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Special Section:
Quantifying human interferences in hydrologic process modeling

Key Points:
- Beijing's groundwater vulnerability to external economic and climate change is assessed using a coupled sociohydro-economic model
- Rapid external economic development or larger precipitation might unintendedly lead to more severe groundwater depletion in the long run
- Strengthening policymakers' views of groundwater depletion is the key to enhancing the sustainability of the coupled human-water system

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:
Y. Zheng,
zhengy@sustech.edu.cn

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Groundwater Vulnerability in a Megacity Under Climate and Economic Changes: A Coupled Sociohydrological Analysis

Bin Li[1,2], Yi Zheng[2], Giuliano Di Baldassarre[3,4], Peng Xu[2], Saket Pande[5], and Murugesu Sivapalan[6,7]

[1]Pearl River Water Resources Research Institute, Guangzhou, China, [2]Southern University of Science and Technology, Shenzhen, China, [3]Centre of Natural Hazards and Disaster Science (CNDS), Uppsala University, Uppsala, Sweden, [4]Department of Earth Sciences, Uppsala University, Uppsala, Sweden, [5]Department of Water Management, Delft University of Technology, Delft, The Netherlands, [6]Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA, [7]Department of Geography and Geographic Information Science, University of Illinois at Urbana-Champaign, Urbana, IL, USA

Abstract Groundwater depletion has become increasingly challenging, and many cities worldwide have adopted drastic policies to relieve water stress due to socioeconomic growth. Located on the declining aquifer of the North China Plain, Beijing, for example, has developed plans to limit the size of the city's population. However, the effect of population displacement under uncertain macroeconomic and climate change remains ambiguous. We adopt a sociohydrological model, with explicit consideration of the dynamics of human-water interactions, to explore the groundwater vulnerability of Beijing. We investigate how human response might shape the development trajectories of the groundwater-population-economy system under different macroscale economic and climate scenarios. Furthermore, we use a machine learning algorithm to identify the decisive factors to be considered for reducing groundwater vulnerability. Our results show that while rapid external economic development or larger annual average precipitation would enable recovery of the groundwater table in the short term, they may slacken human water shortage awareness and result in more acute groundwater depletion in the long run. Strengthening policymaker perceptions of groundwater depletion would prompt timely response policies for controlling population size. Improving the quantity and quality of labor force input to economic development would avoid downturns in the economy due to labor shortages. The outcomes of this study suggest that these strategies would effectively reduce groundwater vulnerability in the long run without causing severe socioeconomic recession. These findings highlight the importance of endogenizing human behavioral dynamics in sustainable urban water management.

1. Introduction

Widespread urban water scarcity acts as a constraint to achieving the sustainable development goals (SDGs; Clark & Wu, 2016; Dolan et al., 2021). A recent study (He et al., 2021) estimated that in 2016, 933 million urban residents worldwide were exposed to water scarcity and projected that this number is likely to grow to 2.065 billion by 2050. The study also suggested that the number of megacities experiencing water scarcity will increase from 9 to 19. Large-scale migration toward cities has become a major source of pressure on urban water supply systems. By 2050, it is projected that 68% of the world's human population would be living in urban areas, a 23.6% increase from 2018 (United Nations, 2019). One of the major drivers that attracts people to move to urban centers is the economic gap between rural areas and urban areas, as the advanced urban economy is often associated with higher living standards, better social welfare, and more employment opportunities (Liu & Li, 2017; Marotzke et al., 2020; Roobavannan et al., 2017; Storper & Scott, 2008; K. H. Zhang & Song, 2003). The gravity of the worsening urban water crisis would, in turn, reshape the development pathways of demographic and economic systems via social adaptations (Aeschbach-Hertig & Gleeson, 2012; Evans et al., 2018; Hari et al., 2021; Jain et al., 2021; Quesnel & Ajami, 2017). This suggests that population size, economy, and hydrology in urban areas are tightly coupled. Addressing water scarcity challenges needs an in-depth understanding of the reciprocal interactions between these systems.

One of the common strategies in response to water scarcity is the overexploitation of groundwater, which causes persistent groundwater depletion in many parts of the world (Döll et al., 2014; Wada et al., 2010). Jasechko and Perrone (2021) analyzed a data set of approximately 39 million groundwater wells distributed worldwide and discovered that up to 20% of the wells are no more than 5 m deeper than the position of the water table. This means that millions of wells are at risk of running dry if water tables further decline by only a few meters. Anthropogenic factors, including expansion of irrigated agriculture, growth of urban demand, ineffective groundwater pricing policies, and changes in lifestyles (e.g., diet), are major drivers of groundwater depletion in many parts of the world (Bierkens et al., 2019, 2021; Gober & Kirkwood, 2010; Gohar et al., 2019; Noori et al., 2021; Ramos et al., 2020; Rodell et al., 2018; Scanlon et al., 2012). The increasing drawdown of groundwater tables may lead to serious hydrogeological and social consequences such as land subsidence and social inequities (Famiglietti & Ferguson, 2021; Noori et al., 2021). Therefore, it is important to investigate groundwater vulnerability in the upcoming Anthropocene (Savenije et al., 2014).

Beijing, China's capital city, is one of the megacities that suffers from water scarcity (J. Wang et al., 2015). Advanced economic development has attracted many people to migrate to the city, and the population size has doubled over the past 30 years. To meet the increasing human water demand, large volumes of groundwater are extracted annually. This caused the groundwater table to decline by approximately 15 m during 1990–2020 (Bierkens et al., 2021; Hyndman et al., 2017). In response to the severe water scarcity, about 1 km^3 of water has been transferred annually to Beijing as part of the South-North Water Diversion Project (SNWDP) since December 2014 (Long et al., 2020). Furthermore, to relieve the pressure of rapid population growth, the government has also developed plans to limit the city's population size. To this end, some labor-intensive industries in Beijing are being transferred to neighboring provinces (T. Li et al., 2019). Since 2017, after four decades of continuous growth, the population size in Beijing has begun to shrink, which represents an important tipping point for the coupled human-water system of the city.

The control of population size in Beijing to mitigate stresses of resource limitation, with water scarcity being a crucial factor, signifies distinct two-way feedbacks between water resources and human society. Numerous models have been built to investigate the dynamics of various coupled human-water systems. Di Baldassarre et al. (2013) formalized the dynamic responses of communities in flood-prone areas to flood events using a set of coupled differential equations. Elshafei et al. (2014) developed a prototype framework for modeling the feedbacks between irrigation activities and hydrologic changes, which has been widely utilized in the sociohydrology literature. Srinivasan (2015) explored the response behaviors of citizens in Chennai city to intermittent water supply conditions. M. Feng et al. (2016) employed six coupled nonlinear ordinary differential equations to investigate the interactive relationships among water supply, power generation, and environment systems in the Hehuang Region, China. More recently, Savelli et al. (2023) simulated the unequal water consumption behaviors of different income groups in Cape Town, South Africa, and discovered that the unsustainable water consumption of the elite exacerbated the water shortage crisis in the city. These studies indicate significant progress in the field of sociohydrology over the past decade.

Despite progress in these efforts, the phenomenon of hydrology-impacted demographical dynamics has rarely been explored. This phenomenon has been observed in many places worldwide, from the ancient Maya civilization (Evans et al., 2018; Kuil et al., 2016) to some modern cities (Black et al., 2011; Marotzke et al., 2020), especially in developing countries (Hari et al., 2021). On the other hand, the shrinkage of population size might have a negative effect on economic growth due to labor shortages. However, most studies attempting to evaluate urban water scarcity have disregarded the dynamic responses of the population and economy to hydrologic change. For example, Gohari et al. (2013) explored the effects of interbasin water diversion projects on alleviating water shortages in the Zayandeh-Rud River Basin under different scenarios of population growth toward 2040. Qin et al. (2018) designed alternative growth scenarios of population and GDP for Beijing city and predicted water demand under these scenarios throughout 2030 using a system dynamic model. Recently, with the availability of shared socioeconomic pathways (SSPs), many studies have employed scenarios from SSPs to evaluate water security challenges, and the study period has been extended to 2100. For example, Yoon et al. (2021) analyzed the water security of Jordan throughout the 21st century by using the population growth scenarios from SSPs as input to the Jordan Water Model. In these studies, regardless of how severe future water conditions are projected to be, population and economic dynamics are assumed to be uninfluenced. This is inconsistent with observations in many cities worldwide, including Beijing.

In previous work, B. Li et al. (2019) built an urban sociohydrological model for Beijing city. Population size is an endogenous variable in the model, the dynamics of which are influenced by the drawdown of the groundwater table. B. Li and Sivapalan (2020) further explored the critical roles of human adaptive actions in the coevolution of groundwater and population. However, there remains a lack of understanding of the system dynamics under future environmental change and possible pathways that need to be invoked to adapt to the changing environment. External economic development (i.e., the economy of other areas of China) and climate change are two important aspects of changing environment that would challenge water management in Beijing city (Gu et al., 2006; W. Yang et al., 2016). On the one hand, China is trying to achieve the *Common Prosperity* goal, which is aimed at narrowing the gap between high-income groups and low-income groups. SDG 10, *reduce inequality within and among countries*, also proposes to achieve and sustain above-average wealth growth for low-income populations. Driven by these goals, the economic gap between Beijing and other provinces of China may be narrowed in the future, which would further influence population migration and the consequent increase in water demand. On the other hand, the groundwater in Beijing is also vulnerable to uncertain climate change. For example, a decade-long drought event during 1999–2009 contributed to the excessive drawdown of the groundwater table in Beijing (J. Wang et al., 2015). Groundwater vulnerability to these changing drivers has rarely been explored from the viewpoint of coupled human-water systems (Hall, 2019).

This study is aimed at identifying the sensitivity of the human-water system coevolution to future uncertain external economic and climate changes and at exploring implications for reducing groundwater vulnerability while maintaining socioeconomic conditions within a safe state. Hereafter, we use the phrase "environmental change" to refer to both external economic (i.e., social environment) change and climate (i.e., natural environment) change for the sake of language simplicity. We extend the previous urban sociohydrological model (B. Li et al., 2019) by linking it with a neoclassical economic model and thus make the economy an endogenous component as well. The main contributions of this work are therefore threefold. First, we present an updated urban sociohydrological model that considers the endogenous dynamics of both population size and the economy. This is an advancement from most of the previous studies that use exogenously specified demographic and economic scenarios as model inputs and therefore is more suitable for understanding the coevolution mechanisms of population, economy, and hydrology (Sivapalan et al., 2012; Thompson et al., 2013). Second, we systematically examine the roles that some key human management actions may play in the coevolution of the coupled system. This would enable us to understand how population, economy, and hydrology might respond to alternative management actions. Third, we explore the effects of plausible future environmental change scenarios on each component of the coupled system and identify key factors that need to be strengthened to reduce groundwater vulnerability.

The remainder of the paper is organized as follows: In Section 2, we describe the methodology that we use to conduct the analyses, including a brief introduction to Beijing city, the model framework, the generation of future environmental change scenarios, and the numerical experiments that are employed. Section 3 presents the details of model outcomes, including the roles of key management actions in the coevolution of system components, the effects of alternative environmental change scenarios, and the classification of model outcomes subject to combinations of key management actions. Section 4 presents a discussion of the results in the context of process understanding and the implications for real-world water management. Section 5 concludes with the lessons learned from the study and opportunities for extensions of this work.

2. Methodology

2.1. Study Area

Beijing lies in the northern North China Plain, with a total area of 16,410 km^2 (Figure 1). For a long time, there has been an increasing mismatch between water demand and water availability in the city (J. Wang et al., 2015). As China's capital city, Beijing has witnessed rapid economic and population growth. By 2020, the GDP per capita of Beijing had grown to be 2.3 times larger than that of China as a whole. Many people are attracted to moving to the city from other parts of China, and the population size doubled from 10.86 million in 1990 to 21.89 million in 2020. This has significantly raised human water demand. However, the long-term average annual precipitation in Beijing is only 585 mm/year, which makes it challenging to generate enough water resources to meet the human demand. For example, in 2020, the renewable water availability in Beijing was just 110 m^3 per capita, far below the absolute scarcity criterion (i.e., 500 m^3/capita/year) of the Falkenmark indicator (Falkenmark et al., 1989). Consequently, overexploitation of groundwater has become a major strategy for securing the water supply (W. Feng et al., 2013), which has caused the groundwater level in the city to drop from approximately 10 m below the land surface to more than 25 m from 1990 to 2015. The scarce water supply has been exacerbated by frequent drought events and has further contributed to groundwater exploitation and drawdown (X. Zhang et al., 2022).

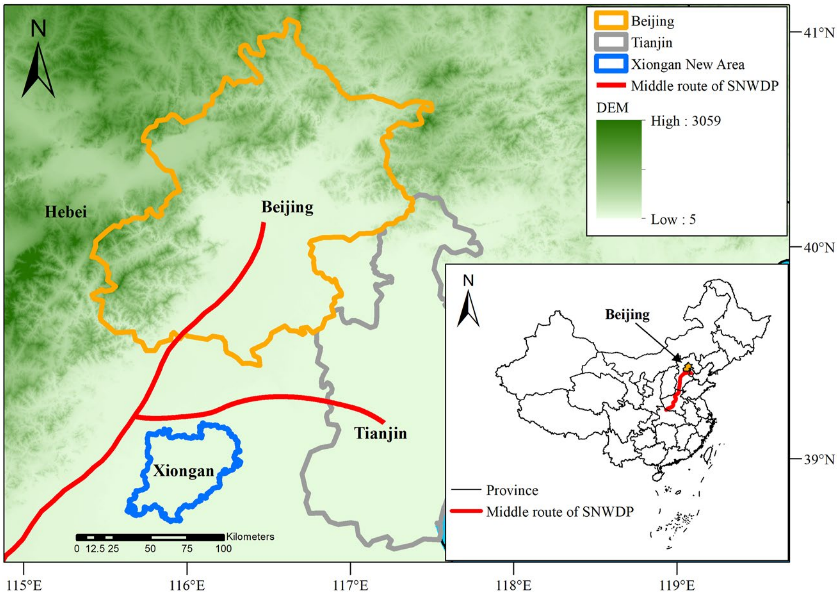

Figure 1. Location of Beijing city. SNWDP: South-North Water Diversion Project.

In response to severe groundwater depletion, a series of countermeasures have been adopted by the city. On the demand side, the water supply to a large area of agricultural land has been cut off over the past decades, and some water-intensive industries have been moved out of the city (Hyndman et al., 2017). These measures reduced the total volume of water consumed by the agriculture and manufacturing sectors from 3.41 to 0.7 km^3/year during 1990–2020. On the supply side, the additional water brought in by the SNWDP has become a significant source of water for the city's water supply system (Long et al., 2020).

Furthermore, recognizing the worsening resource demand-availability imbalance, particularly water shortages, driven by rapid population growth, the government has proposed controlling the population size in Beijing city. Beijing's Urban Master Plan (2004–2020) issued in 2005 proposed limiting the total population size in the city to 18 million by 2020. However, the city failed to achieve this target, and the population size reached 20 million in 2010. In 2017, the government issued a new version of Beijing's Urban Master Plan (2016–2035), which was aimed at moving a fraction of the city's people to other areas by transferring Beijing's noncapital functions (T. Li et al., 2019). In furtherance of this plan, a new economic zone named the Xiongan New Area is now being built approximately 100 km south of Beijing (Lin, 2020). Some labor-intensive industries are moving out of the city, with the expectation that the employees in these industries will also choose to leave the city. In addition, some hospitals, universities, and shopping centers are slated to be moved to the Xiongan New Area (Figure 1) to reduce the attractiveness of Beijing. These measures have begun to show the desired effect: the population size in Beijing has marginally dropped from 21.96 million in 2016 to 21.89 million in 2020. These extensive human adaptations to groundwater depletion make Beijing a great case study to examine groundwater vulnerability from a sociohydrological perspective.

2.2. Model Framework

The urban sociohydrological model developed by B. Li et al. (2019) frames Beijing's water shortage crisis as an outcome of the coevolution of human society and the water supply system. The model links the dynamics of six state variables using a coupled system of nonlinear, ordinary differential equations. These variables include the storage in the water supply reservoirs, groundwater table depth below the land surface, policymaker sensitivity to the variation in groundwater table depth, population size, domestic water use, and productive water use. In the present work, as we aim to explore groundwater vulnerability under uncertain external economic development, we incorporate a Cobb-Douglas type model into the sociohydrological model framework and thus make GDP an endogenous variable. In addition, we adapt the model equations for population and policymaker sensitivity to accommodate the Cobb-Douglas model and to better replicate the shrinkage of population size in Beijing since

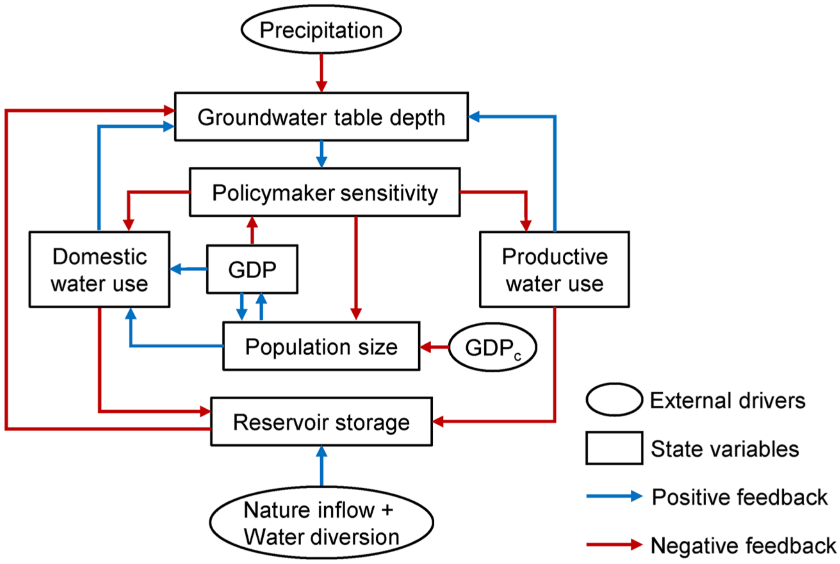

Figure 2. Feedback relationships between the state variables and the external drivers in the sociohydrological model that mimics the coevolution of Beijing's human-water system.

2017. The feedback relationships among the model variables are shown in Figure 2. The extensions of the model are explained below, and the other components that remain the same as those in B. Li et al. (2019) are summarized in Supporting Information S1.

In the model, we assume that the uneven economic development between Beijing and the rest of China is the main driving force that attracts people to migrate to Beijing and thus contributes to its population growth (Gu et al., 2006). While the external economy is an input to the model, the economic conditions of Beijing, which are indicated by its GDP, comprise an endogenous variable in this study. This variable is simulated by a Cobb-Douglas type model (Huang et al., 2019; Leimbach et al., 2017):

$$\mathrm{GDP}(t) = \mathrm{TFP}(t) K(t)^{\rho} L(t)^{1-\rho} \quad (1)$$

$$\mathrm{TFP}(t) = \mathrm{TFP}_0 e^{\varepsilon t} \quad (2)$$

$$L(t) = N \cdot l \cdot h = N \cdot \mathrm{lpe} \quad (3)$$

where TFP is total factor productivity; K is capital stock, which is calculated using the recursive equation from Leimbach et al. (2017); L is labor input; ρ is output elasticity on capital; ε is the rate of growth of TFP; N is population size; l is the proportion of the labor force in the total population; and h is a scaling factor reflecting the effect of education on the quality of the labor force. In this study, lpe, as the product of l and h, represents the labor force participation in economic development.

Following the work of Leimbach et al. (2017), while the values of parameters ε and lpe for simulating historical GDP are obtained by calibration against observation data, they are assumed to be time-varying when projecting to the future economy. This is because there is an expectation that the high development pace of the economy during the decades after World War II cannot be maintained in the long term (Leimbach et al., 2017). Specifically, a long-term rate of TFP growth is assumed to be $\varepsilon_f = 0.7\%$, and the value of ε eventually converges to this long-term value by a transition rate $\zeta = 0.1$:

$$\varepsilon(t) = \varepsilon_f + (\varepsilon_0 - \varepsilon_f) e^{-\zeta t} \quad (4)$$

Additionally, we assume that lpe converges from the initial value (i.e., the value used to model historical GDP) to a final value (i.e., labor force participation at the end of the simulation period) following a linear trend. The labor force participation in the economy in the following analyses is denoted by the final value of lpe. Additionally, GDP in this study is adjusted to the 2015 constant price using a unit of Chinese Yuan (CNY), excluding the effects of price inflation to indicate real economic growth (Huang et al., 2019).

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Population size is closely related to the volume of water demand in the city and therefore is also modeled as a state variable. The evolution of population size is assumed to be driven mainly by a pull force, that is, the economic gap between Beijing and the rest of China, and a push force, that is, policymaker sensitivity to the variation in the groundwater table, modeled as follows (Garcia et al., 2016):

$$\frac{dN}{dt} = N_n + N_m \tag{5}$$

$$N_n = N\psi_n \tag{6}$$

$$N_m = N_{imax}\left(\frac{\mu \cdot \Delta GDP}{1 + \mu \cdot \Delta GDP}\right) - Nr\left(\frac{\alpha \cdot \omega}{1 + \alpha \cdot \omega}\right) \tag{7}$$

$$\Delta GDP = GDP_b - GDP_c \tag{8}$$

where N is population size; N_n is the natural growth of population; N_m is net migration of population; ψ_n is the rate of natural growth; N_{imax} is the maximum annual immigrant population size; μ is an attractiveness parameter, indicating the driving effects of economic gap on population migration; ΔGDP is the difference between the GDP per capita of Beijing (i.e., GDP_b) and the GDP per capita of other provinces of China (i.e., GDP_c); r is the maximum proportion of annual population out-migration; ω is the overall impetus of government response to the drawdown of the groundwater table; and α is a translation parameter indicating the effectiveness of population displacement measures.

The policies to transfer a fraction of people to other provinces are prompted by the increasing realization of the inadequacy of natural resources. In this study, we use the variation in the groundwater table to indicate the change in water resources. There is a gradual shift in water management actions in response to the evolution of water conditions in Beijing city. This includes the restructuring of water management agencies (Fan et al., 2015), the strengthening of water regulation policies and laws (Fu et al., 2018), and the evolution of water issues framed in the news media (Xiong et al., 2016). These changes indicate that the strategies that policymakers adopt to respond to the water crisis are dynamic. According to the work of Elshafei et al. (2014), policymaker sensitivity to changes in water conditions can serve as a precursor to observable management actions. Therefore, in this study, we model policymaker sensitivity to the variation in the groundwater table as a slowly changing state variable (Elshafei et al., 2014):

$$\frac{dV}{dt} = \gamma_v\left(\lambda_G\widetilde{G} - \widetilde{E_{pc}}\right)V \tag{9}$$

$$V^* = \frac{\frac{dV}{dt}}{\max(V_{max} - V_{t5}, 0.01)} \tag{10}$$

$$f(V^*) = \begin{cases} \frac{V^*}{1+V^*}c, & V^* \geq V_{crit} \\ 0, & V^* < V_{crit} \end{cases} \tag{11}$$

$$\omega = f(V^*)_{t10} \tag{12}$$

where V represents policymaker sensitivity to the variation in the groundwater table; γ_v is a parameter that reflects potential effects of the macroscale context (e.g., climate, socioeconomy, and politics); λ_G is policymaker perceptions of groundwater depletion; $\widetilde{E_{pc}}$ is the relative change in the GDP per capita over the past 10 years, reflecting the effects of the level of wealth on policymaker sensitivity; and $\tilde{G}$ is the relative change in the groundwater table over the past 20 years. These time windows reflect the fact that the change in policymaker sensitivity is not instantaneous but is influenced by a period of memory. As the groundwater condition has changed relatively slower than the economic development in the study area, we choose a relatively longer time window for $\tilde{G}$ following the work of Elshafei et al. (2015). V^* is a normalization of policymaker sensitivity; V_{max} is the maximum sensitivity; V_{t5} reflects a period of memory, which is a 5-year moving average of policymaker sensitivity because Chinese government issues a 5-year plan every 5 years for the social and economic development for the whole country and for all provinces; $f(V^*)$ is the translation from policymaker sensitivity to response actions; c reflects the capability

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of policymaker response, indicated by the ratio of the GDP per capita of Beijing and the GDP per capita of China; V_{crit} is a critical value of policymaker sensitivity, only above which would the sensitivity be translated into a response; ω is a 10-year moving average of $f(V^*)$ to account for a time window for a policy to take effect on the socioeconomic development both gradually and in a long-lasting way (Elshafei et al., 2015).

Model equations with regard to other variables and their feedback relationships are described in Text S1 in Supporting Information S1. The ability of the model to reproduce historical development trajectories of the state variables is tested by using observation data from 1988 to 2020, the procedure of which is detailed in Text S2 in Supporting Information S1.

2.3. External Economy and Climate Scenarios

After confirming that the model is capable of capturing the plausible feedbacks between the socioeconomy and water systems of Beijing city, we use it as an analytical tool to assess groundwater vulnerability under alternative environmental change scenarios from 2020 to 2099. The methods to generate the scenarios are detailed as follows: five alternative future external economic development trajectories are generated using an exponential function:

$$\mathrm{GDP_c} = \mathrm{GDP_{c0}} e^{gt} \tag{13}$$

where $\mathrm{GDP_c}$ is the GDP per capita of other provinces of China and g is its rate of growth.

The value of parameter g during the historical period is obtained by calibration against the observation data, whereas for generating future scenarios, it is assumed to eventually converge to a long-term value in the same way as Leimbach et al. (2017) projected future economy:

$$g(t) = g_{\mathrm{f}} + \left(g_0 - g_{\mathrm{f}}\right) e^{-\zeta_g t} \tag{14}$$

where g_0 is the initial rate of growth obtained by calibration; g_{f} is the long-term value of g; and ζ_g is the transition rate, fixed as 0.08 in this study. Five discrete values of g_{f} are set in the range between 0.032 and 0.040, representing the gradient of external economic development (Figure S2 in Supporting Information S1; Roobavannan et al., 2020). The medium development rate, where $g_{\mathrm{f}} = 0.036$, serves as a baseline scenario.

To uncover the driving effects of alternative climate scenarios on groundwater vulnerability, we generate future precipitation scenarios using a first-order autoregressive model (Garcia et al., 2016):

$$P(t) = xP(P(t-1) - mP) + sP\left(1 - xP^2\right)^{0.5} r + mP \tag{15}$$

where P is precipitation; xP is the first-order lag coefficient; mP is average precipitation; sP is the standard deviation of precipitation; and r is a normally distributed random variable with a mean value of 0 and a standard deviation of 1.

We set five discrete values for mP, with a range between 430 mm/year and 646 mm/year (i.e., between 80% and 120% of mean annual precipitation during the historical period), representing the climate gradient (Liao et al., 2021). Scenario $mP = 538$ serves as a baseline scenario. In each scenario, 50 precipitation time series are randomly generated, in consideration of the uncertainty of the time sequence of precipitation (Viglione et al., 2014). All of the results in this study are presented as the median value of the 50 precipitation time series in each climate scenario.

2.4. Analysis Approach

To reveal the effects of environmental change scenarios on human-water coevolution and to gain insights into reducing groundwater vulnerability, we begin by extrapolating past system dynamics into the future under a baseline external economic and climate scenario. From this extrapolation, we evaluate the adequacy of past water management strategies for maintaining a safe development pathway of the groundwater, population, and economic components. This is followed by three numerical experiments to explore the sensitivity of future groundwater vulnerability to alternative parameter settings related to human adaptive behaviors and environmental change scenarios. The effects of the three key parameters that control human adaptation and two external drivers are illustrated in Figure 3.

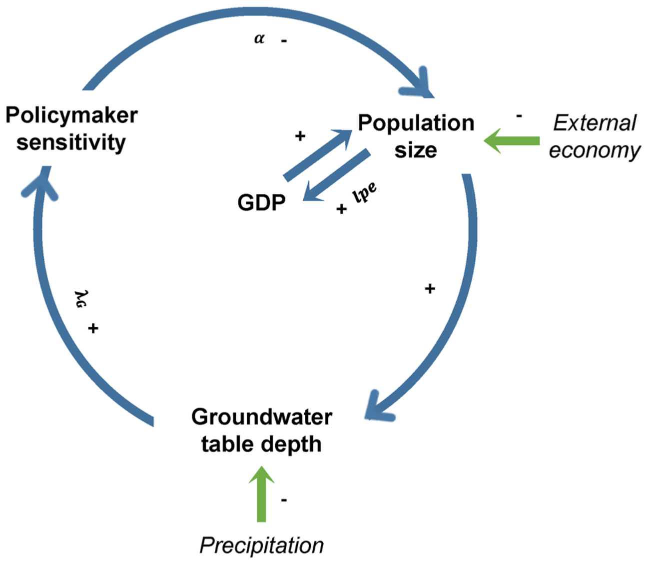

Figure 3. Illustration of the effects of the three parameters and two external drivers analyzed in the numerical experiments. The key social parameters governing the feedbacks include policymaker perceptions of groundwater depletion (λ_G), effectiveness of population displacement policy (α), and labor force participation in economic development (lpe). The two external drivers of the changing environment are precipitation and the external economy (i.e., the economy of other provinces of China).

In the first experiment (Section 3.1), we identify the sensitivity of groundwater table depth, population size, and GDP to alternative human response behaviors by varying the parameters relating to policymaker perceptions of groundwater depletion (i.e., λ_G), effectiveness of population displacement measures (i.e., α), and labor force participation in the economy (i.e., lpe). This is achieved by three systematic explorations of the model parameter space that controls human actions. Prior to this exploration, a preliminary sensitivity analysis is carried out, which reveal that groundwater table depth and population size are primarily sensitive to λ_G and α, and GDP is primarily sensitive to α and lpe (see Figure S3 in Supporting Information S1). Therefore, for groundwater table depth and population size, we explore their sensitivity to λ_G and α, and for GDP, we explore its sensitivity to lpe and α. λ_G indicates the degree of importance that policymakers place on groundwater variation. α reflects the effectiveness of population displacement measures, which is influenced by other factors besides groundwater depletion (e.g., real estate prices, land availability, and culture (W. Yang et al., 2016)). lpe controls the input of the quantity and quality of the labor force to economic sectors. The ranges of the parameter values are chosen based on a trade-off between being consistent with the local characteristics of Beijing city and covering a sufficiently wide range of possibilities of system coevolution. Other parameters are fixed at the calibrated value because they are not related to human behavior or are insensitive parameters.

In the second experiment (Section 3.2), we assess the effects of alternative environmental change scenarios on groundwater table depth, population size, and GDP. First, precipitation is set to the baseline scenario, and the model is run in each of the five distinct external economy scenarios. Then, the external economy is set to the baseline scenario, and the model is run in each of the five distinct precipitation scenarios. In each scenario, the model is run using 3,000 combinations of the parameter set (λ_G, α, and lpe) that are randomly sampled from a uniform distribution. The sample size of 3,000 is determined after preliminary trials, balancing the stability of numerical results and the computational cost. The variation in the distribution of the 3,000 model outcomes across different scenarios is applied to reveal the effects of environmental change.

In the third experiment (Section 3.3), we use the Classification and Regression Trees (CART) algorithm to identify the combinations of the human-related parameter set (λ_G, α, and lpe) that would steer the coupled system toward alternative development pathways across all environmental change scenarios. We run the model with the 3,000 randomly sampled parameter sets in all combinations of the external economic and climate change scenarios ($5 \times 5 = 25$ scenarios in total). The medians of the model outcomes across all of the model runs are calculated and utilized as criteria to group the model outcomes into different classes. These classes are loaded into the CART algorithm as responses, and the corresponding parameter sets are loaded as predictors. The outcomes from the CART analysis are used to identify the key factors that drive the system coevolution and to provide avenues for reducing groundwater vulnerability (Sawicz et al., 2014).

3. Results

3.1. Roles of Key Management Actions

To gain a preliminary understanding of the feedback relationships among groundwater table depth, population size, and GDP in the long-term future, we first tested the ability of the model to reproduce the historical development trajectory of the coupled system. We calibrated and validated the model by comparing the simulation outcomes with observation data during 1988–2020. The calibration period is 2003–2020, and the validation period is 1988–2002. The detailed procedure of the model testing is included in Text S2 and Table S2 in Supporting Information S1. The values of Nash-Sutcliffe efficiency (NSE) for groundwater table depth, population size, and GDP during both the calibration period and validation period are greater than 0.75, and the values of the coefficient of determination (R^2) are greater than 0.9. These results indicate that the model can satisfactorily capture the coupled groundwater-population-economy dynamics of Beijing city. Then, we extended the modeling

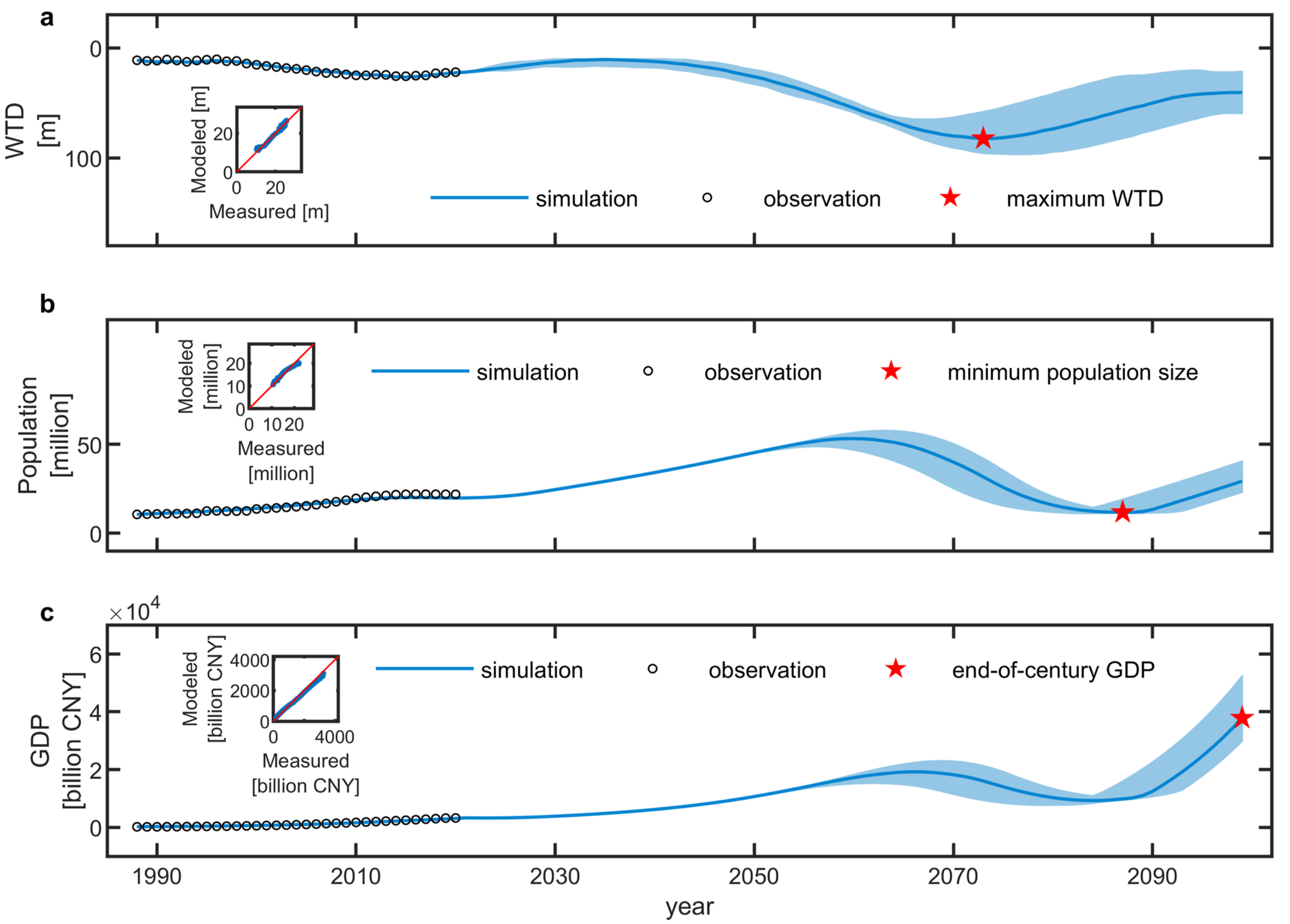

Figure 4. Development trajectories of groundwater table depth (WTD; a), population size (b), and GDP (c) when extrapolating the past dynamics to the future. The historical period is 1988–2020, and the prediction period is 2020–2099. The blue shaded area indicates the uncertainty of the time sequence of future annual precipitation. The red stars correspond to the maximum value of WTD and the minimum value of population size during the prediction period and the end-of-century GDP.

period to 2099 in the baseline scenario with all of the parameters fixed at the calibrated values. Figure 4 shows the temporal dynamics of groundwater table depth, population size, and GDP during the 1988–2099 period. It should be noted that the evolution trajectory shown in Figure 4 is a scenario analysis to examine if the past water management strategies are sufficient to maintain the system within a safe state in the long-term future, and if not, what possible negative consequences might be caused. It is not meant to suggest that the system would certainly develop along this trajectory in the future.

As shown in Figure 4, while the out-transfer of labor-intensive industries slows the rate of population growth at the end of the 2010s, there would soon be a rebound by 2060 (Figure 4b). This is because the shrinkage of population size, as well as the import of water from the SNWDP, changes the groundwater table from drawdown to recovery in 2015 (Figure 4a). The improvement in groundwater conditions slackens policymaker's water shortage awareness and leads to a relaxation of population control measures. When the population size slightly grows again, groundwater is overexploited once again and eventually falls to a maximum of approximately 82 m below the land surface (we assume that the drawdown of the groundwater table is not limited by the actual groundwater storage, Long et al., 2020). This is a catastrophic situation that might lead to serious hydrogeological issues. Therefore, the population control measures would be strengthened again, causing a loss of population size during 2060–2090. As this would result in a labor force shortage, there could also be a recession of GDP (Figure 4c).

These unintended consequences of groundwater depletion and socioeconomic recession suggest that extrapolating past water management strategies to the future is insufficient for maintaining the human-water system in a safe state. Alternative human actions are therefore needed to mediate human-water interactions. To this end, we need first to investigate how human actions impact the system dynamics. As we aim to reduce groundwater vulnerability, one of the metrics on which we would like to focus is the maximum value of groundwater table depth (lowest water table level) during 2020–2099. According to the definition by Hashimoto et al. (1982), the vulnerability of a system can be indicated by the "expected maximum severity of a sojourn into the set of unsatisfactory states." The maximum groundwater table depth (worst case) during the whole modeling period indicates the significance of the likely consequences of groundwater depletion. Therefore, it is used as a metric for groundwater vulnerability in this study. Furthermore, it is undesirable to safeguard groundwater at the expense of socioeconomic advancement. In addition to being advantageous for advancing water sustainability and other pertinent SDGs (Di Baldassarre et al., 2019), simultaneously ensuring the security of interconnected hydrologic, demographic, and economic systems is more consistent with the three-pillar (social, economic, and environmental) conception of sustainability (Purvis et al., 2019). Thus, we also examined the minimum value of population size during the modeling period to ensure that there would not be severe population loss, as well as the end-of-century GDP, in order to obtain a GDP level as high as feasible by the conclusion of our modeling period (Roobavannan et al., 2020). These metrics are illustrated in Figure 4 as red stars, and their sensitivity to human action-related parameters is systematically explored.

Figure 5 shows the sensitivity of groundwater table depth, population size, and GDP to the variations in the key management actions. We stress that the purpose of this sensitivity analysis is to uncover how the parameters that can be altered by human actions would govern the metrics of interest. Therefore, the outcomes cannot be interpreted as predictions of the future states of the metrics. Figure 5a illustrates the sensitivity of groundwater table depth to the interaction between policymaker perceptions of groundwater depletion (i.e., λ_G) and the effectiveness of the population displacement policy (i.e., α). Maintaining a high perception of groundwater drawdown and being capable of transferring a fraction of the human population to other provinces would effectively keep the groundwater table depth within a relatively safe range (e.g., no deeper than 40 m) throughout the whole century. Similarly, Figure 5b illustrates the effects of the same management actions on population size. A weak groundwater perception effect or ineffective population control strategy would result in continuous expansion of population size, whereas overly aggressive population displacement measures might cause severe population loss. Figure 5c demonstrates the effects of interactions between labor force participation in economic development (i.e., lpe) and the effectiveness of population displacement (i.e., α) on GDP. Aggressive population displacement strategies would result in a shortage of labor force, which would in turn constrain economic development. There is also the potential to ensure continuous growth of GDP if there is no strong population displacement and a high input of labor force to economic development (Huang et al., 2019; Leimbach et al., 2017).

3.2. Effects of Uncertain External Economic and Climate Changes

One of the major drivers that attracts people to migrate to Beijing is the advanced state of economic development in the city relative to those in other provinces of China. However, the future development pathway of the external economy is uncertain and cannot be determined by the government of Beijing city. To better adapt to this uncertain factor, we need to understand how it might impact system coevolution in general. To this end, we designed five scenarios of the development trajectory of the external economy. Each scenario develops at an alternative pace and serves as input to the sociohydrological model. In each scenario, the model is run with 3,000 random combinations of the three parameters (i.e., λ_G, α, and lpe) that control management actions. Figures 6a–6c show the distributions of the maximum groundwater table depth, minimum population size, and end-of-century GDP of the 3,000 model outcomes for each scenario. From left to right, with an increase in the rate of growth of the external economy, the maximum groundwater table depth in each scenario steadily increases, with the median value ranging from 33.5 to 35.9 m (Figure 6a). Correspondingly, the median of the minimum population size steadily increases, and the median of the end-of-century GDP steadily decreases (Figures 6b and 6c). The mechanism underpinning these outcomes is described as follows: when the external economy grows at a rapid pace, the economic gap between Beijing and other provinces is narrowed. In this case, the attractiveness of Beijing would decrease, and the rate of growth of the population size of the city would slow. As a result, the rate of drawdown of the groundwater table in the early stages would become relatively milder, which might lull the city into a false sense of water security. Consequently, population control measures might be slackened. Therefore, population size would continue to expand with few limitations in the early stages. After some expansion, the groundwater table would drop to an even worse level, only after which would the population displacement measures be

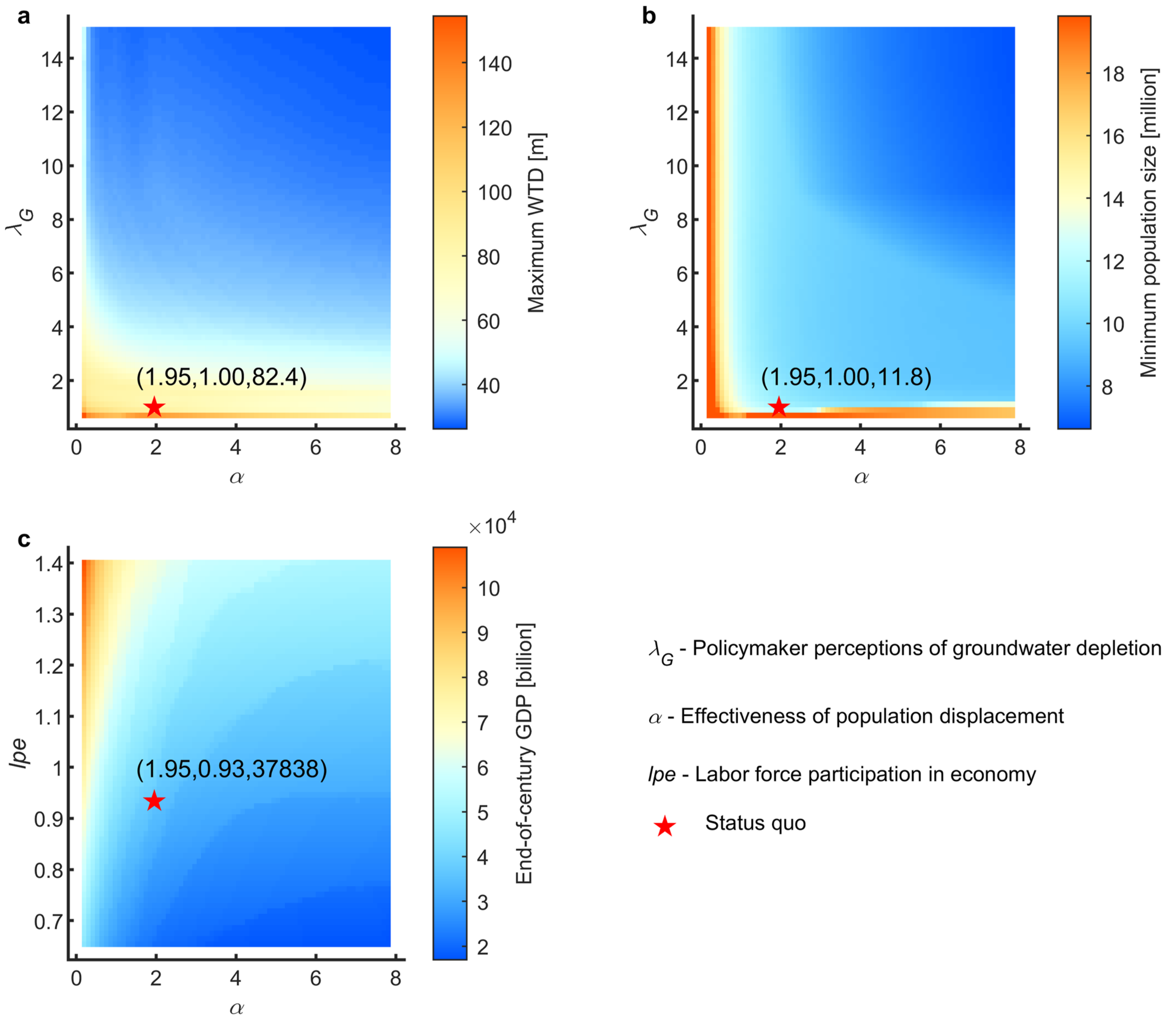

Figure 5. Effects of key management actions on the hydrologic and socioeconomic components. Sensitivity of groundwater table depth (a) and population size (b) to the interactions between policymaker perceptions of groundwater depletion (λ_G) and effectiveness of population displacement policy (α). Interaction effects between labor force participation in economic development (lpe) and effectiveness of population displacement (α) on GDP (c). The red stars correspond to the outcomes of the model run with calibrated parameters.

implemented (see Figure S4 in Supporting Information S1 for a time series comparison between two different external economic scenarios).

It should be noted that while the risk of groundwater depletion rises with increasing external economic development, rapid external economic growth is not necessarily associated with more severe groundwater depletion. The distributions of the maximum groundwater table depth under different scenarios vertically overlap (Figure 6a), which means that through the shifting of some management behaviors, it is possible to maintain a healthy aquifer state even if the external economy rapidly grows (see Figure S5 in Supporting Information S1 for a time series comparison between two different external economic scenarios under alternative management regimes).

Similarly, we used five climate scenarios with alternative average annual precipitation values as input to the model. With an increase in average annual precipitation, the median of the maximum groundwater table depth varies, almost randomly, from 33.0 to 34.7 m, whereas the median of the minimum population size monotonously

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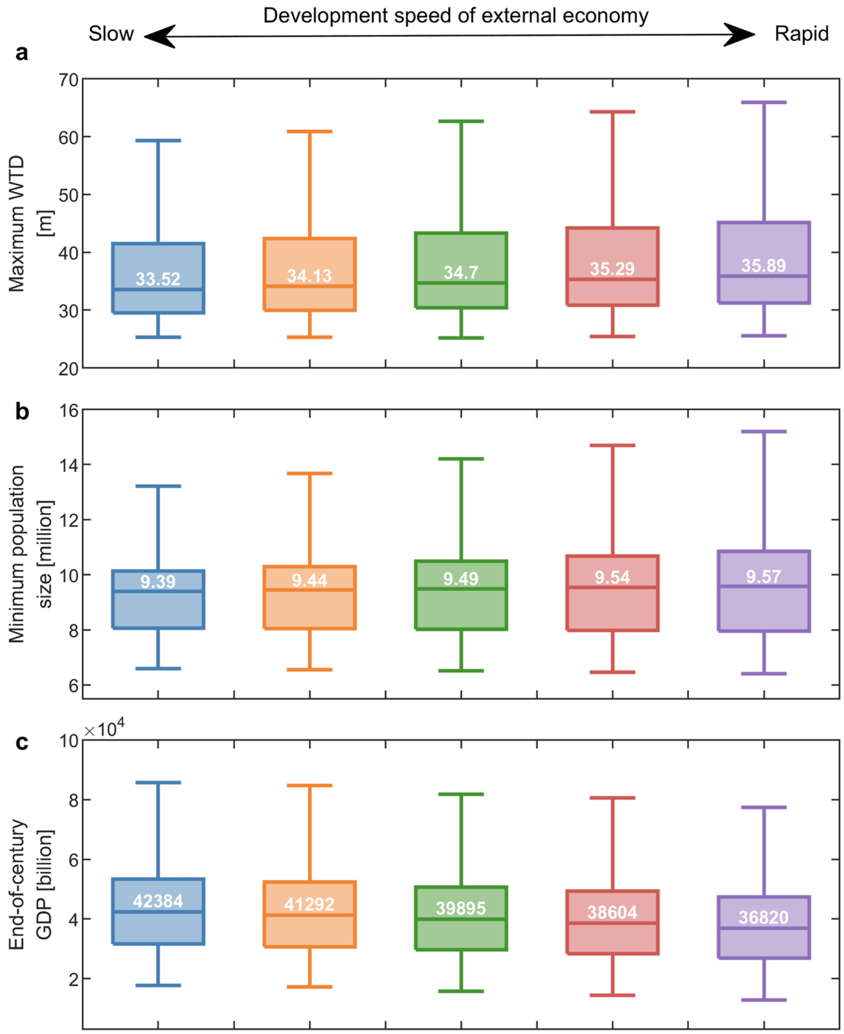

Figure 6. Effects of the rate of growth of the external economy on groundwater table depth (a), population size (b), and GDP (c). Each box shows a distribution of the metric of interest across 3,000 randomly sampled parameter sets that control management actions in the corresponding scenario.

increases and the median of the end-of-century GDP monotonously decreases (Figure 7). This is somewhat counterintuitive, as it indicates that the effects of the increase in average annual precipitation on groundwater table depth are marginal. The explanation for these outcomes is that the effects of larger precipitation on the human-water system are, in fact, twofold. On the one hand, larger precipitation would increase the availability of water for recharging the aquifer, which is positive for preventing groundwater depletion. On the other hand, greater precipitation might also relax human water shortage awareness by slowing the rate of drawdown of the groundwater table. This might in turn decrease the rate of population out-migration and will thus be negative for groundwater conservation. The positive and negative effects would slightly cancel each other out and yield outcomes in which the increase in average annual precipitation has a marginal effect on groundwater table depth. The outcomes for population size and GDP confirm that with an increase in average annual precipitation, measures for transferring people out of the city would be slackened and delayed, which explains why the minimum population size is likely to be larger and the end-of-century GDP is likely to be smaller in the scenarios with larger average annual precipitation. Figures S6–S8 in Supporting Information S1 illustrate three different time series comparisons of the effects of alternative precipitation scenarios on the sociohydrological system coevolution.

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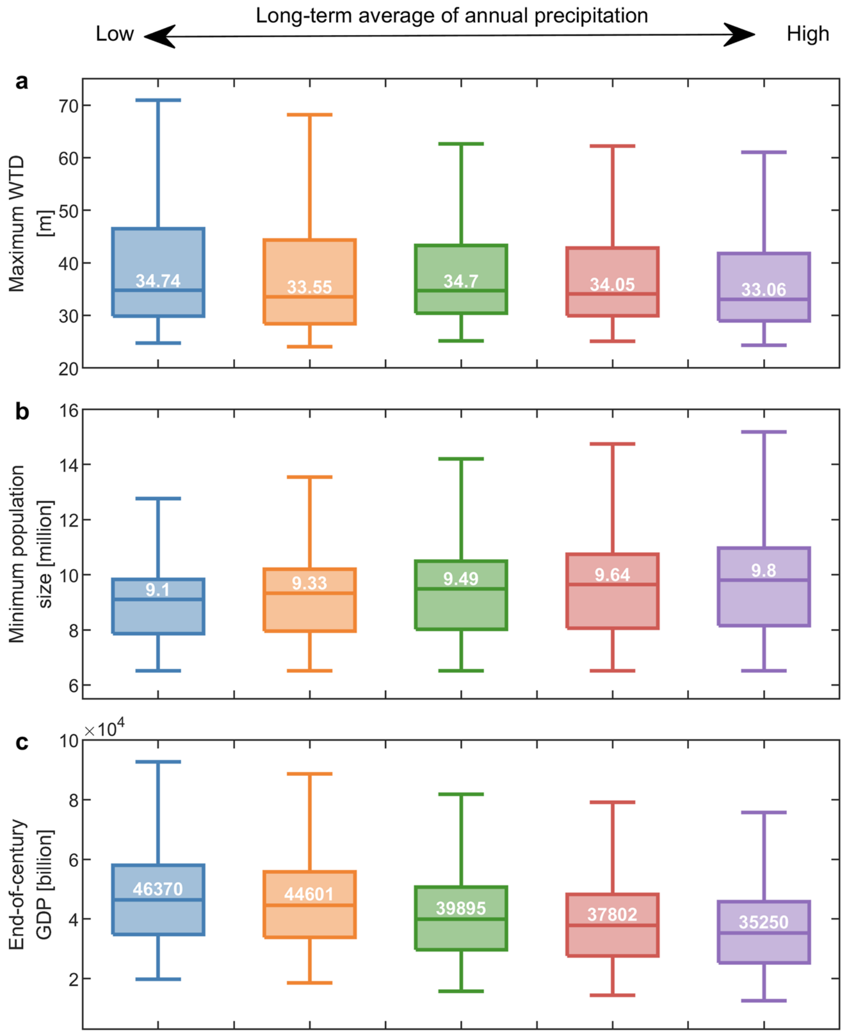

Figure 7. Effects of the average annual precipitation on groundwater table depth (a), population size (b), and GDP (c). Each box shows a distribution of the metric of interest across 3,000 randomly sampled parameter sets that control management actions in the corresponding scenario.

3.3. Key to Reducing Groundwater Vulnerability

The previous sections have analyzed how human adaptive behaviors might govern the social and hydrologic aspects of the coupled system and the potential effects of alternative environmental change scenarios. In this section, we explore the decisive factors for reducing groundwater vulnerability, considering all plausible future scenarios. Specifically, we generated 25 environmental change scenarios by systematically combining five external economic scenarios and five climate scenarios. Each of these scenarios serves as input to the sociohydrological model. In each scenario, the model is run 3,000 times with the 3,000 randomly sampled social parameters (i.e., λ_G, α, and lpe). The outcomes from all of the model runs are analyzed by using the CART algorithm (Breiman et al., 2017; Loh, 2011; Shen, 2018). To use CART, we need first to group the model outcomes into several classes, which is achieved by using the medians of maximum groundwater table depth (i.e., 35 m), minimum population size (i.e., 9.4 million), and end-of-century GDP (i.e., 4.0×10^4 billion) across all of the model runs as division between groups for each variable (i.e., below-median and above-median). The model outcomes are grouped into eight different classes. The classification results are loaded to the CART algorithm as responses, and the corresponding social factors are loaded as predictors. The output from CART is presented in the form of a decision tree, as shown in Figure 8.

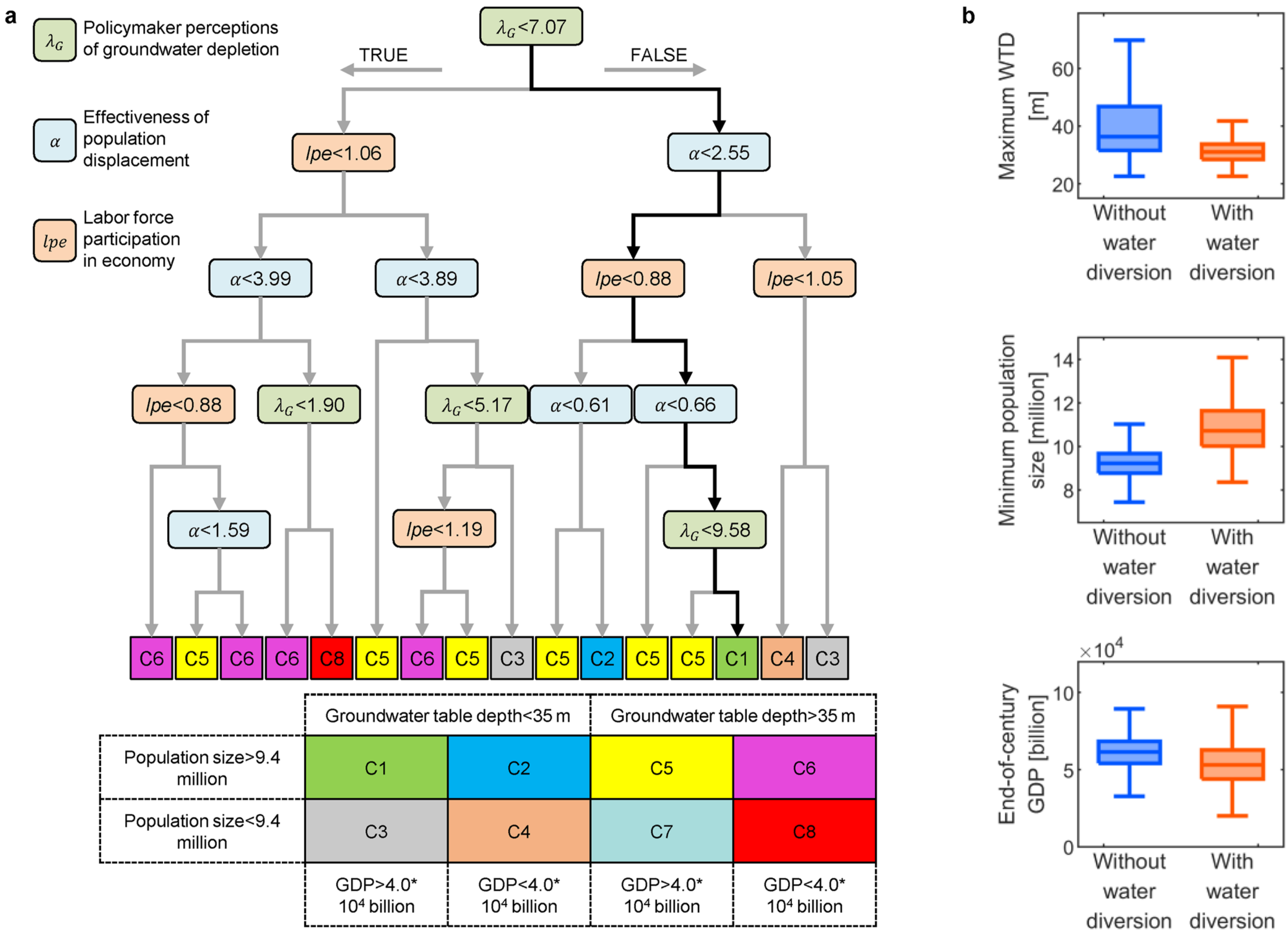

Figure 8. Combination of the key management actions that would steer the system toward alternative development pathways. (a) Classification of the model outcomes and combinations of management actions corresponding to each class. The left branch of each node represents that the logic expression in that node is true, whereas the right branch represents that the logical expression is false. The black highlighted line represents the combination of management actions that could simultaneously steer all the components of the sociohydrological system to develop along a relatively safe pathway. (b) Comparison of the model outcomes from the strategies that can most likely steer the system toward Class 1 in the scenarios with and without the South-North Water Diversion Project.

Analysis results from the algorithm show that policymaker perception of groundwater depletion is the leading factor driving system coevolution (i.e., first split of the decision tree). The effectiveness of the population displacement policy and labor force participation in economic development are subsequent drivers (Figure 8a). The outcomes belonging to Class 1 can simultaneously maintain groundwater, population, and economy within a relatively safe state throughout the century, as in this class, the maximum groundwater table depth is no deeper than the median across all of the scenarios, and the minimum population size and end-of-century GDP are no smaller than their corresponding medians. This indicates that steering the system toward Class 1 is the most favorable choice for reducing groundwater vulnerability without inducing severe population loss and economic recession, thus achieving a balance between groundwater protection and socioeconomic development. The combination of the management actions corresponding to Class 1 is highlighted. It requires that the parameter values related to policymaker perceptions of groundwater depletion (λ_G) be larger than 9.58, effectiveness of population displacement policy (α) be in the range between 0.66 and 2.55, and labor force participation in economic development (lpe) be larger than 0.88. However, the parameter values of λ_G, α, and lpe obtained by calibration against historical data over the past 30 years are 1.00, 1.95, and 0.93, respectively (Figure 5). While α and lpe are within the ideal range, λ_G needs to be approximately 9.6 times larger than during the status quo state.

In addition, to uncover the contributions of the SNWDP to reducing groundwater vulnerability, we also analyzed a hypothetical scenario in which no water is being transferred to Beijing. It should be noted that in reality, the volume of water that can be transferred to Beijing annually depends on the water availability in the donor basin (especially the Danjiangkou Reservoir) and the water demands in other import regions (Beijing is not the only city that receives the transferred water; M. Feng et al., 2019). The volume of annual water transfer from the SNWDP to Beijing is assumed in this study to be fixed at 1 km^3, which is the volume planned by the Ministry of Water Resources of China, as this study focuses on the bidirectional feedbacks between human and water systems in Beijing. In many earlier research (Long et al., 2020; Y. Yang et al., 2011; M. Zhang et al., 2018), this was a common practice. Fixing the annual water diversion volume also makes it easier to separate the effects of external economic and climatic changes on the coevolution of the system. To relax this assumption, a large-scale model that simultaneously considers the donor basin and all of the import regions is needed, which is beyond the scope of this study. A comparison between the model outcomes from the strategies that can most likely steer the system toward Class 1 in the scenarios with and without water diversion is shown in Figure 8b. If there was no water diversion project, the median of the maximum groundwater table depth across alternative combinations of the management actions would be 36.3 m, compared to 31.0 m in the scenario with water diversion. More importantly, in the scenario without water diversion, the probability of severe groundwater depletion is much higher. In addition, the scenario with the water diversion project is associated with a larger population size and a smaller end-of-century economy. This is because the water imported from the SNWDP slows down the drawdown of groundwater table and thus reduces the human awareness of the water shortage. The population displacement measures and the later rebound of population size and economy would be delayed consequently. This is somewhat similar to the effects of larger precipitation, as is shown in Figure 7.

4. Discussion

The effects of external economic development and climate change on the system dynamics, as shown in Figures 6 and 7, potentially provide a basis for a unified understanding of two widely discussed emergent dynamics during the process of human-water interaction. The first dynamic is the rebound effect, which describes the phenomenon that reducing water demand during a period of drought or water scarcity is often followed by a rebound in water consumption when the water crisis is alleviated (Stewart et al., 2014). Another dynamic is the supply-demand cycle, which describes the phenomenon that increasing water supply to meet water demand usually, in turn, encourages more water demand (Di Baldassarre et al., 2018; Kallis, 2010). These two phenomena actually demonstrate the same consequence (i.e., an increase in water consumption) that arises from two different management strategies (i.e., demand-side strategy and supply-side strategy). The model outcomes in Section 3.2 show that both rapid external economic development and greater precipitation could result in more severe groundwater depletion. The mechanism underpinning such an outcome is very similar to the rebound effect and supply-demand cycle. The development of the external economy, in effect, impacts the demand side of human water consumption by impacting the rate of population migration, whereas precipitation impacts the supply side by impacting the volume of water availability. In a deeper sense, the possible groundwater depletion predicted in these scenarios results from a relaxation of human water shortage awareness due to short-term relief of the water stress situation (e.g., temporary slowdown of the rate of groundwater table drawdown). Therefore, despite the main focus of water management actions (demand-oriented or supply-oriented), maintaining constant water shortage awareness is important to achieving long-lasting success for management actions.

Analysis results of the CART algorithm show that policymaker perception of groundwater depletion is the key factor in reducing groundwater vulnerability (Figure 8). In Beijing city, this perception reflects whether the government could maintain constant water shortage awareness and further determine policies with respect to controlling population size and regulating water demand (e.g., by moving out labor-intensive industries and raising the cost of living in the city). Many studies have also recognized the importance of human values in sustainable water management. For example, Gonzales and Ajami (2017) analyzed the evolution of water use in three water utilities in the San Francisco Bay Area. The authors found that after a period of water conservation during drought events, there would be a rebound in water consumption. This rebound phenomenon could be largely attributed to the decrease in social memory regarding the drought. Gohari et al. (2013) discovered that the interbasin water transfer project, which was designed to meet the water demand in the Zayandeh-Rud River Basin, unintendedly encouraged more people to migrate to the basin and thus created even more water demand. Their analyses indicated that the false perception of water availability brought about by the water transfer project led to the neglect of demand management programs. These studies highlight the fundamental role that changing human values would play in stimulating adaptive behavior.

For Beijing city, the analysis results also suggest that policymaker perception of groundwater depletion in the past three decades is approximately 10 times lower than that needed to simultaneously maintain groundwater, human population, and GDP at a relatively safe state. With the serious drawdown of the groundwater table in recent years, the government has increasingly realized the significance of groundwater protection. In 2021, the State Council of China enacted the Groundwater Management Regulation, which is the first law focusing on groundwater protection at the national level in China. To implement this law, the Beijing government also made specific groundwater management plans that propose to constrain the volume of groundwater exploitation and expedite the recovery of groundwater tables by regulating socioeconomic water demands and utilizing the SNWDP. These policies indicate an improvement in policymaker awareness of groundwater importance and prompt the government to implement regulatory policies in a more timely manner. This could help avoid system collapse induced by continuous accumulation of water scarcity leading to water crisis and collapse, as was experienced by the ancient Maya civilization (Evans et al., 2018; Kuil et al., 2016).

To improve policymaker sensitivity to the drawdown of the groundwater table, there are at least three possible avenues to pursue. First, changes in groundwater conditions should be more seriously monitored and valued. In particular, when the rate of drawdown of the groundwater table becomes milder, the city should be conscious of not being lulled into a false sense of water security. Second, collaboration among various government authorities needs to be strengthened (Mullin, 2020; Zeff et al., 2016). As sustainable water management usually involves complex trade-offs between environmental protection and socioeconomic development, multiple management agencies participate in the process of decision-making. Strengthened collaboration among these agencies would facilitate information sharing and also help reach agreement. California is a recent example of governments that seek to achieve groundwater sustainability by promoting collaboration among management agencies (Dobbin & Lubell, 2019). Third, information about groundwater depletion should be propagated using widespread social media. Studies have shown that advertising the reality of climate change would effectively increase human perception of the associated risk (Goldberg et al., 2021). For example, heavy news media coverage of drought events effectively raised public awareness of water shortages in the San Francisco Bay Area (Quesnel & Ajami, 2017). In the same way, this would also be beneficial to making groundwater protection a social norm in Beijing city, which would in turn prompt policymakers to pay more attention to groundwater (Moore et al., 2022; Noll et al., 2022).

These findings highlight the significance of the human dimension in understanding and solving urban water crises. A coupled human-water model can serve as an analytical tool. However, modeling social components is still challenging given the high uncertainty of human behavior. In this context, the question-driven modeling approach could be an effective strategy that advocates focusing on the most relevant variables based on the question of interest and increasing the model complexity only as needed (Garcia et al., 2016; Sivapalan, 2018). This would also facilitate the interpretation of model outcomes (Grayson & Blöschl, 2000). The relatively sparse data on social variables across space and time scales, which are usually obtained through social surveys, are also a constraint to fully testing human-water models. Advances in this regard may be achieved with techniques such as data mining and artificial intelligence.

5. Conclusions

Inspired by the phenomenon of population displacement as an adaptation to water scarcity in Beijing city, this study explored ways to reduce groundwater vulnerability to uncertain environmental changes throughout the twenty-first century. We focused on three interrelated components, groundwater table depth, population size, and GDP, and explored how human adaptive behaviors would govern these components and the possible effects of alternative environmental change scenarios. Using the CART algorithm, we identified the key factors involved in reducing groundwater vulnerability without causing a severe socioeconomic recession.

We discovered that a rapid rate of growth of the external economy or a larger amount of average annual precipitation may have a dual effect on the groundwater of Beijing city. While these factors are expected to reduce the rate of population immigration in Beijing or to increase the volume of groundwater recharge, they may also relax human water shortage awareness and slacken measures taken toward population size control. In the long run, this might lead to even further groundwater depletion. The analysis results also suggest that policymaker perceptions of groundwater depletion will dominate the interaction between human society and the water system and thus play a key role in determining the future water sustainability of Beijing city. To avoid possible undesired consequences, raising policymaker perceptions of groundwater depletion should be prioritized. With effective

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population displacement policies and a high input of labor force to economic sectors, groundwater, population, and economy could be maintained in a relatively safe state.

Although this work has focused on the water sustainability challenges of Beijing city, it still has heuristic value for other major cities that also struggle with water scarcity. The phenomenon of hydroclimate-impacted population migration is not unique to Beijing. This phenomenon has also been observed in many other cities worldwide (Black et al., 2011; Evans et al., 2018; Hari et al., 2021; Kuil et al., 2016; Marotzke et al., 2020). Maintaining the coupled hydrology-population-economic system within a safe development pathway is particularly essential to meet the SDGs (Di Baldassarre et al., 2019). This needs to surpass traditional, narrow, purely water-centered solutions to water scarcity. More broadly, the complexity of institutions, human behavior, and the norms and preferences that underlie the dynamics of human-water interactions are equally (if not more) important for elucidating actionable management strategies (Peng et al., 2021).

The model presented in this study simulates the evolution of the groundwater table by simultaneously considering its response to and impact on the population and economic dynamics. This is more holistic than most previous studies that consider human society as merely an exogenous driver of hydrologic change and therefore is more suitable for water-scarce cities with extensive human responses. The model, which is formed by just a few differential equations, mainly captures the most important processes of human-water feedbacks. This makes it easier to reveal the fundamental mechanisms underpinning human-water coevolution and to identify the most important strategies that need to be strengthened to achieve a sustainable water supply. In addition, the model could also help identify windows of opportunity for adaptive responses. For example, identifying the timing of the turning point of the groundwater table from recovery to drawdown would prompt the government to be more proactive in designing and implementing adaptive policies and thus avoid severe groundwater depletion. However, there are still limitations in the application of such a model. Given its simple nature, it is somewhat weak in supporting the design of more specific water management policies. To do so, sophisticated models that mimic more detailed social and hydrologic processes are needed. For example, in our model, there is no direct feedback from groundwater depletion to the economy. This is because we only mimic the overall GDP of Beijing city. In reality, the government is less likely to limit the development of the overall GDP even if there is groundwater depletion. However, groundwater depletion might have an effect on the economic structure. To reduce water consumption from economic development, policymakers could support the development of high-tech and less water-intensive industries and constrain more water-intensive industries. This would result in less water consumption and contribute even more to the GDP (Q. Wang et al., 2018). To explore the effects of groundwater depletion on the economic structure, a model with more detailed economic processes will be needed (e.g., input-output models). In addition, the parameters explored in this study are assumed to be temporally invariant. In reality, these parameters may shift when circumstances change (Knighton et al., 2021). Nevertheless, the sensitivity of system components to human adaptive behaviors and environmental change scenarios uncovered in this study and the interpretations of the underlying mechanisms could still provide insights into water management in Beijing and beyond. Further improvement of this work could be achieved by advancing the modeling of social components by collaboration with experts from the social and behavioral sciences.

Data Availability Statement

The data about population and GDP of Beijing are available in *Beijing Statistical Yearbook* (https://nj.tjj.beijing.gov.cn/nj/main/2023-tjnj/zk/indexeh.htm). The data about GDP of other provinces of China are available in *China Statistical Yearbook* (https://www.stats.gov.cn/sj/ndsj/2022/indexeh.htm). The data about groundwater table depth are available at *Beijing Water Resources Bulletins* (http://swj.beijing.gov.cn/zwgk/szygb/).

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