Linkages with the quantitative assessment of water resources vulnerability: a new approach for adaptive water management under a changing environment

J. Xia, W. Shi, S. Hong and J.-X. Chen

ABSTRACT

Climate change impact on water resources has been a global hot issue in recent years. In accordance with the latest research progress, a new meaning of water resources vulnerability (WRV) and a concept of adaptive water management have been proposed. For evaluating WRV under the changing environment in the Huai River Basin (HRB), the sixth largest river basin in China, a quantitative assessment model coupling with exposure, droughts risk, sensitivity, and adaptability of water resources system was established. In addition, the adaptive regulation of WRV under five scenarios of water demand control, water efficiency control, pollutant restriction of the water function zone, the minimum water demand control of the ecosystem and integrated control were analyzed in this study. The results indicated that the region with the greatest value of WRV was Xiaoqing River in the benchmark year (2000) and the most unfavorable scenarios in which 33% and 87% of HRB were the extreme vulnerable regions. Among all adaptive regulation scenarios, the most sensitive scenario was the integrated control, followed by the control of water function zone compliance, water use efficiency, water demand and the minimum water demand control of the ecosystem. This study will provide a scientific foundation to integrated water resources management in China.

Key words | adaptive regulation, climate change, Huai River Basin, water resources vulnerability

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INTRODUCTION

In the 21st century, the study of water resources vulnerability (WRV) and adaptive water management (AWM) has been an important requirement for the global and national response to climate change, and also a hot issue for water security over the world. However, the integration of quantitative assessment with vulnerability and adaptation of water resources in changing environments are still in an active exploration stage. The technical report on climate change and water of the United Nations Intergovernmental Panel on Climate Change (IPCC 2007), the Dialogue on Water and Climate (DWC 2003) Workshop Report, and the 'Global International Water Assessment' report organized by the United Nations Environment Programme (UNEP 2006) indicated that adaptive countermeasures of region and watershed-scale should be prioritized to adapt and mitigate the impact of climate change on water resources. The mutual relations between WRV and climate change impacts on the socio-economy can be revealed by systematic study, which improves the adaptability of water resources to climate change. Overall, how to quantify WRV in changing environments and how to establish interactive assessment methods and control systems between WRV and AWM are currently in urgent need of global exploration and research.

Albinet & Margat (1970) proposed the earliest vulnerability concept for groundwater resources. Vulnerability is defined here as the degree to which a system is susceptible to or unable to cope with the adverse effects of climate change (IPCC 2001). The IPCC's special report further pointed out that there existed an inherent relationship

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between climate change events, vulnerability, risk and exposure (IPCC 2012). Since the 1980s, many assessment methods for WRV have been developed based on water scarcity. Brouwer & Falkenmark (1989) analyzed WRV combining the threshold of various factors linking with water dependency and demand–supply balance. Falkenmark & Widstrand (1992) proposed population-driven water shortage or 'water crowding' as the hydrological water scarcity index to represent the response of social adaptability to water shortage. Alcamo *et al.* (2000) set use-to-availability as a percentage of water availability to assess global water scarcity. Ohlsson & Appelgren (1998) defined the quotient of water stress index and the index of human development as the index of social water scarcity. The IPCC's 'Second Assessment Report' proposed the concept of vulnerability as the degree to which a natural or human system was susceptible to climate change (IPCC 1996). Vorosmarty *et al.* (2000) evaluated global WRV as climate change and population growth from 1985 to 2025, and future global WRV estimated with general circulation models and the water balance model. According to the IPCC's definition of WRV, Hamouda *et al.* (2009) selected various factors related to the water resources system to evaluate WRV by a form of radar chart in the eastern part of the Nile River. Sullivan (2011) chose the associated factors of socio-economy, water environment and resources to compute the WRV index using the average weight method.

The IPCC's technical report indicated that strengthening the study of adaptive management strategies of climate change impacts on water resources would contribute to mitigating the impact on the global and regional scales, and further promote recognition of the linkages between WRV and AWM (IPCC 2007). Human interference with the climate system is occurring, and climate change poses risks for human and natural systems. Through adaptation and mitigation, the impacts and risks related to climate change can be reduced and managed (IPCC 2012). AWM study of water shortage began in the 1990s, and Aronson *et al.* (1992) found that adaptation for delaying phenological events to get more water was more obvious when crops were faced with water shortage. It would be better to meet water demand through using a simple input–output model to control the discrete time of water supply (Elbelkacemi *et al.* 2001). However, there was limited information about successful application of AWM, which was mainly caused by the lack of a reasonable assessment framework (Gregory *et al.* 2006). Gregory *et al.* (2006) proposed an adaptive assessment framework and pointed out that the corresponding adaptive strategies should take social, environmental and economic factors into consideration. Pahl-Wostl *et al.* (2005) reported that the main aim of AWM was to understand vulnerability factors from social ecosystem management. The concept of adaptive management strongly suggested that learning processes should become an integral part of any management regime and should be contained in the design of important adaptive polices (Pahl-Wostl 2008). And Lempert & Groves (2010) applied adaptive management as robust decision-making, which was a quantitative decision-analytic approach for supporting decisions with uncertainty conditions.

Over the next 20–50 years, how to respond to environmental changes and maintain sustainable development at regional or national scale is one of the major strategic issues for climate change impacts and water security. As a part of China's effort to alleviate constraints on sustainable socioeconomic development, the State Council promulgated 'The Opinions of Applying the Strictest Water Resources Control System' on 12 January 2012. Prior to this, the 'Three Red Lines' was established to facilitate appropriate management of water resources, and then the 'Construction of the Ecological Civilization' was proposed in 2011. A new concept and definition of WRV and AWM under changing environments was proposed in this study, namely: a renewal dynamic process, taking countermeasures of 'Monitoring – Evaluation – Control – Decision-making' to adverse effects on water resources caused by the changing environment including climate change and human activities. The aim is to put forward the study methods of WRV and adaptive regulation under a changing environment, including the developed function method, the solution of how to improve the utilization efficiency of water resources and the adaptive measures to deal with the impacts of climate change and maintain the security and suitability of water resources.

METHODOLOGY

Assessment of WRV

For a long time, conventional WRV (V) assessment has been mainly based on the average weight method and the radar chart display methods, such as $V = \Sigma W_i X_i$, where W_i is the weight, and X_i is the assessment factor. This method represented the simple formula including some factors, but the linkages with water resources and the impacts of climate change were ignored, and it was not regulated through direct indicators. According to the new research and development of the IPCC's 'Fifth Assessment Report' (IPCC-AR5 2014), WRV under a changing environment is defined as the degree of the adverse impact of climate change on water systems caused by human activities, which is characterized as a combination of disaster, exposure, sensitivity and compression capabilities to deal with disturbances, and is also a function of the adaptability of the water resources system (AWRS). This paper focuses on function system analysis of water resources programming and adaptive management linked to the probability of disasters, exposure, sensitivity, and compression resistance of the water system. WRV can be expressed as:

$$V = P(x_1, x_2, \ldots, x_m; y_1, y_2, \ldots, y_n)^{\beta_1} \times E(x_1, x_2, \ldots, x_m; y_1, y_2, \ldots, y_n)^{\beta_2} \times \left\{\frac{S(x_1, x_2, \ldots, x_m; y_1, y_2, \ldots, y_n)}{C(x_1, x_2, \ldots, x_m; y_1, y_2, \ldots, y_n)}\right\}^{\beta_3} \quad (1)$$

where x_i and y_j are the impact indicators of vulnerability and adaptive regulation variables; β_1, β_2 and β_3 represent corresponding scale factors of each index; $P(t)$ is the probability of a disaster event influencing the water system under climate change, and can also be the risk of droughts, floods and other factors; and $E(t)$, $S(t)$ and $C(t)$ are the exposure, sensitivity and AWRS respectively.

The rainfall-runoff method was usually used in sensitivity analysis, and had a low contact with the temperature under climate change (Fu *et al.* 2007; Gardner 2009). Therefore, it should take into account the elasticity of precipitation and temperature. Chen *et al.* (2014) proposed calculation methods and formulas in accordance with the sensitivity of the basic concepts and definitions:

$$\Delta Q = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial T}\Delta T \quad (2)$$

where ΔQ, ΔP and ΔT are the annual changes in stream flow, precipitation and temperature, respectively; and ∂Q, ∂P and ∂T are the average change in stream flow, precipitation and temperature, respectively. However, the reliability of prediction may be weakened if future climate condition is beyond the historical range that takes account of climate change aggravated by human activities, e.g., greenhouse gas emission and growing population (Gardner 2009).

$$S = 1 - \exp\left(-\frac{\Delta Q}{\Delta P}\right) \quad (3)$$

where S is the *sensitivity* of annual runoff in response to precipitation and temperature changes; this is an important characterization of vulnerability linking with the climate and geography.

AWRS is the reciprocal of water stress, and concerned with adaptation strategies as well as the integrated socio-economic capacity and scientific, technical and management levels to tackle water stress. According to the framework proposed by Falkenmark & Molden (2008), water scarcity exhibits two dimensions: demand-driven water stress (high usage compared to water use-to-availability) and population-driven water shortage (people dependent on the water use-to-availability). These are quantified by population-driven water shortage or 'water crowding' (p/Q: number of people per flow unit of $10^6\,\mathrm{m}^3$/y), water-use-driven mobilization level (r: use-to-availability as a percentage of water availability), and per capita water use (W_D/p: withdrawals in cubic meters per capita per year).

$$C(t) = f(r, P, Q, W_\mathrm{D}, \mu) \quad (4)$$

where f is the undetermined function, and μ represents the proportion of the river length of class V and the total river length. The water amount should reach a level in consideration of the use-to-availability and available water resources. A new formula is expressed as follows:

$$C(t) = C\left\{r, \frac{P}{Q_\mathrm{T}}, \frac{(Q_\mathrm{T} - W_\mathrm{E}) \times \mu}{P}\right\} = \exp\left(-r \cdot k + \frac{P}{Q_\mathrm{T}} \cdot \frac{(Q_\mathrm{T} - W_\mathrm{E}) \times \mu}{P}\right) \quad (5)$$

where p/Q_T and $(Q_\mathrm{T}–W_\mathrm{E})/p$ are population per one million water units and available water resources per capita, respectively; r is the water use-to-availability ratio (%); and k is a recoverability coefficient larger than zero. Utilizing the critical value of 40% water use ratio and 0.4 for adaptability, the value 2.3 is obtained for k (Xia *et al.* 2012).

Exposure is the degree of population, livelihoods, ecological services and resources, facilities or socio-economic, cultural and other assets in a vulnerable position. Floods and droughts, for China, are the key influence factors for WRV and water supply and demand under climate change. Therefore, the drought and socio-economic indicators are selected to quantify exposure:

$$E(t) = f(DI, EI) = DI \times EI \tag{6}$$

where DI is characterized by drought indicators, and also represented by surface humidity index calculated by the ratio of precipitation (P) and potential evapotranspiration (PET). PET can be calculated by using various temperature-based methods (Xia *et al.* 2014). EI is the socio-economic indicator integrating population and gross domestic product (GDP). When the hazards are drought events, P_h, GDP and A are the overall population, GDP and area of the region, respectively. Thus, the formula for calculating the exposure of the region can be expressed as:

$$E(t) = \left(1 - \exp\left(\frac{-P_\mathrm{h} \times GDP}{A}\right)\right) \times \overrightarrow{DI} \tag{7}$$

Disaster risk probability is the possibility of major changes in normal society caused by the interaction between natural disasters and social vulnerability. In the calculation of WRV, selecting the incidents' possibility of affecting water security is set as the measure indicator.

$$P_\mathrm{D} = P(X_\mathrm{i} \in F) = \frac{m}{n} \times 100\% \tag{8}$$

where P_D is the disaster risk probability; X_i is an event indicator at any time; F is essentially a cumulative function of drought occurrence; and m and n are the amount of drought occurrence and the study years, respectively.

Framework of adaptive regulation

The index system of AWM is a complex multi-level architecture, which can be divided into four categories: socio-economic indicators, water resources indicators, ecological indicators and comprehensive indicators. In the index system of vulnerability assessment, AWRS has become a crucial variable among several variables linked to water resources. For example, the linkages with the index system of regulation between 'Three Red Lines' of the Strictest Water Resources Management and Water Ecological Civilization Construction is shown in Figure 1.

AWM under climate change is based on a hydrological model and WRV assessment model in the benchmark year and future scenarios, and the framework of adaptive regulation is shown in Figure 2.

CASE STUDY

Study area and data

The area of the Huai River Basin (HRB) (30°55–36°36′N, 115°55′–121°25′E) is 270,000 km^2, and it is one of the seven largest river basins in China. It is located between the Yangtze River Basin and the Yellow River Basin (Figure 3) and flows through five provinces: Hubei, Henan, Anhui, Shandong and Jiangsu. HRB has a population of 165 million and the average population density is approximately five times greater than the national average level. However, water resources per capita and per unit area are less than one-fifth of the national average level. Annual mean precipitation and water resources of the basin are 888 mm and 83.5 billion m^3 respectively. In addition, 50–80% of annual precipitation is concentrated in the rainy season (June–September). Water resources are uneven in distribution and do not match with population and farmland in HRB. The utilization rate of water resources in the dryland of the northern HRB is higher than that in the wet area of the southern HRB, and it changes greatly for different years. The water use-to-availability ratio of the study area ranged from just the national average (18%) up to 80% from 2000 to 2012 and the percentage of the years which had higher use-to-availability ratios compared with the internationally regarded critical value (40%) was 69.2% (Figure 4). According to the historical records, 12 droughts have occurred in the entire basin from 1949 to 1998.

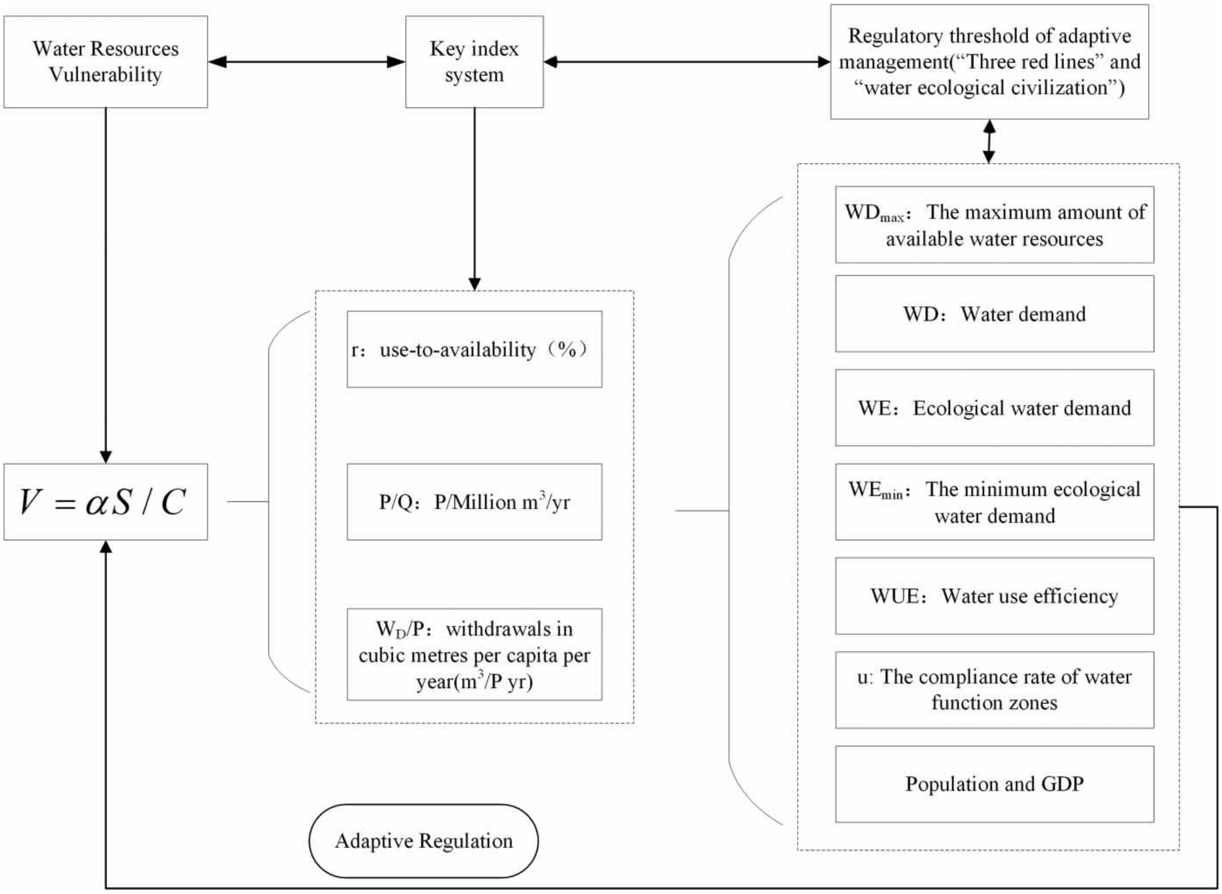

Figure 1 | The link between variables of adaptive regulation of water resources and vulnerability.

The third-class water resource regions (WRRs) include (1) the northern areas above Gate Wangjiaba (GW), (2) southern areas above the GW, (3) northern areas between the Gates Wangjiaba and Bengbu (GWB), (4) southern areas between the GWB, (5) northern areas between the Gate Bengbu and Hongze Lake, (6) southern areas between the Gate Bengbu and Hongze Lake, (7) Gaotian Zone, (8) Lixiahe Zone (LZ), (9) Eastern Lake Zone (ELZ), (10) Western Lake Zone (WLZ), (11) Canal Zone, (12) Yishu Zone, (13) Rigan Zone, (14) Xiaoqing River and (15) Shandong Rivers (SRs).

For flood control and water supply in the HRB, more than 5,700 reservoirs and 5,000 sluices have been constructed in the main streams and tributaries. This provides a useful engineering solution for flood control, irrigation, water supply, etc. Although the GDP of the southern part accounts for only 12.6% of the entire HRB, the amount of water resources accounts for 27.2%. The northern part of the HRB has less water resources, particularly in Shandong province, but it has higher GDP. These factors, including the interannual variability and spatial differences of precipitation, poor regulation and storage capacity of the surface water, etc., contribute to severe drought disaster and the poor utilization of water resources (Figure 5). Over the past ten years, water quality conditions have been improved in the HRB, but pollution accidents have still occurred frequently (Zhai *et al.* 2014). As the Water Resources Bulletin showed in 2012, water quality inferior to Grade IV occupied approximately 50% of the national monitoring stations in the HRB, which means they were severely polluted (MWR 2012).

Scenarios and alternatives

Three representative concentration pathway (RCP) scenarios, RCP2.6, RCP4.5, and RCP8.5, are chosen to

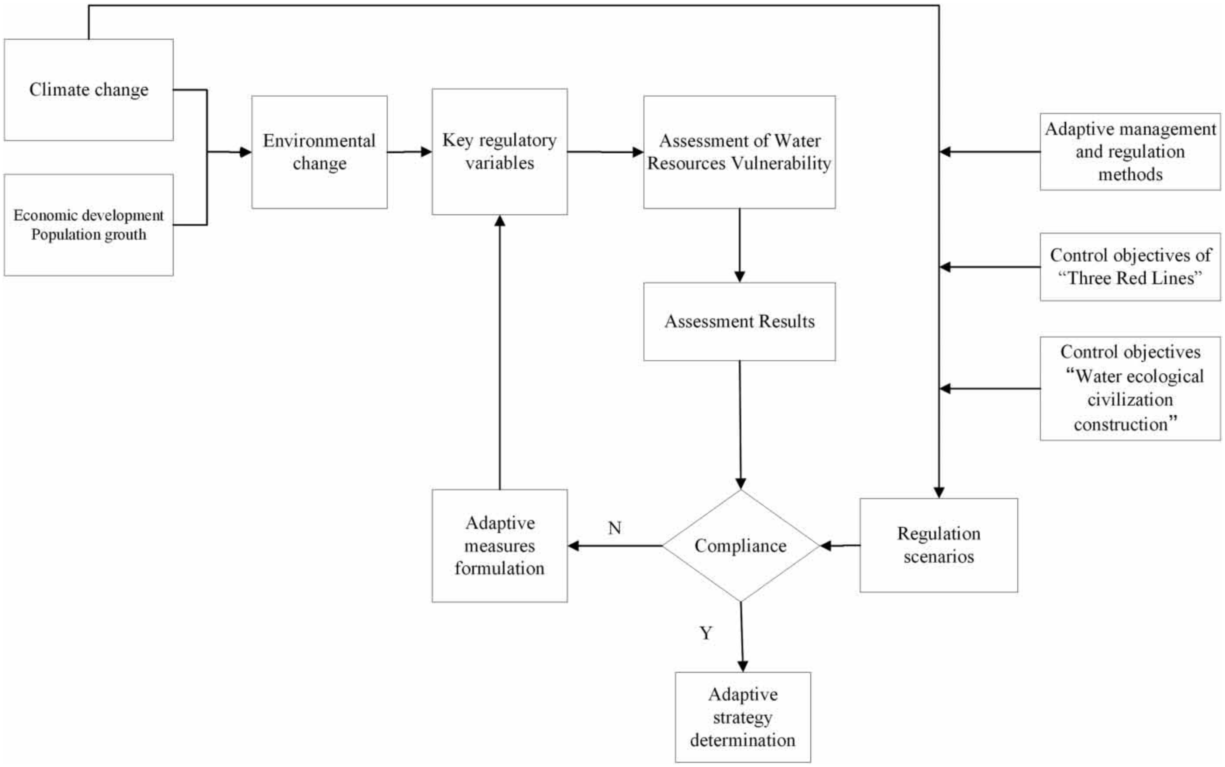

Figure 2 | Concept schematic diagram of adaptive regulation.

represent temperature and precipitation change in 2030, according to the IPCC's latest 'Fifth Assessment Report' (AR5) and multi-mode forecast results (IPCC 2014). The vulnerability is analyzed in 2000 as the base year. RCP4.5 is selected to conduct the analysis of the potential impacts on water resources, which is the closest to future emissions scenarios in 2030. The impact of climate change on water resources in the future is uncertain, so the 'low regret' principle is appropriate for the most unfavorable scenario analysis based on AWM, and it is also an effective way of risk analysis to address the uncertainty of climate change.

According to the 'Three Red Lines' with the strict management of water resources and Ecological Civilization Construction strategy for sustainable development, different adaptation measures of future scenarios are designed based on 'Huai River Basin Integrated Planning (years 2012–2030)'. The effects of different regulatory measures are analyzed for the adaptive regulatory pathways of WRV in the HRB. Five adaptive regulation scenarios are shown in Table 1.

RESULTS AND DISCUSSION

Results

The WRV of different adaptive regulations in 2000 and future scenarios is quantitatively calculated and analyzed for adaptive countermeasures and suggestions to deal with the impacts of climate change on water resources management. Under the benchmark year and the most unfavorable scenario, the socio-economic and water environment situations are evaluated, and WRV is calculated based on a function method coupling with sensitivity, AWRS, exposure and drought risk (Figure 6). The results show that the SRs and LZ are the regions with rapid socio-economic development in 2000, and water pollution is mainly concentrated in the WLZ and southern areas above the GW. The extremely fragile and strongly fragile regions accounted for 33% and 20% of the HRB, respectively (Figure 6(c)). Compared with the WRV distribution, the value of Xiaoqing River is the highest, and it is the focus of AWM

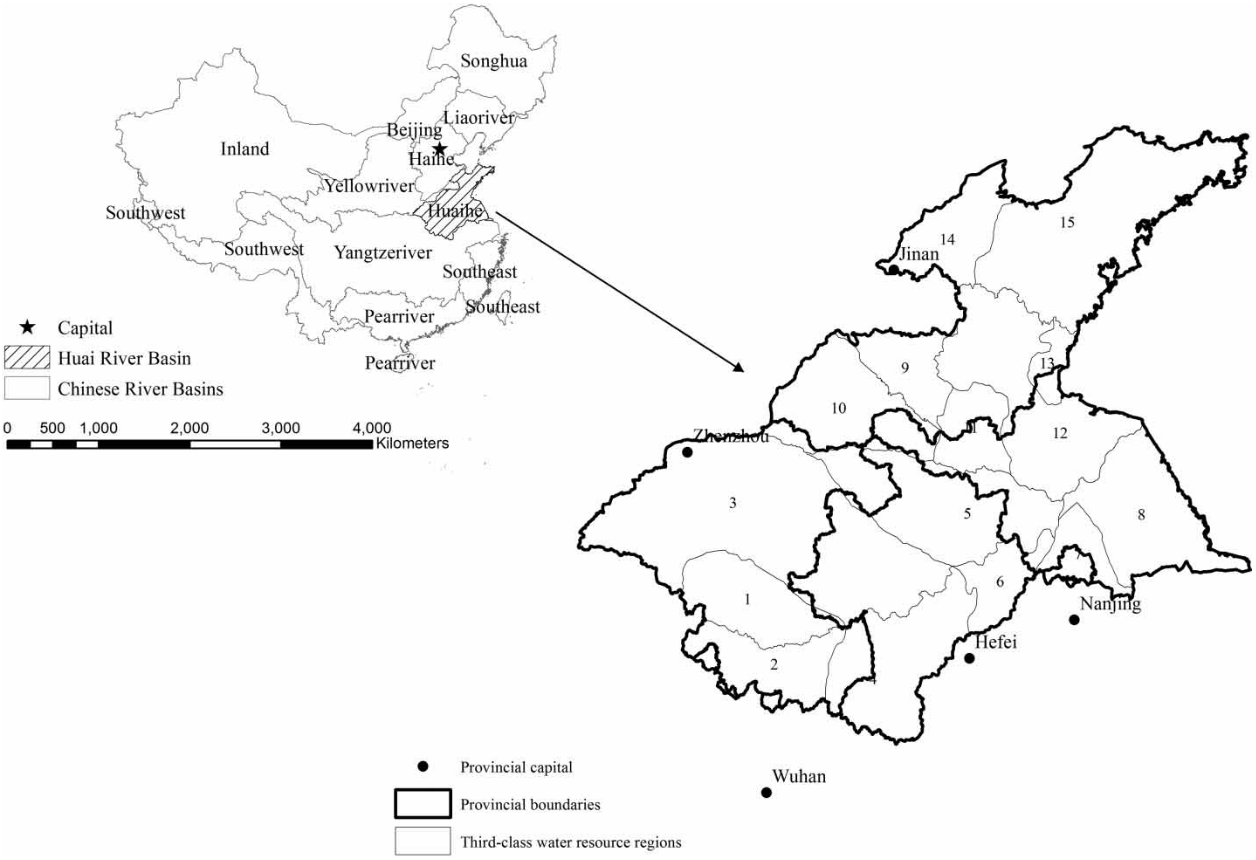

Figure 3 | Location and boundaries of third-class water resource regions (Class III WRRs) of the HRB in China.

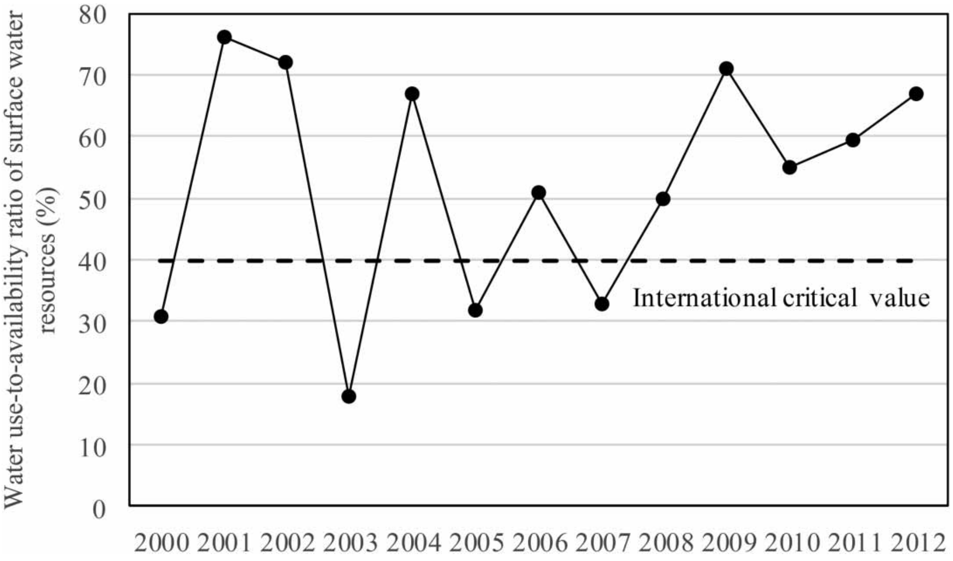

Figure 4 | Water use-to-availability ratios of surface water resources from 2000 to 2012.

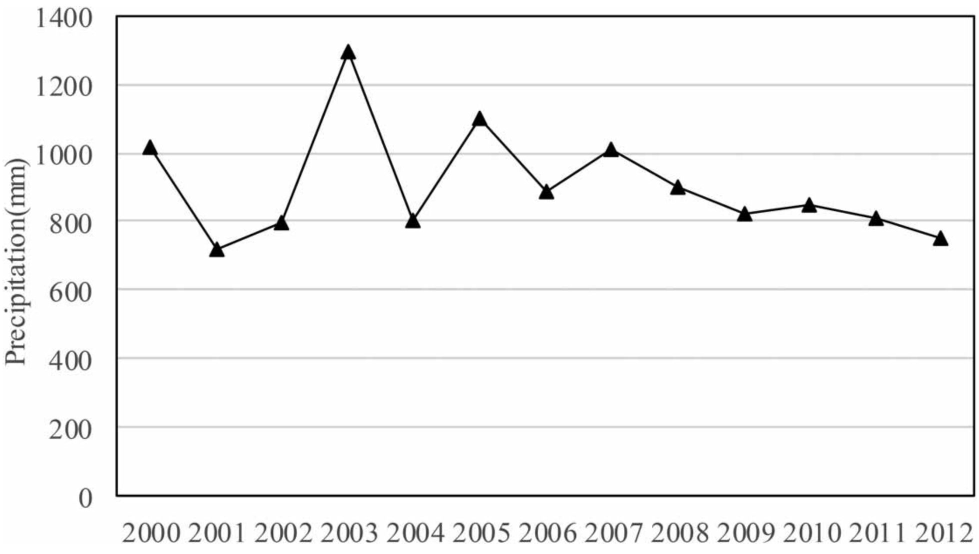

Figure 5 | Precipitation from 2000 to 2012.

Table 1 | Adaptive regulation scenarios in the benchmark year (2000) and future scenarios

	Regulatory variables			
Scenarios	**Water demand**	**Water use efficiency**	**Compliance rate of water function zone**	**The minimum water demand of ecosystem**
S1	√			
S2		√		
S3			√	
S4				√
S5	√	√	√	√

under a changing environment. Under the most unfavorable scenario, the highly fragile regions have significantly diffused, and almost the entire HRB is extremely fragile (Figure 6(e)). The contradiction between water supply and demand linked with floods and droughts, socio-economy and exposure is not only reflected in Xiaoqing River, ELZ, WLZ, Canal Zone and SRs, but also in other regions of HRB.

The results of adaptive regulation show the obvious decrease of WRV in 2000 and the most unfavorable scenario if taking 'Three Red Lines' of the Strictest Water Resources Management and ecological water demand protection regulation. In view of the objective of reducing vulnerability from all regions, the most sensitive single regulation is water function zones compliance followed by controlling of water use efficiency, water demand and the minimum water demand of the ecosystem. Integrated control is the best program of adaptive regulation among all scenarios (Figure 7).

As a result of rapid social and economic development, severe water shortages and environmental problems, the effects are more obvious after the implementation of 'Three Red Lines' in the strict management of water resources and ecological water demand control. As shown in Figure 7, the most sensitive single regulation is water function zones compliance, and then the vulnerability reduces to 27.6%. When the integrated control measures are implemented, the vulnerability reduces to 30.9% (Figure 7(a)). Under the most unfavorable scenario, the effects of adaptive regulation of WRV can be seen in Figure 7(b), the most sensitive single regulation is still water function zones compliance, and the vulnerability reduces to 33.8%. With the integrated control measures, the vulnerability reduces to 36.9% (Figure 7(b)).

Adaptive regulation strategies

Over the past few decades, climate change has caused adverse changes in the hydrological cycle of the HRB. Coupled with the impact of human activities, water problems may be more severe in the HRB. Faced with the potential impact of climate change, adaptive strategies must be taken to avoid disadvantages. According to the

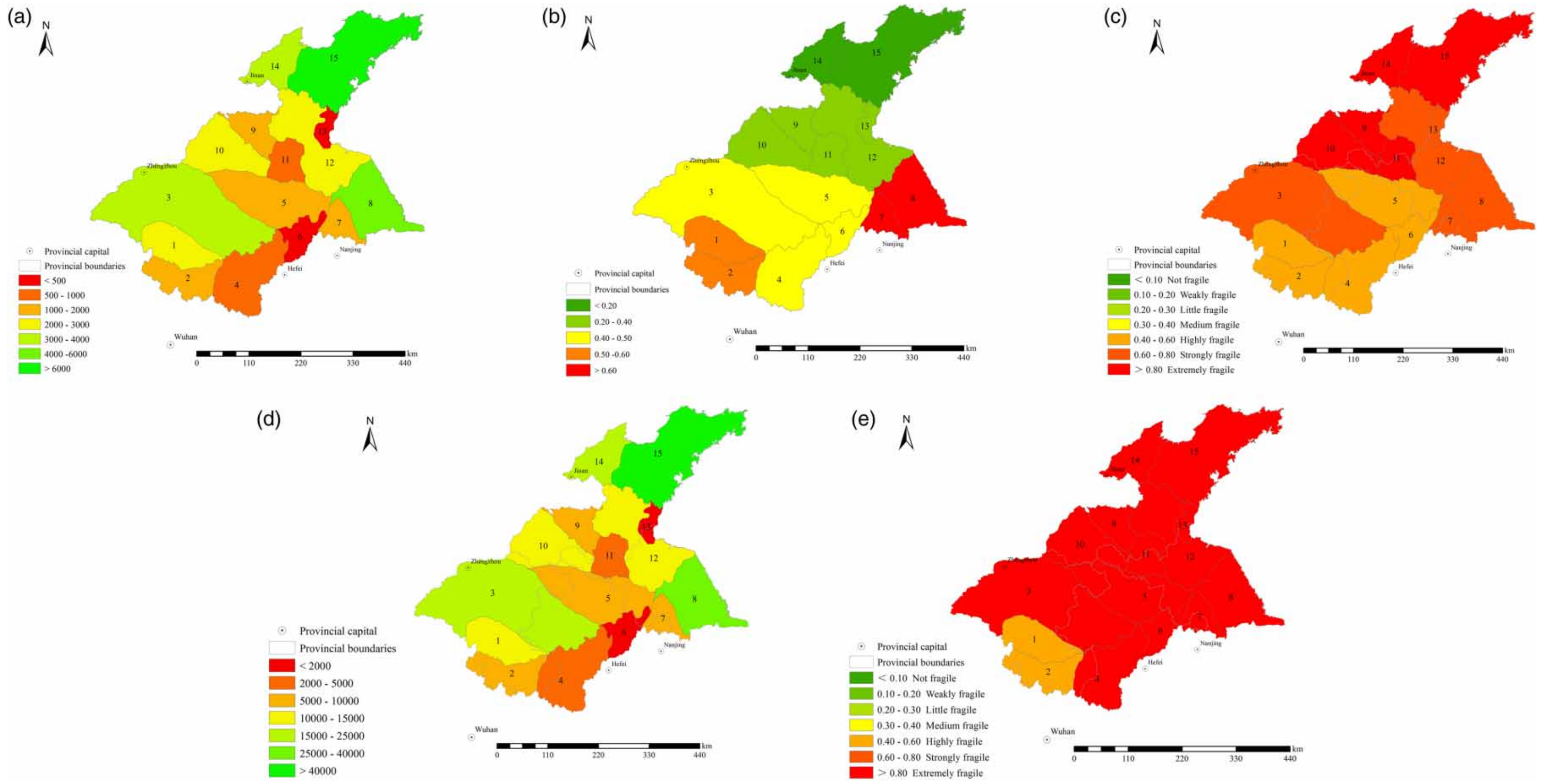

Figure 6 | Socio-economic and water environment and WRV for the Class III WRRs in benchmark year (2000) and the most unfavorable scenarios: (a) GDP per capita in 2000; (b) the class V proportion of the total river length; (c) WRV in 2000; (d) GDP per capita in the most unfavorable scenarios; (e) WRV in the most unfavorable scenarios.

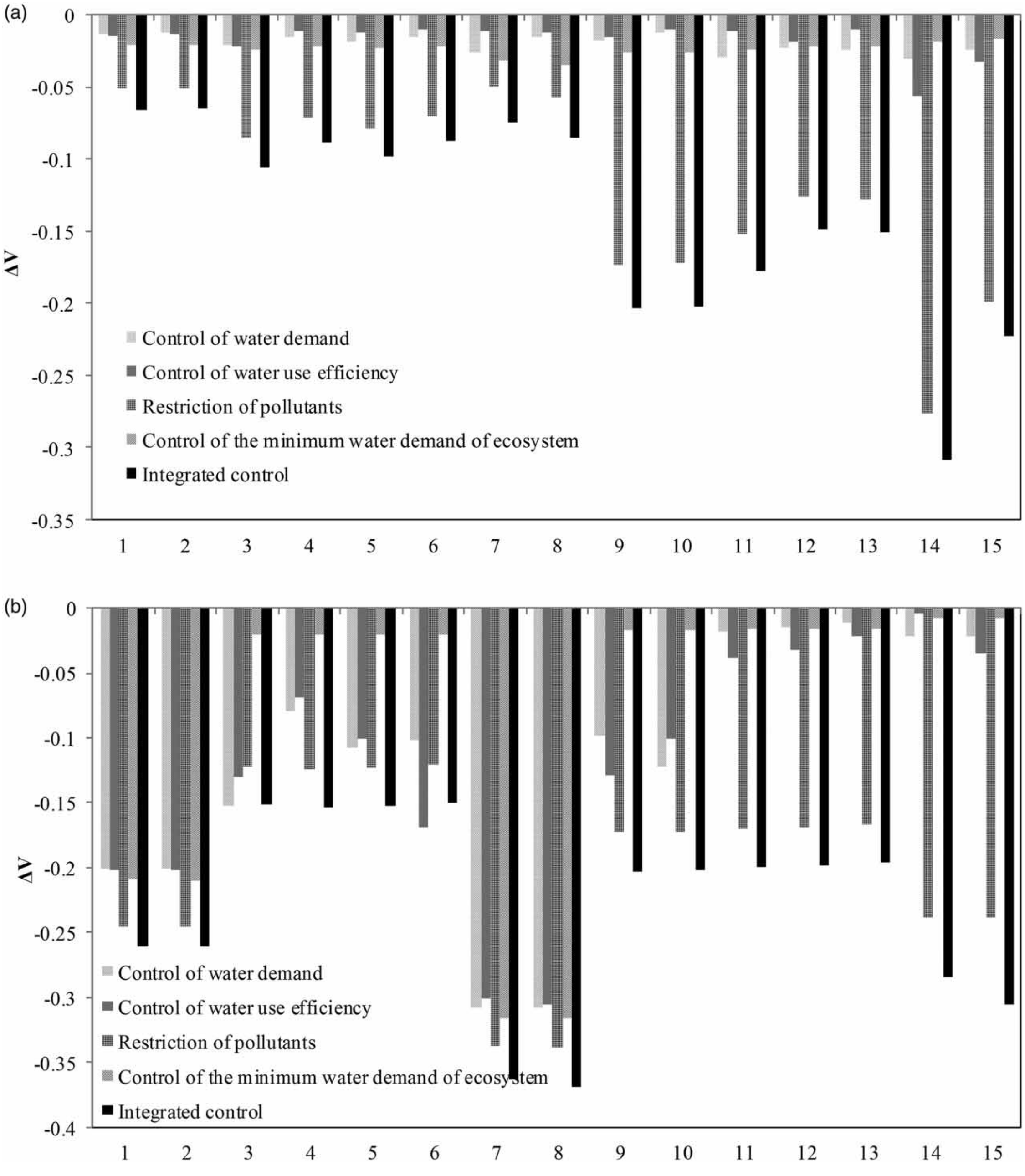

Figure 7 | WRV changes from the adaptive regulation in (a) benchmark year (2000) and (b) the most unfavorable scenarios.

analysis results of WRV and adaptive regulation, the adaptive strategies proposed are as follows:

(1) Based on the water quality standards of water function areas in HRB, implement limits of total pollutant emissions into the river. Restricted measures for the total amount of pollutant emissions include: concerning the severely polluted river and urging local governments to strengthen efforts to control water pollution, limiting the total amount of pollutant emissions from sewage outfall and enterprise, strengthening the measures of supervision and management of water resources protection, and implementing the inspection of important tributaries into the river outfall. Building new management systems,

implementing water management and supervising function areas and protecting drinking water sources will promote the protection and restoration of aquatic ecosystems and improve water environment conditions.

(2) As for large amounts of water consumption, we should focus on the construction of water-saving tanks. With tank-savings transformed at the same time, the work of safeguarding industrial and urban life work should be strengthened. To achieve zero emissions, advanced water-saving pollution control technology and equipment should be applied to new industrial projects, and speed up distribution network construction, actively promote water-saving appliances, and improve the industrial water recycling rate of cities. By 2030, the effective utilization coefficient of irrigation should increase to 0.61, and the construction of a water-saving society should be promoted through comprehensive water conservation, quota management, rationalizing water pricing and water-saving technological transformation.

(3) It will promote the sustainable use of water resources by the development and utilization of 'Red Line', strict planning and management, and water resources allocation. By 2030, the total amount of water use should be controlled within 64.16 billion cubic meters.

CONCLUSION

In the context of global warming, the runoff decrease of HRB, growth of population, development of industry and agriculture and the effects of climate change, and the contradiction between water supply and demand will further exacerbate the water crisis. Adaptive regulation and vulnerability of water resources is an important method to evaluate water systems affected by climate change and human activities, and promote awareness of water issues and raise an important basis for adaptive responses. In accordance with the research and development of the IPCC's technical report, a new definition and concept of WRV and adaptive management are proposed under climate change.

This paper establishes an assessment model of WRV coupling with exposure, droughts risk, sensitivity, and adaptability of water resources systems under climate change. Under the benchmark year and the most unfavorable scenarios, WRV is evaluated by the model. The results show that severe water pollution is mainly concentrated in WLZ and southern areas between the GWB in 2000. In addition, Xiaoqing River is the most fragile region among all third-class regions, and 33% of the HRB is an extremely vulnerable region. Almost the entire study area would be extremely fragile when the most unfavorable scenarios occur. According to 'Three Red Lines' with the strict management of water resources and Ecological Civilization Construction strategy for sustainable development, five regulatory scenarios including the integrated control, control of water function zones compliance, water use efficiency, water demand and minimum water demand of the ecosystem are designed for analyzing WRV and adaptive management. Among adaptive regulations in all scenarios, the most sensitive scenario is the integrated control, followed by the control of water function zones compliance, water use efficiency, and the minimum water demand of the ecosystem.

Overall, research into AWM in changing environments is still in the primary stage in China, and especially, how to implement adaptive management of WRV is a new and difficult water science issue. The assessment system of WRV and adaptive management considering the effect of climate change and human activities based on nonlinear theory and method provides a scientific basis for these issues of planning, allocating and regulating of water resources.

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