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A dynamic model for exploring water-resource management scenarios in an inland arid area: Shanshan County, Northwestern China

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Abstract: Water scarcity is a challenge in many arid and semi-arid regions; this may lead to a series of environmental problems and could be stressed even further by the effects from climate change. This study focused on the water resource management in Shanshan County, an inland arid region located in northwestern China with a long history of groundwater overexploitation. A model of the supply and demand system in the study area from 2006 to 2030, including effects from global climate change, was developed using a system dynamics (SD) modeling tool. This SD model was used to 1) explore the best water-resource management options by testing system responses under various scenarios and 2) identify the principal factors affecting the responses, aiming for a balance of the groundwater system and sustainable socio-economic development. Three causes were identified as primarily responsible for water issues in Shanshan: low water-use efficiency, low water reuse, and increase in industrial water demand. To address these causes, a combined scenario was designed and simulated, which was able to keep the water deficiency under 5% by 2030. The model provided some insights into the dynamic inter-relations that generate system behavior and the key factors in the system that govern water demand and supply. The model as well as the study results may be useful in water resources management in Shanshan and may be applied, with appropriate modifications, to other regions facing similar water management challenges.

Keywords: System dynamics; Water resources management; Northwestern China; Water scarcity

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Introduction

Meeting water needs to sustain lives and support social, economic, and ecological development is one of the major challenges of our time (Frederick et al. 1997; Jones et al. 2009;

Dawadi and Ahmad 2013). It is estimated that one-fifth of the world's population is living under conditions of water scarcity, mainly resulting from the heterogeneous distribution of water in time and space (FAO 2013). This situation is exacerbated by an increase in demand, especially by the growth in population and economic development. Even though agriculture is the largest water user, the industrial demand is on the rise. The enormous growth in water demand requires that water resource managers confront the challenges of managing both water quantity and water quality.

In arid and semi-arid areas, where available, groundwater plays an important role in the overall water supply (Kalra et al. 2013; Choubin et al. 2014; Zhang et al. 2014). Especially in places with a shortage of surface water, groundwater becomes the principal water source. This can lead to depletion of the groundwater, resulting in decreasing well yields, rising costs for pumping, and damage to the ecosystem (Konikow and Kendy 2005). Climate change can exacerbate the water issues (Barnett et al. 2005; Sagarika et al. 2014; Carrier et al. 2016). Several studies show that climate change will increase the frequency of extreme events, such as droughts and floods (Schreider et al. 1996; IPCC 2014). Groundwater is affected by changes in climate, streamflow, infiltration, and land use.

Population growth, economic development, groundwater depletion, and ecological deterioration are occurring in many regions of the world, particularly in arid and semi-arid areas (Gleick 2010; Raneesh 2014). Integrated water-resource management plays an important role in addressing these concerns (Kalra and Ahmad 2012). To address the challenge of water scarcity, a primary focus has been on structural options to increase the water supply, which involves the construction of dams or water transfers (Gleick 1998). This supply-side management has helped substantially with the moderation of regional risks during droughts (Gleick 1998, 2003). However, the use of structural options to increase the supply has high costs economically, ecologically, and environmentally (Wang et al. 2011). An alternative approach is demand-side management, with a primary focus on water conservation, water-use efficiency, and improved infrastructure operations (Dawadi and Ahmad 2013).

Shanshan County, located in the Turpan Basin in northwestern China, is characterized with low precipitation and high evaporation, which results in water scarcity. Currently, 90% of the available water is used in irrigation, which contributes only 10% to the gross domestic product (GDP) in Shanshan; meanwhile, 90% of the GDP comes from industries using only 10% of the available water. Moreover, with natural resources increasingly being discovered in the region, Shanshan is attracting significant investments in gas, petroleum, gold, iron, and coal mining. This will significantly increase the water demand for industries and the related local economy, which will stress even further the existing water resources.

A series of consequences have occurred due to water issues in Shanshan, such as groundwater overexploitation, natural vegetation degradation, desertification, and a decline in biodiversity (He and Zhang 2003; Bruelheide et al. 2003). In this region, water resources are the major constraint for socioeconomic development and the preservation of ecological environments (Fang et al. 2010; Kalra and Ahmad 2011). Since 2010, Shanshan County has implemented a series of policies for water resource management, such as restrictions on the approval of new industrial investments, encouragement of efficient water use, and a decrease the number of pumping wells and the size of farmland areas.

Several studies have been carried out on various aspects of water issues in this region, focusing on evaluating water resources, groundwater systems, and irrigation systems from the viewpoints of socioeconomic development, irrigation techniques, and hydraulic efficiency (Nagasawa et al. 2006; Fang et al. 2010; Abulikemu 2012; Hering and Ingold 2012). Based on a modified Penman formula, Fang (2010) used the concept of virtual water to evaluate surface and groundwater resources. Li (2010) analyzed water resource development and utilization, and pointed to several challenges, and Ablikim (2014) studied the characteristics of surface water with a focus on snowmelt. Chen (2010) studied water use in oil fields, one of the most important industries in the region.

Considering the current challenges, potential risks, and urgent concerns in water management, an integrated understanding of water resources system is required. System dynamics (SD) is an approach that facilitates the identification of dynamic interactions among the components within a system. It can be used to operationalize systems thinking and make strategic decisions (Sterman 2000). System dynamics model have been used successfully for water resources by simulating policy options, management decision making, and stakeholder participation (Winz et al. 2009; Mirchi et al. 2012).

During the last two decades, there has been a tremendous growth in system dynamic applications for water resources management, as indicated in the following studies:

(1) Water resources policy analysis and decision making (Gao and Liu 1997; Simonovic and Fahmy 1999; Ahmad and Simonovic 2004 & 2006; Madani and Mariño 2009; Shrestha et al. 2011 & 2012; Rusuli et al. 2015);

(2) Reservoir regulations and flood management (Ahmad and Simonovic 2000);

(3) Water-quality simulations with related social-environmental issues (Tangirala et al. 2003; Leal Neto et al. 2006; Venkatesan et al. 2011a & b);

(4) Climate-change effects on water resources (Simonovic and Li 2003; Dawadi and Ahmad 2012, 2013; Zhang et al. 2014);

(5) Simulations of hydrologic and geothermal processes (Leaver and Unsworth 2006; Zhang et al. 2016); and

(6) Stakeholder involvements in water management (Ford 1999; Stave 2003; Tidwell et al. 2004; Langsdale et al. 2007, 2009).

Many other applications can be found in the review by Mirchi et al. (2012).

The goal of this study was to identify the key causes of water issues in Shanshan County, and to explore and evaluate water-resource strategies for solving and relieving the water issues and stresses. The water demand-and-supply system in Shanshan was simulated using a system dynamics tool that integrates the operational management of the water infrastructure, various sources of the water supply, the water demand from various water users, and water allocations. In addition, the effects of climate change were considered by using a coefficient of monthly streamflow variability, and ecologic requirements were considered by maintaining a minimum monthly streamflow. Various scenarios were tested for water management options with respect to water sources, irrigation areas, irrigation efficiency, and water demand. Finally, the best options for water resources management were identified.

Results of this study, including causes of water issue and recommended strategies, are expected to help policymakers in water resource management as well as facilitate water sustainability in Shanshan.

1 Study Area

Shanshan County is located in the Uygur Autonomous Region of Xinjiang, northwestern China (42.8667° N, 90.1667° E). It is 3.95×10^4 km^2 in area, taking up 2.4% of the entire Xinjiang Autonomous Region; it has 10 towns and one horticultural farm, as shown in Figure 1a: Shanshan (SS), Lianmuqin (LMQ), Lukeqin (LKQ), Pizhan (PZ), Dongbazha (DBZ), Tuyugou (TYG), Dalangkan (DLK), Dikanxiang (DKX), Huochezhan (HCZ), Qiketai (QKT), and Yuanyichang (YYC). The rural population accounts for approximately 75% of total population in the county.

With typical arid inland climate, and elevation ranging between 1200 m and 3000 m, Shanshan has low precipitation, ranging between 17.6 mm and 25.3 mm per year, based on average of 55 years of data (1956 - 2010). In addition, it has high evaporation at 2751 mm - 3216 mm per year. The average monthly temperature ranges from -11.2°C to 33°C. Three rivers flow across the Shanshan County, the Ertanggou, Kekeya, and Kanerqi Rivers. These rivers are dominated by snowmelt from Bogurda Mountain, which is the southern part of Tian Shan mountain range. Currently, four reservoirs are in service, including two newly constructed reservoirs on the Kekeya River and the Ertanggou River; these became operational in 2015 (Figure 1a). The average annual surface water resources are 243.3 million cubic meters (MCM), and groundwater resources are 166.1 MCM, based on data for 55 years (1956-2010) (IWHR 2011). Both surface water and groundwater are used to meet the water demands and support the socioeconomic development of Shanshan County.

As mining is the leading industry in Shanshan, there are four mining related industrial parks in the county: Stone, Oil, Chemical, and Wanxiang

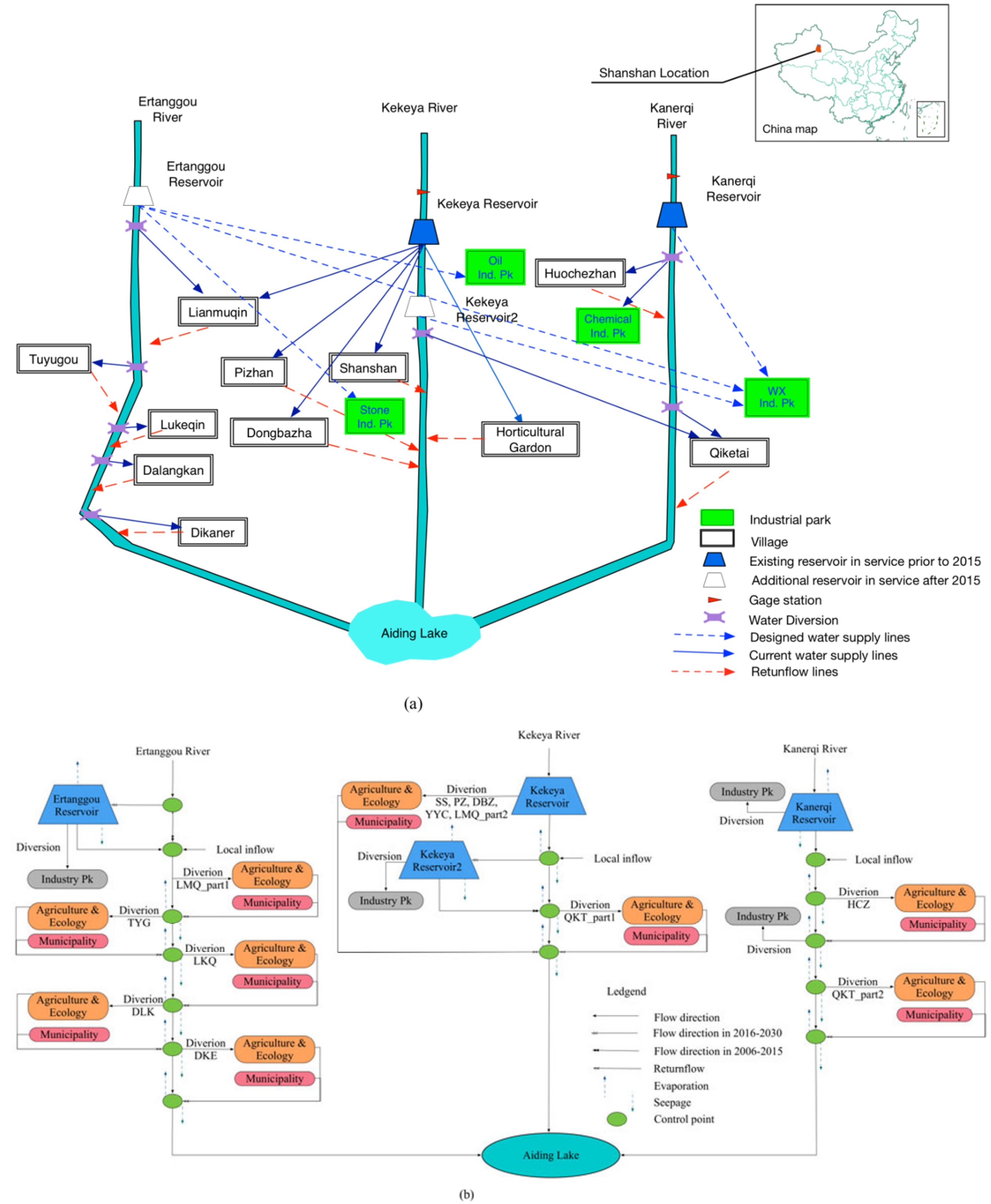

Figure 1 (a) Water supply and demand system in the study area of Shanshan County in northwestern China; and (b) a schematic diagram of conceptualized surface-water flow in the study area.

Industrial Parks (Figure 1a). Along with some rural industries, these industrial parks contribute 90% to the regional GDP, but only consume 10% of the total water. Due to underdevelopment of this region, the livelihood of a large proportion of the population depends on farming with low water-use efficiency. Agriculture uses 90% of the total water (IWHR 2011).

Due to the limited availability of surface water resources, 67% of the current water supplies come from groundwater. The overexploitation of groundwater has resulted in serious ecological and environmental concerns, such as a drop in the groundwater level, streams drying up, a decrease in species diversity, and land subsidence. The water stresses only will increase further due to planned future expansion of industries.

2 Data

This study used data from historical records, official technical reports, and government-sourced bulletins that were collected from the Shanshan Statistics Bureau, the Shanshan Water Conservancy Bureau, the Shanshan Forest Bureau, and the Shanshan Agricultural Bureau (see details in Table 1). To address the issue of missing data from these secondary sources, the study used estimations provided by the China Institute of Water Resources and Hydropower Research (IWHR), which were prepared for a project known as the Development of the Shanshan Water Rights Transference System. In the model, the data consisted of two main categories, 1) population and land use and 2) a water resources system.

2.1 Population and land use

The data from the Shanshan Statistical Bureau showed that the population of the entire Shanshan County, including urban and rural population, increased from 21.49×10^4 in 2006 to 22.68×10^4 in 2010 (Bulletin 2011). In the meantime, the proportion of the rural population remained around 74% to 75% of the total population. Based on the data from the Shanshan Agricultural Bureau, of the total area of Shanshan County mostly consists of the Gobi Desert (88%), with 1% of the land used for farming (437 km^2). Based on national regulations for farming areas, the farmland in Shanshan should be limited to an area of 200 km^2; however, the current farmland area is far beyond this threshold (IWHR 2011; Chen et al. 2015).

2.2 Water resources system

Due to the short length of the record for streamflow gauging (10 - 18 years of observations), the water resources of the three rivers in study area were extended by using a hydrologic analogy method from the China Institute of Water Resources and Hydropower Research (IWHR) for both surface-water resources and groundwater resources. IWHR also was responsible for the Development of the Shanshan Water Rights Transference System project. The water-resource estimation, based on 55 years of extended data, was consistent with the official report from the Shanshan Integrated Water Resources Planning, released by the Shanshan Water Conservancy Bureau, and thus was used in this study (IWHR 2011).

This study simulated the operation of four reservoirs in the study area. The Shanshan Water Conservancy Bureau provided reservoir-design reports, including the water-level storage curve, the water-level area curve, seepage estimations, and evaporation calculations (Table 1). The Shanshan Water Conservancy Bureau provided the data for calculating the water demand for each water user.

Table 1 Data sources for model simulation

Sectors	Data source
Population	*Shanshan Statistical Report for National Economic and Social Development* (2008, 2009, 2010)
Land use	*Shanshan Second Land Survey Report* (2010)
Water resources	*Water Resources Bulletin* (2006, 2007, 2008, 2009, 2010); *Shanshan Integrated Water Resources Planning* (2011); *Development of Shanshan Water Rights Transference System* (2011)
Water demand and supply	*Shanshan 12th Five-year Development Program, Shanshan statistical summary of water supply (2005-2010)*
Hydraulic facilities: reservoirs and diversion devices	Kekeya: Shanshan Water Conservancy Bureau
	Kanerqi: Shanshan Water Conservancy Bureau
	Kekeya2: *Kekeya2 Reservoir Preliminary Design Report*
	Ertanggou: *Ertanggou Reservoir Feasibility Study Report*

This included historical water supply records, irrigation areas, and irrigation quotas categorized by vegetation types and irrigation methods. The records of groundwater extraction for the period 2006-2010 were collected. This period covered groundwater overexploitation to meet the gap between the excessive water demand and the limited supply of surface water.

3 Methods

3.1 System dynamics modeling

A system dynamics (SD) approach was used to model the behavior of a complex water-resource system (Sterman 2000). The model simulation was done on monthly basis for a period from 2006 to 2030. This model captured the dynamics over time between total water supply from both surface water and groundwater and the total demand from 10 towns, one horticultural farm, and four industrial parks. By modeling a complex system with a causal structure – using cause-and-effect loops, delays, and nonlinearity, etc. – the SD model simulated the interrelationships among the system variables by means of the reactions and feedbacks among them. This allowed the observation of the behavior of a modeled system over time. In the past, SD has been applied successfully for other studies in water resource management (Dawadi and Ahmad 2013; Wu et al. 2013; Zhang et al. 2016).

The conceptualized system for water demand and supply (Figure 2a) showed an interactive relationship between the two water sources – the surface water system and the groundwater system – and the six principal water users as described in Sections 3.2 and 3.3. The SD tool used stocks and flows to describe different variables and their changing relationships. Arrows and influence signs were used as the conventions for SD diagrams in order to describe the system variables and the corresponding effects. As shown in Figure 2b, each variable could have influence on another variable by means of cause-and-effect relationships. A positive (+) influence indicates that the cause and effect both changed in the same direction; for example, an increase in stream flow caused an increase in surface water. A negative (-) influence means the opposite.

In this study, the surface water was negatively influenced by its water users (i.e., agriculture, ecology, and industry parks), and was positively affected by the return flow from water users (i.e., agriculture, ecology, and urban municipalities). Similarly, the groundwater was negatively affected by its water users (all six users) either as the only water source or as the complementary water source; it was positively influenced by the infiltration from water users and the surface water, mainly through streambed and reservoir storage. With a priority order for water use among the multiple users for each water source, and a priority order for the water supply for each water user, the SD tool modeled this complex water system and simulated the integrated system responses (Section 3.2 and 3.3).

3.2 Water supply

The surface-water resources in the study area originated from the eastern side of the Tian Shan mountain range, the largest mountain range in mid-Asia. Snowmelt and precipitation (rainfall and snowfall) on this mountainous area are the main contributors to the streamflow. Researchers have reported that the climate change will lead to the changes in streamflow pattern (IPCC 2014; Sagarika et al. 2015a, b; Tamaddun et al. 2016), which will substantially affect the regional water supply.

In the region where the study area was located, a study in the Tarim River Basin under similar climate conditions suggested that the headwater watershed was more susceptible to climate change due to changes in temperature and precipitation (Jiang et al. 2007). Various studies in northwestern China demonstrated that climate change could affect streamflow with changes in regional meteorological conditions (Peng and Xu 2010; Wang et al. 2012). Chen et al. (2006) showed an increasing streamflow tendency in the Yarkant River and the Aksu River, with a trend line slope of 0.13 and 0.41, respectively. In contrast, a study of the Hotan River showed a decreasing trend line slope of 0.13 during the period of 1950-2000 (Chen et al. 2006). The great variations in precipitation and temperature resulted from regional geography and climate characteristics, and substantially influenced the streamflow formation in terms of

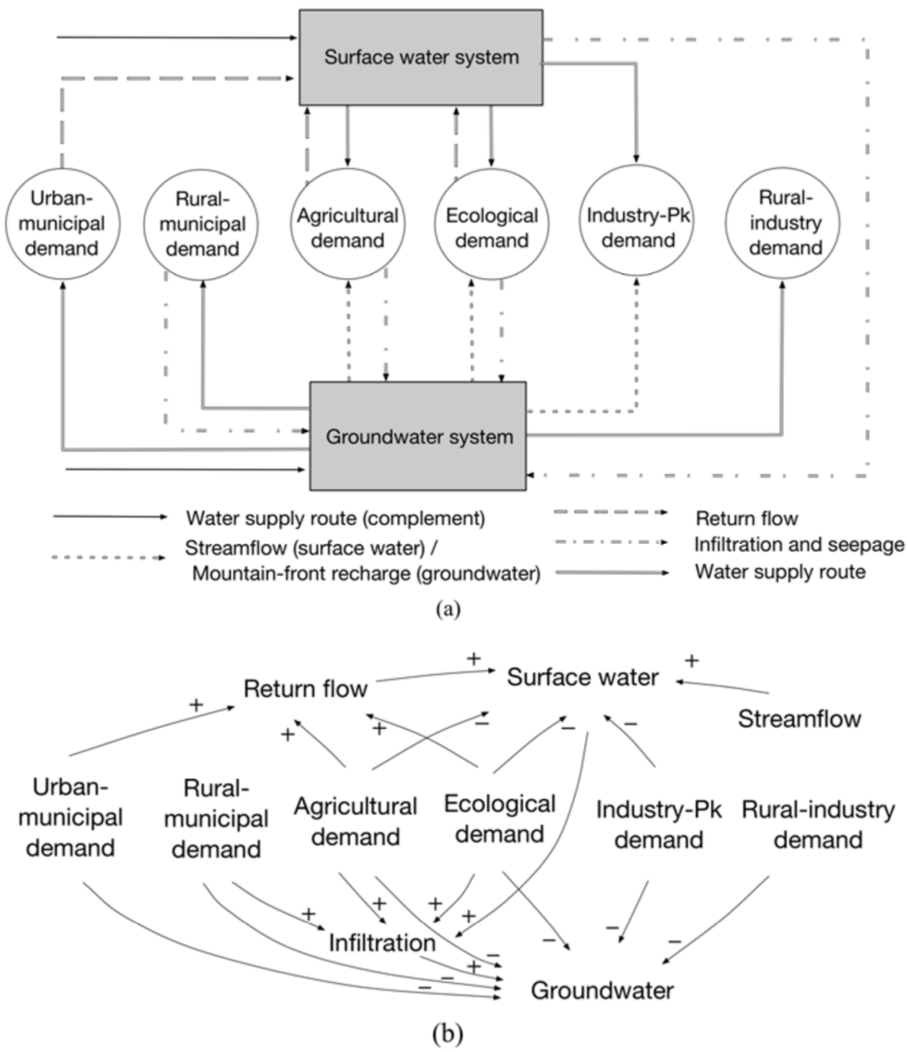

Figure 2 a) Schematic structure of the water demand and supply system with two principal water-supply sources and six main users and (b) a graphical conceptualization of the relationship among selected variables.

volume and timing. Depending on the future projected scenarios and climate models, monthly streamflow variation can be significant (IPCC 2007).

Streamflow, as the main source of surface water supply, was simulated for both historical (2006-2010) and future periods (2011-2030) on a monthly time scale in this study. A coefficient was introduced as a multiplier in the simulation for future monthly streamflow in order to represent a high amount of variation under the effects of climate change. First, mean monthly data from the past 55 years (1956-2010) was considered. Climate change uncertainty in monthly streamflow was introduced by adjusting the flow with a randomly generated variation coefficient between 0.6 and 1.4, where a 0.4 variation was defined as a 40% reduction or increase, respectively. For each month, 100 variation coefficients were generated randomly, and a mean value was calculated.

For the groundwater system, the focus was on the balance between water recharge and water supply. Apart from the piedmont runoff from the foot of the mountain, reservoir seepage, river infiltration, irrigation infiltration, and rural municipal return flow infiltration all were calculated as the recharging sources for the groundwater system. Individually, 1% of the reservoir storage, 65% of the streamflow, and 70% of the rural municipal return flow were considered to be infiltrating into the groundwater system. The computation of the irrigation infiltration was based on the irrigation method used, with a coefficient ranging between 0.01 and 0.4.

3.3 Water demand

Four types of water uses were categorized in the study area: agricultural use, ecological use, industrial use, and municipal use (Figure 1b). As the largest water user, agricultural demand was calculated based on the sum of multiplication of the irrigation area and the irrigation water per unit area for each of the main vegetation types categorized by irrigation methods. Industrial demand was formulated based on actual water-use records (before 2010) and the approved regional economic development plan (after 2010), with a monthly rate of change. Municipal use was estimated by multiplying the increasing population with water demand per capita on a monthly basis.

Agricultural demand is the major source of the total water demand in Shanshan. In order to calculate the water demand, three irrigation methods were used, i.e., flood irrigation (FI), spray irrigation (SI), and drip irrigation (DI). In this study, each irrigation method had five vegetation categories, i.e., vegetables, irrigable plants (cotton and melon-mix-cotton plants), fruit gardens, forest area, and grassland. The total estimation for agricultural water demand was the sum from all irrigation methods with all vegetation categories for each month. Irrigated areas under each irrigation method and vegetation category were changed by the coefficient of changing rate in the area. Equation 1 was used for the computation.

$$W_{Agri,t} = \sum_{it,t}(\sum_{vt,t}(S_{vt,it,t} \times A_{vt,it,t} \times R_{vt,it,t})) \quad (1)$$

where:

W_{Agri} Total water demand of agriculture, monthly;

S Monthly irrigation water per unit area;

A Irrigation area;

R Coefficient of changing rate in area;

vt Vegetation type;

it Irrigation type;

t Monthly time.

Future irrigation demand was estimated based on the changing rate of the irrigation area under each of the vegetation types and the irrigation methods; the change in vegetation types was not considered in this study. The improvement in irrigation water per unit area due to the advances in water-saving techniques was not considered in the study.

Ecological demand represents those artificial plantings of trees that fence around the vegetation area and prevent that area from desertification. The estimation of water demand is consistent with the agriculture since they share the same irrigation system.

Industrial demand includes the water required for industrial parks and rural industries. A development-changing rate was used to estimate the monthly water demand based on the value of previous month and the incremental demand derived from the planned industrial projects that have been approved. The incremental demand was assessed by using the monthly demand that was obtained by evenly distributing the annual water requirement from project reports. This was done because the industrial demand was not expected to significantly change from month to month. Equation 2 was used for the calculation.

$$W_{Ind,t} = R_{Ind,t} \times (W_{Ind,t-1} + W_{IndP,t}) \quad (2)$$

where:

W_{Ind} Total water demand of industry, monthly;

W_{IndP} Total water demand of industry under plan, monthly;

R_{Ind} Coefficient of change rate in industrial development, monthly;

t Monthly time.

Municipal demand was estimated by integrating urban-municipal and rural-municipal water demands. Population is the factor that determines the municipal demand. Estimating a changing rate in urbanization along with the industrial development, with a conservative estimation of no rural population change, is consistent with population statistics of the past five years. Population and water per capita changed along with socioeconomic development. Equations 3 and 4 express the algorithm when calculating municipal demand. The water demand per capita was assumed to remain the same during the model simulation.

$$W_{Muni,t} = P_{u,t} \times wpc_u + P_{r,t} \times wpc_r \quad (3)$$

$$P_{u/r,t} = P_{u/r,t-1} \times R_{pop} \quad (4)$$

where:

W_{muni} Total water demand of municipality;

P_u Urban population;

P_r Rural population;

wpc_u Water demand per capita, urban;

wpc_r Water demand per capita, rural;

R_{pop} Population growth rate;

t Monthly time.

Other demands included minimum streamflow of 1.0 × 10^6 m^3/month, 1.4 × 10^6 m^3/month, and 0.3 × 10^6 m^3/month for the Eertanggou River, the Kekeya River, and the Kanerqi River, respectively. The calculation was based on 15% of the monthly streamflow, on average, to meet the requirements of ecologic conservation in the streams (IWHR 2011).

3.4 Infrastructure regulation

The reservoirs regulate the water released. In this study, due to limited reservoir-storage capacity, a storage-based method (Yeh 1985; Wang et al. 2014) was used to regulate water release. Water users were assigned a priority based on their social and economic importance. In order to satisfy the water demand and ensure the reliability of the water supply, high-priority water users were permitted to use the reservoir storage until the dead-storage level was reached. In contrast, low-priority water users experienced a reduction in supply when the water level in the reservoir was low.

Reservoir operation curves were developed based on the mass balance of the water storage in the reservoir, including the incoming water, evaporation, seepage, water diversion, and water release. The operation curves between the dead-storage level and the flood-control level divided the reservoir storage into three zones, each having specified water users, as shown in Figure 3. Zone 1 (between Level 1 and Level 2) was for the water supply to industrial parks and municipalities that had the highest priority for water use; Zone 2 (between Level 2 and Level 3) was for water supply to future rural industries that had a medium priority; and Zone 3 (above Level 3) was the water supply for ecological use, which is had the lowest priority in the study area. Seasonal variation of the inflow – with high flow in summer and low flow in winter – was represented by operation curves. For example, during the rainy season of summer, low-priority water users in Zone 1 had better chance to be fully supplied as more water is available.

3.5 Water allocation

The water supply from surface water mainly occurs by means of streamflow diversion, and groundwater is supplied by means of pumping (Nagasawa et al. 2006). As shown in Figure 1, regarding use of the surface water of the three rivers – the Ertanggou (ETG), Kekeya (KKY), and Kanerqi (KEQ) Rivers – streamflow was the primary water source for agriculture, industries, and ecology. Return flow from each of the water users (except industries) was estimated to be 10% of the supply; this was added back to the streams and could be supplied to the downstream water users based on the relative location of each town to the river. Apart from the ecological requirement, an evaporation loss of 35% also was considered for the streamflow. Considering the high amount of evaporation and the effective techniques in place for internal water reuse, no return flow was considered in the industries.

Groundwater is the primary water source for rural industries and municipalities. It also is used to supplement the surface-water supply to meet excessive demands for agricultural, industrial, and ecological needs. A groundwater-exploitation threshold of 0.95 (95% of renewable resource) was used to define overexploitation. Figure 2 depicts the recharge and supply variables of groundwater.

3.6 Modeling approach

The system dynamics tool *iThink* 8 (ISEE Systems) was used to develop the model for the water demand-and-supply system. For water sustainability and ecological protection, the groundwater balance was used to evaluate the status of the water system, and the water shortage or groundwater overexploitation was one of the crucial indices.

3.6.1 Model calibration

The developed model was calibrated by comparing the simulated water demand and the historical water supply from both surface water and groundwater sources for each of individual water users, especially for the primary water users (industry and agriculture). The model's performance for the variables of industrial water supply, agricultural water supply, municipal water supply, irrigation area, and population in the study area was examined using coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error (RMSE) to the standard deviation of

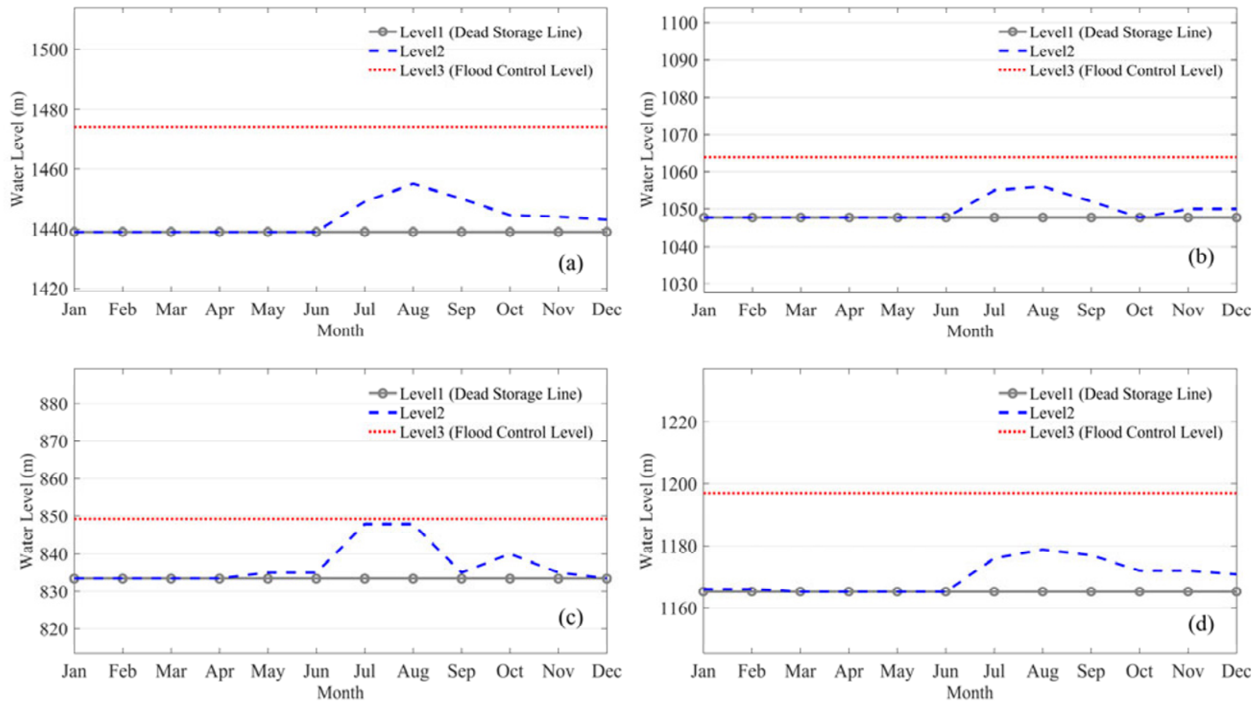

Figure 3 Regulation curves of four reservoirs for three rivers, a) the Ertanggou (ETG), b) the Kekeya (KKY), c) KKY2, and d) the Kanerqi (KEQ).

measured data (RSR) for a period of 2006-2010. R^2 describes the collinearity between observations and model simulations (Moriasi et al. 2007); NSE indicates the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe 1970); PBIAS measures an average tendency whether model simulations tend to be larger or smaller than observations (Gupta et al. 1999); RSR, measures the average of the squares of the errors (Moriasi et al. 2007). As suggested by Moriasi et al. (2007 & 2015), with values $R^2 > 0.6$, NSE>0.5, PBIAS<±15, and RSR≤0.7, model performance can be judged as 'satisfactory'.

3.6.2 Sensitivity analysis

Among all the parameters related to the simulation only the ones used to define the scenarios were selected for sensitivity analysis. The selected parameters were:

(1) Population: water demand per capita from urban and rural area, and net population change rate from urban and rural area;

(2) Industry demand: industry changing rate;

(3) Agricultural demand: irrigation area changing rates under the FI, DI, and SI methods.

A 10% change (increase/decrease) was applied to each parameter to assess the sensitivity of the model results. Changes in water shortage, compared to the status quo scenario in terms of absolute values, were used as indices to evaluate system responses to the changing parameters. A positive value indicated further water stress, and a negative value meant water stress relief. By comparing the resulting changes in water shortage, corresponding to the ±10% changes in each parameter, the sensitivity and robustness of the developed model were evaluated.

3.6.3 Future simulation

In order to explore the water issues in Shanshan, five scenarios were designed to test the systematic reaction to various water-management policies. The sixth scenario was designed as a combination scenario to fulfill the socioeconomic requirement while maintaining sustainability of the water resources. Scenarios were simulated using the calibrated model, as follows:

Scenario 1: Maintain development trends under the current status quo;

Scenario 2: From 2015, use surface water as the main water source for industries instead of groundwater;

Scenario 3: Improve the efficiency of agricultural irrigation, based on Scenario 2;

Scenario 4: Decrease the irrigation area to 200 km^2 by 2030 (half of the current area), based on Scenario 2;
Scenario 5: Reduce the industrial water demand by 60% by 2030, based on Scenario 2;
Scenario 6: Combine Scenarios 4 and 5.

4 Results

4.1 Model calibration

A statistical analysis was performed to compare the model simulations and the historical records with regard to the industrial water supply, the agricultural water supply, the municipal supply, irrigation area, and population. Graphical comparisons of the selected variables are shown in Figure 4. All selected variables show a 'satisfactory' model performance, as defined by Moriasi et al. (2007), with the exception of the industrial water supply, which was categorized as 'not satisfactory'. However, this was expected, and some adjustments were made to address this. Details can be found in Section 5, Discussion.

4.2 Sensitivity analysis

The sensitivity analysis was conducted with a ±10% change in selected parameters. Water shortages were compared to the status quo (Scenario 1).

The least amount of changes occurred in the population sector (Figure 5a). In addition, the changes in water shortage had a symmetrical pattern among the results, increasing or decreasing the parameter value by 10%. Urban changes had a greater influence than rural changes. The resulting water shortages reached 0.5 MCM and 0.1 MCM, with changes in *urban water demand per capita* and *rural water demand per capita*, respectively. The *urban net population change rate* had the second greatest influence on the water shortage change with as much as 0.3 MCM. The least influential effect resulted from the *rural net population change rate*, with the highest value being 0.02 MCM.

In the industrial sector, the greatest changes observed were from the *industry changing rate* (Figure 5b), in which a 10% increase led to a 52.4-MCM increase in water shortage and a 10% decrease resulted in a 37.5-MCM decrease. Apart from differences in water volume, the rate of the changes in water shortage (i.e., water stress and water relief) also had some differences. From 2019 to 2022, even though abrupt water stress was observed, having a 10% rate increase, at the same time, mild relief was found, having a 10% rate decrease.

In the agricultural sector, a 10% variation in the changing rate of the irrigation area resulted in a greater influence than for population and a lesser influence than for industry (Figure 5b, 5c). Among three irrigation methods (FI, SI, and DI), the greatest changes occurred in the FI method. With a 10% change in the *irrigation area changing rate*, by 2030, FI resulted in the greatest water stress, at 15.1 MCM with a 10% increase, and the greatest water relief at 15.9 MCM with a 10% decrease. The results from the changes in the SI and DI methods had relatively minor effects, around 0.3-0.4 MCM (Figure 5c).

4.3 Model simulation

The model was used to explore five scenarios, and analyses were performed on the water supply and water demand.

4.3.1 Streamflow

For the water supply, the simulated monthly streamflow with climate change influences was compared with the historical streamflow, using box plots (Figure 6). With annual observations of 117.4 MCM in the Kekeya River, 93.2 MCM in the Ertanggou River, and 32.3 MCM in the Kanerqi River, the simulated streamflow for the three rivers had a similar shape and magnitude as the historical streamflow, with low flow in winter season and high flow during summer. Most streamflow (more than 80%) occurred in the summer season, from May to September, and less than 20% of the streamflow was distributed over the rest of the months. Compared to the historical streamflow, high variability could be observed, with extreme high and low values.

4.3.2 Modeling results of various scenarios

The simulation results were analyzed and summarized by comparing all six scenarios for

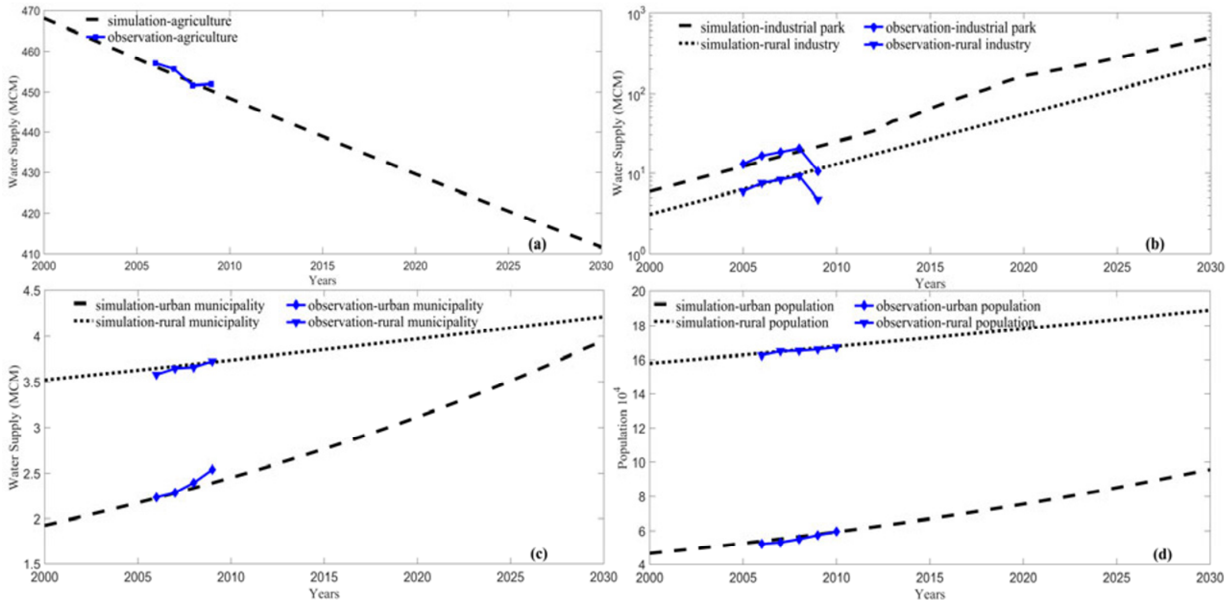

Figure 4 Fitness comparisons between model simulations and available observations during the modeling period of 2000-2030 for (a) agricultural water supply, (b) industrial water supply (industry park and rural industry), (c) municipal water supply (urban and rural), and (d) population (urban and rural).

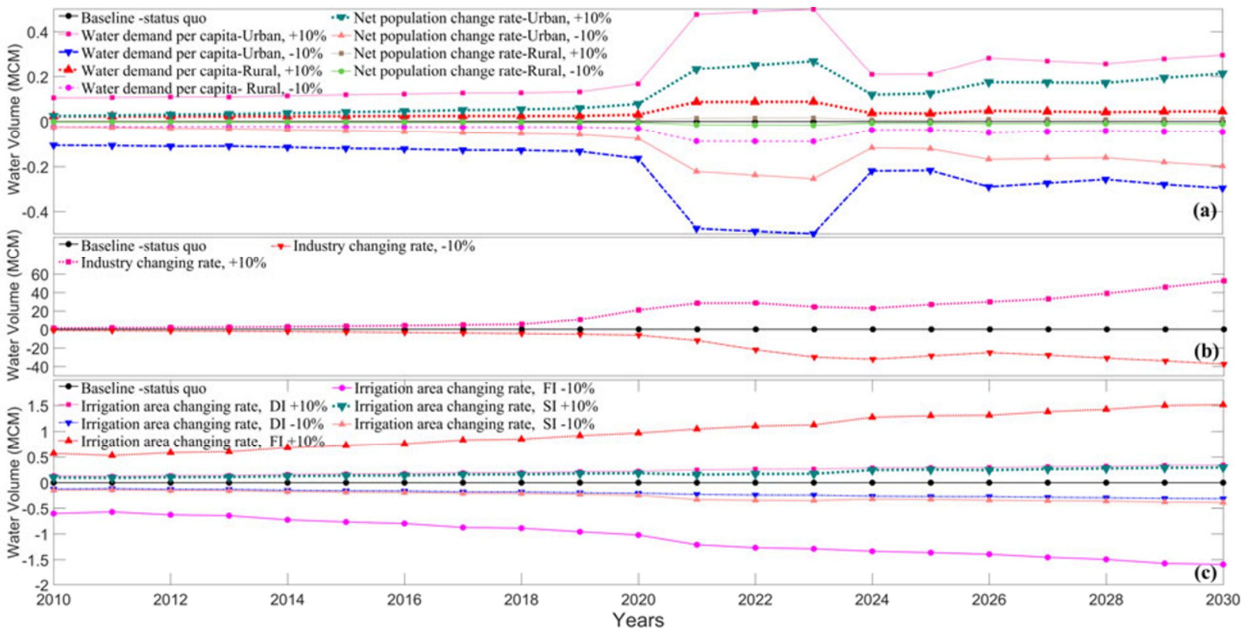

Figure 5 Sensitivity analyses of the determinant parameters: (a) population: water demand per capita from urban areas and rural areas and the net population change rate from urban areas and rural areas; (b) industry: the industry changing rate; and (c) agriculture: irrigation area changing rates of the FI, DI, and SI methods.

the simulation period (2010-2030), including:

(i) Water demand of the main water users, and the water shortage (Figure 7a);

(ii) Agricultural water demand under each irrigation method, compared to the available groundwater and total infiltration (Figure 7b);

(iii) Surface water supply and groundwater supply in ratios (Figure 7c) and volumes (Figure7d);

(iv) Water deficiency (Figure 7e).

(1) Status quo – Scenario 1

Figure 7a shows the results of the simulated water demand for various users in industry, agriculture, and other activities compared to the water shortage in corresponding years during the period used in the model simulation (2010-2030).

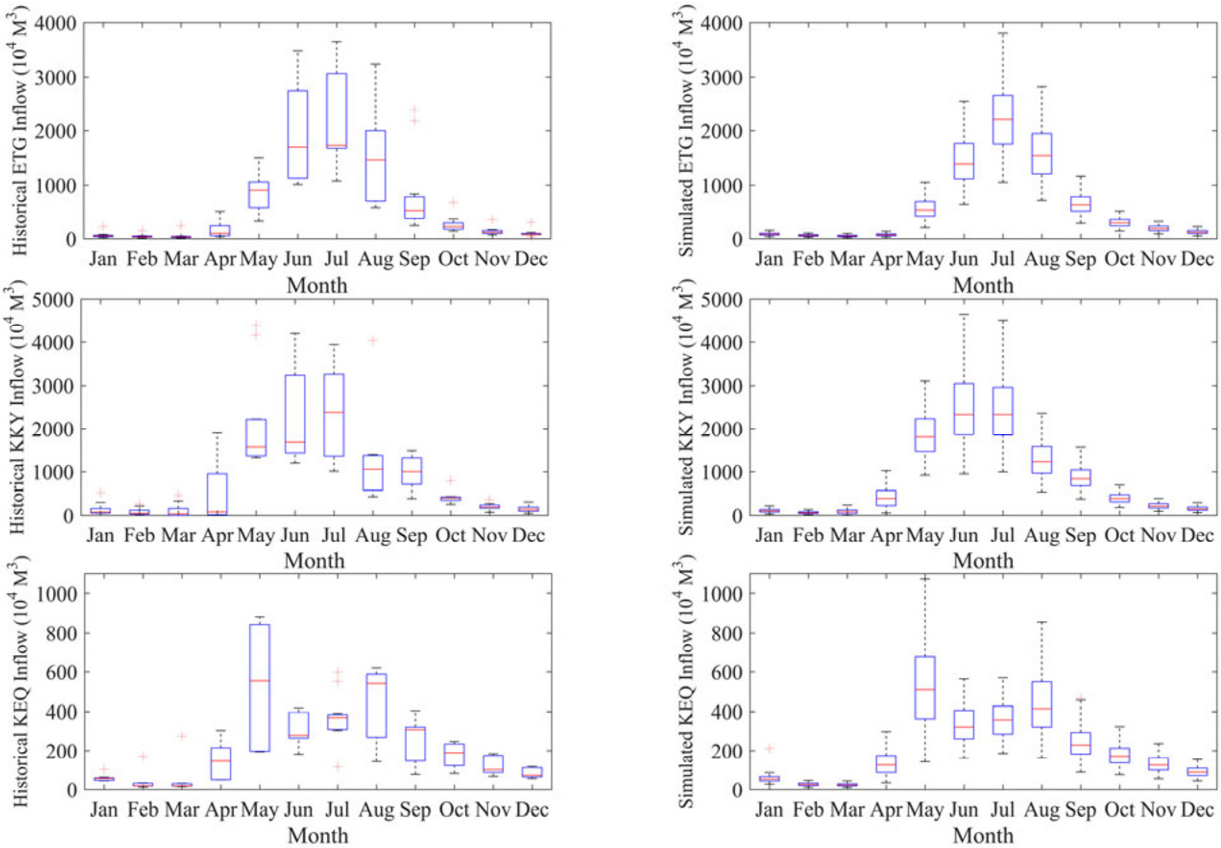

Figure 6 Box plots of historical and future streamflow simulations for the Ertanggou (ETG), Kekeya (KKY), and Kanerqi (KEQ) Rivers.

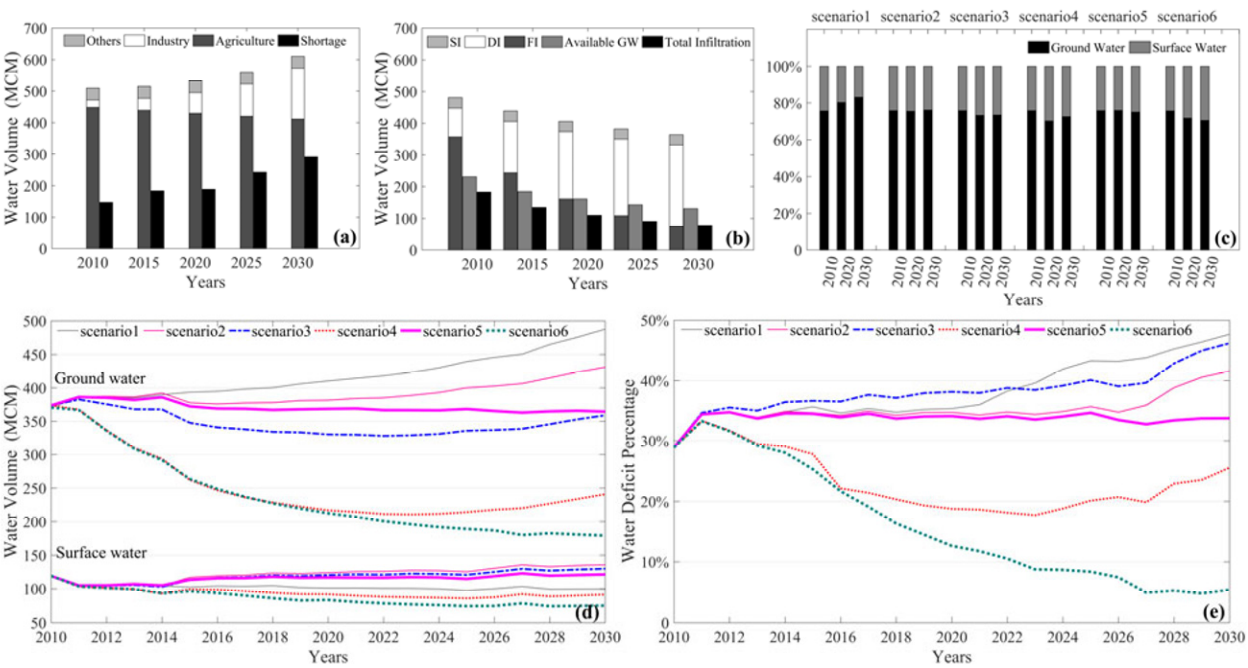

Figure 7 (Top left) Results of Scenario 1: water volume comparisons between user demands of Industry, Agriculture, and Others as well as the groundwater supply shortage for the period of 2010-2030. (Top center) Results of Scenario 3: the agricultural water demand, with various proportions of the irrigation methods, compared to the available groundwater and total infiltration for the period of 2010-2030. (Top right) Comparisons of all scenarios: ratios of the surface water supply and groundwater supply in the total water supply from 2010 to 2030. (Bottom left) Comparison of all scenarios: water supply volumes by sources of surface water and groundwater from 2010 to 2030. (Bottom right) Comparison of all scenarios: water deficit percentages from 2010 to 2030.

During this time, the industrial demand increased substantially from 22.8 MCM in 2010 (3% of the total demand) to 161.3 MCM in 2030 (18% of the total demand). Meanwhile, agriculture accounted for 83% of the total demand in 2010 (448.6 MCM); by 2030, it decreased to 411.7 MCM, accounting for 67% of the total demand. A pattern of an increasing trend was noted regarding water shortage; specifically, from 2010 to 2020, the water shortage increased from 150 MCM to 183.8 MCM. After that, it maintained a level similar to 2020, and then increased until 2030, when it reached 291 MCM. During 20 years in this simulation, water shortage nearly doubled.

(2) Prioritization of surface water supply – Scenario 2

Compared to a gradual decrease in the surface water supply and an increase in groundwater supply in the status quo scenario throughout the simulation period, results of Scenario 2 indicated that the water supply remained at a similar level for both sources (Figure 7c). Specifically, in 2020, there was an increase in surface water supply to about 23.7 MCM (22.6%) and a decrease in groundwater supply to about 30.3 MCM (7%). In 2030, the surface supply increased to 37.4 MCM (36.4%) and the groundwater supply reduced to 58.9 MCM (11.2%), compared to the status quo scenario during the same year. However, when compared to the large amount of total water supplies (surface water supply plus groundwater supply), these changes may not have been clear enough, either in terms of the ratio of total supply (Figure 7c) or the volume (Figure 7d).

(3) Irrigation efficiency improvement – Scenario 3

Among all three irrigation methods – i.e., flooding irrigation, spray irrigation, and drip irrigation – currently, the FI method makes up the largest proportion (74%) of the total irrigation demand. The results of Scenario 3 (Figure 7b) show the water demand under each irrigation method from 2010 to 2030, with comparisons to the available groundwater and total infiltration. When the irrigation method was gradually changed from flood irrigation to drip irrigation from 2010 to 2030, a reduction occurred in the total agricultural demand, total infiltration, and available groundwater. This scenario helped to reduce the agricultural water demand from 412 MCM to 363 MCM by 2030. Infiltration decreased from 183 MCM (79% of the total available groundwater by volume) in 2010, to 78 MCM (69% of the total available groundwater by volume) in 2030. As shown in Figure 7e, the water deficiency in Scenario 3 increased from 29% in 2010 to 46% by 2030; this included a rapid increase, particularly during the last three years of the simulation (2027-2030).

(4) Reduction in irrigation area – Scenario 4

In Scenario 4, the irrigation demand was reduced from 480 MCM in 2010 to 199 MCM by 2030. This resulted in a 43.5% decrease in total infiltration from 183 MCM to 104 MCM, and a 32.7% decrease in available groundwater from 231 MCM to 155.4 MCM. A substantial decrease in the total groundwater supply is evident in Figure 7d, with a bouncing-back trend in the last few years of the simulation. This become more evident in Figure 7e, when the water deficiency went under 20% after 2019 and returned to above 20% in 2025, then kept increasing to 26% by 2030. However, this increase was much lower than the previous three scenarios, which were in the range of 30%-50% (Figure 7e).

(5) Reduction in industrial demand – Scenario 5

A 60% reduction in the industrial demand resulted in a 100 MCM reduction in the total water demand, compared to the status quo scenario in 2030 (Figure 7d); at the same time, water deficiency remained at a high level, increasing from 29% (2010) to 34% (2030) (Figure 7e). The water supply structure did not change because the water supply from surface and groundwater sources remained in similar ratios in 2010, 2020, and 2030. This resulted in 76% from the groundwater supply and 24% from the surface water supply throughout the simulation period, as shown in Figure 7c.

(6) Effective scenario combination – Scenario 6

Scenario 6 is the only scenario that resulted in a continuous decrease in all the variables for the total water demand, total groundwater supply, and the percentage of water deficiency. In Figure 7c and Figure 7d, the groundwater supply showed a continuous decrease from 394 MCM in 2010 (76% of the total water supply) to 184 MCM in 2030 (70.5% of total water supply). A substantial and continuous decrease occurred in water deficiency; it reached below 5%, and then remained at a stable

Table 2 Changes in the variables for all the scenarios in 2030 compared to base case (Scenario 1): total water demand, total water supply from surface water and groundwater, and volumes of return flow and water infiltration (percentage indicates the relative increase/decrease)

Scenario	Water demand		Water supply			
	$\times 10^6$ m^3	Change	Change		Water volume change	
			Surface water	Ground-water	Return flow	Infiltration
1	611	-	-	-	-	-
2	611	0%	36%	-12%	-46%	-13%
3	533	-13%	31%	-27%	-79%	-53%
4	368	-40%	-8%	-51%	-41%	-38%
5	512	-16%	22%	-25%	-24%	-7%
6	269	-56%	-25%	-64%	-33%	-32%

level during the last three years of simulation.

4.3.3 Results of scenario comparisons

(1) Water demand

Table 2 shows the comparison of all the scenarios for water demand and changes in water demand for 2030. Compared to 611 MCM under status quo (Scenario 1) in 2030, apart from combined (Scenario 6), Scenario 4 turned out to be most efficient scenario, with a 40% reduction (243 MCM) in water demand. This was followed by Scenario 5, with a 16% reduction (99 MCM) and Scenario 3 with a 13% reduction (77 MCM). Scenario 6, which is a combined scenario of the two most efficient water reduction scenarios, i.e., Scenario 4 (reduction in agriculture area) and Scenario 5 (reduction in industrial demand); it effectively decreased the water demand by 56% (341 MCM).

(2) Water supply

The scenario results for the annual water supply and for the change in supply for surface water and groundwater in 2030 are shown in Figure 7d and Table 2. With the current water policy (Scenario 1), the surface water supply reached 103 MCM; with the regulated operation of the reservoirs (Scenario 2), the surface supply increased by 36% (140 MCM). In 2030, under the scenarios of improving irrigation efficiency (Scenario 3) and cutting back industrial demand (Scenario 5), a reduction in groundwater supplies of 27% and 25%, respectively, occurred when compared to the status quo scenario. In Scenario 4, the results of the surface water supply showed a reduction (8%), in contrast to increases in the results from Scenarios 2, 3, and 5; in addition, the groundwater supply decreased by 51%. Changes in water supply resulting from Scenario 6 showed significant reductions in both surface water and groundwater by 25% and 64%, respectively.

(3) Water reuse

With regard to water reuse, the changes in return flow and water infiltration are reported in Table 2. Results show that with the operation of new reservoirs (Scenario 2), when compared to the status quo (Scenario 1), the surface return flow was reduced substantially (46%); this was similar to the results of Scenario 4 (41%) with regard to a policy of cutting back the irrigation area. The policy of improving irrigation efficiency (Scenario 3) showed the highest water reduction in both surface return flow (79%) and infiltration (53%). Meanwhile, cutting back in industrial demand (Scenario 5) showed the lowest reduction, with 24% and 7% in return flow and water infiltration, respectively. The results of Scenario 6 showed values of 33% and 32% in terms of reduction in return flow and infiltration, respectively, compared to 41% and 38% resulting from Scenario 4 and 24% and 7% resulting from Scenario 5.

5 Discussions

The sensitivity analysis with changes in the parameters of population, industrial, and agricultural sectors revealed that industrial water use had the most significant influence on the water system. As expected, population due to the low share of municipal demands in total water use had the lowest effect on water shortage. Conversely, instead of agriculture, which was the largest water user in the study area, industry had the greatest influence on water shortage. Because of the substantial water demand from Wanxiang Group Corporation, which reached the highest value in

2019, the water shortage was further stressed by a 10% increasing rate in development, and was mildly relieved by a 10% decreasing rate in development. In agriculture, as anticipated, the FI method had substantial effects on the results due to high weighting in total area and low efficiency. Additionally, by 2030, water relief caused by the 10% decrease (i.e., the changing rate of agriculture area) was larger than the water stress resulting from the same 10% increase. This can be attributed to the large amount of water infiltration under the FI method, which recharged groundwater and improved the water supply in the system.

Model performance during calibration was reasonable as evaluated, using the performance statistics of R^2, NSE, PBIAS, and RSR. The only exception was industrial water demand, for which the actual data was much lower than the model estimates for 2009. This was caused by issues with water-resource fees in 2009, as reported by the Shanshan Water Conservancy Bureau (a personal communication during a visit in 2011). Thus, in this study, the trend before 2009 for industrial development was prioritized with weighting, and this earlier trend was used to estimate the future water demand.

Comparing the six scenarios for water resource management showed a significant gap between water demand and supply, which was compensated by overexploitation of the groundwater. The strategy for water resource management currently being applied in Shanshan will not have enough water conserved from decreasing the agricultural demand to support industry, as the industrial demand increases tremendously, especially during the years close to 2030.

Both Scenarios 3 and 4, i.e., improvement in irrigation efficiency and reduction in irrigated area, resulted in water-shortage relief in the study area. However, situation is more complex, as revealed by the SD model. With reductions in irrigation water per unit area, i.e., improvement in irrigation efficiency, water infiltration – which replenishes the groundwater supply – also reduces. The resulting reduction in water demand was not sufficient to keep a supply-and-demand balance for water when keeping the current changing rate of the agricultural area. Thus, the improvement in irrigation efficiency (Scenario 3) did not relieve the water stresses. Conversely, the reduction in the irrigated area (Scenario 4) directly decreased the infiltration and, most importantly, decreased the demand for irrigation water, which was 83% of the total demand in 2010. This suggests an effective and practical water strategy with a reduction in irrigation area.

The operation of two new reservoirs in 2015 increased the available surface water and helped to reduce the overexploitation of groundwater due to the water shortage; however, this relief was limited by the total surface water that could be stored. Agriculture, the largest water user in the study area, also was the main source of groundwater recharge. A strategy for improving irrigation efficiency reduced the water infiltration, affected the groundwater recharge, and raised concerns regarding water supply to those water users who rely on groundwater. This same concern was raised in the strategy of a direct cutback of water demand for irrigation.

The year 2023 turns out as an important turning point. Before 2023, the total water demand is dominated by agriculture, and water deficiency reduces with the reduction in agricultural demand. After 2023, the water deficiency increases, as rapid growth of industry takes place, erasing the water savings produced through the reduction in agriculture. This provides a rational basis for the design of Scenario 6, which mitigates the stress of water scarcity effectively and controls water use by agriculture and industry, both of which take a heavy toll with regard to their effects on the total water deficiency.

Several limitations exist in this study. Although multiple water policies were tested, no external influences were considered in these policies, for example, the price of agriculture or industrial products, socio-political changes, and effects of significant population change due to migration. All these factors could influence the outcome of scenarios that were simulated. Moreover, during streamflow simulation, 40% of the monthly variability was used to represent climate change. This could be extended further into a combined effect by increasing variability and a shift in streamflow, since the water in the study area is dominated by mountainous rainfall and snowmelt. Furthermore, the reservoir regulation curve resulted from parameters in the reports of the reservoir design. With passing time, changes in these parameters may influence the reservoir functionality; these factors were not considered in this study. Additionally, the water quality was not considered in this study.

6 Conclusions

The major conclusions of this study are summarized as follows. Firstly, the issue of groundwater overexploitation would continue and become more severe and intense under the status quo scenario due to a tremendous increase in demand, especially from industries. Secondly, only limited relief can be provided with two newly constructed reservoirs by increasing the surface water supply because of limited storage capacities and potential streamflow reduction. Thirdly, reducing the irrigation area is a more efficient method in water conservation compared to improving irrigation efficiency, since more efficient irrigation also reduces groundwater recharge. Lastly, there is a limit to industrial growth, even if water is conserved from agriculture.

A combined water-management scenario is recommended to balance between water conservation and water demand for socioeconomic development. In addition, these results provide possible support to help making local water management decisions.

The major contributions of the study are as follows. Using system dynamics approach, this is the first study conducted in Shanshan County to evaluate different water management options that the county is considering. This study used an integrated approach considering different scenarios involving both surface water and groundwater systems; application of such integration is not commonly found in documented literatures. Capturing the effects of climate change using a system dynamics model in the Shanshan County is novel to this study. As the local water is sourced from mountainous areas and has a high sensitivity to the changing climate, consideration of streamflow variability due to climate change provides a more realistic estimation of future flows. This also was the first study to evaluate the role of two new reservoirs that were added to the water supply system in 2015.

The system dynamic model developed was useful in simulating a multi-objective complex system with a certain degree of accuracy. The model was able to provide insights by considering the integrated system rather than each individual component within the system. The proposed model, with appropriate modifications, can be applied to other areas to explore water management options.

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References

Ablikim A, Zhou JW (2014) Surface discharge characteristics of the Turpan Basin, Xinjiang. Journal of Glaciology and Geocryology 36 (3): 717-723. (In Chinese) DOI: 10.7522/j.issn.1000-0240.2014.0086

Abulikemu A (2012) Investigation and analysis on present situation of water resources and basic situation of irrigation and water conservancy constructions in Piqan County. In WIT Transactions on Engineering Sciences 80: 419-424. DOI: 10.2495/AIE120471

Ahmad S, Simonovic SP (2000) System dynamics modeling of reservoir operations for flood management. Journal of Computing in Civil Engineering 14 (3): 190-198. DOI: 10.1061/ (ASCE)0887-3801(2000)14:3(190)

Ahmad S, Simonovic SP (2004) Spatial system dynamics: a new approach for simulation of water resources systems. Journal of Computing in Civil Engineering 18(4): 331-340. DOI: 10.1061/(ASCE)0887-3801(2004)18:4(331)

Ahmad S, Simonovic SP (2006) An intelligent decision support system for management of floods. Water Resources Management 20(3): 391-410. DOI: 10.1007/s11269-006-0326-3

Barnett TP, Adams JC, Lettenmaier DP (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438: 303-309. DOI: 10.1038/nature04141

Bruelheide H, Jandt U, Gries D, et al. (2003) Vegetation changes in a river oasis on the southern rim of the Taklamakan Desert in China between 1956 and 2000. Phytocoenologia 33(4): 801-818. DOI: 10.1127/0340-269X/2003/0033-0801

Carrier C, Kalra A, Ahmad S (2016) Long-range precipitation forecast using paleoclimate reconstructions in the western

United States. Journal of Mountain Science 13(4): 614-632. DOI: 10.1007/s11629-014-3360-2
Chen C, Kalra A, Ahmad S (2015) Exploring Water Management Strategies in Inland Arid Area Using Dynamic Simulation Model, ASCE World Environmental & Water Resources Congress, 1009-1018. DOI: 10.1061/9780784479162.098
Chen P (2010) Study on Water Supply and Water-saving Potential in Turpan-Hami Oilfield. Master thesis, Tsinghua University, Beijing, China. (In Chinese)
Chen Y, Takeuchi K, Xu C, et al. (2006) Regional climate change and its effects on river runoff in the Tarim Basin, China. Hydrological Processes 20(10): 2207–2216. DOI: 10.1002/ hyp. 6200
Choubin B, Sigaroodi SK, Malekian A, et al. (2014) Drought forecasting in a semi-arid watershed using climate signals: a neuro-fuzzy modeling approach. Journal of Mountain Science 11(5): 1593-1605. DOI: 10.1007/s11629-014-3020-6
Dawadi S, Ahmad S (2012) Changing climatic conditions in the Colorado River Basin: implications for water resources management. Journal of Hydrology 430: 127-41. DOI: 10.1016/ j.jhydrol.2012.02.010
Dawadi S, Ahmad S (2013) Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population. Journal of Environmental Management 114: 261-275. DOI: 10.1016/ j.jenvman.2012.10.015
Fang S, Pei H, Liu Z, et al. (2010) Water Resources Assessment and Regional Virtual Water Potential in the Turpan Basin, China. Water Resources Management 24(13): 3321–3332. DOI:10.1007/s11269-010-9608-x
Food and Agriculture Organization of United States (FAO) (2013) Water Scarcity (Available online at: http://www.fao.org/nr/water/topics_scarcity.html, accessed on 06 December 2015)
Ford A (1999) Modeling the Environment: an Introduction to System Dynamics Modeling of Environmental Systems. Washington, DC., Island Press. pp 401.
Frederick KD, Major DC, Eugene ZS (1997) Climate change and water resources. Climatic Change 37(1): 7-23. DOI: 10.1023/ A:1005336924908
Gao Y, Liu C (1997) Research on simulated optimal decision making for a regional water resources system. International Journal of Water Resources Development 13(1): 123-134. DOI: 10.1080/07900629749971
Gleick PH (1998) Water in crisis: paths to sustainable water use. Ecological Applications 8(3): 571-579. DOI: 10.1890/1051-0761(1998)008
Gleick PH (2003) Global freshwater resources: soft-path solutions for the 21st century. Science 302 (5650): 1524-1528. DOI: 10.1126/science.1089967
Gleick PH (2010) Roadmap for sustainable water resources in southwestern North America. Proceedings of the National Academy of Sciences of the United States of America 107 (50): 21300-21305. DOI: 10.1073/pnas.1005473107
Gupta HV, Sorooshian S, Yapo PO (1999) Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. Journal of Hydrologic Engineering 4(2): 135-143. DOI: 10.1061/(ASCE)1084-0699 (1999)4:2(135)
He B, Zhang Y (2003) Issues in water resources demand and supply in arid Xinjiang, China. Proceedings of SPIE, the international society for optical engineering (0277-786X) 4890(1): 285. DOI: 10.1117/12.466760
Hering JG, Ingold KM (2012) Water Resources Management: What Should Be Integrated? Science 336(6086): 1234-1235. DOI: 10.1126/science.1218230
Institute of Water Resources and Hydropower Research (IWHR) (2011) Shanshan Water Rights Transference Program.
IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. p 996.
IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland, IPCC. p 151.
Jiang Y, Zhou C, Cheng W (2007) Streamflow trends and hydrological response to climatic change in Tarim headwater basin. Journal of Geographical Sciences 17(1): 51-61. DOI: 10.1007/s11442-007-0051-8
Jones JA, Vardanian T, Hakopian C (2009) Threats to Global Water Security. Springer Science & Business Media, Dordrecht, Netherlands.
Kalra A, Ahmad S (2011) Evaluating changes and estimating seasonal precipitation for the Colorado River Basin using a stochastic nonparametric disaggregation technique. Water Resources Research 47: W05555. DOI: 10.1029/2010WR 009118
Kalra A, Ahmad S (2012) Estimating annual precipitation for the Colorado River Basin using oceanic-atmospheric oscillations. Water Resources Research 48(6): W06527. DOI: 10.1029/ 2011WR010667
Kalra A, Ahmad S, Nayak A (2013) Increasing streamflow forecast lead time for snowmelt driven catchment based on large scale climate pattern. Advances in Water Resources 53: 150-162. DOI: 10.1016/j.advwatres.2012.11.003
Konikow LF, Kendy E (2005) Groundwater depletion: A global problem. Hydrogeology Journal 13: 317-320. DOI: 10.1007/ s10040-004-0411-8
Langsdale S, Beall A, Carmichael J, et al. (2007) An exploration of water resources futures under climate change using system dynamics modeling. Integrated Assessment 7(1): 51-79.
Langsdale S, Beall A, Carmichael J, et al. (2009) Exploring the implications of climate change on water resources through participatory modeling: case study of the Okanagan Basin, British Columbia. J Water Resources Planning Management 135(5): 373-381. DOI: 10.1061/(ASCE)0733-9496(2009)135: 5(373)
Leal Neto AC, Legey LFL, Gonzalez-Araya MC, et al. (2006) A system dynamics model for the environmental management of the Sepetiba Bay watershed, Brazil. Environmental Management 38(5):879-888. DOI: 10.1007/s00267-005-0211-5
Leaver JD, Unsworth CP (2006) System dynamics modeling of spring behaviour in the Orakeikorako geothermal field, New Zealand. Geothermics 36(2): 101-114. DOI: 10.1016/ j.geothermics.2006.08.001
Li H (2010) The Countermeasure Discussion about the Water Resources Development and Utilization Problems of Turpan Region. Xinjiang Agricultural Sciences/Xinjiang Nongye Kexue 47 (12): 2522-2525. (In Chinese)
Madani K, Mariño MA (2009) System dynamics analysis for managing Iran's Zayandeh-Rud river basin. Water Resources Management 23(11): 2163-2187. DOI: 10.1007/s11269-008-9376-z
Mirchi A, Madani K, Watkins Jr, et al. (2012) Synthesis of system dynamics tools for holistic conceptualization of water resources problems. Water Resources Management 26:2421-2442. DOI: 10.1007/s11269-012-0024-2
Moriasi DN, Arnold JG, Van Liew MW, et al. (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE 50(3):885-900. DOI: 10.13031/2013.23153
Moriasi DN, Gitau MW, Pai N, et al. (2015) Hydrologic and water quality models: Performance measures and evaluation criteria. Transactions of the ASABE. 58(6): 1763-85. DOI: 10.13031/ trans.58.10715
Nagasawa T, Yamamoto T, Jalaldin A (2006) Problems of the irrigation system in the Turpan Basin of China. Sustainable Irrigation Management, Technologies and Policies 1: 37-44. DOI: 10.2495/SI060051
Nash J, Sutcliffe J (1970) River flow forecasting through conceptual models: Part I. A discussion of principles. Journal of Hydrology 10(3):282-290. DOI: 10.1016/0022-1694(70)90

255-6
Peng DZ, Xu ZX (2010) Simulating the Impact of Climate change on streamflow in the Tarim River basin by using a modified semi-distributed monthly water balance model. Hydrological Processes 216: 209-216. DOI: 10.1002/hyp.7485
Raneesh KY (2014) Impact of Climate Change on Water Resources. Earth Science & Climatic Change 5(3):1-5. DOI: 10.4172/2157-7617.1000185
Rusuli Y, Li L, Ahmad S, et al. (2015) Dynamics model to simulate water and salt balance of Bosten Lake in Xinjiang, China. Environmental Earth Sciences 74(3): 2499-2510. DOI: 10.1007/s12665-015-4257-2
Sagarika S, Kalra A, Ahmad S (2014) Evaluating the effect of persistence on long-term trends and analyzing step changes in streamflows of the continental United States. Journal of Hydrology 517: 36-53. DOI: 10.1016/j.jhydrol.2014.05.002
Sagarika S, Kalra A, Ahmad S (2015a) Interconnection between oceanic-atmospheric indices and variability in the US streamflow. Journal of Hydrology 525: 724-736. DOI: 10.1016/j.jhydrol.2015.04.020
Sagarika S, Kalra A, Ahmad S (2015b) Pacific Ocean and SST and Z500 climate variability and western U.S. seasonal streamflow. International Journal of Climatology 36: 1515-1533. DOI: 10.1002/joc.4442
Schreider SY, Jakeman AJ, Pittoc AB, et al. (1996) Climatic Change 34(3): 513-546. DOI: 10.1007/BF00139304
Shrestha E, Ahmad S, Johnson W, et al. (2011) Carbon footprint of water conveyance versus desalination as alternatives to expand water supply. Desalination 280(1): 33-43. DOI: 10.1016/j.desal.2011.06.062
Shrestha E, Ahmad S, Johnson W, et al. (2012) The carbon footprint of water management policy options. Energy Policy 42: 201-12. DOI: 10.1016/j.enpol.2011.11.074
Simonovic SP, Fahmy H (1999) A new modeling approach for water resources policy analysis, Water Resources Research 35 (1): 295-304. DOI: 10.1029/1998WR900023
Simonovic SP, Li L (2003) Methodology for Assessment of Climate Change Impacts on Large-Scale Flood Protection System. Journal of Water Resources Planning and Management 129(10): 361-371. DOI: 10.1061/(ASCE)0733-9496(2003)129:5(361)
Stave KA (2003) A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. Environmental Management 67(4): 303-313. DOI: 10.1016/S0301-4797(02)00205-0
Sterman JD (2000) Business Dynamics: Systems Thinking and Modeling for a Complex World. McGraw-Hill, NY, USA.
Tamaddun K, Kalra A, Ahmad S (2016) Identification of Streamflow Changes across the Continental United States Using Variable Record Lengths. Hydrology 3(2): 24. DOI: 10.3390/hydrology3020024
Tangirala AK, Teegavarapu RSV, Ormsbee L (2003) Modeling adaptive water quality management strategies using system dynamics simulation. Environmental Informatics Archives 1: 245-253. (Available online at: http://www.iseis.org/eia/contents.asp?sn=1, accessed on 06 December 2015)
Tidwell VC, Passell HD, Conrad SH, et al. (2004) System dynamics modeling for community-based water planning: application to the Middle Rio Grande. Aquatic Sciences 66: 357-372. DOI: 10.1007/s00027-004-0722-9
Turpan sixth national population census, the main data bulletin, 2011. (Available online at: http://tjj.tlf.gov.cn/info/1398/70391.htm, accessed on 06 December 2015)
Venkatesan AK, Ahmad S, Johnson W, et al. (2011a) Salinity reduction and energy conservation in direct and indirect potable water reuse. Desalination 272(1-3): 120-127. DOI: 10.1016/j.desal.2011.01.007
Venkatesan AK, Ahmad S, Johnson W, et al. (2011b) System dynamics model to forecast salinity load to the Colorado River due to urbanization within the Las Vegas Valley. Science of The Total Environment 409: 2616-2625. DOI: 10.1016/j.scitotenv. 2011.03.018
Wang XJ, Zhang JY, Shamsuddin S, et al. (2012) Water resources management strategy for adaptation to droughts in China. Mitigation and Adaptation Strategies for Global Change 17(8): 923-937. DOI: 10.1007/s11027-011-9352-4
Wang ZZ, Cheng L, Wang YT, et al. (2014) A multi-reservoir ecological operation model based on subdivision application of reservoir storage capacities. Advances in Water Science 25(3): 435-443. (In Chinese) DOI: 1001-6791(2004)03-0435-09
Winz I, Brierley G, Trowsdale S (2009) The Use of System Dynamics Simulation in Water Resources Management. Water Resources Management 23(7): 1301-1323. DOI: 10.1007/s11 269-008-9328-7
Wu G, Li L, Ahmad S, et al. (2013) A dynamic model for vulnerability assessment of regional water resources in arid areas: a case study of Bayingolin, China. Water Resources Management 27(8): 3085-3101. DOI: 10.1007/ s11269-013-0334-z
Yeh W (1985) Reservoir management and operations models: a state-of-the-art review. Water Resources Research 21(12): 1797-1818. DOI: 10.1029/WR021i012p01797
Zhang F, Ahmad S, Zhang H, et al. (2016) Simulating low and high streamflow driven by snowmelt in an insufficiently gauged Alpine Basin. Stochastic Environmental Research and Risk Assessment 30(1): 59-75. DOI: 10.1007/s00477-015-1028-2
Zhang F, Li LH, Ahmad S, et al. (2014) Using path analysis to identify the influence of climatic factors on spring peak flow dominated by snowmelt in an alpine watershed. Journal of Mountain Science 11(4): 990-1000. DOI: 10.1007/s11629-013-2789-z