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INTEGRATED MODELING OF WATER SUPPLY AND DEMAND UNDER MANAGEMENT OPTIONS AND CLIMATE CHANGE SCENARIOS IN CHIFENG CITY, CHINA[1]

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ABSTRACT: Water resource management is becoming increasingly challenging in northern China because of the rapid increase in water demand and decline in water supply due to climate change. We provide a case study demonstrating the importance of integrated watershed management in sustaining water resources in Chifeng City, northern China. We examine the consequences of various climate change scenarios and adaptive management options on water supply by integrating the Soil and Water Assessment Tool and Water Evaluation and Planning models. We show how integrated modeling is useful in projecting the likely effects of management options using limited information. Our study indicates that constructing more reservoirs can alleviate the current water shortage and groundwater depletion problems. However, this option is not necessarily the most effective measure to solve water supply problems; instead, improving irrigation efficiency and changing cropping structure may be more effective. Furthermore, measures to increase water supply have limited effects on water availability under a continuous drought and a dry-and-warm climate scenario. We conclude that the combined measure of reducing water demand and increasing supply is the most effective and practical solution for the water shortage problems in the study area.

(KEY TERMS: climate change; hydrological modeling; water demand and supply; integrated water management.)

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INTRODUCTION

According to the World Bank, 1.6 billion people currently live in regions with absolute water scarcity and that number is expected to rise to 2.8 billion by 2025 (Alavian *et al.*, 2009). Water resource management is becoming increasingly complex and challenging to managers and policymakers due to the increase of multiple stresses such as climate change, demographic change, groundwater depletion, and rise of energy demand, among other factors (Sun *et al.*, 2008). Adapting to water shortages requires considering both the water supply and demand sides of the water management options (Ed *et al.*, 2001). Demand management refers to strategies to reduce water

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demand from crop irrigation and groundwater withdrawal so that water demand does not exceed water supply. Demand management options may include water pricing and markets, allocation limits, improved water-use efficiency, public and private incentives for adopting irrigation technology, reuse of drainage water, and shifting to less water-intensive crops and fallowing (Tanaka *et al.*, 2006). Strategies of supply management, on the other hand, are used to increase water supplies so that water demands can be met whenever there are needs. Examples of supply management include expanding surface water storage by building levees and aqueducts, developing interbasin transfers, modifying existing operating rules, expanding conjunctive use, and groundwater banking (Medellín-Azuara *et al.*, 2008). In China, the government (i.e., Ministry of Water Resources) has established a policy calling for enhanced water demand management in response to the water crisis across the nation. However, few studies have been conducted to demonstrate how various management options can be effective in different regions. The water management issue becomes more urgent with the increasing threat to limited water resources in the north (Xia *et al.*, 2011).

Integrated simulation models are needed to quantify the balance between water supply and demand (Sun *et al.*, 2008; Caldwell *et al.*, 2012), conduct regional assessment and develop effective water management and conservation plans (Tavernia *et al.*, 2013). Water development projects are mostly based on supply rather than demand management measures, although the focus on the latter is increasing (Ed *et al.*, 2001). Different countries around the world exhibit varying competencies in effectively executing these types of management measures. The concepts of integrated watershed management (Lee *et al.*, 2008; Qi and Altinakar, 2011; Shi *et al.*, 2012; Samaras and Koutitas, 2014) have been well recognized as one of the best approaches for achieving water resource sustainability. However, quantitative tools are still lacking to guide the water resource assessment and use by local watershed managers. In recent years, water management evaluation and planning models (Li *et al.*, 2010) have emerged to examine the balance of water resource supply and demand and optimize reservoir operations. However, these models are mostly confined to water resource research related to runoff and lack analyses of other hydrological components such as evapotranspiration (ET) for different land uses on a physical basis. The Soil and Water Assessment Tool (SWAT) model and other hydrological models (House-Peters and Chang, 2011; Gober *et al.*, 2012; Wijesekara *et al.*, 2014) are sufficient in simulating runoff as well as other hydrological components on a physical basis. However, conventional water supply-oriented simulation models are often inadequate for addressing contemporary water management issues (Yates *et al.*, 2005). Therefore, a comprehensive water resources assessment and management tool considering hydrological responses to climate changes, allocation of water resources, agricultural economy, and other factors is needed in designing water management options. In this article, we developed a SWAT-WEAP combination approach that considered both hydrological processes and water management evaluations and analyses of hydrological components.

China is currently experiencing unprecedented water shortages at various levels as a result of dramatic water use for economic development (Xia *et al.*, 2011). At the national level, China has put tremendous efforts on the management of water resources in recent years that included building reservoirs and large-scale interbasin water transfers (Ren *et al.*, 2002; Gao *et al.*, 2013). By the end of 2007, China had built 86,353 reservoirs with 529 large- and 3,181 medium-sized reservoirs that offer a total capacity of 692.4 Gm^3, globally ranking as the fourth-largest (Jia *et al.*, 2008). For example, the Liao River basin, where Chifeng City is known as one of the most populated centers, where drains are 229,000 km^2 and has 81 large- and medium-sized reservoirs built in past decades to meet the increasing water demand (Ministry of Water Resources of the People's Republic of China, 2009).

At the regional level, the water crisis in northern China is rooted in several major global change issues, including drying and warming climate change, rapid economic development and population growth, groundwater overuse, and pollution from industries. Water shortages have shown detrimental consequences to local economies, human well-being, and the environment. This situation is especially true in the Farming-Pastoral Ecotone in northern China, a region that has seen tremendous land-use changes including grassland and wetland conversion to irrigated croplands, overgrazing, and groundwater overdraw by the mining industries. Consequently, surface water resources in the region are diminishing as evidenced by the dry rivers and declining groundwater table. The region has suffered chronic soil erosion by water and wind and desertification, contributing to dust storms found as far as Beijing (Fu and Wen, 2002).

Chifeng City has been designated as one of the focused areas in northern China's Environmental Evolution Research program that addresses environmental problems, including water shortages and land degradation (Zhang *et al.*, 1997). The city has a total administrative area of 90,021 km^2, encompassing both rural and urban landscapes, and a population of

4.3 million or a population density of 49.1/km^2. The population almost increased threefold since the 1950s, representing the most populous city in Inner Mongolia, a major contributor of the economy of eastern Inner Mongolia in agriculture, animal husbandry, and industry. The total arable land is about 106×10^4 ha, representing a dramatic increase of 38% from the 1950s. The rampant expansion of irrigation farming and the excessive reclamation "wastelands" (Zhang *et al.*, 2002) and rapid industrialization (e.g., coal-burning power plants, minerals, gas, and chemical plants) caused an overexploitation of water resources.

The overexploitation of water resources in the region has resulted in a series of ecological and environmental consequences, including the drying up of rivers and lakes, depletion of groundwater, grassland degradation, and ravaging dust storms. Also, water shortages have intensified the conflicts between upstream and downstream water users and users across the provincial boundaries. The water resource issues in Chifeng City can be summarized as: (1) a high interannual variability of precipitation leads to a high disparity in interannual runoff fluctuations, thus it is difficult to utilize these surface water resources; (2) there is a lack of unified water management planning for conjunct use of surface and groundwater uses (about 75% of the water resources have been utilized in some way with the surface water utilization rate at 55%, and shallow groundwater utilization rate as high as 98% in the plain areas); (3) low water-use efficiency, as the current industrial water reuse rate is less than 60%, the agriculture water use accounted for more than 80% of the total water use, and water-use efficiency for irrigated croplands is less than 0.5; and (4) water rights. The industry and agriculture sectors have the priority of mining groundwater for water supply, causing serious overexploitation of groundwater resources as well as low utilization rates of surface water. Cones of depressions of groundwater have been formed, resulting in serious damage to the groundwater systems and local ecosystems such as wetlands. In addition, the increasingly serious water pollution further intensified the water shortage problems in Chifeng City.

Using Chifeng City as one example, this study examined multiple water resource management scenarios under a changing climate by integrating the SWAT hydrological model and a water management tool, the Water Evaluation and Planning (WEAP) model. The objectives of this study are to explore the following questions. (1) To what extent will building a reservoir or irrigation management by altering the cropping system be potentially beneficial to the water supply in Chifeng City? (2) How do measures of water supply management, through building more reservoirs and irrigation management, interact with a changing climate? (3) How effective is it to incorporate both the water supply and demand sides for solving water shortages in the study basin? The results from this study would provide evidence for the values of integrated water management models for decision making for solving long-term water sustainability issues in a highly stressed region.

METHODOLOGY

Chifeng City and the Laoha River Basin

Chifeng City (41.28°N-45.40°N and 116.35°E-120.98°E) is located in the middle reach of the Laoha River Basin (LRB) (41.05°N-43.50°N and 117.30°E-120.85°E), the southern tributary of the West Liao River. Headwaters of the LRB originate from the Qilaotu Mountains in Hebei Province (Figure 1). The LRB has a total river channel length of 425 km with an elevation of 405-1,935 m and a drainage area of 33,076 km^2, providing the main water supply for Chifeng City. The LRB is classified as having a temperate, semiarid, and semihumid continental climate, characterized as a transition between a warm temperate and a cold temperate zone. The region is featured as a monsoon climate with four distinct seasons. The annual precipitation is 431 mm and falls mainly in June, July, and August with large intra- and interannual variability (Figure 2). The multiyear mean air temperature is 6.9°C with high interannual variability. The long-term average annual pan evaporation is about 1,100-2,500 mm, increasing from the eastern to the western part of the basin. Natural runoff in the basin mainly originates from rainfall.

The land-use types in the studied river basin are dominated by farmland, woodland, and grassland, with small areas of sand and bare lands (Figure 1) (Hao *et al.*, 2011b). The land uses in the LRB have undergone significant changes due to human activities, that is, expansion of croplands and husbandry activities in the past three decades. The crops in the region are dominated by a few dry farming-based grains. The three major crops, foxtail millet, maize, and sorghum, account for over 60% of the total grain and soybean planting area and over 82% of the total grain and soybean yield. Other crops cultivated include broomcorn millet, buckwheat, sweet potato, wheat, rice, and oats. Foxtail millet is typically grown on dry sloped land, whereas maize is mostly cultured on irrigated soils.

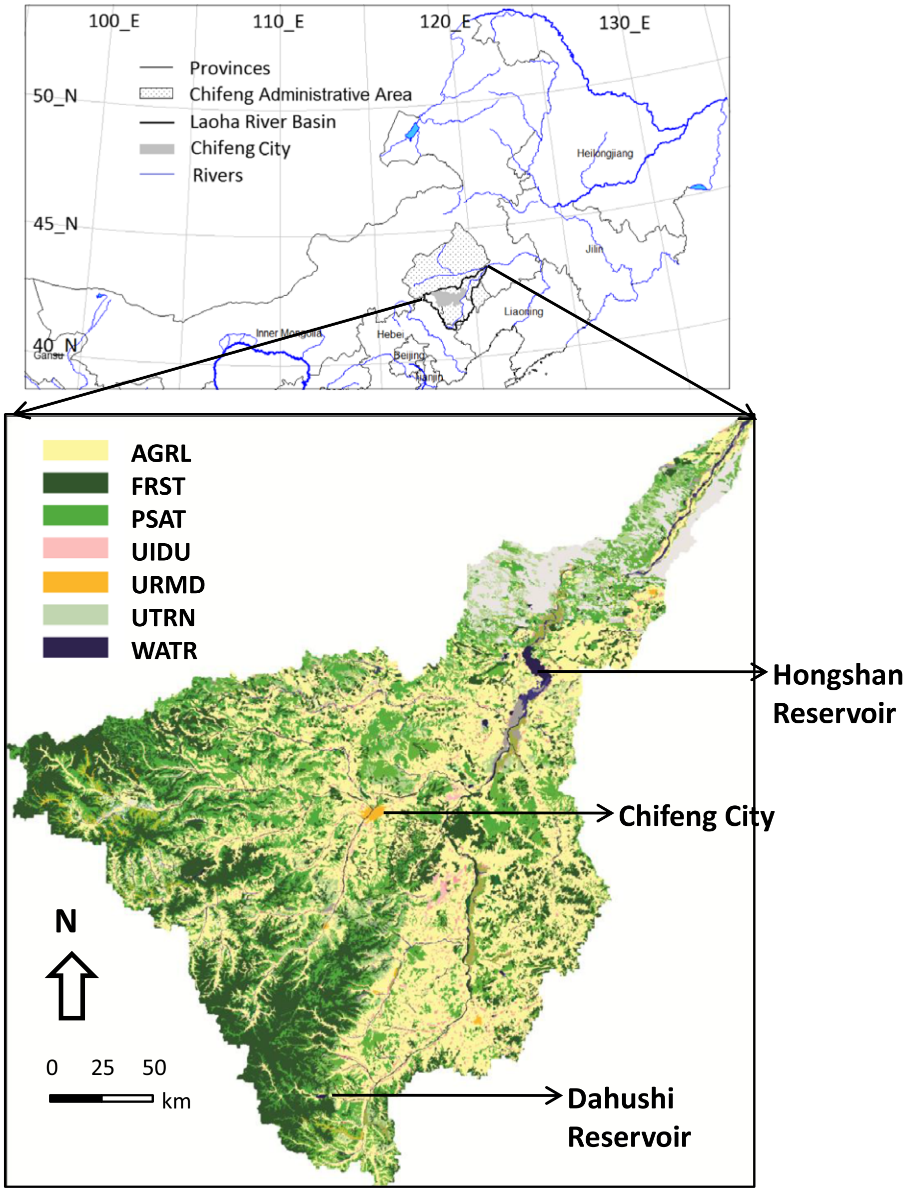

FIGURE 1. Land-Use Types and Location of Hongshan and Dahushi Reservoirs in the Laoha River Basin. AGRL, cultivated crops; FRST, mixed forest; PAST, pasture; UIDU, developed, high intensity; URMD, developed, low intensity; UTRN, construction-used land; WATR, open water.

The LRB has two large reservoirs — the Hongshan and the Dahushi Reservoirs (Figure 1, Table 1). Hongshan Reservoir (42.8°N, 119.7°E), the largest in LRB, is located in Chifeng City with a catchment area of 24,486 km^2 accounting for 74% of the LRB watershed area. The average annual discharge at the Hongshan Reservoir dam site is 738.5 Mm^3 with 67.8% concentrated in the flood season in July and August. The second-largest reservoir, Dahushi, is located in the Heilihe River, a major tributary of the LRB. Dahushi Reservoir has a catchment area of 540 km^2, a total capacity of 120 Mm^3, and an effective irrigation area (EIA) of 149 km^2. Both reservoirs are large-scale reservoirs serving many purposes with a priority given to irrigation, comprehensive flood control, power generation, fish farming, and tourism. In addition, many small- and medium-sized reservoirs were built in recent decades for irrigation and water supply within Chifeng City.

The major water demands come from industrial water use, drinking water for humans and animals, and irrigation use for farmland, livestock foraging base, cultivation, forest seedlings, orchards, afforestation, etc. Irrigation is the largest proportion of water consumed in the study basin. Before the 1980s, the main irrigation water supply was from the surface

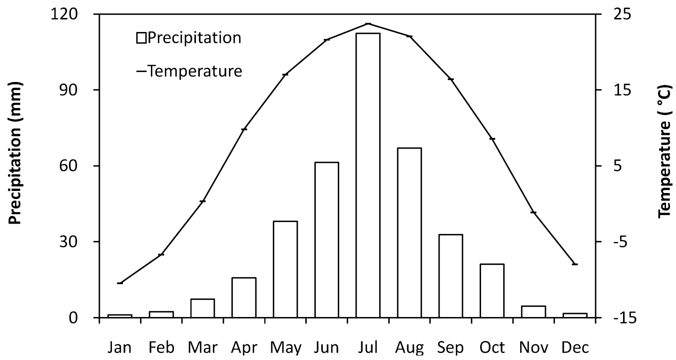

FIGURE 2. Mean (1980-2010) Seasonal Precipitation and Temperatures Recorded at the Chifeng Meteorological Station.

TABLE 1. The Characteristics of the Hongshan and Dahushi Reservoirs.

Characteristics	Hongshan	Dahushi
Watershed area (km^2)	24,486	540
Average annual runoff (10^8 m^3)	12.68	0.63
Completion year	1965	1981
Record water level (m)	445	727
Record storage capacity (10^8 m^3)	25.6	1.2
Normal water level (m)	433.8	719.3
Corresponding storage capacity (10^8 m^3)	8.24	0.7
Flood control level (m)	433.7	717.8
Flood control storage capacity (10^8 m^3)	8.14	0.62
Inactive water level (m)	430.3	700.8
Inactive storage capacity (10^8 m^3)	5.10	0.068

TABLE 2. The Groundwater Distribution and Availability along with the River Valley and Plain in Laoha River Basin.

Location	Available Groundwater (10^4 m^3/yr)	Groundwater Yield (m^3/h)
Rich water sections of middle and lower reaches of Laoha River and Yingjin River (see GW-CF, GW6 in Figure 4)	39.6	100-300
Rich water sections of middle and lower reaches of Beng River (GW4)	2.9	100-200
Rich water sections of middle and lower reaches of Kuntou River (GW2)	4.5	100-200
Relatively rich water sections of Xibo River and Yingjin River (GW1)	4.1	100-200
Relatively rich water sections of branch of Laoha River (GW5)	15.8	100-200

TABLE 3. The Effective Irrigation Area (EIA) for Different Water Conservancy and Irrigation Works in Chifeng City (1949-2002). Unit: 10^4 ha.

Year	Large Irrigation Facility (EIA > 667 ha)	Reservoirs	Pond and Dams	Groundwater Pumping
1982	11.25	5.41	0.54	8.82
1985	16.76	4.61	0.21	7.98
1990	11.39	4.60	0.22	10.95
1995	11.24	4.62	0.23	14.28
2000	14.51	4.71	0.61	16.08
2002	14.91	4.71	0.65	19.37

water from the Hongshan Reservoir. However, since 1984, the reservoir has mainly been used for power generation; thus, surface water for irrigation reduced, promoting more groundwater withdrawal for irrigation. The groundwater resource in the LRB is relatively rich with uneven distribution. The available groundwater along with the river valley and plain in LRB varied from 3×10^4 to 40×10^4 m^3/yr (Table 2). In recent decades, many diversion canals were built for widespread extraction of groundwater to irrigate farmlands and pastures, resulting in severe declines in the groundwater table. The EIA is the sum area of paddy fields and irrigated fields with equipped irrigation facilities. It is a widely used indicator of a region's ability to combat droughts in agriculture in China. The irrigation methods in Chifeng City mainly include reservoir, pumping, pond, and dam. The EIA increased sharply from the 1980s to the 2000s (Table 3). Groundwater has become a main source for crop irrigation in the past decades. In addition, crop land areas have been expanded in the LRB (Hao *et al.*, 2011a). The planting structure has also undergone significant changes in the LRB. During the last 20 years, the rice area has almost increased sixfold. The water consumption of rice is greater than millet, maize, and many other crops due to high evaporation losses in rice paddies.

Integrated Model Development

The SWAT-WEAP combination approach was used in this study (Figure 3) to operationally assess comprehensive water resource management options. The SWAT model (Neitsch *et al.*, 2002) was assigned to the supply side of water resources and mainly used to simulate the incoming flow of those tributaries without measurements (i.e., no hydrological monitoring stations) in the LRB. The SWAT model was calibrated and validated using measured data from the Hongshan Dam hydrological station. A future climate scenario was generated using the built-in weather generator, WXGEN, embedded in the SWAT model,

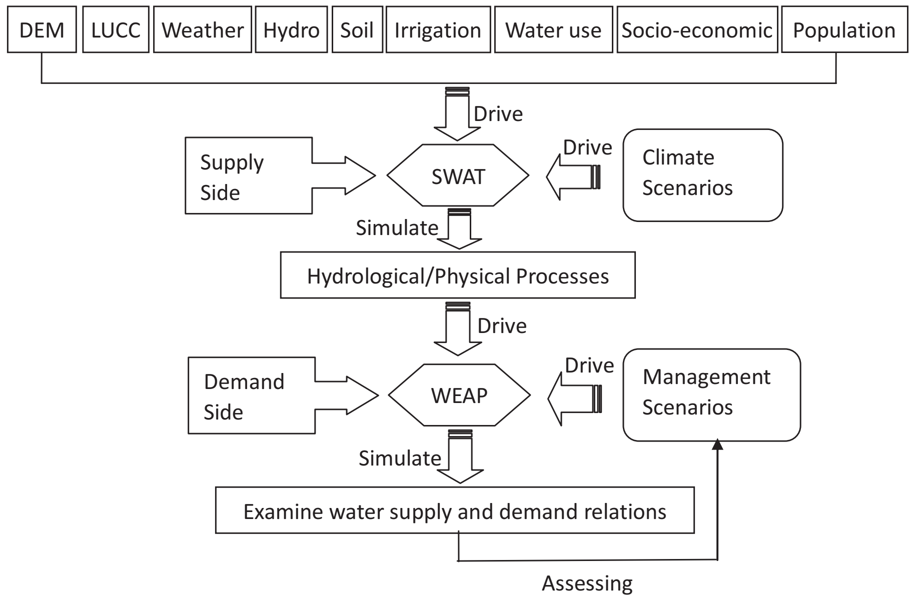

FIGURE 3. Model Flowchart that Illustrates the Integration of the Soil and Water Assessment Tool (SWAT) and Water Evaluation and Planning (WEAP) Models.

and used to drive the SWAT model to simulate the stream inflow of tributaries under various scenarios of climate change. The water yield from each tributary simulated by SWAT was used to drive the WEAP model (Yates *et al.*, 2005), thereby simulating the supply/demand conditions under different water-use patterns. The integrated methodologies were applied to simulate the future status (2010-2040) of water resources by combining different water resource management options and three climate change scenarios.

In a previous study, we reported the SWAT model calibration and validation results (Hao *et al.*, 2011b) that indicated that SWAT accurately replicated the LRB streamflow characteristics. In this article, we focus only on the WEAP model results. The coefficient of determination (R^2) and Nash-Sutcliffe simulation efficiency (E_{NS}) (Nash and Sutcliffe, 1970) were used to evaluate the WEAP model predictions for the period of 1998-2000.

Data and Model Parameterization

The digital elevation model required by SWAT was generated based on a topographic map at a scale of 1:250,000. The meteorological data were acquired from the National Meteorological Information Center of the China Meteorological Administration. Soil data were provided by the Institute of Soil Science (Nanjing) of the Chinese Academy of Sciences (Shi *et al.*, 2006a, b) and Chinese Soil Census Records (National Soil Survey Office, 1995, 1998). Land-use data at a scale of 1:100,000 (1994, 2000) and a soil map at a scale of 1:1,000,000 were provided by the Environmental and Ecological Science Data Center for Western China and the National Natural Science Foundation of China. The hydrological data were acquired from several sources, including the Hydrological Bureau of Chifeng, the Hydrological Yearbook of China, the Water Resources and Environment Information Sharing Network, the Data-Sharing Center of China Water Resources, and the Songliao Water Resources Bulletin. Data related to agriculture, animal husbandry, industry, population, and irrigation were obtained from the Socio-Economic Survey Team for Rural and Pastoral Areas in Inner Mongolia. Other data, such as the water withdrawal locations, water demand points and orders of connection, and water transfer and supply/demand were obtained from field surveys.

For the monthly WEAP simulation, schemes for water supply and demand networks were first established to define the water supply/demand systems of the basin (Figure 4) (Hao *et al.*, 2011a). Considering data accessibility, 2009 was assigned as the baseline year. Each year has 12 time steps starting from January to December. Based on data from the Inner Mongolia Autonomous Region Water Resources Bulletin (2009) as well as the current water consumption status (Kang *et al.*, 2001; Liang *et al.*, 2009; Deng *et al.*, 2011; Fu *et al.*, 2011), the current water consumption rate was set as 67% in the scenario development in this study.

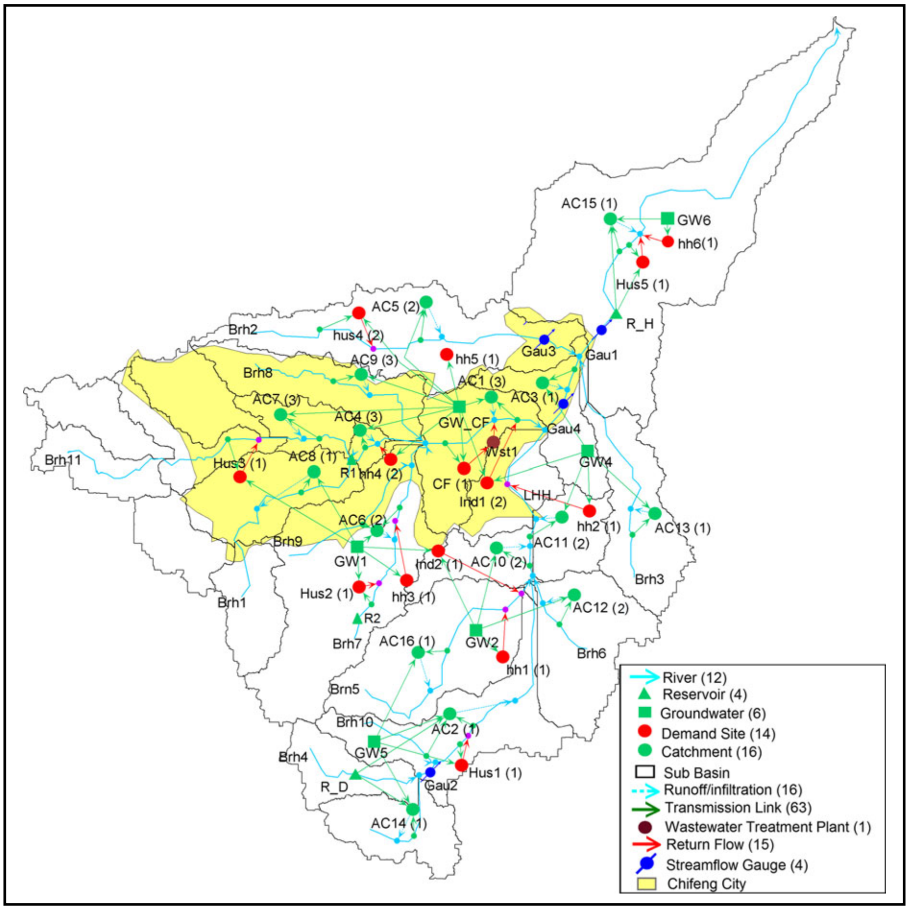

FIGURE 4. The WEAP21 Interface and Schematic of the Laoha River Basin (LRB), Showing the Hydrologic and Infrastructural Linkages after Adding Two Reservoirs. A node represents a physical component such as a water withdrawal point, wastewater treatment plant, aquifer pumping location, reservoir, or special water-use location along a river system. Nodes are linked by lines that represent the natural or man-made water conduits such as river channels, canals, and pipelines. These lines include rivers, diversions, transmission links, and return flow links. A river reach is defined as the section of a river or diversion between two river nodes, or following the last river node. The reach is named by the node above it. Elements in the schematic of the LRB: Brh, river; AC, agricultural catchment; Hus, animal husbandry demand sites; GW, groundwater; Gau, streamflow gauge; X, flow requirement; CF, domestic demand sites in Chifeng urban; hh, domestic demand sites in Chifeng suburbs (hh4) and the rural; Ind, industrial demand sites; R_1, R_2, added reservoirs; R_H, Hongshan Reservoir; R_D: Dahushi Reservoir.

The priorities of water demand were set in the following order: urban domestic, rural domestic, animal husbandry, and industrial and agricultural uses. Three methods are available in WEAP to simulate irrigation demands: (1) the Rainfall-Runoff model, (2) the Irrigation Demands Only version of the FAO Crop Requirements Approach, and (3) the Soil Moisture Method. Of these three methods, the Irrigation Demands Only method is the simplest. The model uses crop coefficients to calculate ET in the catchment and then determines any irrigation demand that may be required to fulfill that portion of the ET requirement not met by natural rainfall. The FAO crop water requirements (for either rain-fed or irrigated) method focuses on crop growth and assumes simplified hydrological and agro-hydrological processes (non-agricultural crops can be included as well). In this article, the irrigation demand was estimated by using the FAO crop requirements method for rain-fed or irrigated lands. We selected maize, an irrigated crop, foxtail millet (rain-fed crop), and rice (paddy field with irrigation) as the major crop types for this study. The standard crop coefficients recommended by the FAO (Allen *et al.*, 1998) were corrected according to the local climate, soil, crop, and irrigation conditions. Monthly precipitation data were obtained from 11 weather stations in the basin and were interpolated by the Inverse Distance Weighted method for the 16 cropland-dominated catchments. In addition, ET data for reference crops were generated using the Penman-Monteith method (Batcher, 1984) and long-term meteorological data. Land-use data for the year 2000, along with statistical data and field surveys, were used to assess the

TABLE 4. Definitions of Climate Change Scenarios.

Climate Scenario	Description
Historic climate (S_H)	1980-2010 climate
Warm-Dry (S_D): warming and drying climate	On top of S_H, temperature changed by +2.8°C in winter, +1.6°C in spring, +2.0°C in summer, and +1.6°C in fall and annual mean temperature changed by +2.0°C and total precipitation reduced by 10%
Warm-Wet (S_W): warming and wetting climate	Same temperature change as S_D but precipitation increased by 10%

TABLE 5. Water Management Scenarios.

Scenarios	Crop Irrigation Demand	Industrial, Domestic, and Animal Husbandry Water Demand	New Reservoirs
Baseline (S_0)	Current (in the year of 2009)	Current (in the year of 2009)	No
No further water management (S_I)	The planting area of irrigated and paddy field increased by 0.25% and that of the rain-fed crop land decreased by 0.25% each year	Future population projected using an arithmetic method (urban population with a 1.3% growth rate and rural population a 1.2% growth rate), extrapolated to estimate the future industrial output in 2010, 2020, 2030, and 2040 and the future animal husbandry demand with a 1.5% increase	No
Changes in reservoirs (S_{II})	As S_I	As S_I	Adding two reservoirs with both total capacity of 0.12 Gm^3
Changes in irrigation and cropping patterns (S_{III})	The irrigation efficiency increased from 0.48 (2010) to 0.6 (2040), the irrigated and paddy field area decreases by 3% and rain-fed crop land area increases by 0.8% each year	As S_{II}	As S_{II}

compositions of land uses such as irrigated fields, paddy fields, and dry fields.

Water Management under Climate Change Scenarios

China's National Assessment Report on Climate Change (NCCAR, 2005) provides climate change projections for seven large regions and seven river basins for the next 20-100 years. Based on the projection results of annual and seasonal air temperature and precipitation scenarios, future climate scenario data (2010-2040) for the LRB were generated using the weather generator, WXGEN, built in the SWAT model. The statistics of daily meteorological variables (e.g., precipitation, maximum temperature, minimum temperature, solar radiation, etc.) such as mean, standard deviation, skewness, and kurtosis were used to develop three climate change scenarios. The three climate scenarios include: (1) Historic (S_H), (2) Warm and Dry (S_D), and (3) Warm and Wet (S_W) to represent a possible range of future climatic conditions that affect water supply and demand (Table 4). We built the future water management scenario using the conditions of 2009 to explore possible changes to the water supply-demand relations in the future (Table 5). Water management scenarios include: (1) Baseline Scenario (S_0): current water management and current industrial, domestic, animal husbandry, and crop irrigation demands in the year of 2009. (2) Scenario I (S_I): maintaining current water management but increasing irrigation, industrial, domestic, and animal husbandry water demands for the period of 2010-2040, future population and domestic water increase considered, and future irrigation demand and animal husbandry demand extrapolated based on the trend of the past two decades. The future industrial water demand was calculated using WEAP based on local water use per industrial output (RMB). Based on the local economic development plan, the future industrial output was estimated using a step function as 4 for the year 2010, 7 for 2020, 15 for 2030, and 20 for 2040 in a unit of billion RMB (1 RMB = US$0.16). (3) Scenario II ($S_{II}$): same as in S_I, but adding two new reservoirs for the period 2010-2040 with the total capacity of 120 Mm^3, respec-

TABLE 6. Definition of Simulation Combinations of Future Climate Change and Water Management Scenarios.

Water Management Scenarios	Climate Scenarios	Simulation Combinations Scenarios
Climate change only; no water management (S_I)	Historic (S_H)	S_{IH}
	Warm-Dry (S_D)	S_{ID}
	Warm-Wet (S_W)	S_{IW}
Adding more reservoirs (S_{II})	Historic (S_H)	S_{IIH}
	Warm-Dry (S_D)	S_{IID}
	Warm-Wet (S_W)	S_{IIW}
Changes in irrigation and cropping patterns (S_{III})	Historic (S_H)	S_{IIIH}
	Warm-Dry (S_D)	S_{IIID}
	Warm-Wet (S_W)	S_{IIIW}

tively, as that of the Dahushi Reservoir. The reservoir R_1 was added in the Xiluga River (Brh 1) and the reservoir R_2 was added in the Xibo River (Brh7) (Figure 4). (4) Scenario III (S_{III}): same as S_{II} except that efficient water-saving irrigation and changes in cropping patterns in all irrigation districts for the period of 2010-2040 were implemented.

We examined the water supply-demand relations using a few indictors including total water demand, demand unmet, and groundwater storage change under the combinations of water management and climate change (a total of 3 × 3 scenarios) (Table 6). Water demand unmet was defined as the amount of water requirement not met by water supply. When demands are not fully met at a particular location or the region as a whole, water shortages occur. The nine hypothetical simulation scenarios covered a large spectrum of possible future water supply stresses in the LRB.

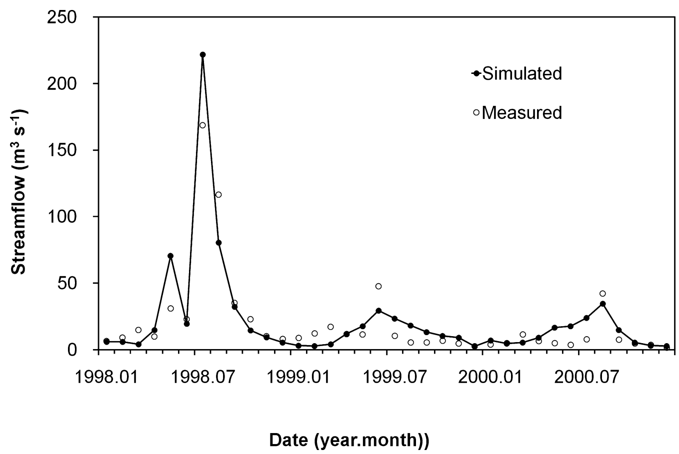

FIGURE 5. A Comparison of Measured Streamflow and Simulated Streamflow by the Water Evaluation and Planning Model for the Time Period of 1998-2000 at the Hongshan Reservoir Dam Site.

RESULTS

Model Calibration and Validation

We performed the model calibration and validation for the SWAT and WEAP separately. Firstly, SWAT model was calibrated for Hongshan's streamflow for the period of 1981-1990 and validated for the period of 1991-2000 (Hao *et al.*, 2011b). The simulated monthly runoffs for the two periods were R^2 = 0.88 and E_{NS} = 0.70, and R^2 = 0.91 and E_{NS} = 0.79 (at the confidence level of 0.90), respectively (Hao *et al.*, 2011b).

The WEAP model was calibrated using the measured monthly runoff at the Hongshan Reservoir dam during 1998-2000. The R^2 and E_{NS} were 0.87 and 0.79, respectively (confidence of 0.90). However, the validation was not performed for the WEAP model due to the limitation of our data sets. The above results indicated that the SWAT and the WEAP could model monthly streamflow reasonably well and could be used for future projection purposes (Figure 5).

Water Supply and Demand under "Status Quo"

Under all three different climate scenarios and water management "status quo," the water supply delivery obviously increased from 2010 to 2040 (Figures 6a-6d). However, the future water supply requirements and unmet demands are projected to increase more under the Warm and Dry (S_{ID}) scenario than under the Warm and Wet scenario (S_{IW}) as well as under the Historic Climate scenario (S_{IH}). The groundwater storage became relatively low under the S_{ID} scenario (Figure 6d), while the differences were small between the S_{ID} and S_{IH} scenarios.

Under the current water management conditions with no improvement in the current water management system (S_I), irrigation, industrial, and domestic and animal husbandry water uses will increase continuously in the future (Figure 6a). The sharp decrease in water supply needs during the

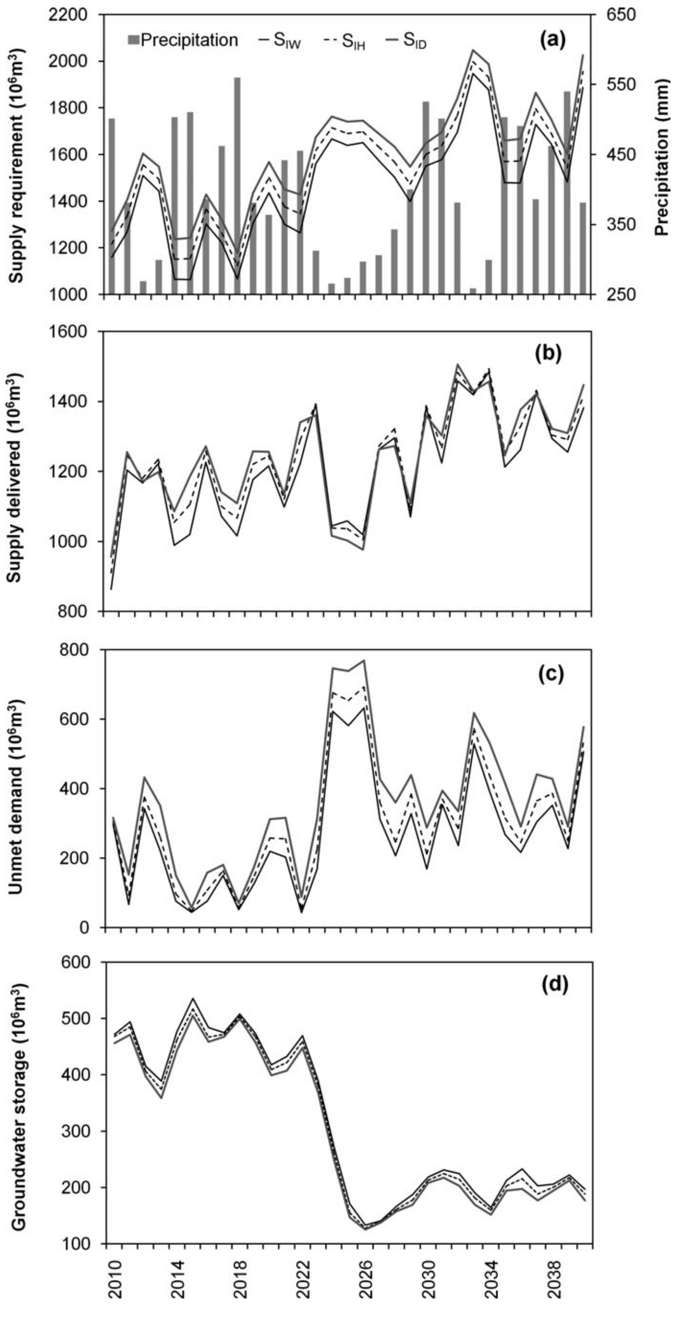

FIGURE 6. Water Supply, Demand, and Storage under Various Scenarios. (a) Water supply requirement (including loss, reuse, and demand-side management); (b) water supply delivered; (c) unmet demand; and (d) groundwater storage without water management applied under three climate scenarios during 2010-2040. See Table 6 for the definitions of S_{IW}, S_{IH}, etc.

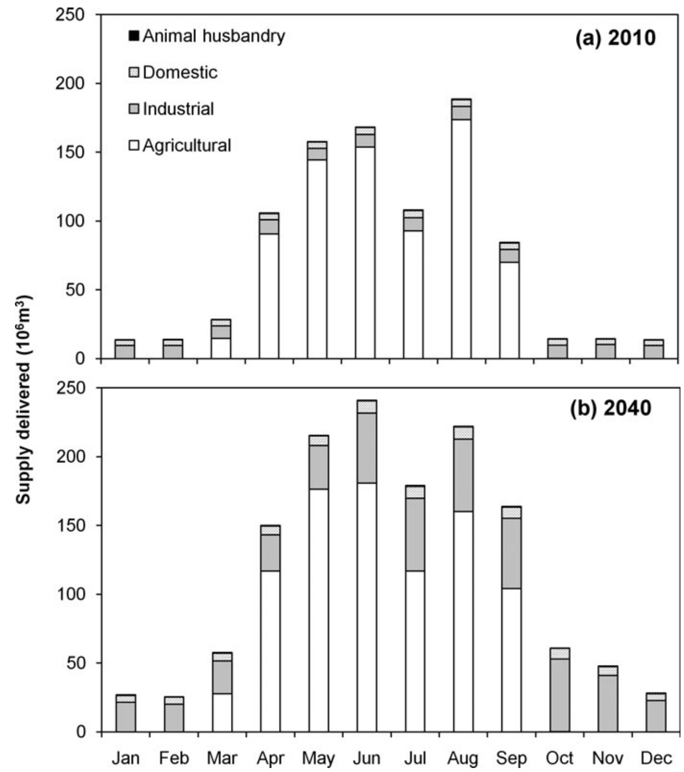

FIGURE 7. Seasonal Water Supply Delivered for Different Demand Sites in the Years of (a) 2010 and (b) 2040 under Current Management Conditions.

periods of 2021-2022 and 2035-2036 is due to a large increase in annual precipitation in the years of 2021 (442 mm), 2022 (455 mm), 2035 (503 mm), and 2036 (490 mm). The long-term (2010-2040) mean precipitation is 399 mm.

The amount of water supply delivered in all demand points does not meet water-use requirements, especially during the drought period (2023-2027) (Figures 6b and 6c). The fastest growth of unmet water is industrial water use, followed by irrigation water use, animal husbandry, urban domestic water, and rural domestic water. The annual change in groundwater storage fluctuates with time and is relatively steady at the early stage (2010-2022), obviously declining halfway into the simulation due to lack of supplies during the continuous drought period (2023-2027), and remains low with some volatility at the later period (Figure 6d).

The seasonal water supply delivered for different demand sites in the years of 2010-2040 is mostly for agriculture, followed by industrial and domestic, and the least for animal husbandry (Figures 7a and 7b). The fastest growth among all of the sectors occurs in industry. For agriculture, the seasonal highest water supply delivered is during the crop growth period from April through September (Figures 7a and 7b).

Integrated Water Management Options under Climate Change

Adding more reservoirs decreased unmet water demand (Figures 8a and 8b) and could potentially alleviate water shortage by increasing water supply

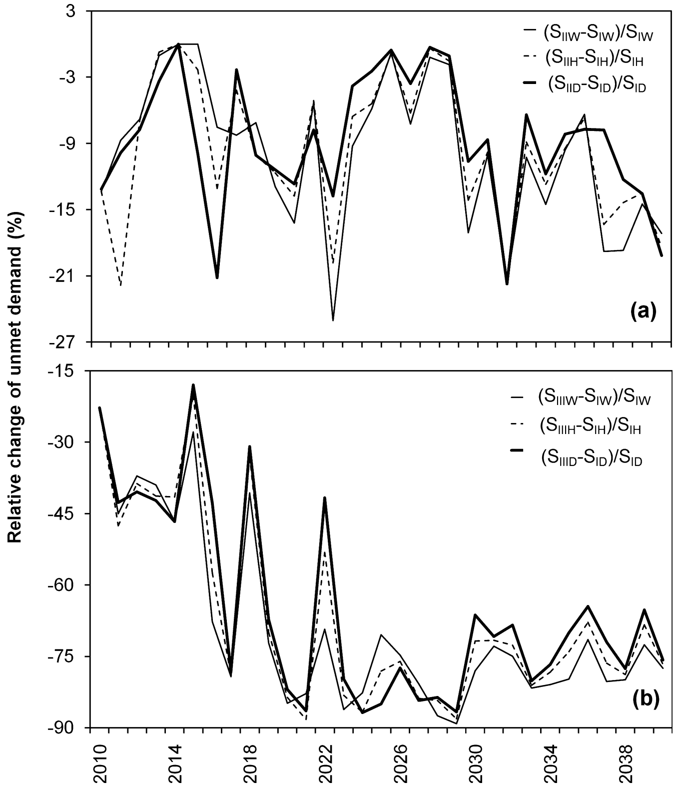

FIGURE 8. Relative Change Rate of Unmet Water Demand during 2010-2040 under Different Management and Climate Scenarios. (a) $(S_{IIW} - S_{IW})/S_{IW}$ (fine line), $(S_{IIH} - S_{IH})/S_{IH}$ (dash line), and $(S_{IID} - S_{ID})/S_{ID}$ (bold line) and (b) $(S_{IIIW} - S_{IW})/S_{IW}$ (fine line), $(S_{IIIH} - S_{IH})/S_{IH}$ (dash line), and $(S_{IIID} - S_{ID})/S_{ID}$ (bold line).

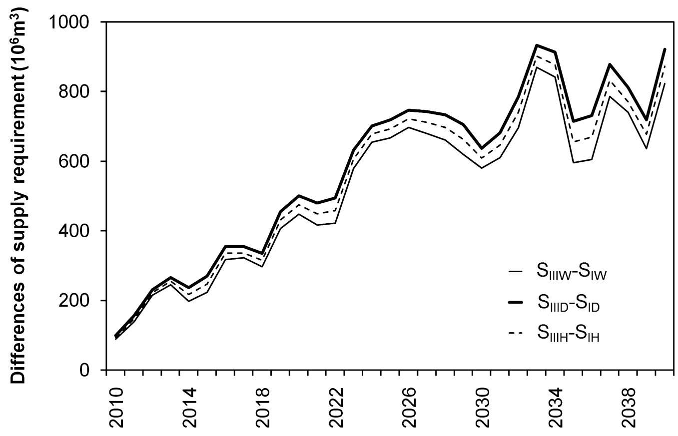

FIGURE 9. Differences in Irrigation Requirements between the S_{IH}, S_{ID}, and S_{IW} and S_{IIIH}, S_{IIID}, and S_{IIIW}, Respectively during 2010-2040.

for both the S_{II} and S_{III} scenarios during the drought seasons or some drought years. Reservoir storage accumulated from wet seasons or years alleviates water shortage the following drought year. However, because the reservoir storage capacity is limited under continuous drought periods, such as during 2023-2027, the alleviation effects diminish (Figure 8a) (i.e., change in unmet water demand = 0).

Under all three climate scenarios, building more reservoirs has apparent alleviation effects on water shortages. However, the effects are different among the climate scenarios. For the Warm and Dry scenario, because of the reduced rainfall and water supply and thus the reservoir storage capacity, the water shortage alleviation effects from adding reservoirs are much lower compared to the other two climate scenarios, especially in the late stage (Figure 8a).

Combining adding reservoirs with the demand side measures (e.g., altering cropping systems and implementing water-saving irrigation strategies) reduces water demand greatly (Figure 8b) and thus makes them more effective for alleviating water shortages than the strategy of adding only two more reservoirs. This is especially true during a continuous drought period, such as 2023-2027 when differences between the effects of the two methods were most obvious (Figure 8b). The obvious decreases in irrigation water requirements as a result of an increase in irrigation efficiency (as calculated S_{III}-S_I) contribute to the effects of the demand management on water stress (Figure 9). Apparently, the effects are most pronounced starting around 2025 and are stabilized afterwards.

In most years, groundwater storage increases after building more reservoirs due to a reduction of groundwater use (Figure 10a). Building more reservoirs also reduces the speed of the groundwater depletion under the three climate scenarios. However, under the Warm and Dry scenario, the increase in groundwater storage is not as obvious as in the other two climate scenarios, suggesting that the reservoir management option is less effective under the Warm and Dry scenario (S_D) (Figure 10a). Combining efficient irrigation and improved cropping systems (S_{III}) reduces the speed of groundwater depletion more effectively under all climate scenarios than only building more reservoirs (S_{II}) (Figures 10a and 10b).

The total unmet domestic and industrial water uses for the urban areas of Chifeng City are the least under the S_{III} scenario, followed by S_{II}, and S_I during 2010-2040 (Figures 11a and 11b). Under the S_{III} management scenario, the unmet water demand for domestic and industrial water uses are similar among all climatic conditions (Figures 11a and 11b). The simulation results indicate that measures used in S_{III} may alleviate domestic and industrial water shortages even under drought conditions (i.e., Warm and Dry climate change conditions). The S_{II} is slightly different from S_I in unmet water demand in the urban

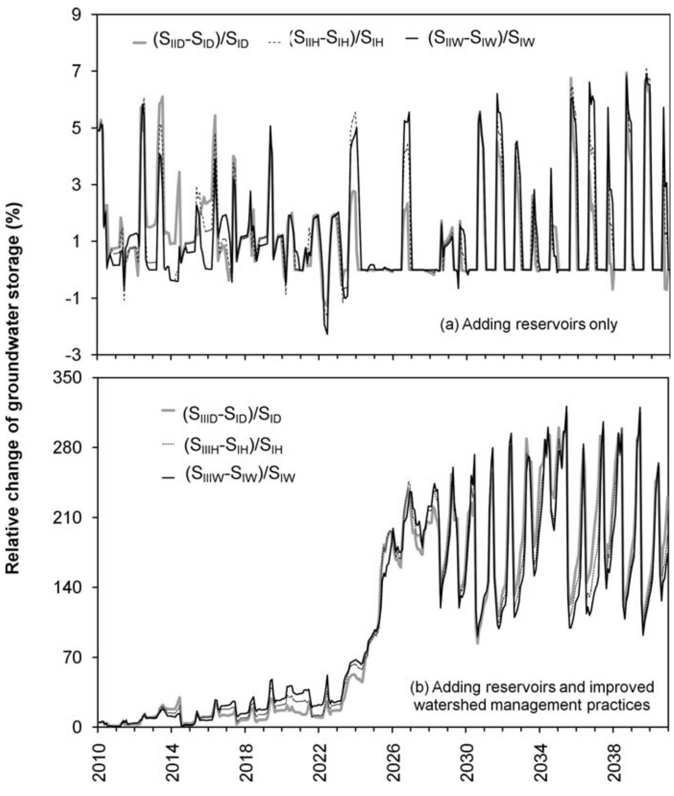

FIGURE 10. Relative Monthly Change (%) in Groundwater Storage under Different Management and Climate Scenarios during 2010-2040. (a) Adding reservoirs only: $(S_{IIW} - S_{IW})/S_{IW}$ (fine line), $(S_{IIH} - S_{IH})/S_{IH}$ (dash line), and $(S_{IID} - S_{ID})/S_{ID}$ (bold grey line) and (b) adding reservoirs + improved watershed management practices: $(S_{IIIW} - S_{IW})/S_{IW}$ (fine line), $(S_{IIIH} - S_{IH})/S_{IH}$ (dash line), and $(S_{IIID} - S_{ID})/S_{ID}$ (bold grey line).

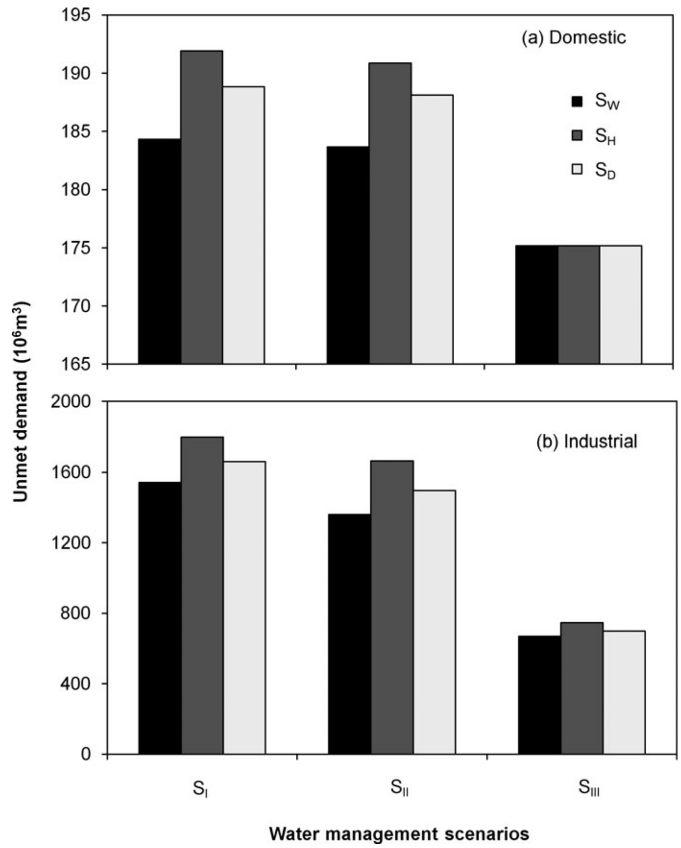

FIGURE 11. Projected Total Unmet Water Demand for (a) Domestic Water Use in the Urban Areas of Chifeng City under Three Management Scenarios and Three Climate Scenarios during 2010-2040 and (b) Industrial Water Use of the Urban Areas of Chifeng City under Three Management Scenarios and Three Climate Scenarios during 2010-2040.

area of Chifeng City. The highest unmet water demand is found under historical conditions for both S_I and S_{II}. Climate change can increase or decrease water supply stress in the urban areas, but the impact is considered relatively small, especially under S_{II} (Figures 11a and 11b).

DISCUSSION

Adding Reservoirs to Meet Future Water Demand

Our modeling results suggest that future water shortages will become more prominent in the LRB under the current climate and water resource management practices. Building more reservoirs is likely to reduce water shortages in this region and to alleviate groundwater depletion problems by utilizing more surface water than groundwater. Reservoirs allow water management agencies to store "surplus" water in high-flow seasons, thus making up for the low-flow seasons. However, under continuous drought conditions that lasted several years, the relief from adding more reservoirs is limited. The reservoir has a positive role in recovering the basin groundwater storage because current agricultural irrigation uses mainly groundwater. However, reservoirs have potentially negative effects on groundwater reserves. There is also a high environmental cost to adding more reservoirs in the study basin; for example, the reduction of environmental flows threatening aquatic biota downstream. Therefore, expanding reservoir capacity might be the last option for solving water shortage challenges in the LRB. Our results are similar to findings from a study by Swiech *et al.* (2012). They evaluated the impacts of a reservoir for improving water use in irrigation in the Yarabamba region in Peru. Their results also showed that the reservoir might alleviate the current water shortages, but the interests and actions of upstream and downstream areas appear to also be important.

Comprehensive Water Management: The Best Solution

Our scenario analysis suggests that combining reservoir management and the reduction in the irrigation water demand by altering the cropping system and improving irrigation is much more effective than building more reservoirs. The findings are consistent with the notion that water supply side measures should be combined with demand management to effectively ease the water shortage problems in China. Future climate change is likely to increase variability of precipitation resulting in an increase of drought frequency. Water management measures from the demand side such as changing cropping structure and increasing water-saving irrigation areas are effective not only for reducing the vulnerability of water resources but also for coping with climate change. Few studies have examined the climate impacts on irrigation water requirements or potential adaptation paths to climate change (Purkey *et al.*, 2008; Joyce *et al.*, 2011). Models are needed to examine the effectiveness of new irrigation management technology that can meet crop water demands under a changing climate.

Under a water management "business as usual" scenario, a water shortage will increase significantly due to the expansion of cropland and population rise in the studied basin. Future climate change is likely to aggravate the water shortage problems. The differences in water shortage for meeting crop irrigation under climate change scenarios mainly occur in the growing season when water use is the highest. Climate change has obvious effects on irrigation water use, but relatively small effects on water supply and availability to urban and industrial water users. Under a warm and dry climate, building more reservoirs also has limited relief for surface water shortage.

Water Demand Management by Adjusting Cropland Composition

Our study suggests that the driving force of the water resource vulnerability in the LRB is mainly derived from agricultural irrigation. The past 40 years was the fastest growth period of irrigation area in the LRB history and the increased irrigation area still gives priority to crop production. In order to reduce agricultural water use, water-saving irrigation technology such as spray irrigation, subsurface irrigation, and drip irrigation should be introduced and actively promoted. In addition, our modeling results show that there is large potential to reduce water use but increase water-use benefits by adjusting cropland composition. In the LRB, dry land area accounts for 74% of arable land, which is suitable for the large-scale cultivation of coarse cereals. After the 1970s, with the development of hybrids and the improvement of planting conditions, the cultivated area of three major crops (i.e., wheat, maize, and rice) increased, while that of coarse cereals reduced. Wheat, maize, and rice are all high-water-consumption crops. In recent years, more attention has been given to nutrition balance and the consumption of cereals has increased. The current market prices of rice and wheat are often lower than those of coarse cereals such as millet, buckwheat, sorghum, etc. The hilly topography in the LRB is more suitable for the cultivation of low-water-consumption coarse cereals. Therefore, to adjust planting structure to expand the crop planting areas of low-water-consumption crops (e.g., millet) is conducive to local economic development in addition to alleviating water shortages. Therefore, there is a large potential to shift crop land structure from irrigation-intensive to rain-fed agriculture.

In addition to the global climate change threat to local water resources and ecosystems, sufficient evidence has shown that the LRB is suffering from desertification and the land has become more arid either due to an increase in water loss from climate warming or water resource exhaustion due to human activities (e.g., groundwater withdrawal) (Fu and Wen, 2002). Water shortages and associated socioeconomic factors add more pressure to future water resource management. More stringent and bold water resource management policies are needed.

Climate Change and Water Management

Our integrated modeling study suggests that adding more reservoirs and improving irrigation efficiency are the best approaches to meeting water demands in the study basin, even under the worst case of climate change. Similarly, Mehta *et al.* (2013) assessed the potential effects of climate change and adaptive management on the irrigation water supply in the Cache Creek watershed in California using WEAP. They showed that increases in demand from climate change alone exceeded water-use reductions from changing cropping patterns by an order of magnitude. Maximum water savings occurred by combining diversified water-efficient cropping patterns with irrigation technology improvements, which decreased demand to 0.12 below the historical mean, thereby also reducing groundwater pumping. Our findings suggest that strategic planning for building reservoirs along with changes in cropping patterns and improving irrigation technologies will be essential for agricultural adaptation to climate change. These results all suggest that water resource management practices considering both supply and demand are more effective and practical than supply only, especially in tackling climate change in water-stressed regions in northern China.

Groundwater and Comprehensive Water Management

Frequent droughts and groundwater depletion are critical constraints to improving agricultural productivity in the LRB. The local government has been promoting integrated watershed management in drought-prone areas to address these constraints. However, groundwater is a free common property resource and this has accelerated private irrigation investments and depletions of aquifers. Many previous research results showed that efficient water-saving irrigation and changes in cropping patterns might alleviate the groundwater depletion. Hu *et al.* (2010) used an integrated crop-growth and groundwater model and ensured groundwater recovery via agricultural water-saving to test agricultural water-saving and sustainable groundwater management in the Shijiazhuang Irrigation District of northern China. The model results showed that a 29%, or 136 mm, reduction in irrigation could stop groundwater drawdown in the plain. An additional 10% reduction in irrigation pumping (i.e., a total of 39% or 182 mm) would induce groundwater recovery and restoration to the pre-development hydrological conditions of 1956 in about 74 years. Yang *et al.* (2006) found that optimizing irrigation management for wheat can reduce groundwater depletion in the piedmont region of the Taihang Mountains in northern China using a DSSAT-wheat model. Shu *et al.* (2012) applied the integrated hydrological model MIKE SHE to a part of the North China Plain to examine the dynamics of the hydrological system and to assess water management options to restore depleted groundwater resources. The model analysis verified that groundwater tables in the region are subject to steep declines (up to 1 m/yr) due to decades of intensive exploitation of the groundwater resources for crop irrigation, primarily the widespread crop rotation of irrigated winter wheat and mostly rain-fed summer maize. Therefore, optimizing irrigation management and changes in cropping patterns can alleviate the groundwater depletion.

These studies do not answer how irrigation management measures combined with others such as reservoir construction can alleviate groundwater stress under future climate change. Our findings suggest that building more reservoirs can reduce the speed of the groundwater depletion under the three climate scenarios. However, adding more reservoirs is not necessarily the most effective measure to solve water supply problems. Combining efficient water-saving irrigation and adjusting cropping patterns helps groundwater recovery more effectively than only building more reservoirs under two climate change scenarios of the warm and dry scenario and the warm and wet scenario.

Water Supply and Demand Modeling

Our research adopted a SWAT-WEAP integrated approach to provide an operational methodology for assessing the water resource management. The modeling system considers both the water supply and demand sides in evaluating water stress under both climate change and management scenarios. Some studies have also integrated the SWAT and WEAP models. Giertz *et al.* (2010) assessed the impacts of global change on water resources and soil degradation in Benin using both models. The WatManSup Project (2007) applied the two models to help water managers to make the decision to choose the most suitable water management tool or combined tools in the Kitui catchment in Kenya. The results showed that the SWAT model is a strong tool that is able to support water managers and policymakers in that region. The study clearly demonstrated that the strong aspect of the WEAP model is that the framework is already in place so that evaluation of alternative water allocations can be performed on the fly. Examples in Kitui include the impact of more dams or a change in crops.

In this study, the SWAT was applied to describing the physical processes related to water, while the WEAP was mainly used to evaluate the impact of human interference in water distribution and allocation. The case study also shows that the SWAT model can support water managers and policymakers, as physical processes and human interventions can be analyzed in great detail. All components of the water balance were analyzed, which can be used to evaluate scenarios such as climate change. The WEAP model was powerful in evaluating current and future options in water resources.

Future Studies

Further research is needed to improve our understanding of the complex issues investigated in this study. In this study, climate change scenarios were specified based on China's national climate change assessment report of 2005. Another option is to use regional climate models to obtain more physically consistent and the most up-to-date downscaling climate change scenarios for the SWAT-WEAP modeling. In order to develop better science-based sustainable water management strategies, future research should focus on the combined effects of short-term and long-term climate change including extreme weather and climate events and land-use options, urbanization planning, and economic growth on water resources.

Uncertainties exist in model parameterization for both the SWAT and WEAP models and assumptions are made based on literature or limited field studies. For example, water consumption by major crops in the study basin was estimated by the modified FAO reference ET method, but ET fluxes have not been verified with measurements. More field-based studies and station-based monitoring would reduce the uncertainties in model parameterization. In addition, a one-way data connection was used in integrating the SWAT and WEAP models. An approach of tighter coupling between the two models with two-way feedback mechanisms is needed in future studies to reflect the true interactions of watershed hydrological processes, water balance, and management options. The validation was not performed for the WEAP model due to the limitation of our data sets. Although the calibration results indicated that the WEAP could model monthly streamflow well, the validation should be performed in future studies based on long-term data sets.

Besides the climate, irrigation management, and surface and groundwater availability examined in this study, future studies should also assess the effects of other factors such as water pricing and markets, water allocation limits, and wastewater reuse on the water supply (Tanaka *et al.*, 2006).

With simulating models being increasingly used to provide policy-relevant information, it is critically important to address the public need for high-quality models for decision making and to establish public confidence in these models. An important element in establishing such confidence is to make the models as accessible as possible to the broader public and stakeholder community. In the decision-making process, models are used more or less depending on a variety of factors, one of which is the credibility of the model (Curry, 2010). There is still a long way to go to develop high-quality models for decision making, especially for those countries, such as China, which lacks long-term historical observation data.

CONCLUSIONS

Urbanization, increasing population, economic growth, and major changes in hydrological and climatic conditions all impact water supplies in Chifeng City. Our study concludes that adding reservoirs can increase the surface water supply, which may alleviate the current water shortages of the domestic, agricultural, and industrial sectors and basin groundwater depletion in the LRB. However, this option is not necessarily the most effective measure for solving large city water supply problems given all other negative impacts on ecosystems. Under continuous droughts, the alleviation of supply-side measures by increasing reservoir capacity is limited. Our study indicates that improving irrigation efficiency and adjusting planting structure may be of more importance than only adding reservoir storage. The most effective and practical measures for reducing water shortage can be realized by diversifying water-efficient cropping systems, improving irrigation technology, and reducing groundwater pumping. Demand improvement measures, i.e., adjusting planting structure and implementing high-efficiency water-saving irrigation technology, are not only the effective measures reducing the vulnerability of water resources but also the adaptation methods to reduce water demand so that water demand does not exceed limited water supply (Ed *et al.*, 2001) to cope with climate change.

With shrinking resources and a deteriorating environment and the rising cost of freshwater resources, traditional water management practices and water-use patterns that are mainly related to supply-side measures should be shifted to the “most stringent” water demand management. Solving modern water supply issues should consider demand management measures to achieve the goals of the sustainable use of water resources in water-stressed regions in northern China.

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