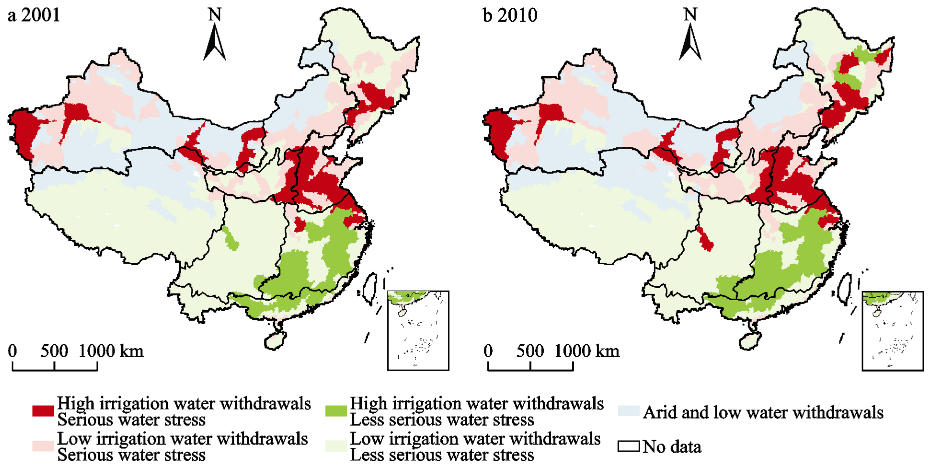

Fig. 5 Spatial distribution of irrigation water withdrawals overlaid with baseline water stress in China

investigated, which was mainly caused by the variation in size of the analysis units; however, associations between different scales were also apparent. At the regional scale, the largest irrigation water withdrawals occurred in the Middle-Lower Yangtze River region, while at the provincial scale, the largest irrigation water withdrawals occurred in Xinjiang. This was mainly due to the relatively small area of the provincial units in the Middle-Lower Yangtze River region. In contrast, the lowest irrigation water withdrawals at the regional and provincial scales were spatially consistent, being located in the Qinghai-Tibet Plateau. During 2001–2010, the irrigation water withdrawals of the Northeast region increased dramatically, which was consistent with the increases in Heilongjiang, Jilin, and Liaoning. Over the study period, the largest decrease in irrigation water withdrawals occurred in Huang-Huai-Hai Plain region, while the withdrawals in Shandong, Henan, and Hebei also decreased. Overall, the numerical characteristics were easier to analyze at larger scales (i.e., regional and provincial scales), whereas at smaller scales (i.e., prefectural scale), the analysis might lead to redundancy and complication because of the large number of units.

In both years, the spatial variation of the irrigation water withdrawals was largest at the prefectural scale and smallest at the provincial scale. During 2001–2010, the changes in spatial variation at different scales also displayed different trends. At the regional scale, the spatial variation decreased, while at the provincial and prefectural scales, the spatial variation increased. The increasing rate in this variation at the prefectural scale was larger than that at the provincial scale. These results indicated that it was essential to analyze the spatial variation of irrigation water withdrawals at different scales.

The spatial association analysis, including the global and local analysis at the provincial and prefectural scales, also produced different results. At the provincial scale, the global Moran's *I* was significant at the 0.1 level, indicating that the distribution of irrigation water withdrawals was negatively associated, while at the prefectural scale, the Moran's *I* was significant at the 0.01 level, indicating that there were positively clustered phenomena globally. In 2010, the global negative association decreased at the provincial scale, while the global positive association increased at the prefectural scale. In addition, the local analysis was consistent with the results of the global association analysis at each scale. The LISA analysis indicated that Xinjiang was the only high-low outlier at the provincial scale, while there were many significant clusters and outliers at the prefectural scale.

Overall, it is necessary to take different scales into account when considering the numerical characteristics, the spatial variation, and the spatial association of irrigation water withdrawals in China. A multi-scale analysis of the spatial variation is very important and misleading information may be obtained when results are obtained at only one scale. In addition, numerical features at larger scales can reflect the macro pattern more directly, such as where the irrigation water withdrawals are higher and lower. In contrast, spatial association phenomena are easier to detect at the smaller scale, with more specific information regarding the spatial clusters or outliers among the irrigation water withdrawals. Spatial agglomeration details may be ignored at larger scales.

4.2 Implications for water saving

The overlay of the irrigation water withdrawals with water stress can provide useful information to guide water-saving policies in China. Different areas need to implement different policies to relieve the local water stress. Areas with a high level of irrigation water withdrawal and serious water stress urgently need to develop water-saving irrigation practices; because a high level of irrigation water withdrawal is a factor that causes water stress in such locations. These areas are mainly located in the Huang-Huai-Hai Plain region, the Northeast region, the east of the Loess Plateau region, and Gansu-Xinjiang region. In 2010, the water stress got severe in Northeast China as the irrigation water withdrawals increased. This was largely due to the expansion of the area of irrigated land in the region. The effective irrigation area increased by 44.07%, from 49 557.5 km^2 in 2001 to 71 395.6 km^2 in 2010, and the sown area of rice, which requires large amounts of irrigation water, increased by 48.77% from 27 693.7 km^2 in 2001 to 41 998.7 km^2 in 2010 (National Bureau of Statistics of China, 2002; 2011). The increase in the effective irrigation area and sown area of rice were both clustered in Heilongjiang.

Areas with high irrigation water withdrawal and less serious water stress are mainly located in the Middle-Lower Yangtze River region and the South region.

Although the irrigation water withdrawals are relatively high in these locations compared with other areas in China, they also have relatively abundant water resources. However, these locations should also consider their local water stress, because they may risk being transformed into serious water stress regions, such as has occurred in the eastern areas of Sichuan (Fig. 5).

Areas with low irrigation water withdrawal and serious water stress are widely located in the northern part of China and the coastal regions in the east and south. In these locations, industrial and domestic water withdrawals may also be contributing to the high water stress. Local government in these areas needs to save water not only from the agricultural sector, but also from the industrial and domestic sectors.

Although the total irrigation water withdrawals in China decreased during 2001–2010, the water stress in the northern part of China worsened. One reason for this may be the increased irrigation water withdrawals in the Northeast region, while the decreased irrigation water withdrawals in the southern part of China did not contribute significantly to a relief of the overall water stress. In the future, government needs to implement policies to reduce irrigation water withdrawals in the north, especially in the Northeast region, the Huang-Huai-Hai Plain region, and Xinjiang-Gansu region, by improving irrigation technology, strengthening water saving management, or implementing an irrigation price policy (Blanke *et al.*, 2007; Wang *et al.*, 2016a).

5 Conclusions

This study analyzed the spatial patterns of irrigation water withdrawals in China and confirmed that a multi-scale analysis of the spatial pattern was necessary. New information was acquired regarding the numerical features, spatial variation, and spatial association of the irrigation water withdrawals in China in 2001 and 2010 at the regional, provincial, and prefectural scales. In addition, by overlaying with water stress data, it was possible to identify specific areas where it was important for certain sectors to save water.

The results showed that the total irrigation water used in China decreased by 3.03% from 3.47×10^{11} m^3 in 2001 to 3.36×10^{11} m^3 in 2010. The largest irrigation water withdrawals were in the Middle-Lower Yangtze River region at the regional scale, and in Xinjiang at the provincial scale. In contrast, the lowest irrigation water withdrawals occurred in the Qinghai-Tibet Plateau, at both scales. In addition, the spatial variation displayed an apparent scale effect, while the spatial association could be analyzed better at the prefectural scale. It was found that significant spatial agglomerations were detected at the prefectural scale and the LISA analysis revealed a wide area of low-value clusters and several high-value clusters. By overlaying the irrigation water withdrawals with the water stress, we identified areas with high irrigation water withdrawal and serious water stress, located in the Huang-Huai-Hai Plain region, the Northeast region, the east of the Loess Plateau region, the east and the west of Gansu-Xinjiang region. There is an urgent need for these places to develop water-saving irrigation techniques. In contrast, areas of low irrigation water withdrawal and serious water stress should consider saving water not only from the agricultural sector, but also from the industrial and domestic sectors.

This study has acquired useful spatial information regarding irrigation water withdrawals, with implications for water saving in China. Factors that influence the spatial pattern of irrigation water withdrawals and its changes were analyzed from the view of irrigated land; however, other factors such as technologies and management policy were less studied due the data availability. Future researches should explore these factors systematically and thus give important guidance on water-saving advices and policies.

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