

# Water Resources Research<sup>®</sup>



## RESEARCH ARTICLE

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## Evaluating Distributed Policies for Conjunctive Surface Water-Groundwater Management in Large River Basins: Water Uses Versus Hydrological Impacts

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### Key Points:

- This study proposes and evaluates a distributed policy design scheme featuring spatially variable and temporally dynamic water policies
- It is possible to mitigate aquifer depletion without reducing the total water supply by adjusting water policies between dry and wet years
- Hydrological externality effects among nearby districts are explicitly quantified by assessing spatially varying water management policies

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### Supporting Information:

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

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**Abstract** It is imperative to understand the interconnectedness of water use and hydrological impacts for water policy design underlying varying hydrological conditions across space and over time. However, such analysis remains difficult, constrained by the lack of appropriate modeling tools that fully integrate water policies, water use, and hydrological processes with high spatiotemporal resolutions. To address this challenge, this study proposes a *distributed* policy design scheme featuring spatially variable and temporally dynamic policies for conjunctive surface water-groundwater management in large river basins. A fully integrated modeling framework is developed to tightly couple (a) an agent-based model for farmers' water use under distributed water policies and (b) a physically based hydrological model for surface water-groundwater processes. The modeling framework is applied to the Heihe River Basin to assess water use and hydrological impacts under distributed water policies. By using the distributed policy scheme to adjust a water policy (e.g., groundwater tax) across space and over time, we found that hydrological outcomes can be improved without adversely reducing agricultural water supply. For example, by shifting the implementation of a high groundwater tax from dry to wet years, a rise of the water table by 0.28 m (0.03–0.95 m across different irrigation districts) can be achieved while the total water supply is maintained at a similar level. Furthermore, hydrological externality effects among nearby districts can be explicitly identified and quantified based on assessments of spatially varying water policies. This study highlights the need for water policy design to consider spatiotemporal variations in the physical hydrological system.

## 1. Introduction

Water scarcity and its associated societal, economic and environmental issues are common challenges in many arid and semiarid river basins around the world (Cheng et al., 2014; Elshafei et al., 2015; van Oel et al., 2010). To support the efficient management of limited surface water (SW) and/or groundwater (GW) resources, it is important to understand the interactions between human activities (e.g., farmers' irrigation water use) and hydrological processes in the context of particular water management policies, especially in heavily managed areas with intensive agriculture as the main consumer of freshwater (Arnold et al., 2015; Badham et al., 2019; Harou et al., 2009; Li et al., 2021; Sivapalan et al., 2012). However, in large river basins, hydrological and climate conditions typically exhibit significant spatial variations. The implementation of a water management policy may result in heterogeneous impacts on farmers' water uses in different locations, as well as the consequent hydrological, economic, and environmental outcomes (Duke et al., 2020; Palazzo & Brozović, 2014). As a result, unintended water uses and hydrological responses due to the implementation of the policy, which may vary from upstream to downstream and from dry to wet years, can deviate from the original goals of the policy.

Some studies have explicitly assessed the spatially heterogeneous impacts of water policies on agricultural water use in the context of river basin management (Du et al., 2020; Hrozencik et al., 2017; Khan & Brown, 2019; Mulligan et al., 2014). For example, Mulligan et al. (2014) applied a coupled economic-groundwater model to an agricultural river basin and showed that the heterogeneity of the river basin and farmer characteristics can

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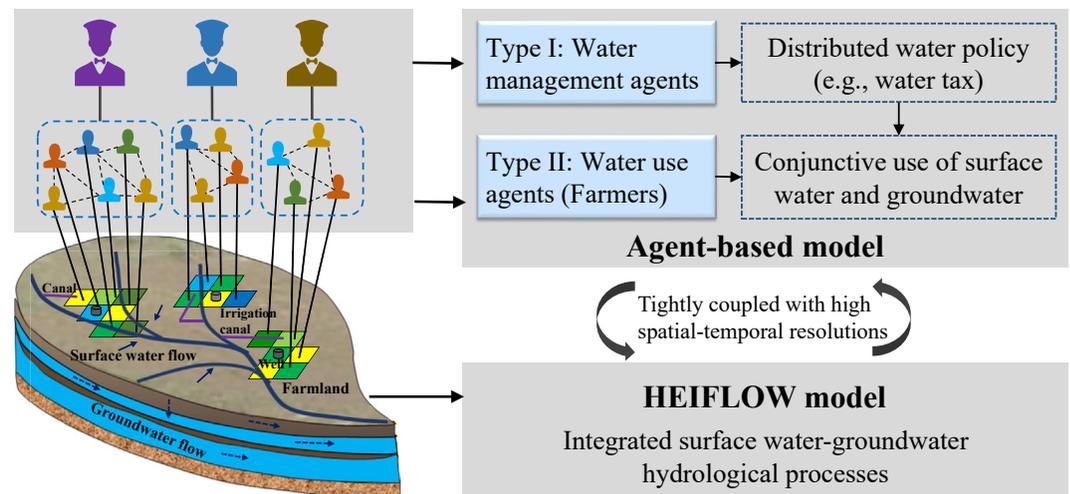
weaken the benefits of water management policies (e.g., taxes and quotas for water use). Similarly, Hrozencik et al. (2017) evaluated the impacts of water policies in the Republican River Basin and found that hydrological outcomes exhibited significant spatial variations across the river basin. In a recent study, we developed a fully integrated model to explicitly evaluate the hydrological impacts associated with various policies (water taxes) and found that human-hydrological interactions under a water policy can exhibit spatially variable and temporally dynamic characteristics (Du et al., 2020). Heterogeneities in farmers' irrigation activities and responses to external hydrological and climate drivers have also been identified and verified based on observations from satellite-based remote sensing (Lawston et al., 2017; Nie et al., 2020). These studies have highlighted the importance of considering the variations in human-hydrological interactions to support location-dependent policy design, especially in large river basins with variable hydrological and climate conditions.

The necessity to consider hydrological impacts of location-dependent water policies is also warranted by policy externality issues at the river basin scale. For example, a farmer's excessive GW pumping in one area may result in the depletion of the water table in nearby areas due to hydrological connectivity (Bracken et al., 2013; Pringle, 2003). In this regard, a change in a user's water consumption under a water policy can lead to unintended hydrological consequences for other users. Given that river basin management usually involves multiple self-interested stakeholders, policy externality issues can result in conflicts of interest between water users (Brozović et al., 2010; Garrick et al., 2020; Kuwayama & Brozović, 2013; Madani & Dinar, 2013; Shah, 1988). It is, therefore, necessary for basin managers to apply different policies to water users and impose stricter regulations on those whose water abstractions can result in high externality effects for other users and/or the environment.

Motivated by the above research needs, this study emphasizes that the design of water policies should account for temporal-spatial variations in hydrological conditions in the management of the river basin. We hypothesize that improved hydrological outcomes can be achieved by adjusting a water policy across space and over time while maintaining the existing water use amount. To test this hypothesis, we propose a *distributed* policy design scheme featuring spatially variable and temporally dynamic (referred to as “distributed” hereinafter) policies for conjunctive SW-GW management. The proposed distributed policy design scheme is also expected to identify and quantitatively assess hydrological externality effects among nearby areas, which can guide the design of more equitable and mutually acceptable policies for regulating farmers' water use in a large river basin.

In our prior work (Du et al., 2020), an agent-based model (ABM) was developed and coupled with a distributed SW-GW model to assess the impacts of water policy on farmers' conjunctive water uses (i.e., SW diversion and GW pumping) and hydrological conditions. However, similar to those in other studies (e.g., Mulligan et al., 2014), the ABM in Du et al. (2020) was limited to the case in which a basin-level centralized manager applies uniform policies to the entire river basin. In this study, we improve the ABM of Du et al. (2020) by incorporating a distributed policy design scheme that includes multiple decentralized water management agents in the system. Each local water manager can adopt time-varying policies in their administrative area. With this extension, the new modeling framework in this study can simulate the impacts of spatially variable and temporally dynamic policies on water use and hydrological responses across a river basin. Furthermore, the integrated SW-GW hydrological model in our framework extends the scope of some recent studies that focused on coupling ABMs with GW models (e.g., MODFLOW) for GW management (Hu, Cai, et al., 2015; Khan & Brown, 2019; Lei et al., 2019; Noël & Cai, 2017).

We apply the modeling framework to the Heihe River Basin (HRB), the second largest endorheic river basin in China and a region with intensive agriculture. Using a water tax as an example policy instrument (Brown & Rogers, 2006; Duke et al., 2020; Iglesias & Blanco, 2008), we design a set of distributed water policy scenarios with water taxes varying from region to region and from year to year. Through a set of scenario analyses, the modeling results highlight the unique benefits of applying distributed policies for river basin management. For example, by using the distributed policy scheme to adjust the water policy between dry and wet years it is possible to mitigate aquifer depletion problems without adversely reducing the total water supply to agriculture. Furthermore, the assessments of spatially variable policies enable basin managers to identify and explicitly quantify policy externality effects among irrigation districts. Our simulation results have yielded a number of policy implications to support the management of conjunctive SW-GW resources and advance our understanding of human-hydrological interactions in large river basins.



**Figure 1.** The modeling framework, which integrates an agent-based model and Hydrological-Ecological Integrated watershed-scale FLOW to simulate the interaction between farmers' conjunctive water use based on distributed water management policies and SW-GW hydrological processes.

The remainder of this paper is structured as follows. Section 2 introduces the modeling framework of this study. Section 3 introduces the case study area and water management policies. Section 4 presents the modeling results. Section 5 discusses some policy implications associated with the modeling results. Section 6 concludes this article.

## 2. Methodology

### 2.1. Overview of the Modeling Framework

As illustrated in Figure 1, the modeling framework in this study consists of an agent-based model (ABM) and an integrated SW-GW model Hydrological-Ecological Integrated watershed-scale FLOW model (HEIFLOW). The ABM simulates farmers' conjunctive use of SW and GW under distributed water policies. Two types of agents are incorporated into the ABM (a) water resource management agents (i.e., local water managers, type I) and (b) water use agents (i.e., farmers, type II). HEIFLOW is a physically based hydrological model that simulates integrated SW and GW flow processes. Detailed introductions to the two models and their coupling processes are described in turn as follows.

### 2.2. The ABM for Distributed Water Policies and Farmers' Conjunctive Water Use

As mentioned above, in our prior work (Du et al., 2020), an ABM was developed to simulate farmers' conjunctive use of GW and SW under a uniform applied water policy. Given that this study focuses on distributed water policies, we improve the ABM as follows. First, differing from the prior ABM, which considers only one centralized water management agent in a system, this study incorporates multiple decentralized water management agents in the model. Each water management agent can implement local policies to regulate farmers' water uses in the corresponding administrative region. Second, the prior ABM considers temporally static policies (e.g., a fixed water tax over time). In this study, we improve the ABM and allow each water management agent to update its policies each year. With the above model improvements, the ABM in this study can simulate *distributed* (i.e., spatially variable and temporally dynamic) water policies for river basin management.

To meet management goals, basin managers may consider various policies (e.g., water taxes, the establishment of water rights, and temporal restrictions on water abstraction) to regulate farmers' water uses. Following previous studies (Duke et al., 2020; Iglesias & Blanco, 2008; Mulligan et al., 2014; T. Sun et al., 2016), this study uses a water tax as an example to develop distributed water policies to regulate the fractions of SW and GW use in a river basin. Let  $\phi_{SW}$  and  $\phi_{GW}$  denote the tax rates for SW and GW, respectively. The cost for using GW, denoted by  $C_{GW}$ , consists of GW tax  $\phi_{GW}$  and pumping cost  $\phi_{pumping}$ , as shown in Equation 1.

$$C_{GW} = \phi_{GW} + \phi_{\text{pumping}} \quad (1)$$

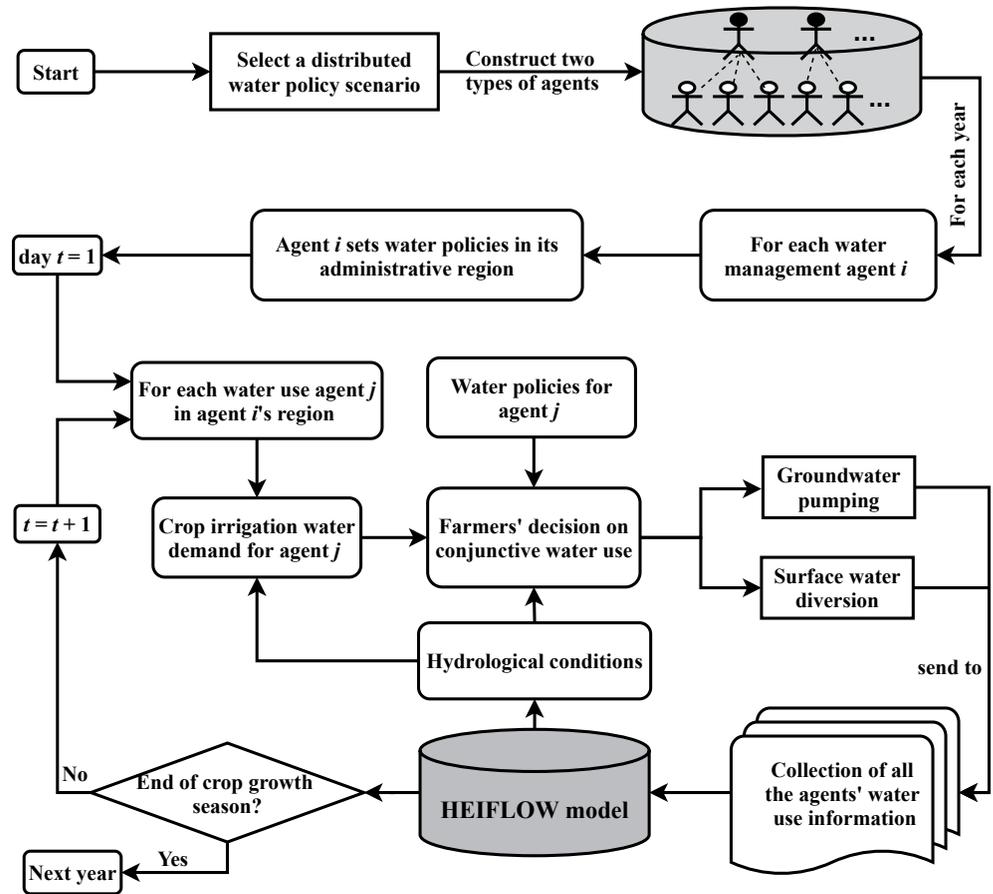
Note that the pumping cost  $\phi_{\text{pumping}}$  is a function of pumping lift (associated with the depth to the water table), pumping efficiency, and electricity/fuel price for pumping. For a more detailed description of the pumping cost, see the description by Rothausen and Conway (2011). In comparison, the cost of using SW, denoted by  $C_{SW}$ , is a SW tax  $\phi_{SW}$  (i.e.,  $C_{SW} = \phi_{SW}$ ), and diverting costs in regions with gravity flows from open irrigation canals to farmlands are neglected.

Farmers' irrigation decisions are based on maintaining soil moisture to reduce crop yield loss due to a water deficit (Allen et al., 1998; Foster et al., 2014). After the total irrigation demand is determined, farmers need to consider the amounts of SW and GW to be used. We assume that farmers' decisions regarding conjunctive water use are based on a heuristic economic optimization principle. That is, a farmer will use the water resource with the lowest cost as their primary choice, followed by that with the next-highest cost, and so on. If the primary water resource is not sufficient to meet the irrigation demand, another type of water resource will be used to meet the remainder of the demand. Given that farmers may live in areas with different hydrological conditions and management policies, their conjunctive use of GW and SW may vary. It is also noteworthy that water management policies in this study focus on regulating the fractions of SW and GW use while maintaining the total water use. For a detailed description of farmers' decisions regarding conjunctive water use, see Du et al. (2020).

### 2.3. Integration of HEIFLOW and the ABM

HEIFLOW model is a physically based three-dimensional hydrological model (Han et al., 2021; Li et al., 2021; Tian et al., 2018). HEIFLOW is primarily based on Coupled Ground-Water and Surface-Water Flow Model (GSFLOW), which is a distributed hydrological model that simulates integrated GW and SW flow processes across the land surface, in subsurface areas, and within streams and lakes (Markstrom et al., 2008). GSFLOW integrates two widely used hydrological models: (a) the Precipitation-Runoff Modeling System, which simulates SW flow processes (e.g., streamflow, runoff, and infiltration) as a response to climate and land surface conditions, and (b) the Modular Ground-Water Flow Model, which simulates GW flow processes in aquifers and water exchange between surface and subsurface systems. HEIFLOW incorporates additional modules and features to improve the functionality of GSFLOW, including (a) an advanced hydraulic engine provided by the Storm Water Management Model to simulate highly engineered systems for farmland irrigation (Tian, Zheng, Zheng, et al., 2015), (b) a general ecological module to simulate various types of vegetation growth for a given climate and management condition (Z. Sun et al., 2018), (c) an improved soil module to simulate the detailed spatial coverage of irrigation in multiple soil layers (Han et al., 2021), and (d) a graphical modeling platform to incorporate adaptive land use inputs (Tian et al., 2018). Due to these advances, HEIFLOW has been successfully applied to manage conjunctive SW and GW water resources in large river basins with the objective of addressing water demand conflicts between agriculture and ecosystems (Zheng et al., 2020).

In this study, the ABM and HEIFLOW are tightly coupled. That is, the source code of the ABM is embedded into HEIFLOW, making the coupled model computationally tractable for simulating human-hydrological interactions in large river basins. Figure 2 illustrates the flowchart of the coupled ABM-HEIFLOW modeling framework. The model starts with selecting the water management scenario and preparing datasets to construct the two types of agents (Type-I water management agents and Type-II water use agents). For each simulation year, the water policy scenario includes specific water management policies (e.g., tax rates for SW and GW in each year) to be implemented in each administrative region in a river basin. The connections between water management agents and water use agents are also constructed so that water policies can be enforced for each water use agent in a river basin. Next, at each time step (daily in this study), Type-II agents (farmers) determine their conjunctive use of SW and GW based on irrigation demands and water policies. Then, all of the agents' irrigation information is compiled and transferred to HEIFLOW to generate hydrological conditions for the next time step.



**Figure 2.** Flowchart of the integration of the agent-based model and Hydrological-Ecological Integrated watershed-scale FLOW for simulating farmers' conjunctive water use under the influence of distributed water management policies.

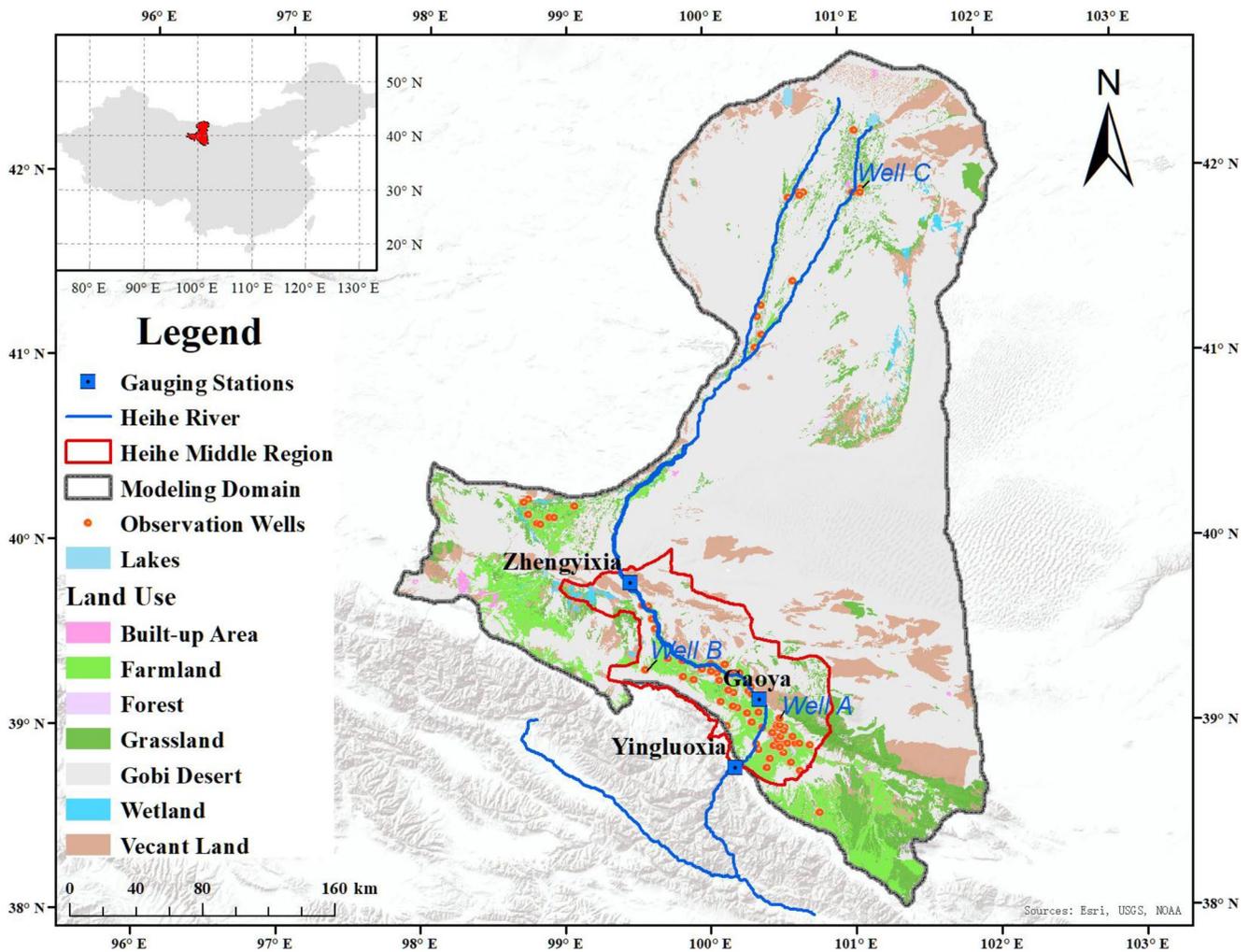
### 3. Study Area and Policy Scenario Design

#### 3.1. Case Study Area

We apply the proposed modeling framework to the Heihe River Basin (HRB) as a case study. The HRB, covering a total area of 143,000 km<sup>2</sup>, is the second-largest endorheic river basin in northwestern China (Figure 3). The water resource management system in the HRB involves a basin-level water authority (the Heihe River Bureau) and dozens of regional water management institutes. In the basin's water management practice, farmers' water uses are subject to water policies and regulations enforced by local water institutes. In this regard, water policy is uniform within the administrative domain of a water institute but may vary from one management area to another. The HRB thus represents an ideal test case for distributed water management policies using the proposed human-hydrological modeling framework.

The HRB exhibits a distinct alpine-oasis-desert landscape from the upstream to downstream sections of the basin. The upstream region is a mountainous area that receives water inputs from precipitation, frozen soil, glaciers, and snowmelt from the Qilian Mountains on the margin of the Qinghai-Tibetan Plateau (Liu et al., 2018). The midstream part of the basin is an agricultural oasis with intensive agriculture that consumes most of the water resources in the river basin. The Heihe River, which is the major SW resource in the watershed, originates from the Qilian Mountains and flows northward into two terminal lakes. The downstream area is an arid area with sparse vegetation and a poor ecosystem (Figure 3).

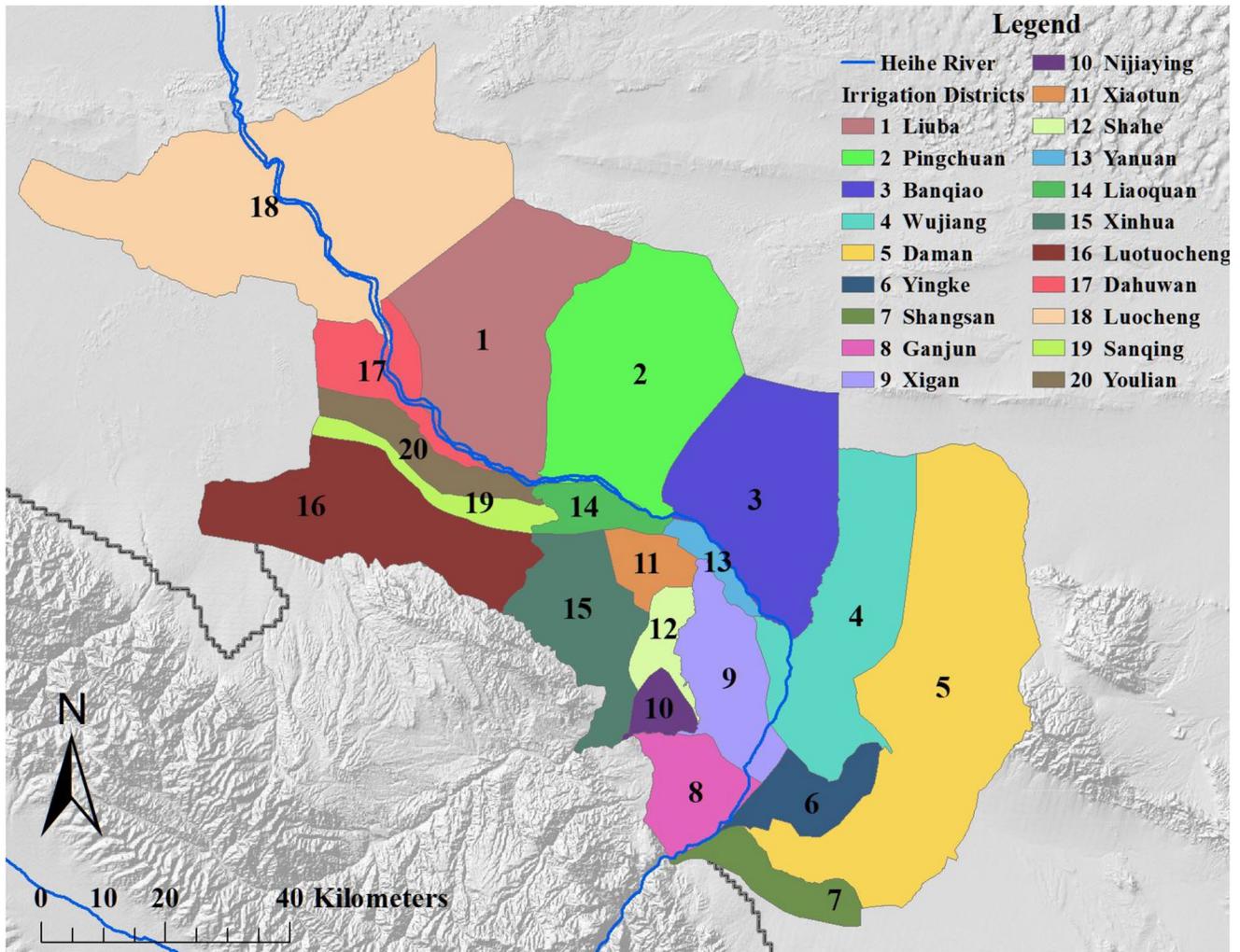
The midstream area of the HRB consists of 20 large irrigation districts (Figure 4). In the past several decades, the HRB has experienced intensive agricultural development (Hu, Lu, et al., 2015). For example, the area of irrigated cropland expanded by a factor of three, from 100,000 ha in the 1950s to 300,000 ha in the 2000s (T.



**Figure 3.** Map of the Heihe River Basin in China (the red line marks the boundary of the midstream area of the river basin).

Sun et al., 2016). The basin does not have a mechanism for retiring cropland from irrigation. The major planted crops in the HRB are corn and wheat, accounting for more than 80% of the cropland area. The basin is a semiarid area with annual precipitation of 189 mm, and most of the irrigation demands are satisfied by diverting SW from streamflow and by pumping GW from aquifers. Complicated agricultural infrastructures and irrigation canals have been constructed for water conveyance from water diversion gates to croplands in each irrigation district. The midstream area of the HRB is a heavily managed area where irrigation schedules are strictly regulated by local governments. The irrigation schedule is similar from year to year in each irrigation district but may vary from district to district.

The ecosystem downstream of the basin highly depends on the outflow from the midstream area of the HRB. However, decades of intensive water consumption in the midstream area have significantly depleted aquifers and reduced streamflow available to the downstream region, resulting in a series of ecological and environmental problems, such as salinization, desertification, the deterioration of ecosystems, and the shrinkage of the two-terminal lakes in the HRB (Li et al., 2018). To address this issue, the central government of China implemented a water allocation plan in the 2000s that specified the annual environmental flows to be maintained under different hydrological conditions. The water allocation regulation has reduced SW diversion from streams but, to some extent, encouraged unregulated GW pumping and exacerbated aquifer depletion issues in the midstream area of the HRB (Tian, Zheng, Wu, et al., 2015). Therefore, assessing the interaction between GW pumping, SW diversion, and the associated hydrological and environmental outcomes is imperative for supporting the effective management of water resources in the HRB. In this study, we specifically focus on testing whether it is feasible to

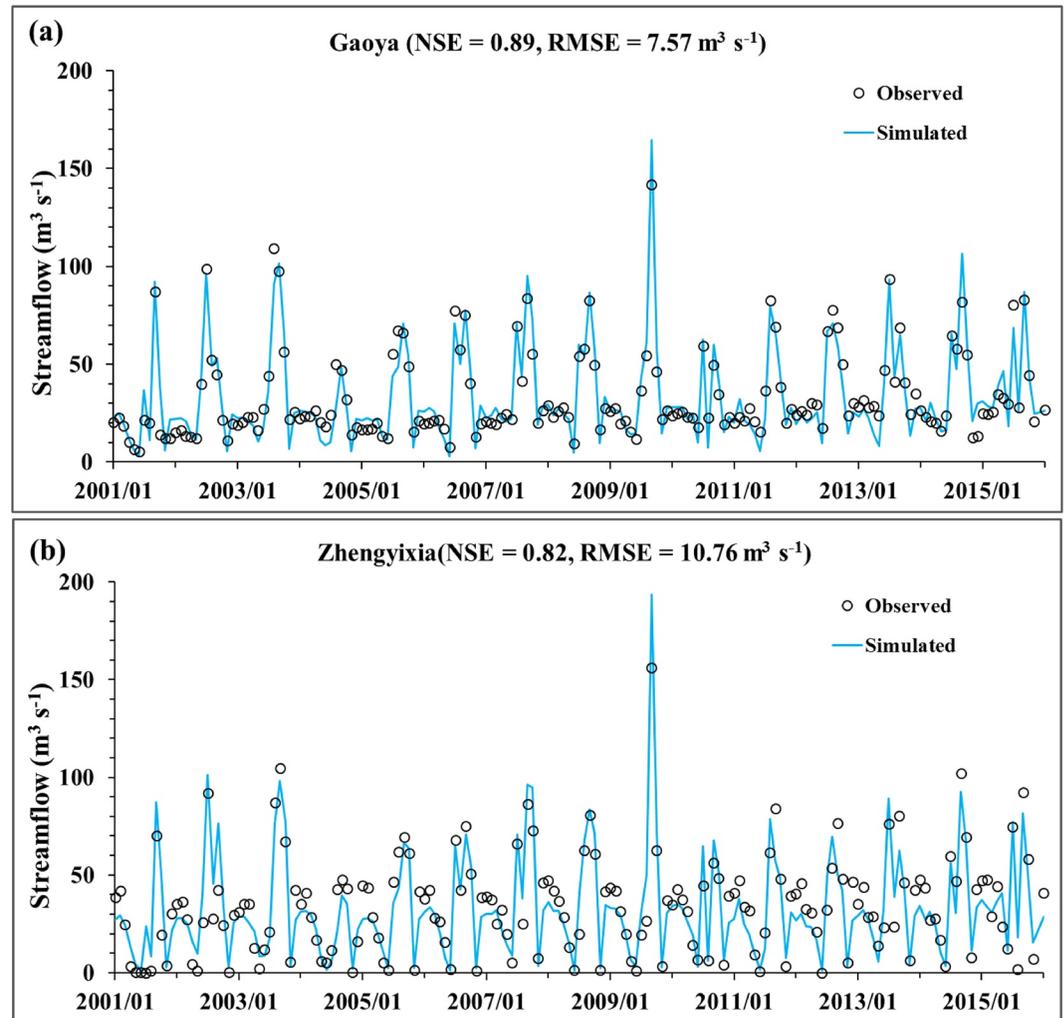


**Figure 4.** Map of the 20 irrigation districts in the midstream area of the Heihe River Basin (the boundary of the irrigation districts is marked with the red outline in Figure 3).

adjust the conjunctive use of SW and GW over time and across space to achieve improved hydrological outcomes (e.g., mitigation of water table drawdown and streamflow depletion) while still maintaining the total amount of irrigation water use.

### 3.2. Model Setup and Validation

Various types of data were collected to construct the model, including hydrological, land use, soil type, climate, meteorological, streamflow, borehole, aqueduct, and river network data. For a detailed list of the data used in the model setup, see Table S1 in Supporting Information S1. The model was validated by comparing the simulated and observed streamflows at the Gaoya and Zhengyixia gauging stations collected from the water authority of the HRB (Figure 5). The Nash-Sutcliffe efficiency values for the streamflows at the two gauging stations are 0.89 (Gaoya station) and 0.82 (Zhengyixia station), which are satisfactory values for watershed model validation (Moriasi et al., 2007). Simulated groundwater levels are compared and validated with observed groundwater levels in 47 monitoring wells across the river basin (illustrated by the red dots in Figure 3). Figure 6 presents the comparison of water table levels in three representative monitoring wells.

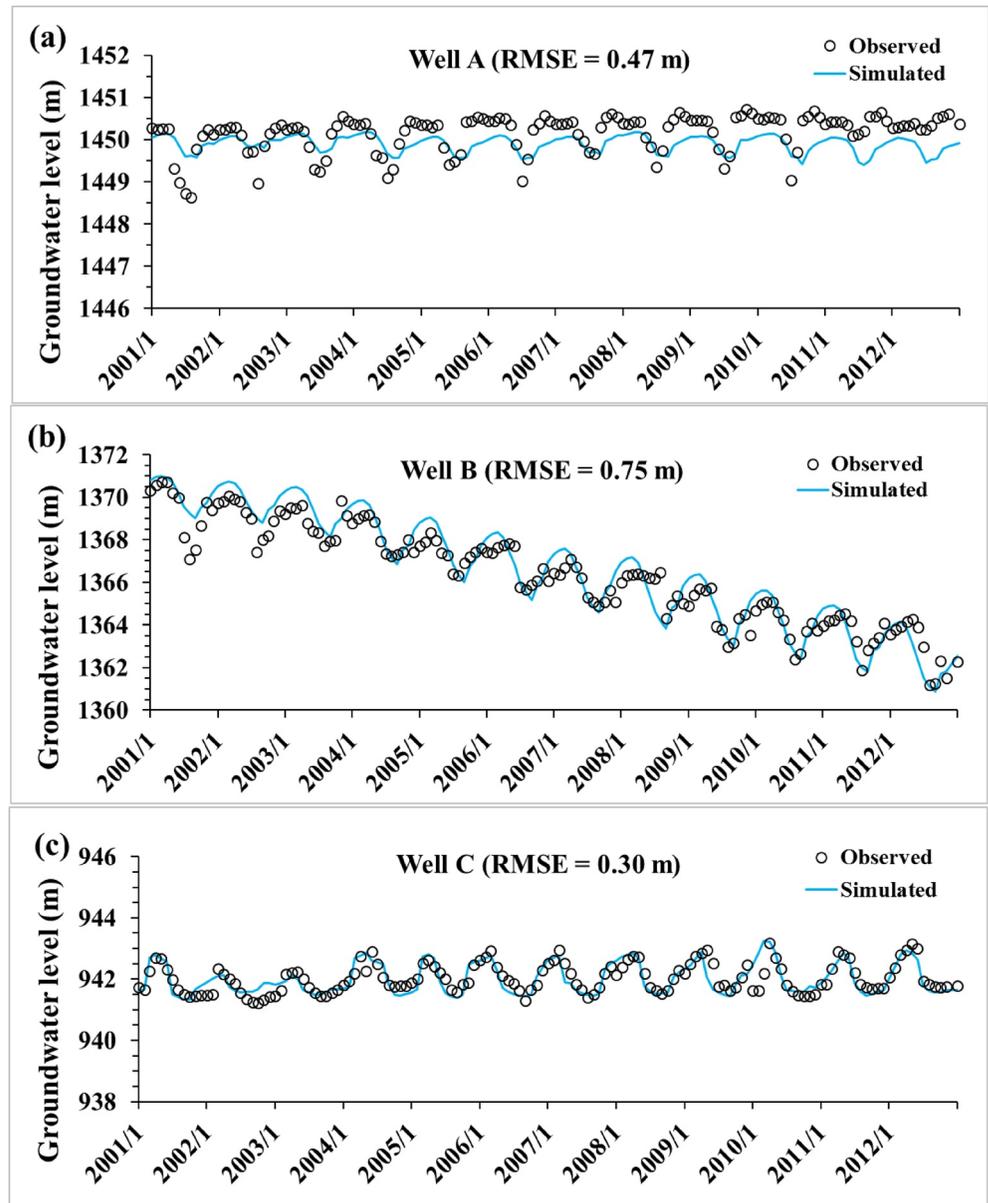


**Figure 5.** Simulated and observed streamflows at (a) the Gaoya gauging station and (b) the Zhengyixia gauging station in the Heihe River Basin.

### 3.3. Scenario Design for Distributed Water Policies

We apply a scenario-based analysis to explore the role of distributed water policies (in this case, water taxes) for river basin management in a 16-year simulation period (from 2001 to 2016). The SW tax  $\phi_{SW}$  is set at a constant rate of 0.2 RBM/m<sup>3</sup>, representing the current water pricing for SW diversion in the basin (note that 1 RBM is approximately 0.16 US dollars based on the currency exchange rate in 2021). In this study, the scenario of distributed water policy is represented by GW tax  $\phi_{GW}$ , given that the GW pricing plan has not been well implemented in the river basin. Spatial and temporal variations in the distributed water policies are set for each irrigation district and year, suggesting that the GW tax can vary from one irrigation district to another and from 1 year to another.

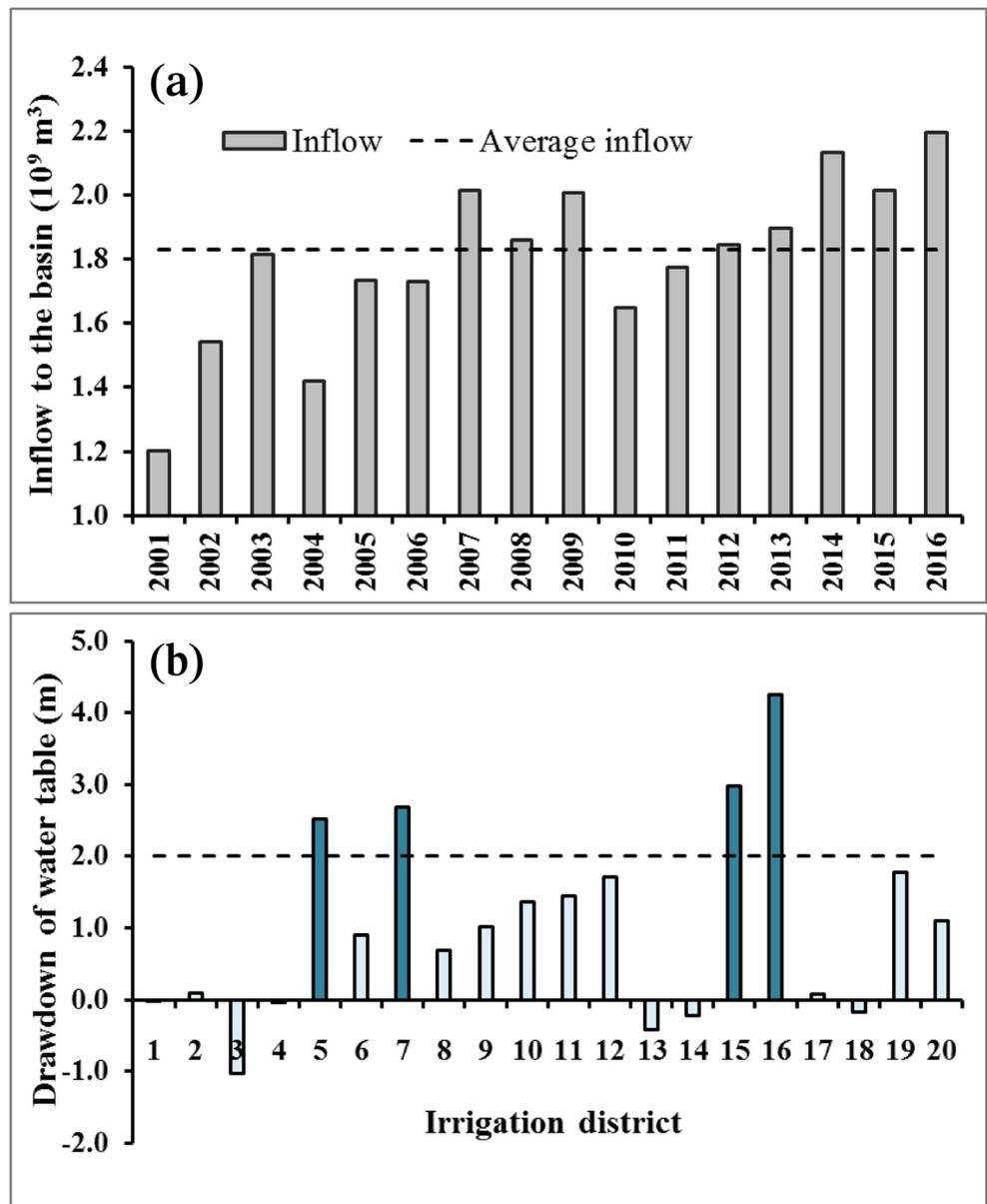
The design of distributed water policy scenarios is based on (a) inflow to the river basin in different years (with temporal variation) and (b) drawdown of the water table in different irrigation districts (with spatial variation). In terms of temporal variation of the basin's inflow, it is observed that two periods (2001–2006 and 2010–2011, totally 8 years) have inflows that are less than the average inflow, and they are classified as dry years in the 16-year simulation period. In contrast, the other two periods (2007–2009 and 2012–2016, 8 years in total) are classified as wet years with inflows greater than the average (Figure 7a). Therefore, tax rates for water use could vary between dry and wet years to reflect the temporally dynamic feature of the distributed water policies. In terms of spatial variation, four irrigation districts (5, 7, 15, and 16) experienced significantly higher levels of water table drawdown (>2 m) than the other 16 irrigation districts (Figure 7b). Therefore, the water taxes in these



**Figure 6.** Simulated and observed water table elevations at three monitoring wells.

four districts are set differently from those in the other 16 districts to reflect the spatially variant features of the distributed water policies.

In the modeling framework, each water manager (Type I agent) can implement a water tax in its administrative region based on local hydrological conditions. In this regard, in the case study site consisting of 20 irrigation districts, water taxes may vary from region to region and from year to year. Farmers (Type II agents) in each irrigation district will respond to the local management policies and adjust their surface water and groundwater use accordingly. Based on the spatial-temporal variations in hydrological conditions in the HRB, as discussed in the above section, we test four types of water policies (A, B, C, and D) to explore the role of distributed policies in the management of large river basins under the two-layer hierarchical water management scheme (Table 1). Among them, the type A policy represents the baseline, spatially uniform, and temporally fixed water management policy, in which a GW tax is uniformly applied in the river basin for the entire simulation period (i.e., all of the farmers in the study area have the same GW tax rate and the tax rate does not change over time). In comparison, the type B policy applies spatially uniform but temporally dynamic GW taxes in the watershed,



**Figure 7.** Spatial-temporal variations in hydrological conditions in the study area in terms of (a) inflow to the river basin and (b) drawdown of the water table in different irrigation districts from 2001 to 2016. Note that a positive value of water table drawdown means that the depth to water table increases from 2001 to 2016, whereas a negative value is indicative of a rise in water table elevation (i.e., the depth to water table decreases from 2001 to 2016).

considering the variation in water availabilities between dry and wet years. The type C policy applies spatially variant but temporally fixed GW taxes, considering the spatially heterogeneous hydrological conditions across the river basin. Finally, the type D policy applies spatially variant and temporally dynamic GW taxes in the river basin. For each of the four types of policies, a high and a low tax rate are assessed to reflect different levels of policy stringency for regulating GW abstraction. Detailed descriptions of the four types of water policies and the associated eight water management scenarios are presented in Table 1. The modeling results for the eight water management scenarios (A1, A2, B1, B2, C1, C2, D1, and D2) are presented in Section 4.

**Table 1**  
*Scenario Design for Water Management Policies in the Study Area*

Policy type	Scenario	Policy description
A: Spatially uniform, temporally fixed	A1	Baseline scenario, representing the historical water management condition in which a GW tax is not implemented in the river basin.
	A2	All of the water management agents in the river basin apply a high GW tax in the irrigation districts for the entire simulation period.
B: Spatially uniform, temporally dynamic	B1	All of the water management agents apply a low (high) GW tax <sup>a</sup> in the irrigation districts in wet (dry) years <sup>b</sup>
	B2	All of the water management agents apply a high (low) GW tax in the irrigation districts in wet (dry) years.
C: Spatially variant, temporally fixed	C1	In the irrigation districts with high (low) levels of water table drawdown <sup>c</sup> , the water management agents apply a low (high) GW tax for the entire simulation period.
	C2	In the irrigation districts with high (low) levels of water table drawdown, the water management agents apply a high (low) GW tax for the entire simulation period.
D: Spatially variant, temporally dynamic	D1	In the districts with high levels of water table drawdown, the water management agents apply a low GW tax for the entire simulation period. In the districts with low levels of water table drawdown, a low (high) GW tax is applied by the water management agents in wet (dry) years.
	D2	In the districts with high levels of water table drawdown, the water management agents apply a high GW tax for the entire simulation period. In the districts with low levels of water table drawdown, a high (low) GW tax is implemented by the water management agents in wet (dry) years.

<sup>a</sup>Low and high GW tax rates are set at 0.01 and 0.20 RMB/m<sup>3</sup>, respectively, ensuring that GW (SW) is farmers' primary water resource choice in the low (high) GW tax scenario. <sup>b</sup>Dry years (2001–2006 and 2010–2011) are the years in which inflows to the basin are less than the average inflow during the 16-year simulation period. The other 8 years (2007–2009 and 2012–2016) are considered as wet years. <sup>c</sup>Among the 20 irrigation districts, four of them (5, 7, 15, and 16) have noticeable higher levels of water table drawdown (>2 m) than the others.

## 4. Results

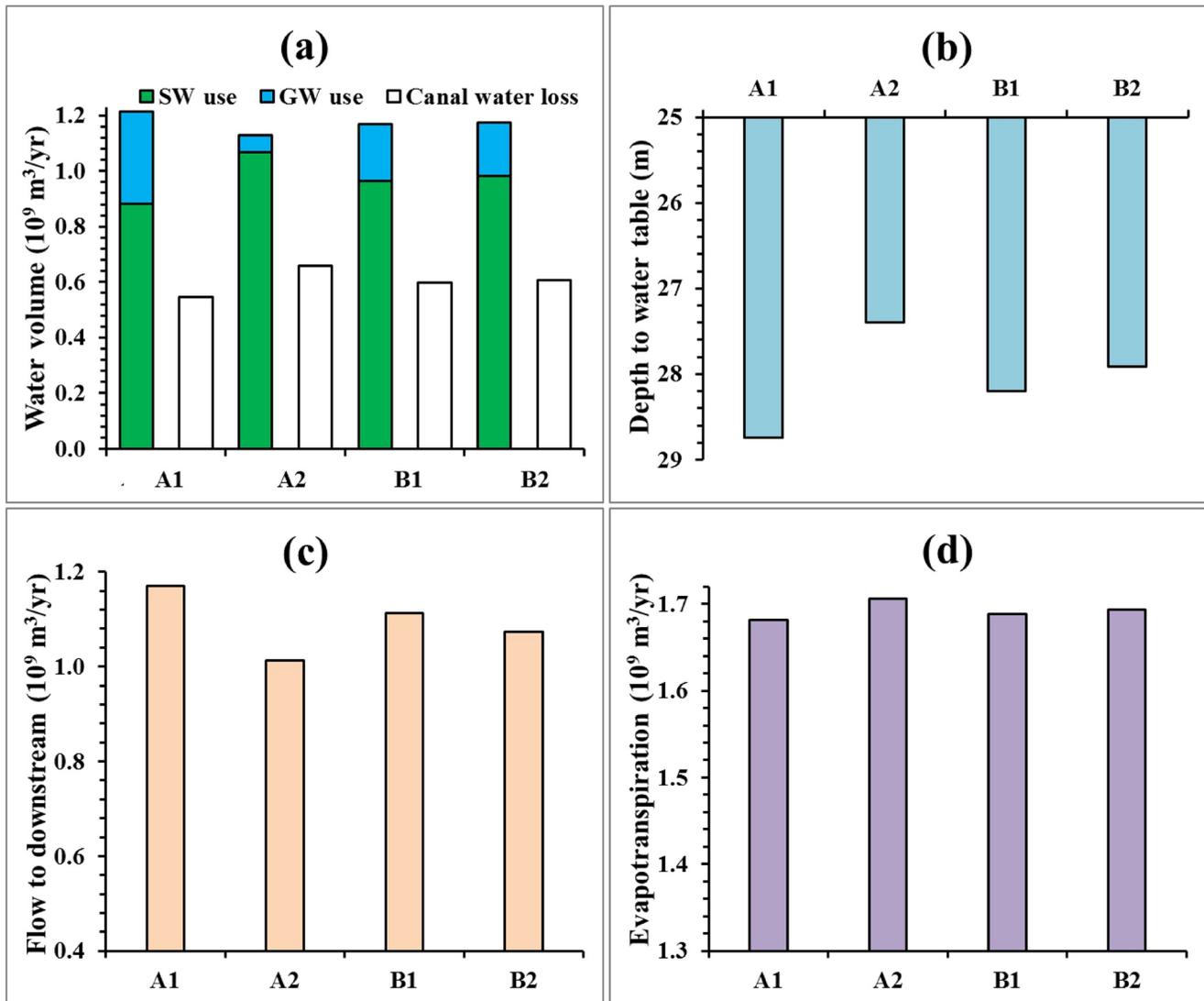
With the policy scenarios listed in Table 1, we run the model over a period from 2000 to 2016 at the daily time step under each scenario. Following our prior work on modeling hydrological processes in the study area (Tian, Zheng, Zheng, et al., 2015), the first year (2000) is used as a warm-up period to establish the initial soil conditions for the model, and the modeling results for 2000 are excluded from the analysis. Therefore, we only analyze the modeling results from 2001 to 2016 (a total of 16 years).

As introduced in the methodology section, the proposed distributed policy scheme enables a GW tax to vary over time and across different districts in the river basin. Policy scenarios with different GW taxes change the fractions of SW and GW use, which results in different hydrological outcomes. The following sections present the primary modeling results.

### 4.1. Impacts of Water Policies on Hydrological Outcomes at the River Basin Scale

This section analyzes the modeling results of A1 (the scenario with a low GW tax) and A2 (the scenario with a high GW tax) to assess the role of the GW tax as a policy instrument for water resource management. The following model outputs are presented at the river basin scale: the conjunctive use of SW and GW, the depth to water table, the outflow for ecosystem conservation downstream, and total evapotranspiration.

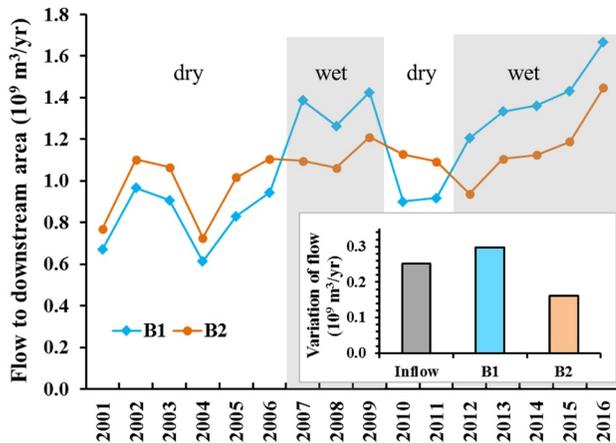
Figure 8 shows that applying a high GW tax in the HRB results in (a) an increase in SW diversion and the consequent increase in water loss in irrigation canals, (b) a decrease in the amount of river flow to downstream



**Figure 8.** Comparison of the four water policy scenarios in terms of (a) the amount of surface water and groundwater used for farmland irrigation and water loss during conveyance in irrigation canals, (b) depth to water table, (c) flow to the downstream area of the Heihe River Basin, and (d) total evapotranspiration of the 20 irrigation districts.

areas, and (c) a rise in the water table (corresponding to less aquifer depletion). The impacts of the GW tax on the conjunctive use of SW and GW in each year are provided in Figure S1 in Supporting Information S1. These results show that it is effective to use a GW tax as a policy instrument to regulate farmers' conjunctive use of SW and GW and to mitigate unintended hydrological consequences of water consumption (e.g., aquifer depletion). For example, by shifting the policy from A1 (the low GW tax scenario) to A2 (the high GW tax scenario), GW use is reduced from 0.33 billion  $\text{m}^3/\text{year}$  to 0.06 billion  $\text{m}^3/\text{year}$ , thereby decreasing the depth to the water table from 28.7 to 27.4 m. In other words, a rise in the water table by 1.3 m can be achieved if a high GW tax is strictly implemented in the basin to reduce farmers' GW abstraction. However, with a high GW tax implemented in the basin, SW becomes a less costly water resource than GW. As a result, SW diversion increases from 1.43 billion  $\text{m}^3/\text{year}$  for A1 to 1.73 billion  $\text{m}^3/\text{year}$  for A2, and the annual average streamflow to the downstream area of the basin is presented in Figure S2 in Supporting Information S1).

The comparison of the modeling results between A1 and A2 suggests that there is a strong trade-off between aquifer conservation in the midstream area and ecological conservation in the downstream area of the HRB. On



**Figure 9.** Flow to the downstream area of the Heihe River Basin from 2001 to 2016 (the main figure) and the variation in river flow (the embedded figure).

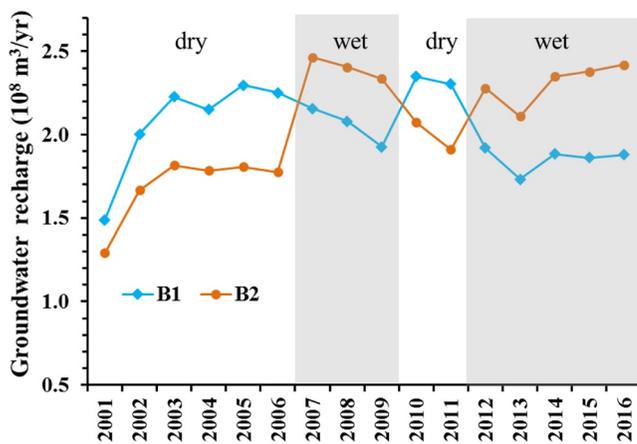
the one hand, implementing a high GW tax can reduce GW pumping and mitigate aquifer depletion in the midstream area, but the associated increase in SW diversion can exacerbate water shortages in the downstream area due to reduced river flow. On the other hand, implementing a low GW tax could exacerbate unregulated GW abstraction and the consequent depleted aquifer issue in the midstream area, but as a result, more river flow will be available for ecological conservation downstream. Policy makers can adjust GW taxes to address water conflicts between the midstream and downstream areas. Importantly, we find that implementing a high GW tax in the basin will not noticeably affect the total water use because the reduction in GW use is offset by the increased use of SW, and vice versa. Therefore, there are no noticeable differences in terms of total water applied to the farmland and total evapotranspiration between A1 and A2 (Figure 8d).

#### 4.2. Temporally Dynamic Policies and Hydrological Impacts at the River Basin Scale

The above section has analyzed the modeling results of spatially uniform and temporally fixed policies (A1 and A2) in which a GW tax does not change over time. This section focuses on assessing the hydrological impacts of temporally dynamic water policies (B1 and B2) in which a GW tax is uniformly applied in the basin but the tax rate changes over time based on the inflow to the basin. As noted previously, B1 and B2 both implement a high/low GW tax for a total of eight years in the 16-year simulation period. However, B1 applies a high GW tax in the dry years (2001-2006 and 2010-2011) and a low GW tax in the wet years (2007-2009 and 2012-2016). In contrast, B2 applies a low GW tax in dry years and a high GW tax in wet years. We find that the modeling results between B1 and B2 are different although the two policy scenarios have the same length of the high GW period (8 years). Specifically, at the river basin scale, the changes in annual average water use and the consequent hydrological outcomes from B1 to B2 are 0.4% for total water use (a decrease of  $1.4 \times 10^7$  m<sup>3</sup> for GW use and an increase of  $1.9 \times 10^7$  m<sup>3</sup> for SW), 0.3% for total evapotranspiration, -3.6% for the flow to downstream areas, and -0.9% for the depth to the water table. A comparison between B1 and B2 suggests that improved hydrological outcomes can be achieved by adjusting the specific time window of the high GW tax from dry to wet years (e.g., increase GW pumping/reduce SW diversion during dry years when streamflow is scarce), but the differences in the hydrological outcomes between B1 and B2 are not significant at the river basin scale (Section 4.3 will narrow down the analysis scope from the basin scale to the irrigation district scale for assessing the spatially heterogeneous hydrological impacts).

Temporally dynamic water management policies can significantly affect GW and SW hydrological processes in a river basin over time. First, influenced by the variation in the GW tax rate between dry and wet years, the fractions of SW and GW use will change over time, which can further affect river flow regimes. Recall that B1 applies a high GW tax in the dry years and a low GW tax in the wet years (B2 applies a low GW tax in the dry years and a high GW tax in the wet years). As expected, in the dry years, more SW is diverted from the river for B1 than B2 (Figure S1 in Supporting Information S1), and the flow to the downstream areas for B1 is smaller than that for B2 (Figure 9). In contrast, in the wet years, B2 diverts more water from the river than B1, and the flow to the downstream areas for B2 is smaller than B1. Because B1 increases SW diversion during dry years and reduces SW diversion during wet years, the variation in the flow to the downstream area is, therefore, larger than the inflow variation. In contrast, B2 has a small variation in river flow for ecological conservation downstream because B2 increases (reduces) SW diversion during wet (dry) years (Figure 9).

Second, changes in the conjunctive use of SW and GW, due to the variation in the GW tax rate over time, can also affect SW-GW interactions, which are illustrated here by the differences in GW recharge rates between dry and wet years. As shown in Figure 10, the GW recharge rate for B1 is larger than that for B2 in the dry years (2001-2006 and 2010-2011). This is because the amount of SW diversion and the consequent seepage loss due to percolation in irrigation canals for B1 is larger than those for B2 during dry years (Figure S3 in Supporting Information S1). In contrast, B1 has a smaller GW recharge rate than B2 due to reduced percolation from irrigation canals during wet years (2007-2009 and 2012-2016). These modeling results can provide some policy implications to enhance water management in large river basins between dry and wet years, which will be discussed in Section 5.



**Figure 10.** Comparison of groundwater recharge for policy scenarios B1 and B2.

### 4.3. Spatially Heterogeneous Impacts of Temporally Dynamic Water Policies

In the above sections, the modeling results are analyzed at the river basin scale. However, large river basins typically exhibit significant spatial heterogeneities in physical and socioeconomic conditions, resulting in spatially variant hydrological responses to a water policy. Instead of analyzing hydrological outcomes at the river basin scale (Sections 4.1 and 4.2), this section focuses on assessing the spatially heterogeneous hydrological impacts at different locations (irrigation districts) in the river basin under temporally dynamic policy scenarios. We first analyze the fractions of SW and GW use in the 20 irrigation districts under policy scenarios B1 and B2. Overall, at the river basin scale, GW accounts for 17.5% of the total water use under policy scenario B1. However, the reliance on the two sources of water (SW and GW) is highly spatially heterogeneous in the study area (Figure 11). Some irrigation districts highly depend on SW for irrigation, while others depend on GW. For example, among the 20 irrigation districts, districts 7 and 8 highly rely on SW because these two districts have deep water tables (>100 m). The high pumping cost in these areas makes SW the most economic resource available.

In comparison, districts 12 and 17 have shallow water tables (<20 m) and thus consume large portions of GW due to the low GW pumping costs (Figure 11a). Spatial heterogeneity can also be observed in the impacts of temporally dynamic water policies on changes in the conjunctive use of SW and GW among the 20 irrigation districts. Figure 11b compares the change in GW use fractions from B1 to B2. If a high GW tax is implemented in wet years instead of dry years (from B1 to B2), the fraction of GW use will be reduced at the river basin level, but the change in the GW use fraction varies significantly among the districts. For regions with deep water tables (e.g., districts 7 and 8), SW is the dominant source of water due to the high GW pumping cost; therefore, the change in GW policies from B1 to B2 does not affect the GW use fraction. In contrast, the irrigation districts with shallow water tables (e.g., districts 12 and 17) will experience a significant reduction in the GW use fraction from B1 to B2.

Next, we explore the impacts of temporally dynamic water policies on the depth to the water table, an important hydrological indicator associated with aquifer depletion problems in the case study area. Before we discuss the modeling results, it is important to note that the depth to water table (DWT) is the depth between land surface and water table, while the drawdown of the water table is the change of DWT by comparing aquifer conditions in a time period. In this regard, the drawdown of the water table can be either a positive or a negative value. For example, a positive value of the water table drawdown is indicative of an increase in the depth to the water table, while a negative value indicates that water table elevation rises due to groundwater recharge.

Figure 12a presents the spatial distribution of DWT in the 20 irrigation districts under the policy scenario B1. The DWT is higher in the upstream portion of the watershed (e.g., districts 7 and 8, which are close to mountainous areas) and in regions that are far from the Heihe River (e.g., districts 5 and 16). Notably, regions located downstream and near the Heihe River typically have shallow water tables (e.g., districts 14, 20, and 18). A comparison of the modeling results shows that, almost universally across the watershed, the DWT decreases when the water policy shifts from B1 to B2 (Figure 12b). For example, the depth to the water table in district 16 decreases by 0.9 m (a rise in the water table by 0.9 m) from B1 to B2, indicative of a significant hydrological improvement in terms of aquifer conservation. However, some districts (e.g., districts 13 and 14) do not exhibit such a significant hydrological improvement from B1 to B2, mainly because district 16 experiences a larger reduction in GW use fraction than districts 13 and 14. Furthermore, district 16 is far from the Heihe River and the GW recharge from the river is slow, while districts 13 and 14, which are close to the Heihe River, can receive rapid SW recharge to offset pumping-induced GW depletion. The comparison between B1 and B2 suggests that it is most effective to mitigate water table drawdown if a stringent GW policy (a high GW tax) is enforced during the wet years in the 16-year management period.

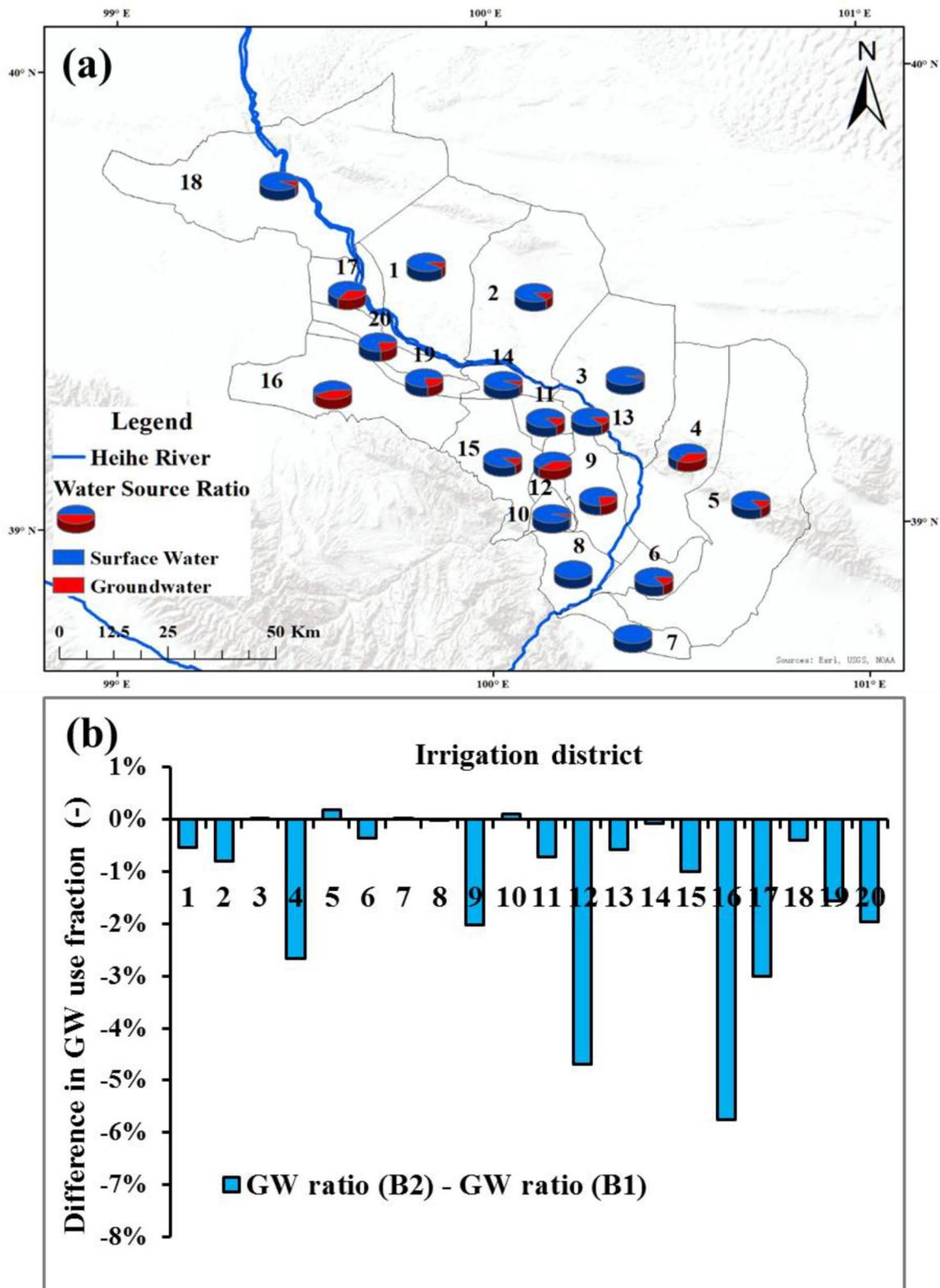
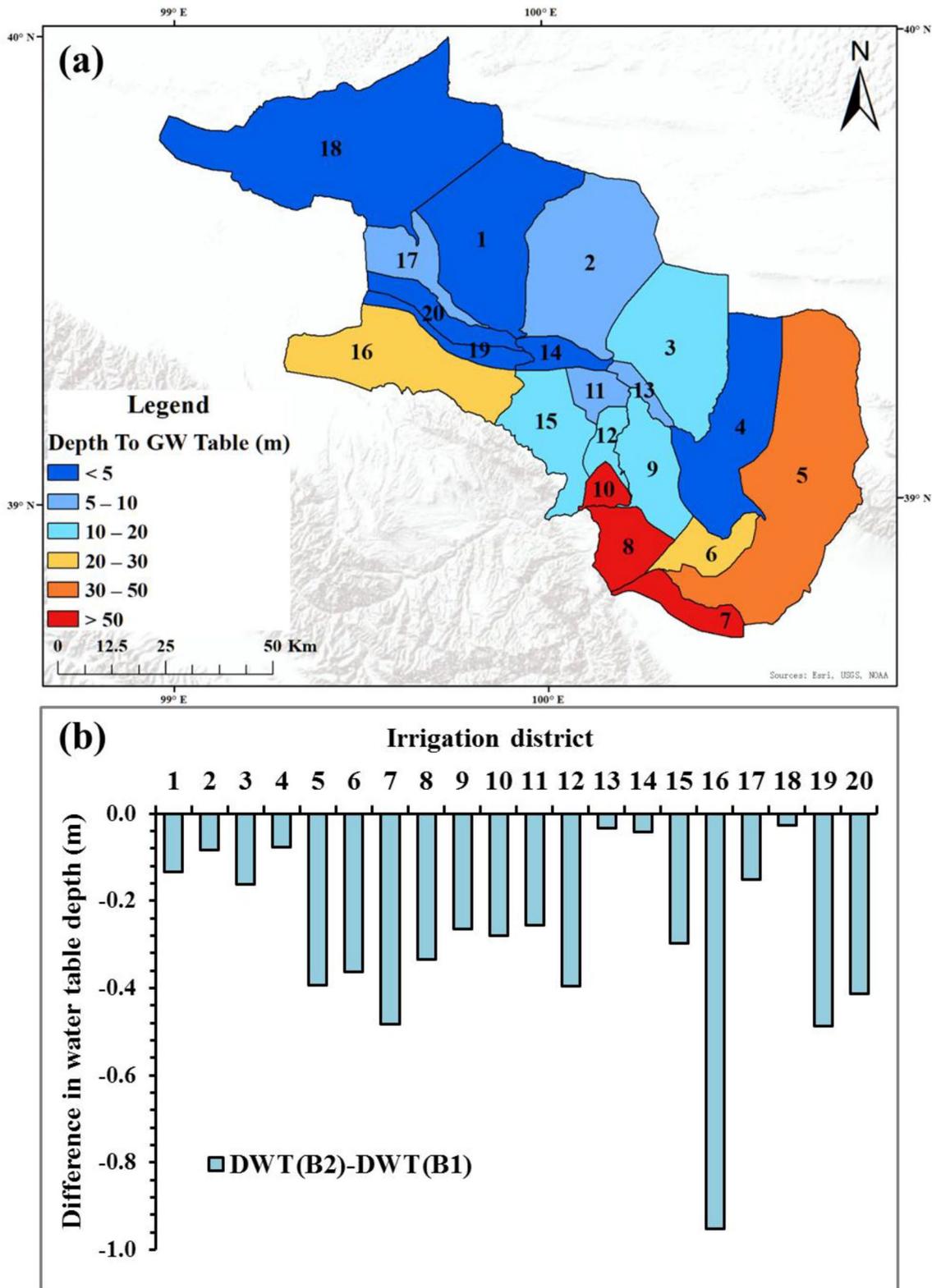
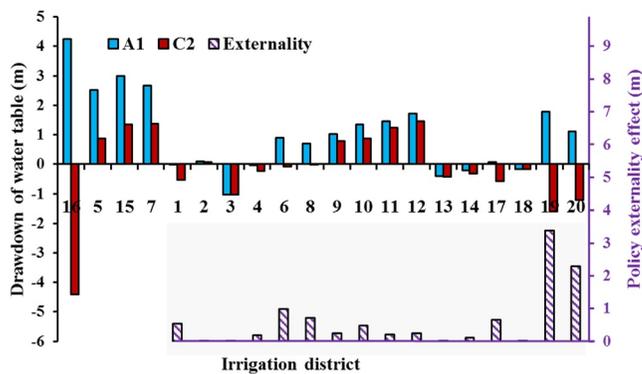


Figure 11. (a) The fractions of groundwater and surface water use under policy scenario B1 and (b) the change in GW use fraction from B1 to B2.



**Figure 12.** (a) The depth to water table under policy scenario B1, and (b) the difference in water table depth between B1 to B2. Note that a negative value for the difference in water table depth means that water table elevation for B2 is higher than B1.



**Figure 13.** Water table drawdowns from 2001 to 2016 in the 20 irrigation districts under policy scenarios A1 and C2. Note that four irrigation districts (16, 5, 15, and 7) implement a high groundwater (GW) tax for C2. The other districts implement a low GW tax in both policy scenarios.

#### 4.4. Impacts of Spatially Variable Policies and Policy Externality Analysis

The above two sections (Sections 4.2 and 4.3) explore the hydrological impacts of temporally dynamic policies (B1 and B2). In this section, we compare the type A and type C policies to assess the role of spatially variable policies for water management in the river basin, where some irrigation districts have a higher/lower GW tax rate than others.

Under policy scenario A1, a low GW tax is uniformly applied in the river basin, which encourages GW pumping and thereby results in a high level of water table drawdown. However, some districts (e.g., 16, 5, 15, and 7) experience a higher level of water table drawdown (>2.5 m) than others (Figure 13). Based on the differences in the water table drawdown in the 20 districts under policy scenario A1, policy scenario C2 includes spatially variable water policies that apply different GW tax rates across the river basin. Specifically, C2 implements a high GW tax in four districts (16, 5, 15, and 7) with high water table drawdowns while maintaining a low GW tax in the other 16 districts. Figure 13 compares water table drawdowns in the 20

irrigation districts between A1 and C2. As expected, the high GW tax under C2 effectively reduces water table drawdowns in the four irrigation districts (16, 5, 15, and 7) due to the high GW tax. For example, the water table drawdown in district 16 is a negative value (−4.4 m) for C2, indicating that the water table in this region can rise by 4.4 m if the high GW tax is implemented.

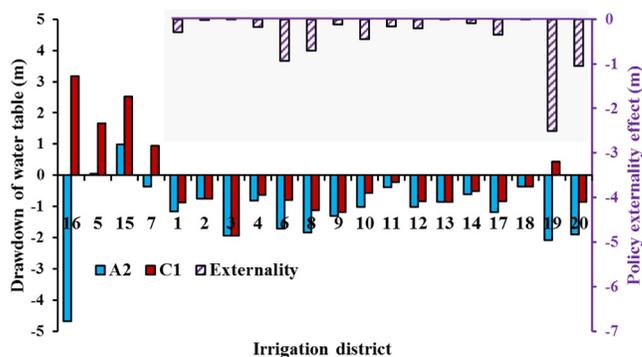
Importantly, significant policy externality effects can be identified and quantified by comparing the spatially uniform policy (A1) and the spatially variable policy (C2). Note that a high GW tax is implemented in only four districts (16, 5, 15, and 7) in C2 (A1 and C2 both implement a low GW tax in the other 16 districts). We can see that the water table drawdowns in the other 16 districts vary due to the changes in water policy in the four districts (positive externality effects). For example, the water table in districts 19 and 20 rises because their neighboring districts (e.g., 15 and 16) apply a high GW tax for C2. In other words, districts 19 and 20 are “free riders” under this circumstance, benefiting from the restrictions on GW pumping in their neighboring districts. In this regard, the stringent GW regulation can be relaxed in these districts without causing aquifer depletion due to hydrological connectivity, as long as the neighboring districts enforce the stringent GW policy.

Contrary to the free rider problem discussed above, Figure 14 presents the case in which some irrigation districts are adversely affected by the extensive pumping of aquifers in neighboring districts (negative externality effects). Policy scenario A2 implements a high GW tax uniformly in all 20 districts, resulting in a rise in the water table in most regions (the negative values for water table drawdown are shown in Figure 14). However, policy scenario C1 considers the case in which four districts (16, 5, 15, and 7) relax the stringent GW policy and the other 16 districts

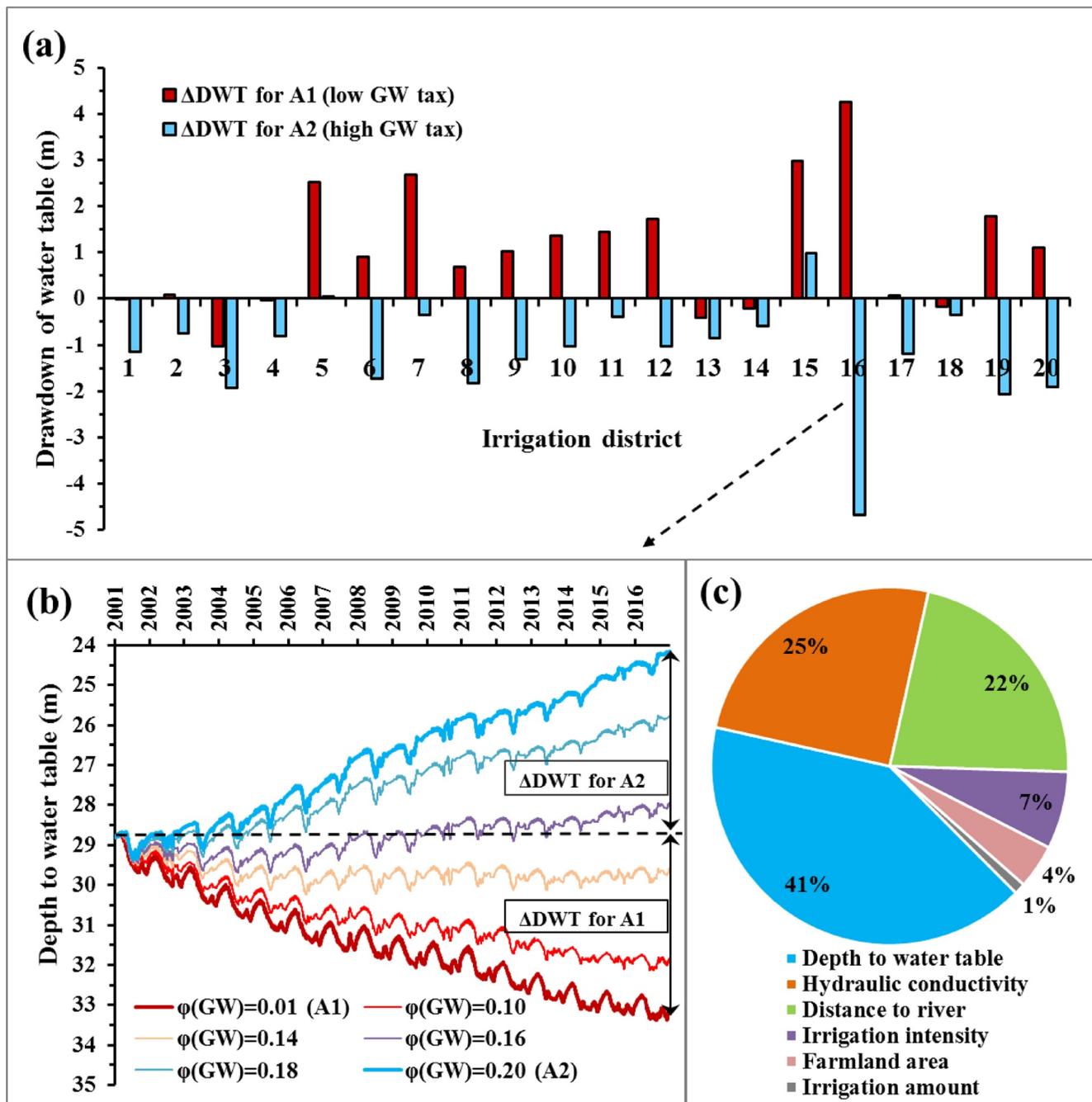
implement the high GW tax. By comparing water table drawdowns between A2 and C1, we find that the increased GW abstractions in these four districts not only deplete aquifers in these districts but also result in an increase in water table drawdowns in the other 16 districts (Figure 14). In this regard, these four irrigation districts should take some responsibility for the water table drawdowns in the other 16 districts. To resolve this adverse policy externality issue, basin planners could impose stricter GW regulations in these four districts to avoid GW overexploitation. Some policy and modeling implications associated with the externality analyses will be discussed in the next section.

#### 4.5. Identifying the Key Drivers That Affect Hydrological Impacts of Water Policies

The above sections have demonstrated that hydrological responses to a water policy could exhibit significant spatial heterogeneity across the river basin. In this section, we explore the following question that warrants investigation before implementing a water policy in a particular area: What are the key



**Figure 14.** Water table drawdowns from 2001 to 2016 in the 20 irrigation districts under policy scenarios A2 and C1. Note that low groundwater (GW) tax is implemented in four districts (16, 5, 15, and 7) under policy scenario C1. The other 16 districts enforce a high GW tax in both scenarios.



**Figure 15.** (a) The extent of water table fluctuations as a response to various water policies; (b) water table fluctuations in irrigation district 16 under various groundwater tax scenarios; (c) the relative importance of the key variables that affect hydrological responses.

drivers that affect hydrological responses to a water policy? With the integrated modeling framework presented in this study, we use the water table as an example to address this question by evaluating water table fluctuations under various water policies (e.g., GW tax). First, using a particular irrigation district (district 16) as an example, Figure 15b plots the water table fluctuations from 2001 to 2016 under various policy scenarios, with the GW tax varying from 0.01 RMB/m<sup>3</sup> to 0.20 RMB/m<sup>3</sup>. The result shows that, in general, the water table will rise as the GW tax increases. At the end of the 16-year management period, this irrigation district is expected to experience a drawdown of the water table by 4.25 m under the low GW tax scenario but a rise in the water table by 4.67 m

under the high GW tax scenario. Therefore, the GW policy has the potential to affect the water table by 8.92 m in this region within the 16-year management period.

Next, following the analysis of irrigation district 16, Figure 15a presents the ranges of water table fluctuations in all 20 irrigation districts. The results show that the water table drawdown from 2001 to 2016 varies greatly between the low and high GW tax scenarios, and the water table fluctuations in the 20 districts can be categorized into two patterns. The first pattern is that the water table declines under the low GW tax scenario but rises under the high GW tax scenario. This pattern applies to most of the irrigation districts (e.g., districts 16, 19, 20, 12, 6, and 8), which suggests that in most of the irrigation districts, the aquifer depletion issue can be resolved if a stringent GW policy is implemented. The other pattern shows that the water table either rises (e.g., districts 3 and 12) or declines (e.g., districts 5 and 15) under the various policies. In these districts, adjusting the GW tax is not able to reverse the trend of water table fluctuations, but the degree of water table fluctuations can be mitigated.

Finally, based on the heterogeneous hydrological responses to various water policies in different irrigation districts as shown in Figure 15a, we examine the relative importance of the following aquifer properties that may affect the hydrological responses to water policies: the depth to the water table, the distance to rivers, hydraulic conductivity, the farmland area, the total volume of irrigation, and the per-area irrigation intensity. The Akaike information criterion method for variable importance analysis is applied (Hughes & King, 2003; Snipes & Taylor, 2014), and the relative importance of each factor that influences the hydrological responses are presented in Figure 15c. The results show that the extent of the hydrological response to water policies is mainly controlled by the following three variables: the depth to the water table, the distance to rivers, and hydraulic conductivity. The results agree with common knowledge of subsurface hydrological processes and SW-GW interactions in semiarid river basins. For example, the depth to the water table is an important factor in determining the GW pumping cost and therefore has a significant influence on GW use and the consequent water table drawdowns. The distance to rivers and hydraulic conductivity can affect the GW flow process and the interactions between SW and GW. Irrigation districts that are close to rivers typically can receive more rapid SW recharge from streamflow than those that are far from rivers. Therefore, GW pumping will have less impact on water table drawdown in districts that are close to rivers due to rapid SW-GW exchange.

## 5. Discussion

### 5.1. Implications for Distributed Policies to Support Water Management

This study proposes a distributed policy design scheme featuring spatially variable and temporally dynamic policies in large river basins. Based on the modeling results of various water policies (e.g., tax rate on water use) presented in the above sections, several implications are obtained and discussed by using the proposed distributed policy design scheme to support the management of large river basins.

First, the analyses of hydrological responses to temporally dynamic policies highlight the importance of adjusting water policies between wet and dry years to enhance water resource management. In a conjunctive SW-GW system, the water volume from river flow and aquifer could exhibit significant annual and/or seasonal variability. It is therefore necessary for basin managers to adjust GW and SW policies to achieve improved hydrological and environmental outcomes (B. Wu et al., 2015; X. Wu et al., 2015). For example, during wet years when river flow is abundant, a stringent GW policy can be implemented (e.g., apply a high GW tax in the river basin) to increase SW diversion and reduce GW abstraction. However, during dry years when river flow is scarce, the stringent GW policy should be revised (e.g., apply a low GW tax) to increase GW abstraction and reduce SW diversion. The modeling results in this study show that by shifting the implementation of a high GW tax from dry years (with less river flow) to wet years (with more river flow), aquifer depletion issues could be mitigated without adversely affecting the total water supply. Furthermore, such policy adjustment can reduce the variation and uncertainty in water availability to the downstream area of the basin. The important role played by adjusting the time window in policy implementation was also evidenced by a recent study that compared soft and hard water use constraints for GW management in the Republican River Basin of the United States (Young et al., 2021). Hydrological outcomes can be changed by adjusting water policies between dry and wet years. Water managers can be informed by hydroclimatic forecasts, based on which they decide the level of water tax that varies between a dry and a wet year. However, such long-term weather forecasts are typically subjected to large uncertainty. Studies may incorporate an inflow prediction model into the proposed model to conduct in-depth work in this research direction.

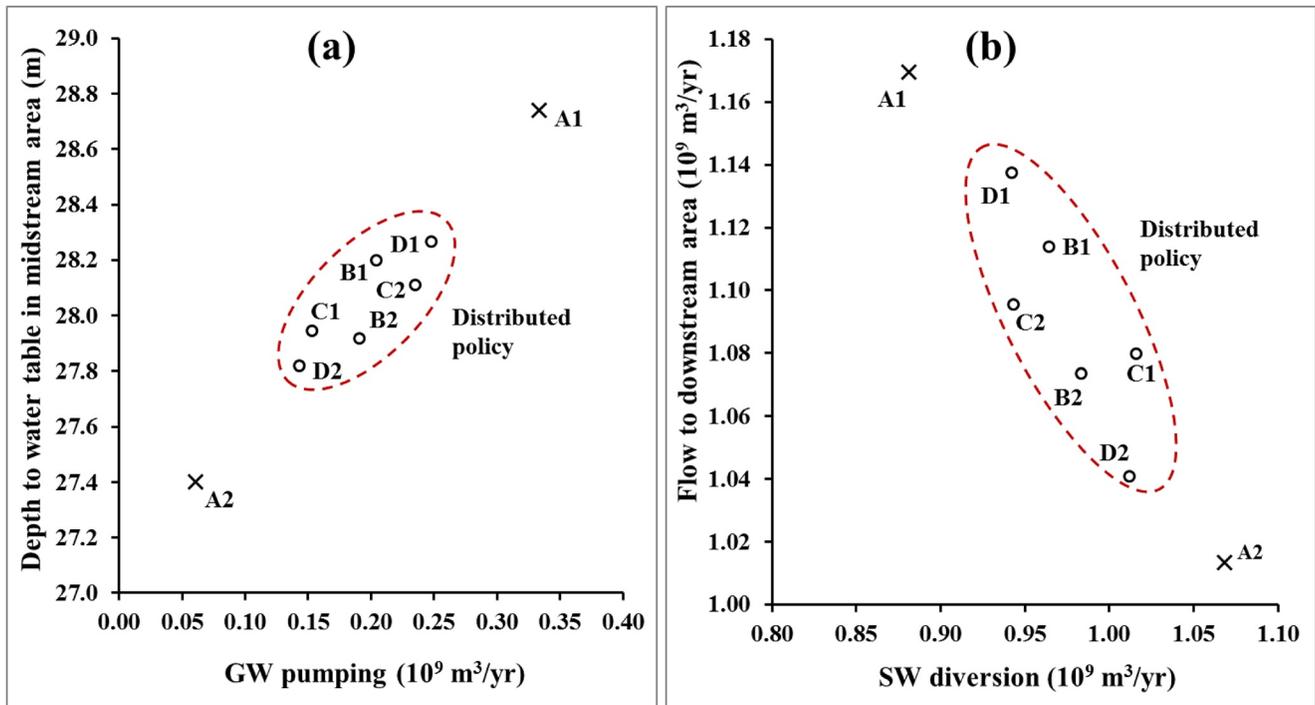
Second, the spatially heterogeneous hydrological responses across the river basin highlight the importance of understanding local (e.g., at the irrigation district level) hydrological responses to a water policy, which can be used by basin managers to improve location-dependent policy design. Given that policy implementation is typically associated with various institutional costs, to meet a particular management goal, it would be more effective to implement a policy in regions with more intensive hydrological responses to the policy. For example, our analysis shows that the depth to the water table in some irrigation districts (e.g., 16 and 19) responds more actively to water policies than other districts (e.g., 13 and 14) when a low GW tax rate is adjusted to a high GW tax rate (Figure S5 in Supporting Information S1). In this regard, in the HRB, it is better to implement stringent water policies in districts 16 and 19 than in districts 13 and 14 if the management goal is to mitigate aquifer depletion issues. Furthermore, the heterogeneous hydrological responses among different regions emphasize the importance of performance evaluation before implementing a policy in a particular region because an effective policy in one district might not work as well as expected when implemented in another district, and vice versa (Du et al., 2020; Hrozencik et al., 2017). Basin managers need to scrutinize the factors that could affect policy performance. Our analyses indicate that the distance to rivers, hydraulic conductivity, and depth to the water table are among the most important factors that could affect the aquifer depletion outcomes of a water policy. These modeling results could be used to support policy design and assessment before a particular water management policy is actually applied in the watershed.

Third, the modeling results regarding policy externality analyses emphasize the importance of accounting for hydrological externality effects among nearby regions and/or water users to support coordinated water management. In a river basin with a large number of water users, water table drawdown in a particular area could be affected by multiple water users' GW pumping activities and even by those who are located out of the area due to hydrological connectivity in surface and subsurface systems (Bracken et al., 2013; Pringle, 2003). GW abstraction may also lead to river flow reduction in nearby streams. Such hydrological externality effects between water users have led to conflicts of interest in many water management practices worldwide (Kuwayama & Brozović, 2013). River basin managers, therefore, need to account for these hydrological externality effects when designing policies to regulate stakeholders' water abstractions. For example, in our studied river basin, four irrigation districts (5, 7, 15, and 16) among the 20 irrigation districts could experience high levels of water table drawdown (>2 m) if an aquifer conservation policy (e.g., GW tax) is not strictly implemented. However, the modeling results show that implementing a stringent aquifer conservation policy (e.g., a high GW tax) only in these four districts would not be able to achieve maximum potential reductions in water table drawdown if their nearby districts do not take active actions to restrict GW pumping (Figure S6 in Supporting Information S1). This is because water table drawdowns in these districts could be affected and exacerbated by GW pumping in their nearby areas. In this regard, a high GW tax should be implemented not only in these four districts but also in their nearby areas to achieve ideal hydrological outcomes. From a hydrological connectivity perspective, considering that these districts share some degree of responsibility for aquifer depletion issues in their nearby districts, they should receive an incentive for aquifer depletion mitigation and/or penalization for aquifer depletion exacerbation in their nearby areas. In this study, the explicit quantification of hydrological externality effects, as shown by Figures 13 and 14, can be used to determine the degrees of incentives or penalties to be imposed on each irrigation district, supporting the design of more equitable and mutually acceptable policies for coordinated water management.

## 5.2. Model Implications for Integrated Model Development

As noted previously, a rich body of literature has integrated ABM and hydrological models to examine the role of uniform policies (e.g., taxes and/or quotas for water use) for water resource management, focusing on the management of GW resources (Hu, Cai, et al., 2015; Khan & Brown, 2019; Lei et al., 2019; Mulligan et al., 2014; Noël & Cai, 2017). In this study, we propose a distributed policy design scheme featuring spatially variant and temporally dynamic policies for integrated SW and GW management. By incorporating the distributed policy design scheme into a coupled ABM and HEIFLOW model, a number of unique functionalities and benefits of our modeling framework are demonstrated through the case study in the HRB, which can provide some implications for future model development for water resource management.

First, by using the distributed policy scheme to adjust water policies between dry and wet years and across irrigation districts, our modeling results show that improved hydrological outcomes (e.g., mitigation of aquifer depletion) can be achieved without reducing the total water supply for agricultural irrigation. This model functionality



**Figure 16.** Distributed water policy to regulate conjunctive surface water-groundwater use and (a) depth to water table in the midstream area of the Heihe River Basin (HRB) and (b) flow to the downstream area of the HRB.

has the potential to address the challenge of improving the environment and ecosystems while ensuring that water-related economic and social benefits are not adversely affected (Loucks, 2006). Furthermore, the comparison of hydrological impacts of spatially variant policies can explicitly quantify hydrological externality effects among nearby irrigation districts. This model functionality allows basin managers and policy makers to design more equitable policies to address externality issues among nearby water users in common-pool resource management (Madani & Dinar, 2013; Muller et al., 2017).

Second, addressing the conflict between aquifer conservation in the midstream area and ecological water demand in the downstream area has become a management challenge in the HRB (Yao et al., 2018; Zheng et al., 2020). We find that our proposed modeling framework, by adopting distributed policies to adjust the conjunctive use of SW and GW over time and across space, can provide more flexible solutions to address the conflict between the upstream and downstream areas. As shown in Figure 16, either a high or low GW use fraction will be achieved under the uniform policy scenario (A1 for the low GW tax scenario and A2 for the high GW tax scenario). As a result, a uniform policy will either lead to (1) an exacerbated aquifer depletion in the midstream area but a significant increase in river flow downstream under policy A1 or (2) significant mitigation of aquifer depletion issues in the midstream area but a sharp reduction in river flow for the downstream area under policy A2. Such intensive trade-offs could possibly aggravate water use conflicts between the midstream and downstream areas. Contrary to the intensive trade-offs associated with uniform policies, the proposed distributed water management policies (e.g., types B, C, and D) could provide more flexible solutions to alleviate water conflicts between midstream and downstream areas. As shown in Figure 16, one can see that the distributed water policies are associated with a larger buffer zone (circled by the red dashed line) to address conflicts of interest between midstream and downstream areas so that improvements in one side's hydrological outcomes are not necessarily based on the other side's significant loss of interest. Such management policies and their hydrological outcomes could possibly be mutually acceptable for both sides.

With the aforementioned functionalities and the associated benefits, future studies could follow this model development approach and adopt a distributed policy design scheme for mechanism design and policy evaluation, especially when managing water resources in large river basins with spatially heterogeneous hydrological properties. Furthermore, conjunctive use of SW and GW is a common practice in many regions worldwide. Future

model developments can adopt integrated SW-GW hydrological models (e.g., HEIFLOW, GSFLOW) to assess the role of distributed policies for water resource management in a conjunctive system.

### 5.3. Limitations and Future Research Directions

Our modeling framework and simulations have a number of limitations that warrant future research for extensions and improvements. First, based on our research emphasis and scope, this study conducted a scenario-based analysis with a limited number of policy scenarios, considering the change in groundwater tax rates between dry and wet years and among regions with high and low water table drawdowns. Our simulations indeed show that improved hydrological outcomes can be achieved when water policies are adjusted between dry and wet years and across irrigation districts. However, it is not expected that the global optimal distributed policy has been obtained with such a limited number of policy scenarios. Future work can extend our current research scope by applying an optimization approach to obtaining the optimal water policy when a specific management goal is given. To do this, a great number of policy scenarios should be designed that allow each irrigation district to test a different groundwater tax rate each year. For example, the model needs to conduct 3,200 simulations if 10 groundwater tax rates are available for the test (10 tax rates $\times$ 16 years $\times$ 20 districts). However, such analysis would be extremely computationally expensive, if not impossible, for the proposed physically based integrated SW-GW hydrological model with complicated numerical simulation (the model takes approximately 4 hr for one simulation). Rather, it would be more computationally and technically feasible to develop a statistically based surrogate model to mimic our physically based model to perform optimization-based policy analysis (Hussain et al., 2015; Kourakos & Mantoglou, 2013; Song et al., 2018; Zhang et al., 2017).

Second, regarding the distributed policy scheme, the water policy (GW tax) in this study is designed to vary from 1 year to another based on the variation in water availability between dry and wet years. However, in many river basins, water availability from basin inflow and/or precipitation may also exhibit intra-annual variability between dry and wet seasons, which would require basin managers to adjust water policies within a year or even within a season. Therefore, future model developments can apply a finer temporal resolution for water management policy design (e.g., apply a seasonal or monthly based water tax to regulate farmers' water use; Brennan, 2006; Pesic et al., 2013).

Third, this study uses taxation on water use as an example policy instrument for water resource management. Specifically, this study has sought to address such a water management question: Without reducing the total water supply, how can policy makers use a GW tax to adjust the conjunctive use of SW and GW over time and across space to achieve improved hydrological outcomes? Given that monitoring the pumping activities of all pumping wells in large river basins could be challenging and costly in practice, adjusting the electricity price for pumping activities could be an alternative policy for regulating GW use (Brown & Rogers, 2006). Importantly, we acknowledge that other water policies (e.g., quotas or caps for total water use, water markets for water rights reallocation, and temporal restrictions on water diversion) could be alternative policy instruments to regulate farmers' water consumption (Delorit & Block, 2018; Du et al., 2021; Foster et al., 2017; Khan & Brown, 2019). Future studies can examine these additional policy instruments using the ABM developed in this study. In particular, future research can explore how to combine various policy instruments (e.g., a cap for restricting total water consumption and a water tax for adjusting the fractions of SW and GW use) to support effective water resource management.

Finally, the scope of this study is focused on exploring the hydrological outcomes of distributed water policies without assessing the corresponding social and economic consequences. An interesting research extension would be examining the economic and social consequences of distributed water policies when sufficient socioeconomic data for each irrigation district in the river basin become available. Furthermore, in real-world water management practices, it can be socially and politically challenging to implement different policies within a river basin. To address these research gaps, future studies will need to incorporate a socioeconomic module into the modeling framework and explore social and economic outcomes associated with distributed water policies (Lund, 2015; Marston & Cai, 2016; Smith et al., 2020; Yang & Wi, 2018). We envision that these extensions can improve the design and implementation of distributed water policies to support water resource management and advance our understanding of the interactions between hydrological processes and human activities in large river basins.

## 6. Conclusions

The heterogeneous hydrological responses to water policies and policy externalities among water users require the design of distributed (i.e., spatially variable and temporally dynamic) policies to support water resource management. In this study, we developed a tightly coupled modeling framework that integrates (a) an ABM for farmers' conjunctive use of SW and GW under the influence of distributed water policies and (b) a physically based three-dimensional GW-SW model (HEIFLOW). The modeling framework is applied to the HRB, the second largest endorheic river basin in China. Through a set of distributed water policy scenarios, we performed a systematic evaluation of the impacts of distributed water management policies (i.e., GW tax) on farmers' water use and the consequent hydrological impacts. The major modeling results and implications are summarized as follows.

First, hydrological responses to water policies exhibit significant spatial heterogeneity in large river basins. Therefore, the disruptors of hydrologic processes should be evaluated and considered in distributed policy design based on local physical characteristics, the connectedness between upstream and downstream areas, and the temporal variations in hydrological conditions. In a large river basin, some districts have more active hydrological responses to a water policy than other districts. The variations in hydrological responses can be attributed to three major factors: the depth to the water table, hydraulic conductivity, and the distance to rivers. Furthermore, hydrological responses to water policies in a particular region can also be affected by water policies in its neighboring areas. Policy externality issues can result in conflicts of interest among water users. Basin planners should scrutinize these factors to inform the design of location-dependent policies for river basin management.

Second, it is feasible to adjust water policies over time and across space to improve hydrological outcomes without adversely reducing the total water supply. At our case study site, for example, by shifting the implementation of a high GW tax from dry to wet years, the aquifer depletion issue can be mitigated without reducing the total water supply for agricultural irrigation. Therefore, it is recommended that basin managers adjust GW policies between dry and wet years to take advantage of aquifers as underground "reservoirs" to buffer against variations in the water availability of the watershed. In our case study area, policies can be designed to reduce GW pumping and increase SW diversion during wet years when SW is abundant. In contrast, during dry years, policies can be adjusted to increase GW abstraction (increase the buffer zone of the GW deficit) so that more GW can be recharged during wet years. Eventually, spatially and temporally variable water policies should be implemented to support water resource management, especially in large river basins with heterogeneous hydrological properties.

It is noteworthy that this study still has a number of limitations that warrant future research. Recommended future research directions include, but are not limited to, developing surrogate models to obtain the global optimal water policy for water resource management, applying a finer temporal resolution for adjusting the water policy over time, incorporating other types of policies to enhance the flexibility in water management policy instruments, and exploring the political, social and economic outcomes of distributed water policies. These extensions and improvements are expected to further enhance the management of conjunctive water resources with distributed water policies and advance our understanding of human-hydrological interactions in large river basins.

## Data Availability Statement

The data used in this study can be accessed from the National Tibetan Plateau/Third Pole Environment Data Center (<http://data.tpdac.ac.cn/en/>). These include the hydrogeological map of Heihe River Basin (<http://www.tpdac.ac.cn/en/data/96eb358d-d112-46ac-9118-3cf5e016f33d/>), climate forcing data (<http://www.tpdac.ac.cn/en/data/750bbc87-63e9-4dff-b5aa-7f97a4173f18>), irrigation districts and canals (<http://www.tpdac.ac.cn/en/data/5c2579c9-be7d-45fb-8402-46d0d276b4c4/>), land use and land cover (<http://www.tpdac.ac.cn/en/data/515cdd0e-47c5-4696-bc22-28e603e6ea8e/> and <http://www.tpdac.ac.cn/en/data/320690e1-f8aa-4c51-a189-4c82f7e64b39/>), ET remote sensing products (<http://www.tpdac.ac.cn/en/data/18f1824f-d145-408c-a21a-57f2368b7efb/>) and HEIFLOW simulation results (<http://www.tpdac.ac.cn/en/data/21d2947d-88a1-4fe7-82fa-1c16fba6ddb/>).

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1 *Supporting Information*

2 **Evaluating distributed policies for conjunctive surface water-**  
3 **groundwater management in large river basins: Water uses versus**  
4 **hydrological impacts**

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21

22 The *Supporting Information* file provides (1) a table that presents the data sources for  
23 developing the integrated surface water-groundwater model (HEIFLOW), and (2) six

24 additional figures on the modeling results to support the presentation and discussion of the  
 25 article.

26

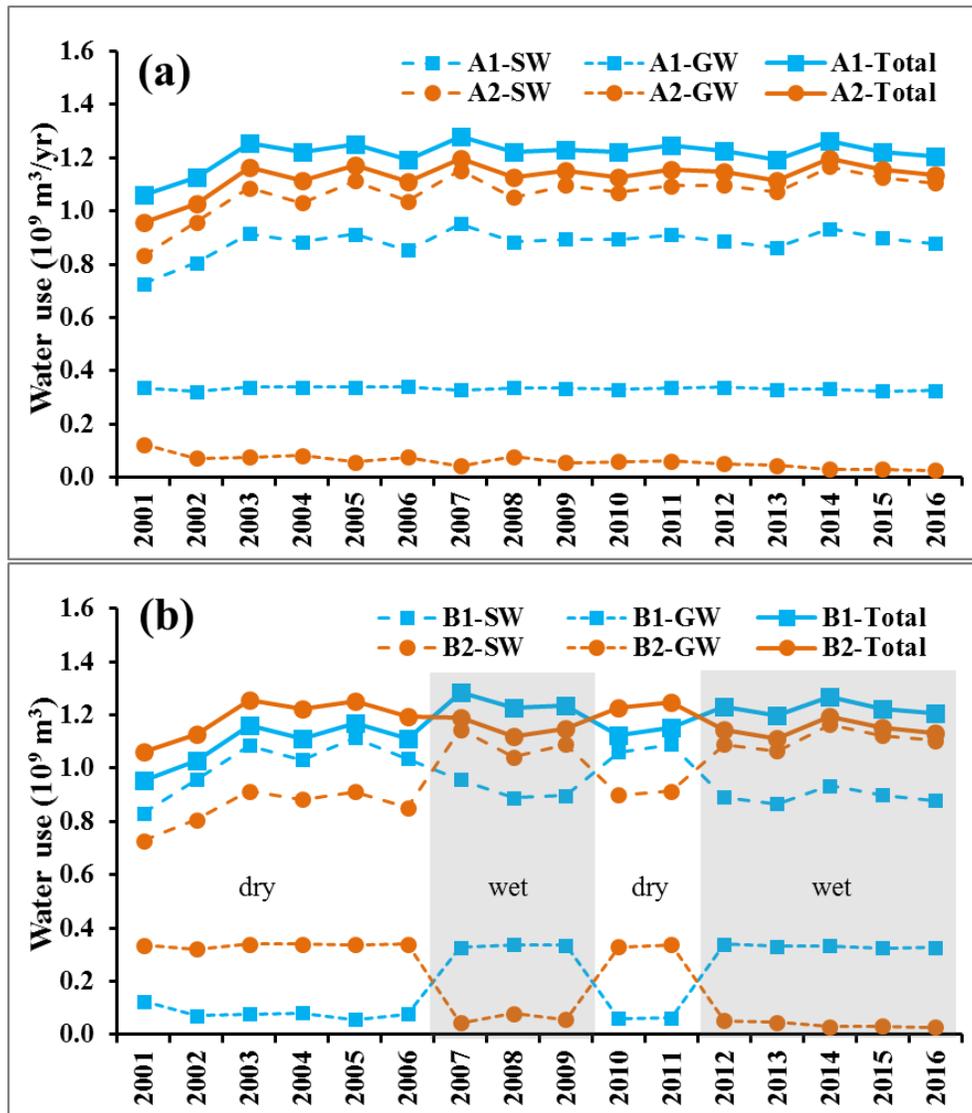
**Table S1.** List of data for constructing the HEIFLOW model

Category	Data	Spatial resolution	Data format
	DEM	90 m×90 m	Raster
	Land use	1:100,000	Shape file
	Soil type	1:1,000,000	Raster
	River network	1:100,000	Shape file
	Irrigation canals	1:100,000	Shape file
Input data for model setup & parameterization	Hydrogeology map	1:500,000	Shape file
	Borehole data	257 locations	Paper document
	Boundary river inflow	15 stations	Excel file
	Boundary GW inflow	Boundary grids	Paper document
	Model-derived climate data	3 km×3 km	NetCDF file
	Meteorological observations	19 stations	Excel file
	Surface water diversion data	46 districts	Excel file
Data for model calibration and validation	Groundwater pumping data	46 districts	Excel file
	Stream flow	4 stations	Excel file
Data for crosscheck & process interpretation	Groundwater level	47 wells	Excel file
	ET	1 km×1 km	Raster
	LAI	1 km×1 km	Raster

Note:

(1) The list of the data sources has been reported in our prior work. For details of these data sources and model development process for HEIFLOW, see Tian et al. (2018).

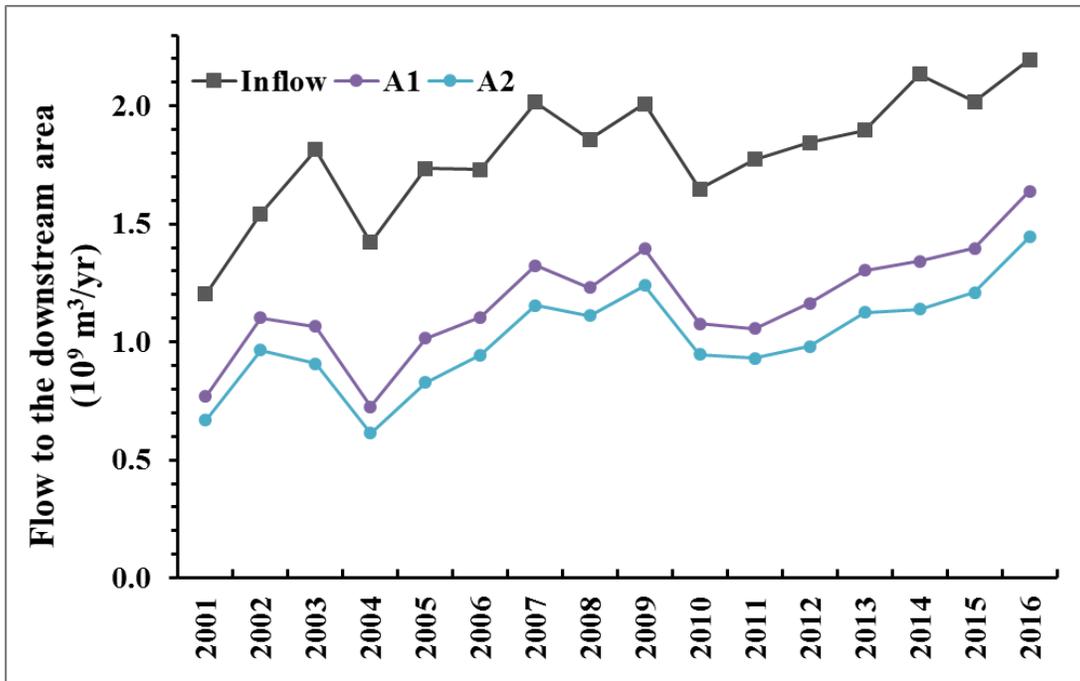
(2) The original data sources are from 2000 to 2012. With recent years' effort for data collection, the data used in this study are from 2000 to 2016.



28

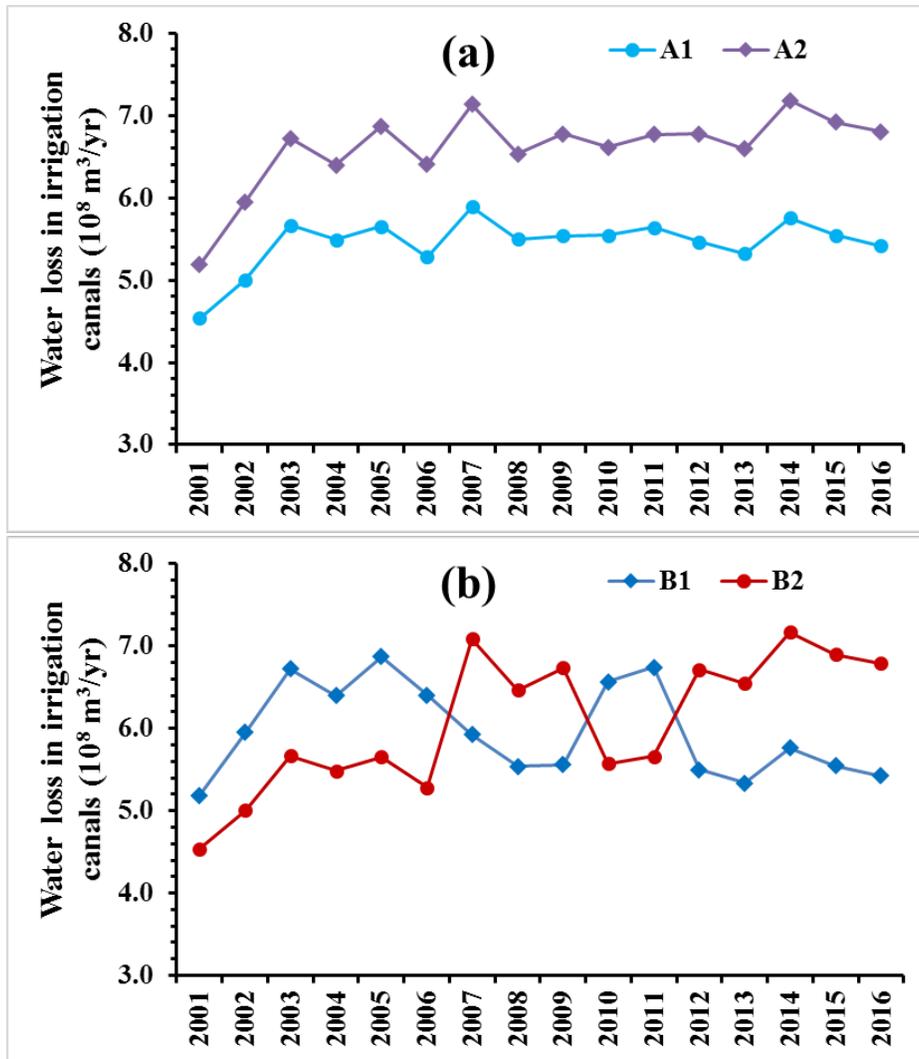
29 **Figure S1.** Conjunctive use of surface water (SW) and groundwater (GW) from 2001 to  
 30 2016 under four policy scenarios A1, A2, B1, and B2

31



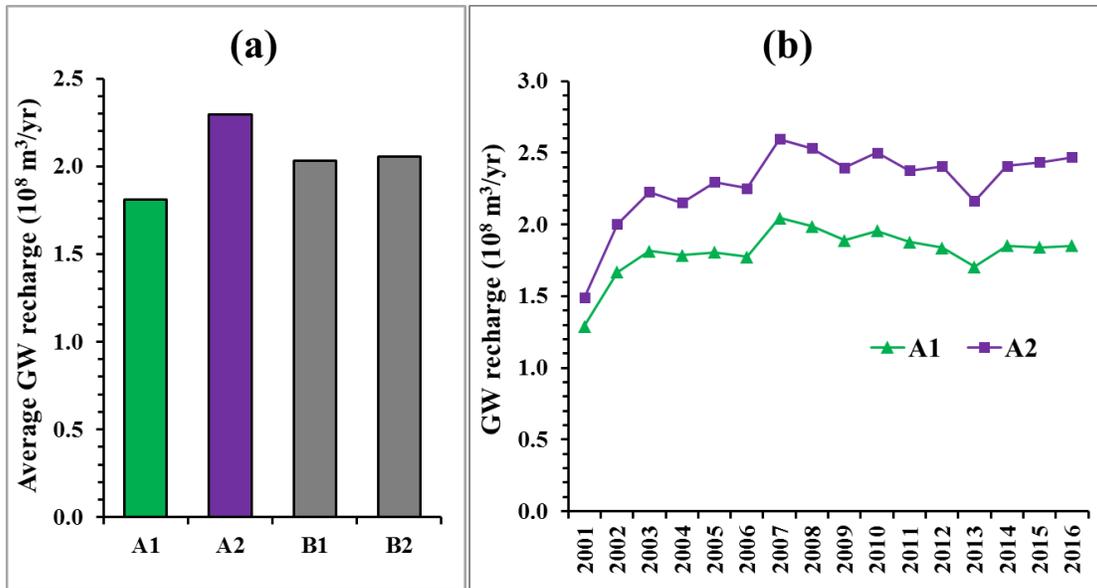
32

33 **Figure S2.** Flow to the downstream area of the basin under policy scenarios A1 and A2



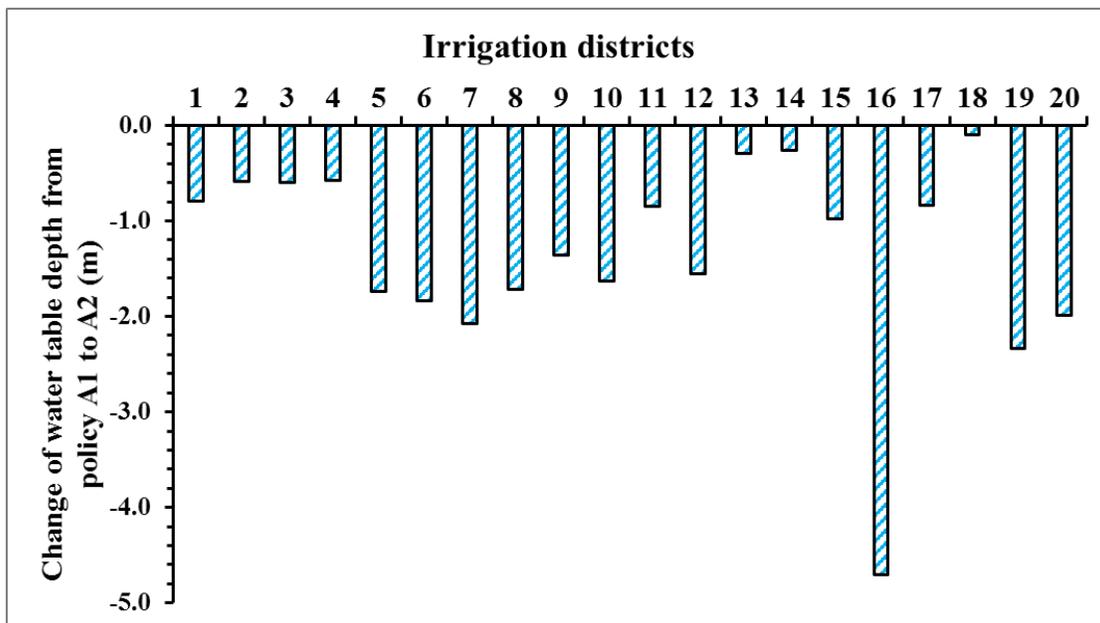
34

35 **Figure S3.** Comparison of water loss during conveyance in irrigation canals for the four  
 36 policy scenarios



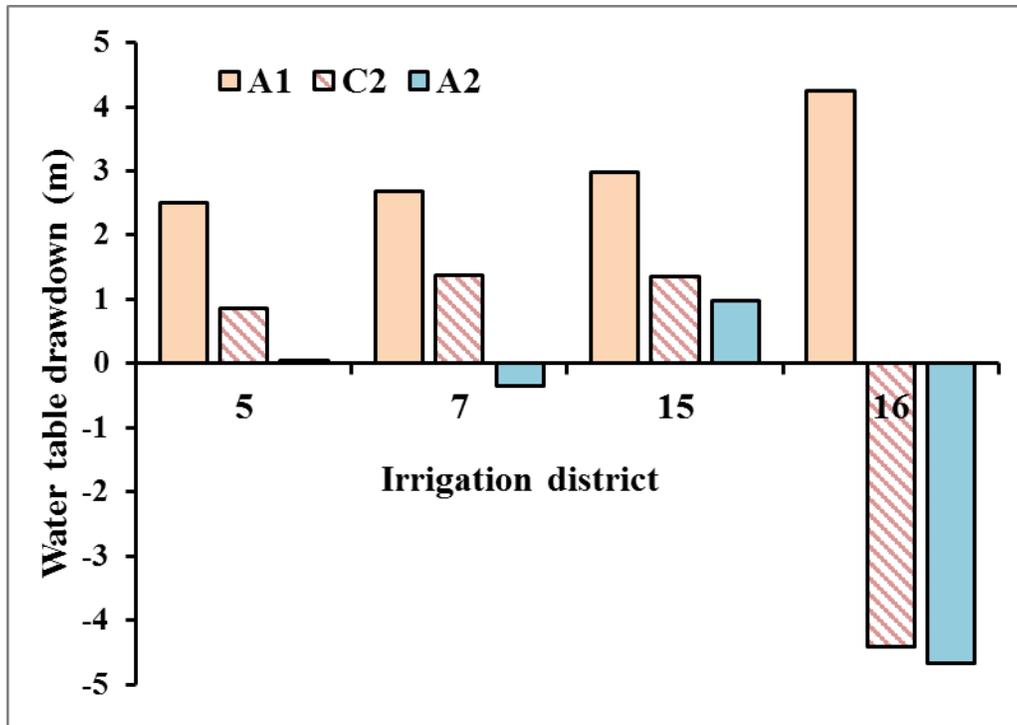
37

38 **Figure S4.** (a) Annual average GW recharge and (b) year-over-year GW recharge



39

40 **Figure S5.** Change of water table depth from policy A1 (the low GW tax scenario) and A2  
 41 (the high GW tax scenario) in the twenty irrigation districts



42

43 **Figure S6.** Water table drawdown from 2001 to 2016 for four irrigation districts (5, 7, 15  
 44 and 16) under three policy scenarios A1, C2 and A2. Note that policy A1 applies a low  
 45 GW tax in all of the twenty irrigation districts in the basin. C2 applies a high GW tax only  
 46 in the four irrigation districts (5, 7, 15 and 16) and the other sixteen districts have a low  
 47 GW tax. A2 applies a high GW tax in all of the twenty irrigation districts.

48

49 **References**

50 Tian, Y., Zheng, Y., Han, F., Zheng, C., & Li, X. (2018). A comprehensive graphical  
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