

# Vulnerability of Water Resources and Its Spatial Heterogeneity in Haihe River Basin, China

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**Abstract:** To manage water resources effectively, a multiscale assessment of the vulnerability of water resources on the basis of political boundaries and watersheds is necessary. This study addressed issues on the vulnerability of water resources and provided a multiscale comparison of spatial heterogeneity under a climate change background. Using improved quantitative evaluation methods of vulnerability, the Theil index and the Shannon-Weaver index, we evaluated the vulnerability of water resources and its spatial heterogeneity in the Haihe River Basin in four scales, namely, second-class water resource regions (Class II WRRs), third-class water resource regions (Class III WRRs), Province-Class II WRRs, and Province-Class III WRRs. Results show that vulnerability enhances from the north to south in the different scales, and shows obvious spatial heterogeneity instead of moving toward convergence in multiscale assessment results. Among the Class II WRRs, the Tuhai-Majia River is the most vulnerable area, and the vulnerability of the Luanhe River is lower than that of the north of the Haihe River Basin, which in turn is lower than that of the south of the Haihe River Basin. In the scales of Class III WRRs and Province-Class III WRRs, the vulnerability shows obvious spatial heterogeneity and diversity measured by the Theil index and the Shannon-Weaver index. Multiscale vulnerability assessment results based on political boundaries and the watersheds of the Haihe River Basin innovatively provided in this paper are important and useful to characterize the real spatial pattern of the vulnerability of water resources and improve water resource management.

**Keywords:** water resource vulnerability assessment; Theil index; Shannon-Weaver index; spatial heterogeneity; Haihe River Basin

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## 1 Introduction

The vulnerability of water resources is a global issue, which is also one of the major strategic issues of sustainable development in China. The vulnerability of water resources not only affects the actual capacity to protect water resources but also has an important influence on other related systems. The Intergovernmental Panel

on Climate Change (IPCC) technical report states that, 'Climate change on freshwater systems adversely affected, will add to the stress effects, such as population growth, changes in economic activity, land-use change' (Bates *et al.*, 2008). China is one of the 13 countries in the world that experience water scarcity. The results of previous research indicate that in the future, river runoff may decrease in the northern China and increase in the

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southern China under climate change. The frequency of droughts, floods, and other disasters could increase, exacerbating the vulnerability of water resources and leading to a severe supply-and-demand situation (Lin *et al.*, 2006).

The vulnerability of water resources is an important topic that is at the forefront of the world hydrology and water resource research areas. Research on the vulnerability of water resources began in the 1970s when Albinet and Margat (1975) proposed the concept of groundwater vulnerability. The vulnerability of water resources is defined as the loss caused by water shortage (Hashimoto *et al.*, 1982), the degree of damage or adverse effects caused by climate change (IPCC, 1996), water pressure (Falkenmark and Widstrand, 1992), the ratio of water intake to water availability (Raskin *et al.*, 1997), the freshwater criticality (Alcamo *et al.*, 1997) and the propensity or predisposition that is adversely affected by diverse historical, social, economic, political, cultural, institutional, natural resource, and environmental conditions and processes (IPCC, 2012). Previous research has examined this issue on a global, basin, and administrative region scales. Vorosmarty *et al.* (2000) predicted the vulnerability of water resources at the global scale in 2025 on the basis of the global climate model and water balance model scenarios by using a  $0.5^\circ \times 0.5^\circ$  grid assessment unit. The results of this research showed that the vulnerability of water resources varies across regions. Alcamo *et al.*, (1997) utilized the criticality index in combination with the criticality ratio and water availability per capita to assess global water scarcity. Barry (2006) proposed a comprehensive vulnerability indicator to assess vulnerability on national, regional, and public scales. Sharma (2003) reported that the northeastern region of India is extremely rich in water resources; however, the continuous increase in human interference and mismanagement has rendered these resources in a fragile state. The vulnerability of water resources in several regions in China has been discussed. Some researchers selected water resource regions or watersheds, such as the Haihe River (Xia *et al.*, 2012b), Heihe River (Huang *et al.*, 2004), Chanhe River (Bai *et al.*, 2012), and West Liaohe River (Hao and Wang, 2012), as study areas. Administrative districts, such as Hebei Province (Chen *et al.*, 2008), Hunan Province (Zou *et al.*, 2008), and Shanxi Province (Xia *et al.*, 2012c), have also been selected as the study

areas. Some researchers paid attention to typical areas such as the source region of the Huanghe (Yellow) River (Wu and Zhou, 2002), the Huanghe River Delta (Liu *et al.*, 2012), and the Changma irrigation area at the Shule River Basin in Uygur Autonomous Region of Xinjiang (Zhang *et al.*, 2012). Vulnerability of water resources also exists in the trans-boundary regions in China (Feng and He, 2009). Different indicators have been employed to assess the vulnerability in above papers as the different areas condition or different scales. Perveen and James (2011) explored the applicability of water stress and scarcity indicators in  $0.5^\circ$ ,  $1^\circ$ , and  $5^\circ$  scales and showed that only area-independent 'scaled' indicators can be applied to the cross-scale assessment of water resource vulnerability. Xia *et al.* (2012c) selected scale-independent indicators to assess the vulnerability of water resources by using the function method and found that provincial scale results are helpful in showing the characteristics of the vulnerability of general regional water resources.

For the Haihe River Basin, we just found few assessment results from the basin scales (Lyu *et al.*, 2012; Xia *et al.*, 2012b). However, multiscale vulnerability assessments based on political boundaries and watersheds are needed and useful for the Haihe River Basin but are not found in former literature. The Haihe River Basin accounts only for approximately 1.3% of the total water resources in China, while supporting a population that accounts for approximately 10% of China, approximately 15% of the industrial production and 10% of the total agricultural output (Yang, 2003), and this region is considered as the most vulnerable basin in China. To manage water resources effectively, the functions and legal statuses of basin commissions and administrative institutes are defined by China's Water Law, which was amended in 2002 (People's Congress, 2002). These basin commissions are given greater authority in the allocation and centralized control of all diversion projects (Shen, 2004). However, the administration of water resources is largely based on political boundaries rather than on watersheds (Cheng and Hu, 2012).

Although many researchers studied the vulnerability assessment across the world, there are still some questions remaining unclear, especially in the Haihe River Basin: Is the vulnerability high in the Haihe River Basin? How does the vulnerability distribute in different scales? What are the differences among multiscale vul-

nerability assessment results and how to assess quantitatively their heterogeneity? Therefore, multiscale vulnerability is assessed on basin, sub-basin, provincial, and combined political boundary and watershed scales with an improved vulnerability assessment method in this study. Then the spatial heterogeneity of the vulnerability in the Haihe River Basin is evaluated by using quantitative evaluation indexes. The results are important to characterize the spatial pattern of the vulnerability of water resources and improve water resource management.

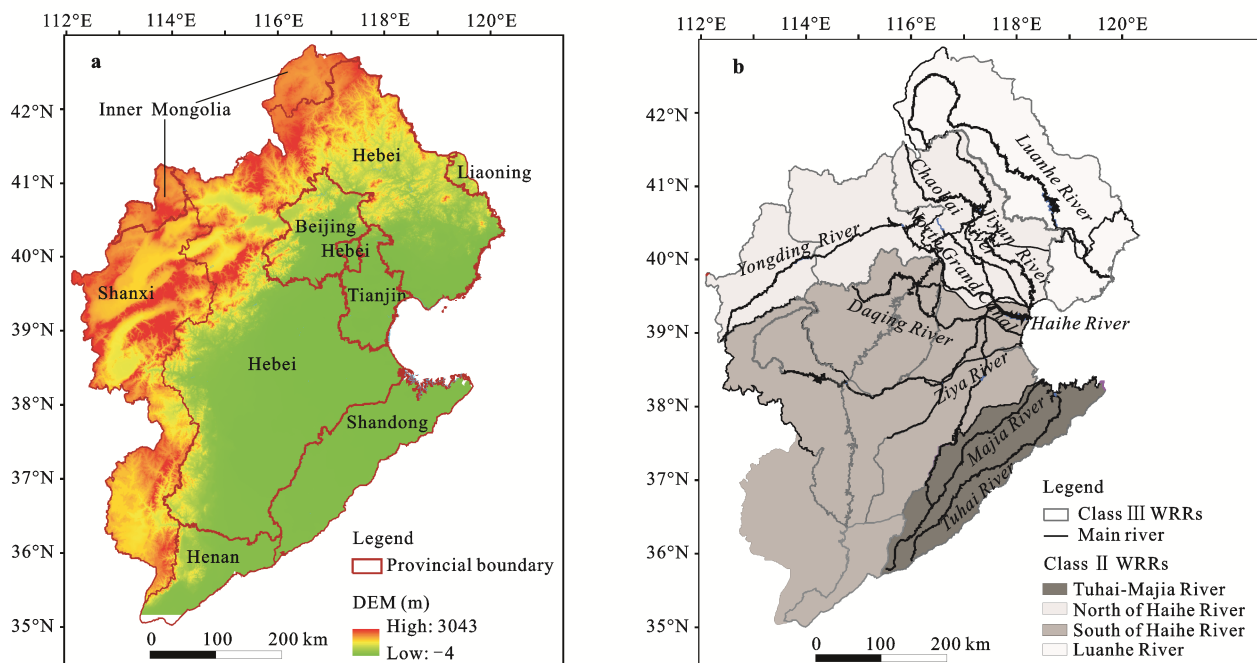
## 2 Study Area and Data

### 2.1 Study area

The Haihe River Basin ( $34^{\circ}58'–42^{\circ}50'N$ ,  $112^{\circ}05'–119^{\circ}55'E$ ) is situated in the northern China and is composed of Hebei Province (HB), Beijing Municipality (BJ), Tianjin Municipality (TJ), parts of Inner Mongolia Autonomous Region (IM), as well as Shanxi (SX), Henan (HN), Liaoning (LN), and Shandong provinces (SD) (Fig. 1a). The basin has an elevation of 0–3050 m. The Asian Monsoon climate is the predominant climate of the basin, with cold and dry winter and hot and rainy summer. The mountain areas are concentrated in the northern and western areas of the basin, and the central, eastern, and southern parts of the basin are plain areas.

Several rivers, namely, the Luanhe River, Yongding River, Chaobai River, Beiyun River, Daqing River, Ziya River, Majia River, and Tuhai River, can be found in this basin (Fig. 1b).

The Haihe River Basin is the first-class water resources region (Class I WRR) as Haihe River is one of the major rivers and the special natural geographical location in China. Class III WRRs are generated on the consideration of convenience of water analysis and calculation. Meanwhile, Class II WRR is the union of all the sub-basins next to each other which have the similar characters of development and utilization of water resources in the Class III WRRs. The total area of the Haihe River Basin is approximately  $319\,651\text{ km}^2$  and includes four Class II WRRs. These four Class II WRRs are the Luanhe River (LR), the north of the Haihe River (NHR), the south of the Haihe River (SHR) and the Tuhai-Majia River (TMR) (Fig. 1b), which account for 17.1%, 26.0%, 46.6%, and 10.3% of the total area of the Haihe River Basin, respectively. The average water resource of this basin is approximately  $370.30 \times 10^8\text{ m}^3/\text{yr}$ , which is only approximately 1.3% of the water resources in China. However, this basin supplies for 10% of the national population and contributes to 15% of the industrial production in China. In 2008, the total



**Fig. 1** Political boundary and digital elevation of Haihe River Basin (a) and boundaries of second-class water resource regions (Class II WRRs) and third-class water resource regions (Class III WRRs), main rivers and tributaries (b)

amount of water resources in the basin is only  $294.50 \times 10^8 \text{ m}^3$ . The LR, NHR, SHR, and TMR account for 14.4%, 26.2%, 51.3%, and 8.0% of the total water resources in the Haihe River Basin, respectively. The amount of water resources in the north and south of the Haihe River is higher than the average value. In 2008, the total water consumption in the basin is  $373.39 \times 10^8 \text{ m}^3$ , with the LR, NHR, SHR, and TMR accounting for 10.2%, 21.5%, 49.9%, and 18.4%, respectively. The water resources distributions of the Haihe River Basin in BJ, TJ, HB, SX, HN, SD, IM, and LN are 11.6%, 6.2%, 52.7%, 12.1%, 8.8%, 7.0%, 1.2%, and 0.3%, respectively. The water consumption distributions are 9.4%, 6.0%, 51.5%, 5.4%, 10.6%, 16.5%, 0.6%, and 0.1%, respectively. Additional details are presented in Table 1.

## 2.2 Data

The precipitation in 2008 is 541 mm ( $1729.28 \times 10^8 \text{ m}^3$ ), which is only 1% above the average precipitation in 1956–2000. We obtained monitoring data of surface water capacity, water resource quantity, average water resource quantity, water consumption, gross domestic product (GDP), and the population in 2008 based on Class II WRRs, Class III WRRs, Province-Class II

WRRs, and Province-Class III WRRs. Data on average surface water capacity, average water resource quantity, water resource quantity in 2008 and water consumption in 2008 are derived from the Haihe River Water Resources Bulletin<sup>①</sup>, and the Integrated Planning of Water Resources in Haihe River Basin<sup>②</sup>. The average temperature and precipitation from 1961 to 2006 in the scale of  $0.5^\circ \times 0.5^\circ$  are calculated by using the method from the China Meteorological Administration (Xie *et al.*, 2007; Xu *et al.*, 2009) and the gauge observations from over 751 stations in the China Meteorological Administration. These stations are maintained according to standard methods, and the data undergo quality control by the China Meteorological Administration.

## 3 Methodology

### 3.1 Assessment method of water resources vulnerability

To assess water resources vulnerability in water supply and demand under a changing climate, a method integrating the sensitivity of a water system to climate change and its adaptive capacity to tackle water stress as caused by various factors was developed. The vulner-

**Table 1** Water quantity in Haihe River Basin

	Area (km <sup>2</sup> )	Surface water capacity in 2008 ( $10^8 \text{ m}^3$ )	Water resources in 2008 ( $10^8 \text{ m}^3$ )	Average water resources (1956–2000) ( $10^8 \text{ m}^3$ )	Water consumption in 2008 ( $10^8 \text{ m}^3$ )
LR	54530	26.75	42.40	63.20	38.08
NHR	83115	35.54	77.25	89.30	80.31
SHR	148994	60.59	151.20	178.50	186.21
TMR	33012	4.05	23.65	39.30	68.80
Total	319651	126.93	294.50	370.30	373.39
BJ	16410	12.79	34.21	37.30	35.08
TJ	11920	13.61	18.30	15.70	22.33
HB	171624	60.44	155.26	197.20	192.18
SX	59133	22.83	35.70	48.60	20.26
HN	15336	10.54	25.97	27.60	39.66
SD	30942	3.09	20.66	37.10	61.44
IM	12576	2.74	3.51	4.70	2.06
LN	1710	0.88	0.88	2.10	0.38

Notes: LR, Luanhe River; NHR, north of Haihe River; SHR, south of the Haihe River; TMR, Tuhai-Majia River; BJ, Beijing; TJ, Tianjin; HB, Hebei; SX, Shanxi; HN, Henan; SD, Shandong; IM, Inner Mongolia Autonomous Region; LN, Liaoning

① HRWCC (Haihe River Water Conservancy Committee), 2008. *Haihe River Water Resources Bulletin*. Tianjin: Haihe River Water Conservancy Committee, 1–50. (in Chinese)

② HRWCC, 2010. *Integrated Planning of Water Resources in Haihe River Basin*. (unpublished). (in Chinese)

Ability was expressed as a function of sensitivity  $S(t)$  and adaptability  $C(t)$  of the water resource system (Xia *et al.*, 2012a):

$$V(t) = \frac{S(t)}{C(t)} \quad (1)$$

where  $V(t)$  is the water resource vulnerability at time  $t$ ; and  $S(t)$  and  $C(t)$  are the sensitivity and adaptability of the water system at time  $t$ , respectively.  $S(t)$  is related to the natural characteristics of the water system, and  $C(t)$  is concerned with adaptation strategies, including the integrated socioeconomic capacity and the scientific technical and management levels required to handle water stress.  $S(t)$  indicates the sensitivity of the water system to climate change. According to two-parameter climate elasticity of stream flow index ( $e_{P,\Delta T}$ ) of Fu *et al.* (2007), the stream flow-precipitation-temperature relationship can be expressed as follows:

$$e_{P,\Delta T} = \frac{dR_{P,\Delta T}/\bar{R}}{dP_{P,\Delta T}/\bar{P}} = \frac{R_{P,\Delta T} - \bar{R}}{P_{P,\Delta T} - \bar{P}} \frac{\bar{P}}{\bar{R}} \quad (2)$$

where  $R_{P,\Delta T}$  and  $P_{P,\Delta T}$  are stream flow and precipitation, respectively;  $dP_{P,\Delta T}$  is the average change in precipitation and temperature, respectively; and  $\bar{P}$ ,  $\bar{T}$  and  $\bar{R}$  are average precipitation, temperature, and stream flow, respectively;  $dR_{P,\Delta T}$  is the average changes in runoff with precipitation and temperature change.

In Fu *et al.* (2007),  $dR_{P,\Delta T}$  was obtained from the stream flow-precipitation-temperature interpolated surface. Based on historical records, the prediction is reliable when future climate falls in the climate range condition of the historical data. However, the reliability of prediction may be weakened if future climate condition is beyond the historical range by taking account of climate change aggravated by human activities, e.g., greenhouse gas emission and growing population (Gardner, 2009). To overcome the shortcomings of the method of Fu *et al.* (2007), we employed Gardner function (Gardner, 2009) to calculate  $dR_{P,\Delta T}$  in the method of Fu *et al.* (2007):

$$dR_{P,\Delta T} = \exp(-PET/\bar{P}) \times (1 + PET/\bar{P}) \times dP - [5544 \times 10^{10} \times \exp(-PET/\bar{P}) \times \exp(-4620/T_K) \times T_K^{-2}] \times dT_K \quad (3)$$

where  $PET$  is the mean annual potential evapotranspiration (mm), which can be calculated by using various

temperature based methods.  $T_K$  is the temperature in Kelvin.  $dP$  and  $dT_K$  are the changes of precipitation and temperature, respectively. The method presented by Holland (1978) needs only the mean annual temperature is given by the follows:

$$PET = 1.2 \times 10^{10} \times \exp(-4620/T_K) \quad (4)$$

Theoretically, the elasticity rate range is  $(-\infty, +\infty)$ . The elasticity rate is very high when the tendency leans toward infinity and negative infinity; therefore, we can use the following equation to convert the range of  $e_{P,\Delta T}$  into  $[0, 1]$  for ease of comparison:

$$S(t) = \begin{cases} 1 - \exp(-e_{P,\Delta T}) & e_{P,\Delta T} \geq 0 \\ 1 - \exp(e_{P,\Delta T}) & e_{P,\Delta T} < 0 \end{cases} \quad (5)$$

Based on Equation (5), we can observe that  $S(t)$  tends to be 1 when the elasticity rate approaches infinity and negative infinity and tends to be 0 when the elasticity rate approaches 0 (Fig. 2).

Water adaptability, which is the reciprocal of water stress, is concerned with adaptation strategies as well as the integrated socio-economic capacity, scientific, technical and management levels to tackle water stress. The links between population ( $P_H$ ) driven water stress or 'water crowding' ( $P_H/Q$ : population per water unit), water-use driven mobilization level ( $r$ : use-to-availability as a percentage of water availability), and per capita water use ( $W/P_H$ : water intake in cubic meters per capita per year) can be used to determine  $C(t)$  (Xia *et al.*, 2012a; 2012c):

$$C(t) = \exp(-2.3 \times r - \frac{P_H}{Q} \times \frac{W}{P_H}) \quad (6)$$

Thus, we can obtain  $V(t)$  by using Equation (7):

$$V(t) = \frac{1 - \exp(-|e_{P,\Delta T}|)}{\exp(-2.3 \times r - \frac{P_H}{Q} \times \frac{W}{P_H}) / \exp(-3.3)} \quad (7)$$

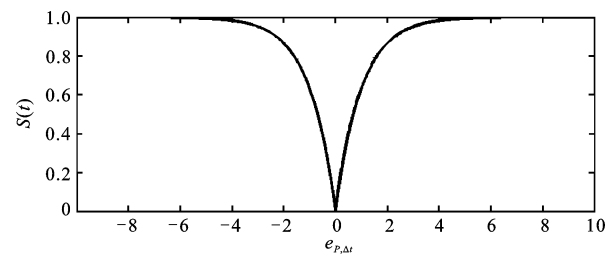


Fig. 2  $S(t)$  equation conversion of  $e_{P,\Delta T}$

According to Xia *et al.* (2012a; 2012b), the vulnerability of water resources can be classified into five classes, namely, not fragile, weakly fragile, fragile, strongly fragile, and extremely fragile. These five classes can be expressed as class I, II, III, IV, and V, respectively. Class IV and V are classified further into subclasses to obtain more information. The classes of water resources vulnerability are shown in Table 2.

3.2 Heterogeneity assessment of water resource vulnerability

3.2.1 Multiscale design

The Haihe River Basin is selected as the study area in this paper, sub-basin below it are Class II WRRs and Class III WRRs. Only the province scale has been selected from Country-Province-City-County Administrative Region scales. Province-Class II WRR and Province-Class III WRR scales are produced by using the province boundary to clip Class II WRR and Class III WRR boundaries respectively. Thus, the water resources

vulnerability assessment and heterogeneity analysis are performed on 4 Class II WRR units, 15 Class III WRRs units, 16 Province-Class II WRRs units, and 35 Province-Class III WRR units (Fig. 3) in this study. Vulnerability and heterogeneity are assessed based on these scales.

3.2.2 Quantification of heterogeneity

Spatial differences in the scales can be intuitively reflected by a digital map and be measured by using quantitative methods, such as the Theil index. The Theil index can be deconstructed into independent differences between groups and within-group differences and is widely used to measure relative gaps between the different regional developments. This study used the Theil index to analyze the spatial differences in the multiscale vulnerability of water resources in the Haihe River Basin. The spatial differences are divided into two parts:  $T_{BR}$  (inter-basin indicator) and  $T_{WR}$  (internal basin indicator). The Theil index can be calculated by using Equation (8) (Xu *et al.*, 2005):

Table 2 Classification of water resources vulnerability ( $V(t)$ )

$V(t)$	Class	Subclass	Description
$0 \leq V(t) \leq 0.05$	I		Not fragile
$0.05 < V(t) \leq 0.10$	II		Weakly fragile
$0.10 < V(t) \leq 0.20$	III		Fragile
$0.20 < V(t) \leq 0.40$	IV		
		IV <sub>1</sub>	Strongly fragile 1st grade
		IV <sub>2</sub>	Strongly fragile 2nd grade
$V(t) > 0.40$	V		
		V <sub>1</sub>	Extremely fragile 1st grade
		V <sub>2</sub>	Extremely fragile 2nd grade
		V <sub>3</sub>	Extremely fragile 3rd grade
		V <sub>4</sub>	Extremely fragile 4th grade

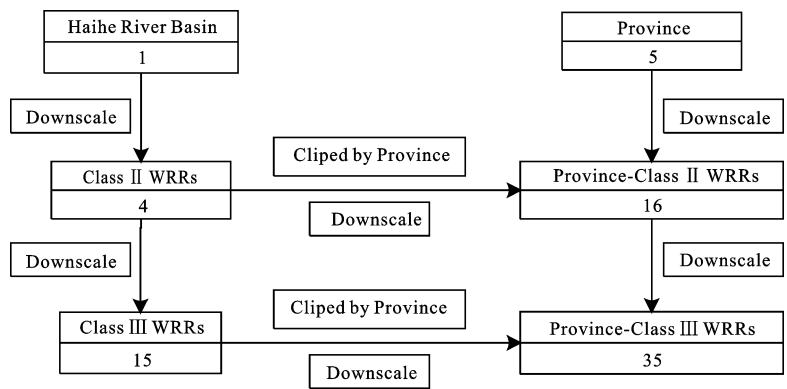


Fig. 3 Multiscales employed in this study

$$Theil = T_{BR} + T_{WR} = \sum_{i=1}^n V_i \log \frac{V_i}{d_i} + \sum_{i=1}^n V_i \left[ \sum_{j=1}^m V_{ij} \log \frac{V_{ij}}{d_{ij}} \right] \quad (8)$$

where  $n$  and  $m$  are the basin/area number and basin/area partition number, respectively;  $v_i$  is the share of the  $i$ th basin/area partition of the total area;  $v_{ij}$  is the share of the  $j$ th partition in the  $i$ th basin/area;  $d_i$  is the share of the  $i$ th basin/area partition in China; and  $d_{ij}$  is the share of the  $j$ th partition in the total  $i$ th basin/area in China. The higher the *Theil* index is, the larger the differences in vulnerability among assessment units. This study uses only the Haihe River Basin as the study area, so nationwide comparison is unnecessary.  $d_i$  can be equal to  $v_i$ . The  $I$  within a scale can be ignored, therefore  $d_j$  represents the share of the  $j$ th basin/area partition in the total area. In this manuscript, we can simplify the calculation by letting  $\log()$  function return the natural logarithm (base  $e$ ) of a number, and Equation (8) can be simplified as Equation (9):

$$Theil = \sum_{i=1}^n V_i \left[ \sum_{j=1}^m V_{ij} \ln \frac{V_{ij}}{d_{ij}} \right] = \sum_{j=1}^m V_j \ln \frac{V_j}{d_j} \quad (9)$$

The *Theil* index can measure the spatial differences in the vulnerability of water resources among different scales. However, it is unable to show the diversity of the vulnerability. Therefore, the Shannon-Weaver index, which is proven to be efficient in the assessment of biodiversity or economic system diversity (Xu *et al.*, 2002), is applied in this study to analyze the diversity of vulnerability ( $H$ ):

$$H = -\sum_{j=1}^m V_j \ln V_j \quad (10)$$

## 4 Results

### 4.1 Vulnerability of water resources in Class II WRRs and Class III WRRs

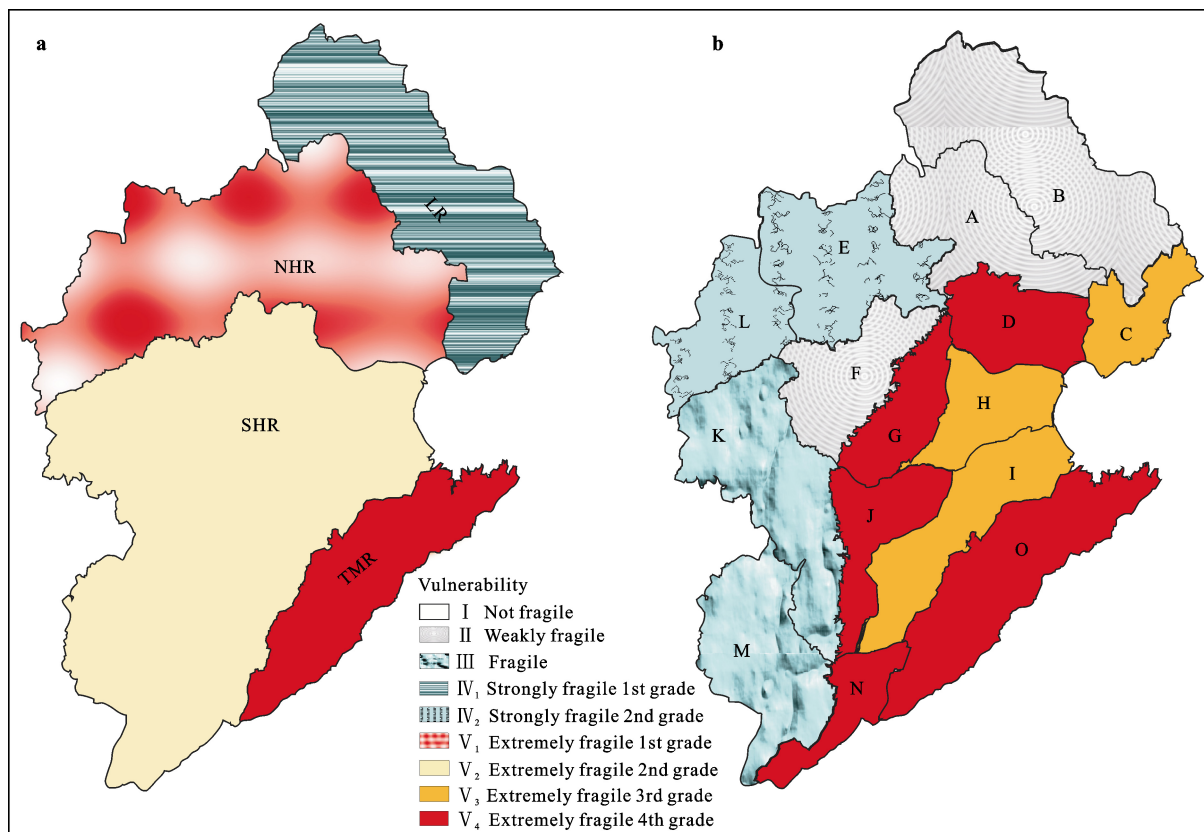
The average vulnerability of water resources of the Class II WRRs and Class III WRRs were calculated based on the average water resource quantity, precipitation, and temperature from 1956 to 2000. The results are shown in Fig. 4. The vulnerability of water resources in the Class II WRR scale increases from the north to south (Fig. 4a). The vulnerability of the LR is lower

than that of NHR Basin, which in turn is lower than that of SHR Basin. The TMR River is the most vulnerable. Compared to the vulnerability of Class II WRRs, it is obviously different in the Class III WRRs. A total of five vulnerability classes are included in the Class III WRR scale, which is one more than the number of vulnerability classes in the Class II WRR scale (Fig. 4b). The vulnerability of the Class III WRR scale has a greater vulnerability grade span from II–V<sub>4</sub> than the Class II WRR scale does. Also, the lower units in mountain areas are separated from the Class II WRR units. The water shortage status of the plain areas is serious, and their vulnerability is high. However, the vulnerability distribution from the north to south in the Class II WRR scale is not evident in the Class III WRR scale.

The vulnerability of water resources in 2008 (Fig. 5) is more serious than the annual average (Fig. 4). The vulnerability assessment results show that the spatial distribution of vulnerability in 2008 is similar to the average of the Class II WRR scale; however, the vulnerability classes of all of the units increase by one class with the exception of the TMR. The vulnerability class of TMR remains at the extremely fragile 4th sub class (Figs. 4a and 5a). The vulnerability of water resources in the mountain areas of the Class III WRR scale is lower than in the Class II WRR scale. Figure 5b shows that the mountain area units A, B, M and K are experiencing lower than moderate fragile vulnerability; however, the plain areas, namely, units C, D, G, H, I, J, O and N, are experiencing over high vulnerability. The number of vulnerability classes in the Class III WRR scale is seven in 2008, three classes more than the vulnerability classes in the Class II WRR scale. The Class III WRR scale is significantly more diverse than the Class II WRR scale.

The deficit between water supply and water consumption in different water resources regions is the main reason for the formation of water resources vulnerability. In Class II WRRs scale, the water supply pressure (water consumption/water resources quantity) is highest in the TMR, NHR is lower than SHR, and LR is the lowest (Fig. 6, Table 1), hence the vulnerability sequence of these Class III WRRs is as the same with the water supply pressure. In Class III WRRs scale, the





**Fig. 4** Average vulnerability of water resources in Haihe River Basin. (a) Vulnerability in the Class II WRR scale, (b) Vulnerability in the Class III WRR scale. LR, the Luanhe River; NHR, north of the Haihe River; SHR, south of the Haihe River; and TMR, Tuhai-Majia River. A, mountain areas of the three northern rivers; B, mountain areas of LR; C, plain areas of LR; D, downstream plains of the Chaobai River, Jiyun River, the north canal, and Yongding River; E, the area between the Cetian reservoir and the Sanjiadian station; F, mountain area of the Daqing River; G, plain areas west of Baiyangdian; H, plain areas east of Baiyangdian; I, Heilonggang and Yundong plains; J, plain areas of the Ziya River; K, mountain areas of the Ziya River; L, upstream areas above the Cetian reservoir in the Yongding River; M, mountain areas of the Zhangwei River; N, plain areas of the Zhangwei River; O, TMR

mountain areas are departed from the plain areas, as the difference of runoff condition and water consumption the vulnerability differs from mountains to plains. As shown in Fig. 6, the water consumption in mountain areas such as unit A, B, E, F, K, L, M was lower than water resources quantity, so the vulnerability of water resources are low, while in the plain areas such as unit C, D, G, H, I, J, N, O, water consumption is far higher than water resources quantity, so the vulnerability is more serious than that in mountain areas.

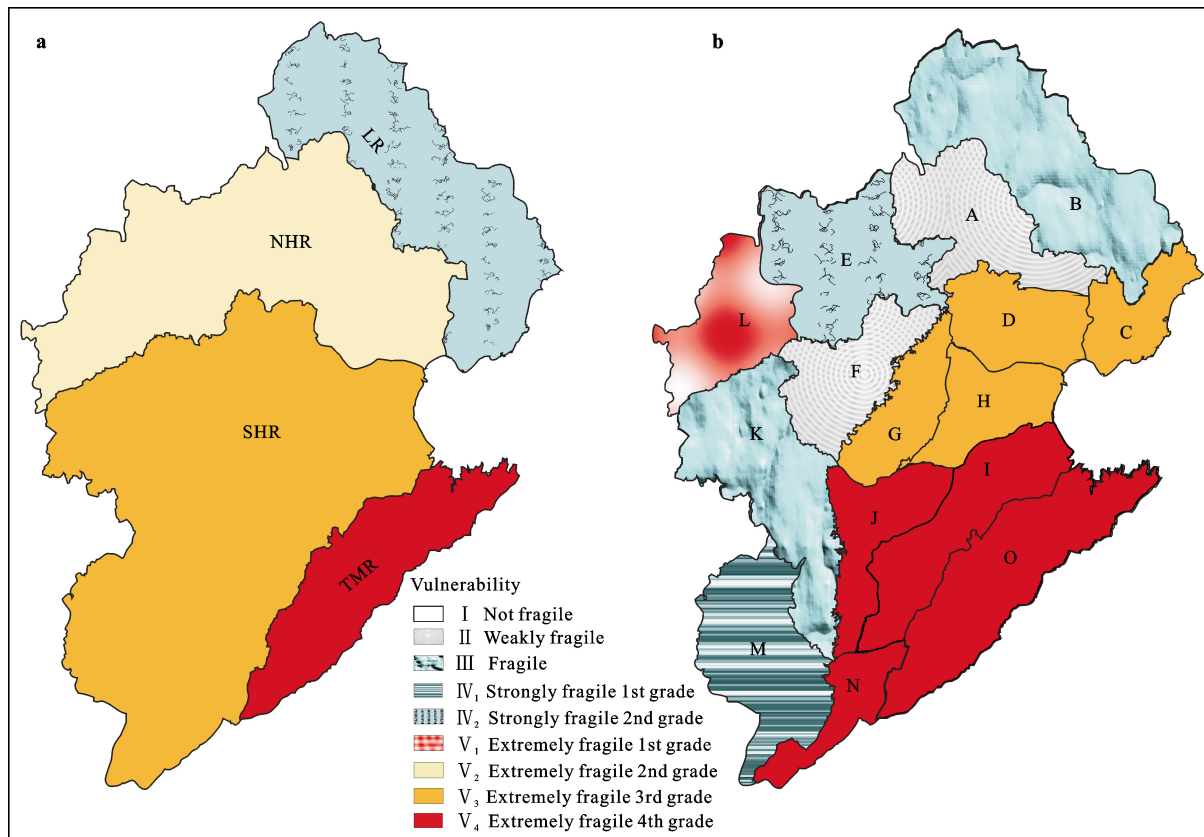
#### 4.2 Spatial differences of vulnerability of water resources in Province-Class II WRR scale

To analyze the vulnerability further, the vulnerability in the Province-Class II WRR scale is assessed, and the results are shown in Fig. 7. The units with the highest vulnerability classes are the SD-TMR unit and the

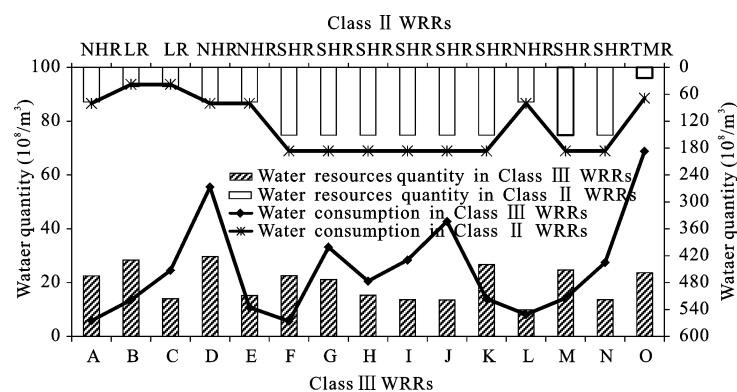
HN-TMR unit. The HB-TMR unit is in the extremely fragile 1st grade class, but is in the extremely fragile 4th grade class in the Class II WRRs scale. The total number of vulnerability classes in the Province-Class II WRR scale is more than that of the Class II WRR scale. Besides, the number of vulnerability classes in the Province-Class II WRR scale is seven (Fig. 7), two more than in Class III WRR scale (Fig. 4b). The vulnerability class of a single unit varies across different scales.

Figure 7 shows the spatial difference of the vulnerability in a provincial administrative region. In Beijing, the vulnerability in NHR is more serious than that in SHR. In IM, the LR vulnerability is less serious than that in NHR. In HB, the vulnerability is sorted by grade in the following descending order: TMR < NHR < SHR. In SX, the vulnerability in NHR is more serious than





**Fig. 5** Vulnerability of water resources in Haihe River Basin in 2008. The names of Class III WRRs are same as given in Fig. 4

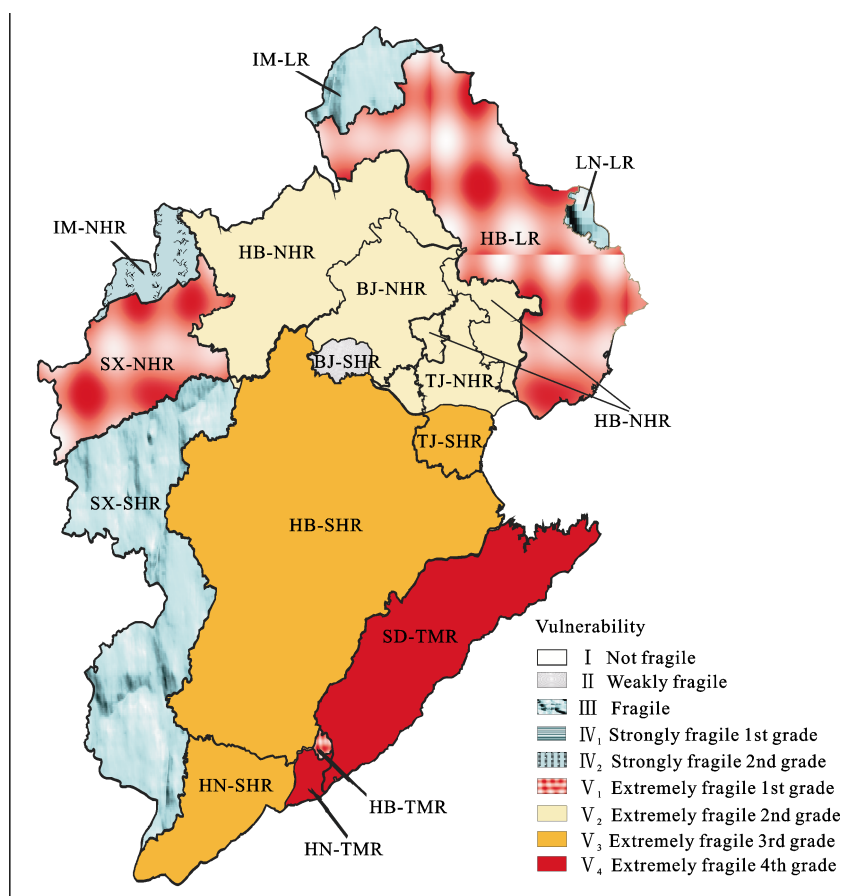


**Fig. 6** Water consumption and water resources quantity in Haihe River Basin in Class III WRR scale and Class II WRR scale. The names of Class III WRRs are same as given in Fig. 4

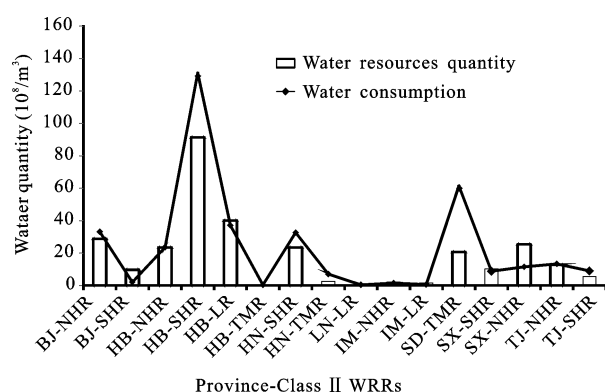
that in SHR. As the results above, the spatial distribution of vulnerability of water resources in the Province-Class II WRR scale is significantly different from that in the Class II WRR scale.

As shown above, the vulnerability is different in the Class II WRR scale and the Province-Class II WRR scale (Figs. 5 and 7). The differences come from the changes of water resources quantity and consumption demand in the new units in the Province-Class II

WRR scale (Fig. 8). As we know, one Class II WRR unit contains more than one Province-Class II WRR, the vulnerability of one Class II WRR presents the average vulnerability of all the Province-Class II WRRs contained in the unit. However, the vulnerability in the Province-Class II WRR scale shows the vulnerability of each Province-Class II WRR unit. By downscaling scales, the covered information in the Class II WRR scale is presented. Taking one Class II



**Fig. 7** Vulnerability of water resources in Haihe River Basin in Province-Class II WRR scale. BJ-NHR, the NHR Basin in BJ; BJ-SHR, the SHR Basin in BJ; TJ-NHR, the NHR Basin in TJ; TJ-SHR, the SHR Basin in TJ; HB-NHR, the NHR Basin in HB; HB-SHR, the SHR Basin in HB; HB-LR, the LR Basin in HB; HB-TMR, the TMR Basin in HB; IM-LR, the LR Basin in IM; IM-NHR, the NHR Basin in IM; SX-NHR, the NHR Basin in SX; SX-SHR, the SHR Basin in SX; HN-SHR, the SHR Basin in HN; HN-TMR, the TMR Basin in HN; SD-TMR, the TMR Basin in SD; LN-LR, the LR Basin in LN



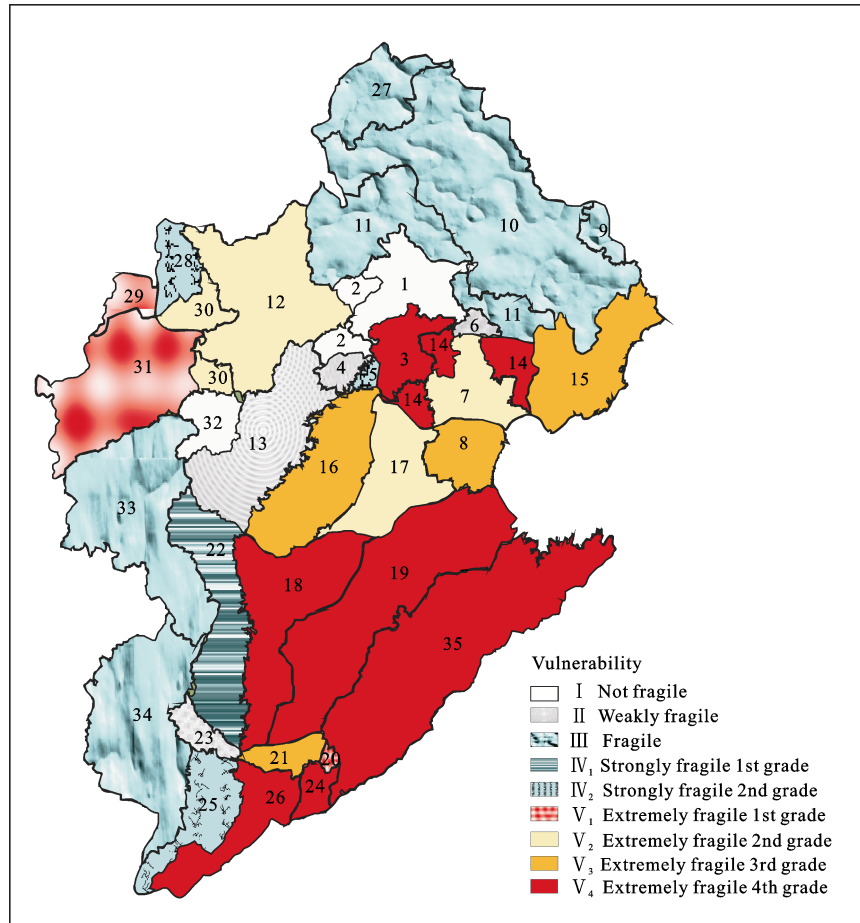
**Fig. 8** Water consumption and water resources quantity in Haihe River Basin in Province-Class II WRR scale. The names of Province-Class II WRRs are same as given in Fig. 7

WRR, the NHR, as an example, it contains 5 Province-Class II WRRs, namely (Fig. 8), BJ-NHR, TJ-NHR, HB-NHR, IM-NHR, SX-NHR. The NHR is

extremely fragile 2nd grade in the Class II WRR scale. However, all the units are extremely fragile 2nd grade in the Province-Class II WRR scale except the unit of IM-NHR.

#### 4.3 Spatial differences of vulnerability of water resources in Province-Class III WRR scale

A total of 35 units in the Province-Class III WRR scale are generated by overlaying the boundaries of Class III WRRs and provincial administrative boundaries. The vulnerability assessment results are shown in Fig. 9. Additional information is revealed in the Province-Class III WRR scale compared with other scales. For example, the assessment results of vulnerability show that some areas are not-fragile but not shown in other scales above, such as units 1, 2, and 32. Weakly fragile areas, such as units 4 and 6, are separated from the NHR



**Fig. 9** Vulnerability of water resources in Haihe River Basin in Province-Class III WRR scale. 1, mountain areas of the three northern rivers in BJ; 2, the area between the Cetian reservoir and the Sanjiadian station in BJ; 3, downstream plains of the Chaibai River, the Jiyun River, the north canal, and the Yongding River in BJ; 4, mountain area of the Daqing River in BJ; 5, plain areas west of Baiyangdian in BJ; 6, mountain areas of the three northern rivers in TJ; 7, downstream plains of the Chaibai River, the Jiyun River, the north canal, and the Yongding River in TJ; 8, plain areas east of Baiyangdian in TJ; 9, mountain areas of the LR in LN; 10, mountain areas of the LR in HB; 11, mountain areas of the three northern rivers in HB; 12, the area between the Cetian reservoir and the Sanjiadian station in HB; 13, mountain area of the Daqing River in HB; 14, downstream plains of the Chaibai River, the Jiyun River, the north canal, and the Yongding River in HB; 15, plain areas of the LR in HB; 16, plain areas west of Baiyangdian in HB; 17, plain areas east of Baiyangdian in HB; 18, plain areas of the Ziya River in HB; 19, Heilonggang and Yundong plains in HB; 20, TMR in HB; 21, plain areas of the Zhangwei River in HB; 22, mountain areas of the Ziya River in HB; 23, mountain areas of the Zhangwei River in HB; 24, TMR in HN; 25, mountain areas of the Zhangwei River in HN; 26, plain areas of the Zhangwei River in HN; 27, mountain areas of the LR in IM; 28, the area between the Cetian reservoir and the Sanjiadian station in IM; 29, upstream areas above the Cetian reservoir in the Yongding River in IM; 30, the area between the Cetian reservoir and the Sanjiadian station in SX; 31, upstream areas above the Cetian reservoir in the Yongding River in SX; 32, mountain area of the Daqing River in SX; 33, mountain areas of the Ziya River in SX; 34, mountain areas of the Zhangwei River in SX; 35, TMR in SD

which is in extremely fragile 2nd grade. And the areas that are in the extremely fragile 4th grade class include units 3, 14, 18, 19, 35, 24, and 26.

There are 35 units in the Province-Class III WRR scale, 20 assessment units more than in the Class III WRR scale and 19 more than in the Province-Class II WRR scale. Since the water consumption and water resources quantity in different scales are different, the

vulnerability in the Province-Class III WRR scale are different with others.

#### 4.4 Heterogeneity quantification of vulnerability of water resources

In this study, the spatial difference in vulnerability of water resources among different scales is measured by using the Theil index, and the diversity in vulnerability

of water resources among different scales is measured by using the Shannon-Weaver index (Table 3). The Theil index decreases successively with downscaling, such as in the Class II WRR, Class III WRR, and Province-Class III WRR scales, or in the Class II WRR, Province-Class II WRR, and Province-Class III WRR scales. This trend suggests that the vulnerability has more vulnerability grades when the scales decreased. Thus, the vulnerability distributions in the Class III WRR scale are more homogeneous than those in the Class II WRR scale. Similarly, the vulnerability distributions in the Province-Class III WRR scale are more homogeneous than those in the Province-Class II WRR scale.

The Shannon-Weaver index shows the diversity of each vulnerability assessment across different scales (Table 3). As the table shows, the diversity of vulnerability increases successively with downscaling, such as in the Class II WRR, Class III WRR, and Province-Class III WRR scales. By using the Shannon-Weaver index, the spatial heterogeneities are measured, the results are similar as the results measured by the Theil index. The more the diversity of vulnerability is, the more homogeneous the vulnerability distribution is. By contrast, less diversity indicates the assessment units are in convergent vulnerability grades. Based on the assessment results of Shannon-Weaver index and the Theil index, we find that 1) the heterogeneity of water resources vulnerability is different across multiple scales. 2) The scale decrease results in diversity increase, and vice versa. 3) There is no downscaling relationship between the Province-Class II WRR scale and the Class III WRR scale. However the heterogeneity in the Province-Class II WRR scale is more than that in the Class III WRR scale.

## 5 Discussion

### 5.1 Results comparison

The vulnerability of water resources in the Haihe River Basin was assessed in the Class III WRR scale in previous studies (Lyu *et al.*, 2012; Xia *et al.*, 2012b). Thus, the vulnerability results in the Class III WRR scale in Xia's and Lyu's papers are compared against the results in this paper. In the three papers, there are some conclusions in common: the vulnerability in the Haihe River Basin is high, the vulnerability in plain areas are more than the mountain areas, and the vulnerability decrease from south to north in the whole basin. However, the vulnerabilities in plain areas shown in Fig. 6 of Xia *et al.*'s study (2012a) and in the current study are higher than the result assessed by Lyu *et al.* (2012). Similarly, which unit is more vulnerable between the TMR (unit I), and the Heilonggang and Yundong plains (unit O) is different in the three papers. There are three possible explanations for this result: first, the start and end time of the date series is different as that the average value in 1956–2005 was selected in the study of Lyu *et al.* (2012), and the average value in 1956–2000 and 2008 were selected in this study. Second, the integrated index obtained from the water resource, socioeconomic, and ecology systems in the study of Lyu *et al.* (2012) is calculated by using weighted values, which is greatly influenced by subjective factors (Xia *et al.*, 2012b). Therefore, the vulnerability of plain areas in Lyu's study is lower than in the present study as that the serious water deficit was not adequately weighted in the former's study. Additionally, transit water was not considered in both this study and the study of Xia *et al.* (2012b); thus, the vulnerability in TMR as calculated in the two studies is higher than the result from Lyu *et al.* (2012). Third, the greatest difference between this study and the study

**Table 3** Diversity and heterogeneity of vulnerability of water resources

	Not	Weak	Fragile	Strong 1st	Strong 2nd	Extremely 1st	Extremely 2nd	Extremely 3rd	Extremely 4th	Theil index	Shannon- Weaver
Class II WRRs	0	0	0	0	1	0	1	1	1	0.811	1.386
Class III WRRs	0	2	2	1	1	1	0	4	4	0.413	1.748
Province-Class II WRRs	0	1	3	0	1	3	3	3	2	0.335	1.862
Province-Class III WRRs	3	3	7	1	3	3	4	4	7	0.114	2.083

of Xia *et al.* (2012b) is a result of the difference in the classification of class IV and V, which were classified further into subclasses in Table 2 in this study.

### 5.2 Multiscale vulnerability assessment is helpful to improving water resources management

The water resources management authority (WRMA) consists of several institutes, which in turn can be sorted into administrative region institutes and water resources region institutes. As the spatial heterogeneity significantly changes across the Class II WRR, Class III WRR, Province-Class II WRR and Province-Class III WRR scales. Thus the single-scale vulnerability assessment result, e.g., Class II WRRs, is not adequate for water management for different water management institute. Basing on the multi-scales assessment results in this article, water resource managers in different institutes can chose the scientific vulnerability results and develop adaptive management policies according to the assessment results. Take unit 1 (Fig. 9), which is situated in BJ, as an example. The unit is not fragile in the Province-Class III WRR scale, but extremely fragile (2nd grade) in the Province-Class II WRR scale. If only the vulnerability result in the Province-Class II WRR scale was provided to BJ water authority, many adaptive policies would be taken to guarantee the water supply in this unit. However, the truth is unit 1 is in the mountain areas of BJ, and there are few people and industrial production distributed in this unit, water demand can be satisfied by the water supply in it.

### 5.3 Uncertainty analysis

This study is focused on the scale effects of the vulnerability of water resources and heterogeneity. However, given the lack of water resource statistics and the uncertainty of climate change, several important issues must be addressed in the future: 1) multiscale adaptive management methods and measurements must be discussed, 2) the structure of water consumption and supply should be analyzed under climate change, and 3) whether the vulnerability of water resources will increase or not under climate change is an issue that requires further research.

## 6 Conclusions

This study assessed the vulnerability of water resources

by using an improved vulnerability assessment method, and measured its heterogeneity with the Shannon-Weaver Index and the Theil index based on the Class II WRR, Class III WRR, Province-Class II WRR, and Province-Class III WRR scales.

The vulnerability of water resources in the Haihe River Basin enhances from the north to south, and is lower in the mountain areas than in the plain areas. The TMR is the most vulnerable, and the vulnerability of LR is lower than that of NHR Basin, which in turn is lower than that of SHR Basin. However, the vulnerability is different in the Class II WRR, Class III WRR, Province-Class II WRR, and Province-Class III WRR scales. The diversity of vulnerability increases successively with downscaling, such as in the Class II WRR, Class III WRR, and Province-Class III WRR scales. The more the diversity of vulnerability is, the more homogeneous the vulnerability distribution is. Downscaling scales are helpful to presenting the actual vulnerability of water resources and its heterogeneity. Based on the Shannon-Weaver Index and the Theil index, we can observe that vulnerability varies across the Class II WRR and Class III WRR scales and the Province-Class II WRR and Province-Class III WRR scales.

In this study, assessment results of multiscale vulnerability based on political boundaries and the watersheds of the Haihe River Basin are innovatively provided. These results are necessary and useful for water resource management.

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