Evaluation of urban water resource security under urban expansion using a system dynamics model

Yu-Ting Chang, Hai-Long Liu, An-Ming Bao, Xi Chen and Ling Wang

ABSTRACT

Because of rapid economic development and urbanization, water shortage has become a serious problem in the arid region of China. To investigate urban water resource security, the supply demand pressure of water resources and the urban expansion index were analyzed under different developing scenarios in this paper. Based on the economic data of Urumqi, a typical inland city in the arid area, under the present development scenario from 2011 to 2030, a system dynamics model was constructed to simulate the water resource security. The results show that there will be great influence of urban expansion on water resource security in Urumqi in the future. Water resources are projected to become increasingly scarce if the urban expansion is left unchanged in terms of population, economic growth and water-use efficiency. To find a sustainable method for water resource use, four scenarios of urban expansion were set up based on the sensitive variables. Based on comparison of water consumption under the different scenarios, the harmonize scheme for urban water resource security is the best choice for the development of Urumqi. If the impact of urban expansion on urban water resource security alleviates in the future, the main parameters would have to reach a new standard of water use. Reducing the sewage and increasing the reuse proportion of wastewater are also very important for relieving the stress of water shortage. This research can serve as a reference for water resource allocation and urban planning in arid areas.

Key words | arid area, system dynamics, urban expansion, water resources security

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INTRODUCTION

In recent years, because of rapid economic development and urbanization, water shortage has become a serious problem in the arid region of China (Peters & Meybeck 2000; Vörösmarty *et al.* 2000; Palmer *et al.* 2004). Water resource security has received considerable attention because of its vital role in the ecology and environment, as well as in economic and social development (Falkenmark & Widstrand 1992; Niemczynowicz 1999; Bogardi *et al.* 2012). As one of the core measuring indices, the carrying capacity of water resources could evaluate the risk of water resources (Rijsberman & Van De Ven 2000; Xia & Zhu 2002). This has recently become a focus of research (Al-Otaibi & Abdel-Jawad 2007; McDonald 2008). Numerous evaluations of water resource security have been conducted in the irrigation area of an oasis (Ji *et al.* 2006; Cook & Bakker 2012). However, the stress of urban water use has also increased because of rapid urbanization in the oasis (Chen *et al.* 2011). Research on evaluating the water resource security and obtaining a sustainable water-use plan in the arid area is not sufficient.

Many methods have been used to evaluate water resource security, such as the Analysis Hierarchy Process (Jaber & Mohsen 2001), fuzzy clustering (Han *et al.* 2003), neural networks and system dynamics (SD) (Sun & Chi 2008). System dynamics is an approach to describing the behavior of complex systems with time (Simonovic & Fahmy 1999; Ahmad & Simonovic 2000). The internal feedback loops and time delays in the entire system could be integrated (Forrester *et al.* 1976; Sterman 2000). A complex

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water resource system usually includes many types of subjective variables (Danielson 1979). Many methods are still not fully satisfactory, partly because most deal with over-simplified systems (Yeh 1985; Ahmad & Simonovic 2000). Thus, SD are well suited for the modeling of and application to water resources problems (Keyes & Palmer 1993; Fletcher 1998; Li & Simonovic 2002). This method was first used for evaluating the carrying capacity of water resources in the 1990s (Motohashi & Nishi 1991; Feng *et al.* 2008), although the SD model cannot adequately represent changing processes in space (Ahmad & Simonovic 2004). An SD model is less useful in predicting exact future system states than for specifying how alternative choices would alter the tendency to move towards each of those conditions (Vennix 1996; Li & Simonovic 2002). Therefore, coupling development scenarios are very necessary in an SD model for predicting water resources security.

Urumqi, a megalopolis in the arid area of China, is facing the dilemma of water shortage for maintaining domestic life, agriculture and environmental requirements because of rapid urbanization of the last 20 years. A quantitative study of water resource carrying capacity was conducted along the Urumqi valley (Shi & Qu 1992), but an evaluation of future water resource security has not yet been reported.

To evaluate the water resource security of Urumqi, an SD model was constructed based on an urban expansion index for describing the development of Urumqi; then the water resource carrying capacity during the period of 2006–2030 was evaluated with the consideration of climate change, population growth and industrial development; lastly, an optimal scheme was proposed for the sustainable utilization of water resources based on the SD model. This research could serve as a reference for water resource allocation and urban planning in the arid area of China.

DATA AND METHODS

Description of the study area

The study area, Urumqi, is located in the arid area of northwestern China. It covers a surface area of approximately 14,216.3 km^2 between latitudes 42°45′32″–44°08′00″N and longitudes 86°37′33″–88°58′24 E (Figure 1). The climate in this area is dry. The average annual precipitation is 286.3 mm, and the average annual temperature is 6.9 °C, with a maximum annual temperature of approximately 23.7 °C and minimum annual temperature of approximately −12.6 °C; the annual average water resource is 11.38×10^8 m^3. The amount of water available to the average person decreased from 729.54 to 377.8 m^3/year during 1995–2012. The population increased by 2 million, and the economy increased six-fold in this period. The urban water resource security was badly affected.

Construction of the system dynamics model

The SD method was introduced in this paper for evaluating the urban water resource security. A water resource system is a complex system that affects both the socio-economic and ecological systems (Hunter 1998; Rijsberman & Van de Ven 2000). Thus, the factors in the SD model for water resource carrying capacity of Urumqi are closely correlated with the economy, eco-environment and population. The system was divided into two components, water demand (WD) and water supply, and five subsystems: economic WD subsystem, social life WD subsystem, ecology and environmental WD subsystem, water resources subsystem and recycled water subsystem. They consist of three feedback loops. The economy, social life and environment belong to the WD system, and the water resources and recycled water belong to the water supply system. The relationship of these subsystems are expressed in Figure 2.

The elements of the subsystems influence significantly and interact with each other (Figure 3). Their relationships form multiple feedback loops.

Generally, WD is determined by the ecological water, life water and economic water. Life water is determined by the population and water consumption quota. Ecological water includes urban afforestation water and street flushing water. Economic water depends on the primary, secondary and tertiary industry. Water supply depends on the water resource quantity and reclaimed water. The gap between supply and demand could reflect the degree of water shortage, and vice versa.

The SD model in this study was developed within The Vensim Personal Learning Edition (VENSIM PLE)

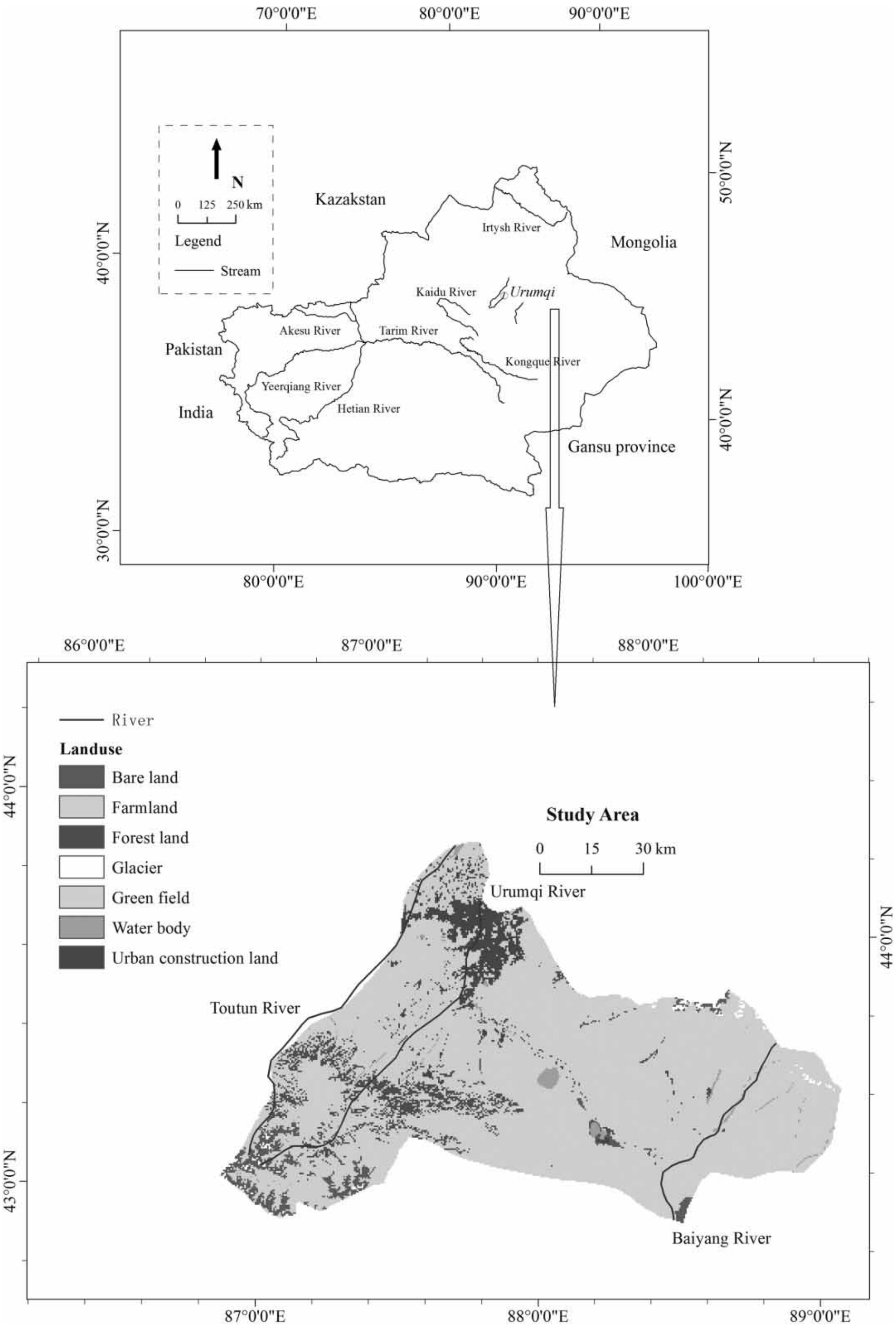

Figure 1 | Relief map of the studied area.

software, a visual modeling tool (Shiflet & Shiflet 2011). VENSIM PLE provides a simple and flexible way of building simulation models from causal loops or stock and flow diagrams (Figure 4). Variables are listed in Table 1.

Available data

We obtained data on water resources, including the water consumption of each industry and the environment and

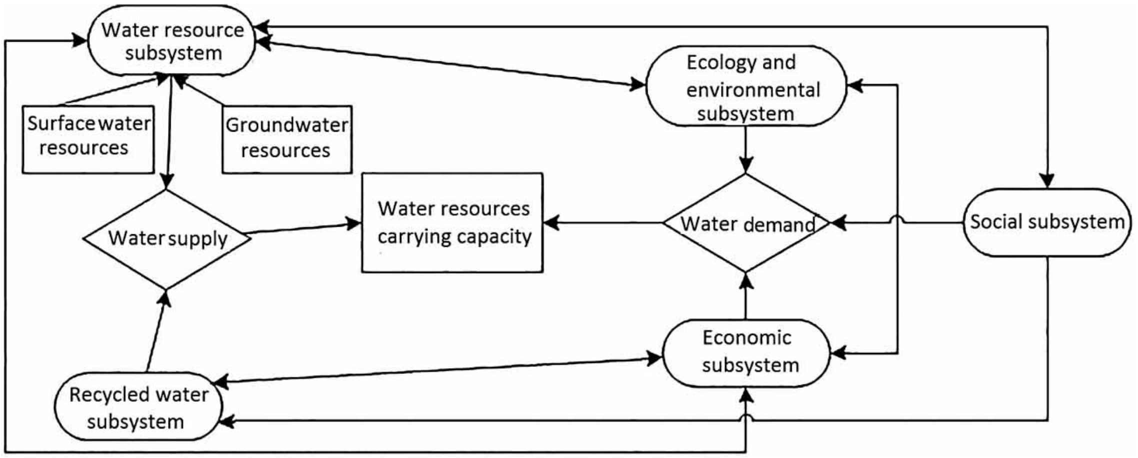

Figure 2 | Analysis of urban water resources system structure.

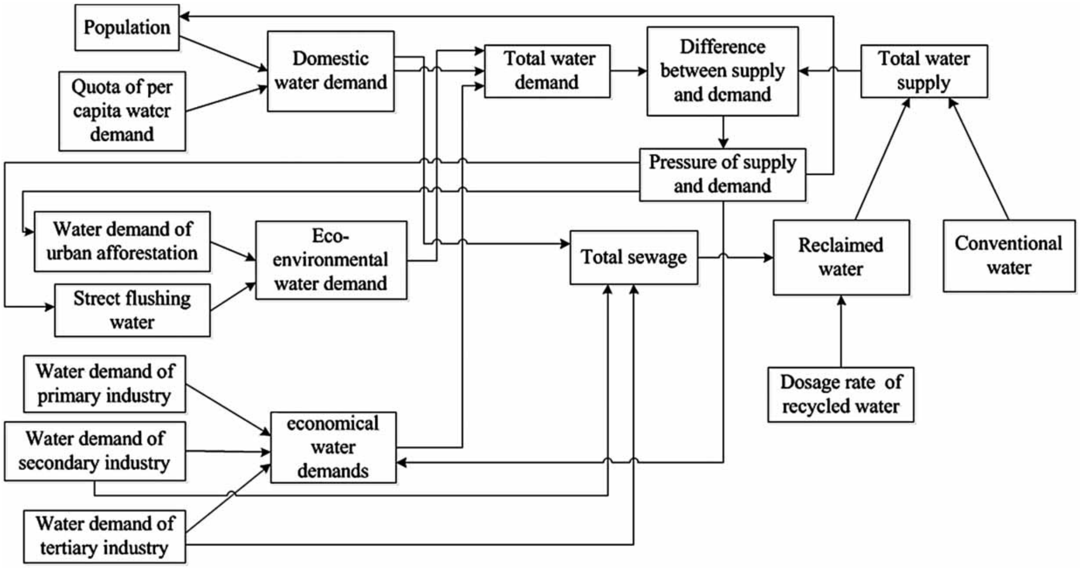

Figure 3 | Subsystem diagram for urban water resources system.

the water supply from the Xinjiang water resources bulletin (2006–2011) edited by the Xinjiang Department of Water Resources. Population, gross domestic product (GDP) of each industry and land use area data (2006–2011) were obtained from the Urumqi Statistical Yearbook edited by the Xinjiang Statistics Department (http://tongji.cnki.net/kns55/Navi/NaviSearch.aspx). The population, GDP of each industry and land use area (2011–2020) were acquired from the urban master planning of Urumqi and the 12th 5-year plan of Urumqi edited by the Urumqi Planning and Management Bureau (http://www.ans.com.cn).

Determination of model variables and parameters

The variables in the SD model are mainly categorized into flow variables, flow rate variables, constants, auxiliary variables and table functions. These variables required relational inputs into the VENSIM software. The flow variables express the cumulative quantities, the flow rate variables express the rate of change to cumulative quantities, and the constants do not change over time in a time interval. The table functions are used to express the non-linear relationship between some variables in the model. There are 58 variables and parameters (Table 1).

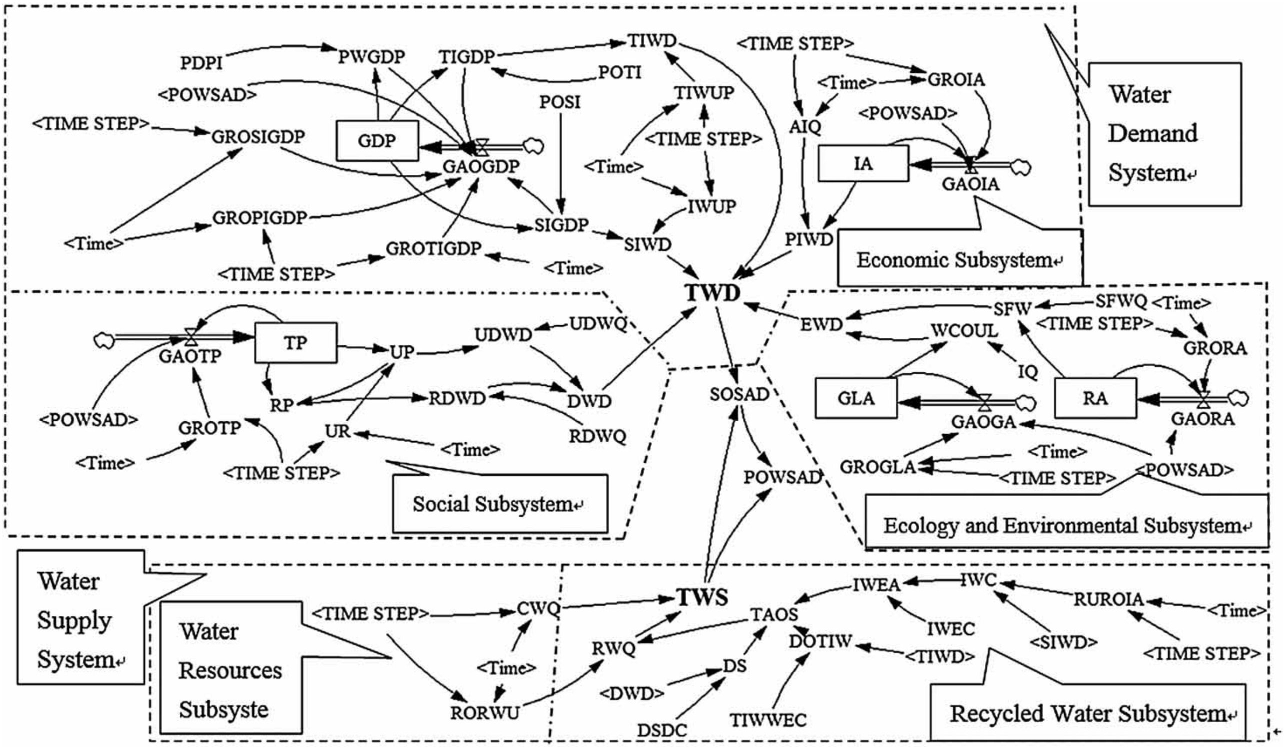

Figure 4 | The flow diagram for urban water resource system.

The causal and logical relationships among the variables, flow rates and table functions were constructed into mathematical relations (i.e., state and auxiliary equations) using linear regression; more details about the constructing equations can be found in Mohapatra *et al.* (1994).

The parameters were obtained based on the urban master planning of Urumqi (2011–2020), the 12th 5-Year Plan of Urumqi, the water resources bulletin (2006–2011) and the statistical yearbook (2006–2011). The results are listed in Table 2. Owing to the uncertainty of climate factors, the annual average water resources (11.38×10^8 m^3) was selected as the reference value in the future. The area of cultivated land was assumed to remain at a constant level of 67.23 km^2, as in 2011, and irrigated with water saving irrigation methods.

Model verification

The changes of WD, GDP and population during 2007–2011 were simulated using the above model based on the base year of 2006. The results are shown in Table 3.

Compared with the original data during the same periods, Table 3 shows that the relative error is less than 5%, so it is precise and available to evaluate the water resource security.

Sensitivity degree analysis

To analyze the influence of system variables on the urban water resource security, the sensitivity analysis method was introduced. The sensitivity degree can be defined as follows (Guo *et al.* 2001):

$$S_Q = \left| \frac{\Delta Q_{(t)}}{Q_{(t)}} \cdot \frac{X_{(t)}}{\Delta X_{(t)}} \right| \tag{1}$$

where S_Q is the sensitivity degree of state Q to variable X; t is time; $Q_{(t)}$ denotes the system state at time t; $X_{(t)}$ represents the system variable affecting the system state at time t; $\Delta Q_{(t)}$ and $\Delta X_{(t)}$ denote increments of state Q and variable X at time t, respectively.

Table 1 | Variables description

System	Subsystem	Abbreviation	Description	Unit
Water demand	Economic	IA	Irrigation area	10^3 hm^2
		GDP	Gross domestic product	10^8 Yuan
		GAOGDP	Growth amount of GDP	10^8 Yuan/year
		GAOIA	Growth amount of irrigation area	10^3 hm^2/year
		PWGDP	Primary industrial GDP	10^8 Yuan
		PIWD	Primary industrial water demand	10^8 m^3
		SIGDP	Secondary industrial GDP	10^8 Yuan
		SIWD	Secondary industrial water demand	10^8 m^3
		TIGDP	Tertiary industrial GDP	10^8 Yuan
		TIWD	Tertiary industrial water demand	10^8 m^3
		POPI	Proportion of primary industrial GDP	–
		POSI	Proportion of secondary industrial GDP	–
		POTI	Proportion of tertiary industrial GDP	–
		IS	Industrial structure	–
		GROPIGDP	Growth rate of primary industrial GDP	1/year
		GROSIGDP	Growth rate of secondary industrial GDP	1/year
		GROTIGDP	Growth rate of tertiary industrial GDP	1/year
		GROIA	Growth rate of irrigation area	1/year
		RUROIA	Repetitive use rate of industrial water	1/year
		AIQ	Agricultural irrigation quota	m^3/mu
		IWUP	Industrial water used per 10^4 Yuan	10^8 m^3
		TIWUP	Tertiary industrial water used per 10^4 Yuan	10^8 m^3
	Social life	TP	Total population	10^4 persons
		GAOTP	Growth amount of total population	10^4 persons/year
		RP	Rural population	10^4 persons
		UP	Urban population	10^4 persons
		RDWQ	Rural domestic water quota	L/person/day
		UDWQ	Urban domestic water quota	L/person/day
		GROTP	Growth rate of total population	1/year
		UR	Urbanization rate	1/year
		RDWD	Rural domestic water demand	10^8 m^3
		UDWD	Urban domestic water demand	10^8 m^3
		DWD	Domestic water demand	10^8 m^3
	Ecology and environment	EWD	Ecology and environmental water demand	10^8 m^3
		SFW	Street flushing water	10^8 m^3
		WCOUL	Water consumption of urban landscaping	10^8 m^3
		SFWQ	Street flushing water quota	m^3/m^2/year
		IQ	Irrigation quota	m^3/hm^2/year
		GROGLA	Growth rate of green land area	1/year
		GRORA	Growth rate of road area	1/year

(*continued*)

Table 1 | continued

System	Subsystem	Abbreviation	Description	Unit
		GLA	Green land area	hm^2
		RA	Road area	$10^4\ m^2$
		GAOGA	Growth amount of green area	hm^2/year
		GAORA	Growth amount of road area	$10^4\ m^2$/year
		TWD	Total water demand	$10^8\ m^3$
Water supply	Water resources	CWQ	Conventional water quantity	$10^8\ m^3$
	Recycled water	IWC	Industrial water consumption	$10^8\ m^3$
		IWEA	Industrial wastewater emission amount	$10^8\ m^3$
		TAOS	Total amount of sewage	$10^8\ m^3$
		DS	Domestic sewage	$10^8\ m^3$
		DOTIW	Drainage of tertiary industrial wastewater	$10^8\ m^3$
		IWEC	Industrial wastewater emission coefficient	–
		TIWWEC	Tertiary industrial wastewater emission coefficient	–
		DSDC	Domestic sewage discharge coefficient	–
		RORWU	Rate of reclaimed water use	1/year
		TWS	Total water supply	$10^8\ m^3$
		DSP	Demand–supply pressure	–
		SOSAD	Shortfall of supply and demand	$10^8\ m^3$

For n state variables (Q_1, $Q_2 \ldots Q_n$), the general sensitivity degree of a variable at time t can be defined as follows:

$$S = \frac{1}{n}\sum_{i=1}^{n} S_{Q_i} \tag{2}$$

where n denotes the number of state variables; S_{Qi} is the sensitivity degree of state Q_i; S is the general sensitivity degree of the n states over the parameter X.

For the study system, 19 variables are identified for representing system states of population growth, industrial and agricultural development, wastewater reuse and urbanization level, and seven parameters are analyzed to examine their impacts on the system states. To examine the sensitivity degree of each state variable, each parameter is increased (or decreased) by 10% per 1 year for the study horizon of 2007–2030.

Urban expansion index

Urbanization is a long and complicated process, which has many influencing factors. The population, economy, industrial structure, infrastructure construction, living standards and environment usually were used to represent the urbanization (Camagni *et al.* 2002; Deng *et al.* 2008). Based on the results of the sensitivity degree analysis (Table 4), an urban expansion index was set up to describe the urban development and analyze the relationship with water resource security. The factors include the urbanization level, industrial structure, living standards and the environment. The urban expansion index is expressed as: $Y = \log\ (y_1 \cdot\ y_2 \cdot\ y_3 \cdot\ y_4)$, where y_1 is the urbanization level, which is equal to the ratio of the non-agricultural population to the total population; y_2 is the industrial structure, which is equal to the ratio of the third industrial production to the GDP; y_3 is the living standard, which is equal to the GDP per person; y_4 is the environment which, is equal to the green area per person.

RESULTS AND DISCUSSION

Sensitivity analysis

Based on Equation (1), five sensitivity degree values can be obtained for each parameter–variable pair. Their average represents the general sensitivity degree of the parameter to the

Table 2 | Variables and parameters in the urban water resources SD model

Variables	2006	2011	2015	2020	2030
GDP	683.68	1,338.52	2,700.00	4,200.00	8,500.00
POPI	1.54	1.49	1.20	1.00	1.00
POSI	42.84	44.86	45.30	40.00	29.00
POTI	55.62	53.65	53.00	59.00	70.00
GROPIGDP	14.25	9.02	4.17	10.23	10.23
GROSIGDP	18.90	12.15	6.28	4.25	4.25
GROTIGDP	18.49	11.80	11.94	12.72	12.72
IA	56.80	61.97	64.00	65.00	67.00
GAOIA	1.25	0.66	0.26	0.28	0
TP	221.03	243.03	365.85	430.33	506.18
GAOTP	4.64	3.79	6.54	4.69	4.69
UR	76.10	73.80	84.50	87.00	91.50
AIQ	697.00	730.00	650.00	580.00	500.00
IWUP	48.96	40.81	35.00	30.00	25.00
TIWUP	6.70	2.92	2.75	2.50	2.30
UDWQ	213.00	156.90	156.90	156.90	156.90
RDWQ	61.00	69.30	69.30	69.30	69.30
CWQ	9.52	9.85	10.09	10.59	11.09
GLA	14,415.00	17,316.00	53,115.30	215,345.00	754,225.00
GROGLA	8.05	29.35	25.03	20.43	17.68
RA	1,474.00	2,005.00	2,684.28	3,886.30	8,223.96
GRORA	1.24	7.53	7.63	7.75	7.86
IQ	30.00	30.00	30.00	30.00	30.00
SFWQ	0.73	0.73	0.73	0.73	0.73
RORWU	37.00	27.00	30.00	35.00	40.00
RUROLA	23.56	34.89	36.00	38.00	40.00
DSDC	56.39	53.25	53.25	53.25	53.25
IWEC	41.84	58.68	58.68	58.68	58.68
TIWWEC	59.26	53.33	53.33	53.33	53.33

Table 3 | Verification results in the urban water resources SD model

Item	Type	2007	2008	2009	2010	2011
TWD (10^8 m^3)	Historical data	9	9.93	12.13	11.12	10.68
	Simulated data	8.92	9.95	12.12	10.92	10.55
	Relative error (%)	−0.60	−0.86	0.28	−0.11	−1.25
GDP (10^8 Yuan)	Historical data	810.57	982.37	1,087.50	1,338.52	1,690.03
	Simulated data	811.08	990.67	1,096.26	1,349.42	1,703.26
	Relative error (%)	−0.06	−0.85	−0.81	−0.81	−0.78
TP (10^4 persons)	Historical data	231.29	236.05	241.20	243.03	249.35
	Simulated data	231.30	236.08	241.22	243.06	249.37
	Relative error (%)	0.01	0.01	0.01	0.01	0.01

Table 4 | Results of sensitivity analysis for the urban water resources SD model

No.	Var./Para.	TP	GDP	TWD	TWS	POWSAD	TAOS	SIGDP	Average
1	GROTP	0.0891	0.0001	0.0129	0.0017	1.2106	0.0436	0.0001	0.1940
2	UR	0.0001	0.7413	0.1030	0.0136	3.5859	0.3410	0.0008	0.6837
3	UDWQ	0.0002	0.0010	0.1437	0.0190	3.1160	0.4720	0.0011	0.5361
4	RDWQ	0	0.0001	0.0147	0.0019	1.3803	0.0496	0.0001	0.2067
5	AIQ	0.0010	0.0059	0.6486	0.0001	15.8827	0.0035	0.0059	2.3640
6	GROIA	0	0.0002	0.0564	0	4.6222	0.0001	0.0002	0.6685
7	IWUP	0.0002	0.0014	0.2059	0.0184	1.7276	0.4552	0.0014	0.3443
8	TIWUP	0	0.0002	0.0223	0.0031	0.1256	0.0798	0.0002	0.0330
9	GROPIGDP	0	0.0051	0.0012	0.0001	2.7065	0.0026	0.0051	0.3886
10	GROSIGDP	0	0.2634	0.0608	0.0058	2.5839	0.1377	0.2634	0.4736
11	GROTIGDP	0	0.2471	0.0566	0.0054	2.4765	0.1286	0.2471	0.4516
12	POPI	0.0002	0.2606	0.1732	0.0159	15.7601	0.4176	0.8533	2.4973
13	POSI	0.0002	0.1381	0.2284	0.0201	4.9111	0.4904	1.1256	0.9877
14	POTI	0.0001	0.1433	0.0488	0.0028	3.4326	0.0762	0.4280	0.5903
15	DSDC	0.0066	0.0002	0.0001	0.0209	7.7949	0.5181	0.0002	1.1916
16	IWEC	0.2463	0.0002	0.0001	0.0185	9.5457	0.4561	0.0002	1.4667
17	RORWU	0.0001	0.0004	0.0001	0.0424	4.1440	0.0002	0.0004	0.5982
18	RUROIA	0	0.0001	0	0.0075	0.6273	0.1835	0.0001	0.1169
19	GROGLA	0	0	0.0001	0	0.0146	0	0.0001	0.0021
20	IQ	0	0	0.0006	0	0.1076	0	0	0.0155
21	GRORA	0	0	0.0037	0	0.5506	0	0	0.0792
22	SFWQ	0	0.0001	0.0147	0	1.3570	0.0001	0.0001	0.1960

variable. Furthermore, according to Equation (2), an average can be obtained for all 19 system states to the parameter.

Table 4 shows the results of the sensitivity degree analyses. The results indicate that the study system responds to most of the parameters with a low degree of sensitivity. This fact demonstrates that the developed SD model can undertake effective prediction of the system's behaviors.

Effect of urban expansion on water resource security

Using year 2011 as the current year, the water resource balance and development of Urumqi from 2012 to 2030 was simulated.

Prediction of urban expansion

To quantitatively analyze the urban development, four variables of the urban expansion index were calculated according to the data (Table 5).

Table 5 shows that the urban expansion index would increase with time, i.e. the urban expansion would continue into the future. In addition, the urbanization level, industrial structure, living standards and environment would all increase gradually.

Prediction of urban water supply and demand

Based on the SD model, the trend of urban water supply and demand from 2012 to 2030 was simulated. The demand–supply pressure index, the ratio of the difference between the demand and supply to the total water supply, was calculated. The results are shown in Figure 5.

Figure 5 shows that the total water demand (TWD) of Urumqi increases with time. The proportion of agricultural water decreases, while the industrial water, living water and environmental water increase. The greatest water consumption is from agricultural water, followed by industrial

Table 5 | The urban expansion index of Urumqi city

Year	y_1	y_2	y_3	y_4	Y
2011	0.7350	0.5365	55,076.3280	71.2505	6.1896
2012	0.7625	0.5361	60,073.3923	89.8145	6.3435
2013	0.7900	0.5358	64,521.4247	111.2023	6.4824
2014	0.8175	0.5354	68,240.4562	135.2383	6.6063
2015	0.8450	0.5350	71,074.7600	161.5511	6.7152
2016	0.8500	0.5460	72,902.7542	189.5625	6.8071
2017	0.8550	0.5570	75,026.5971	221.5652	6.8985
2018	0.8600	0.5680	77,477.7548	257.9510	6.9896
2019	0.8650	0.5790	80,292.7787	299.1165	7.0802
2020	0.8700	0.5900	83,515.0145	345.4554	7.1705
2021	0.8745	0.6010	87,195.2037	397.3510	7.2603
2022	0.8790	0.6120	91,113.9023	455.9814	7.3493
2023	0.8835	0.6230	95,288.4522	522.0452	7.4374
2024	0.8880	0.6340	99,737.4744	596.2903	7.5248
2025	0.8925	0.6450	104,481.3551	679.5016	7.6114
2026	0.8970	0.6560	109,541.6170	772.5123	7.6972
2027	0.9015	0.6670	114,942.2615	876.1903	7.7822
2028	0.9060	0.6780	120,709.2173	991.4428	7.8664
2029	0.9105	0.6890	126,869.6482	1119.2018	7.9498
2030	0.9150	0.7000	133,454.2085	1260.4368	8.0324

water. However, industrial water exceeds agricultural water after 2027 with economic development.

Figure 6(a) indicates that the TWD is greater than the water supply. The reuse water remains at a low level. According to the 12th 5-year plan of Urumqi, no other water source could be added and the exploitation amount has reached its limits. However, one million Yuan of industrial output value approximately requires 32.7 m^3 of water at present, approximately five times that of developed countries; the industrial water recycling rate is 37%, far less than the 75–80% in developed countries. Thus, water conservation is the key factor. If the current water-use efficiency in Urumqi during 2011–2030 remains constant, the water resource security would be damaged. Figure 6(b) shows that the demand–supply pressure index is positive from 2011, which means that water shortage is currently occurring. The projection of the demand–supply pressure shows a sharp increase in 2020. Then, the increasing trend continues during 2020–2030.

In all, there is great influence of urban expansion on the future water resource security of Urumqi. The change of water-use structure is mainly due to the urbanization process. The water resources would become increasingly scarce if the urban expansion remains unchanged in terms of population, economic growth and water-use efficiency. The regional development is currently unsustainable with serious ecological, environmental and social economic problems.

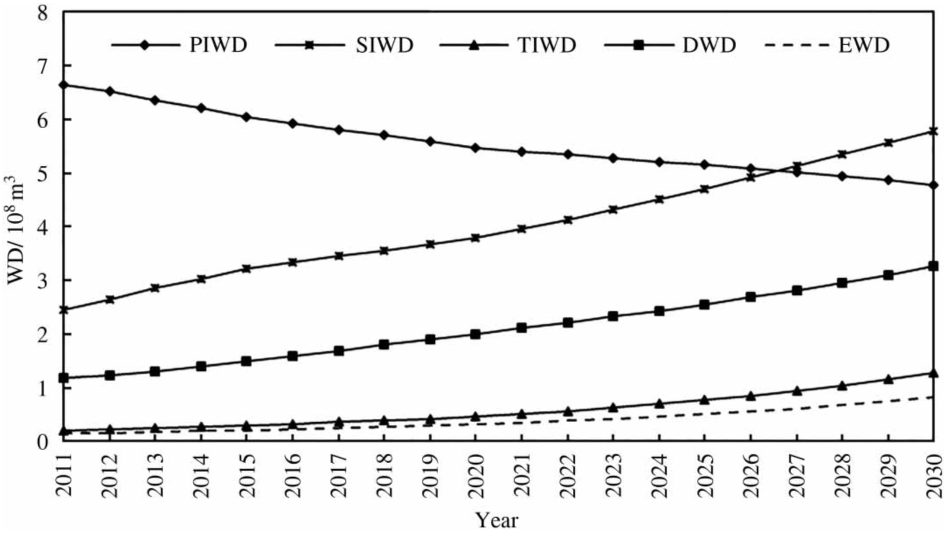

Figure 5 | The prediction of WD in Urumqi.

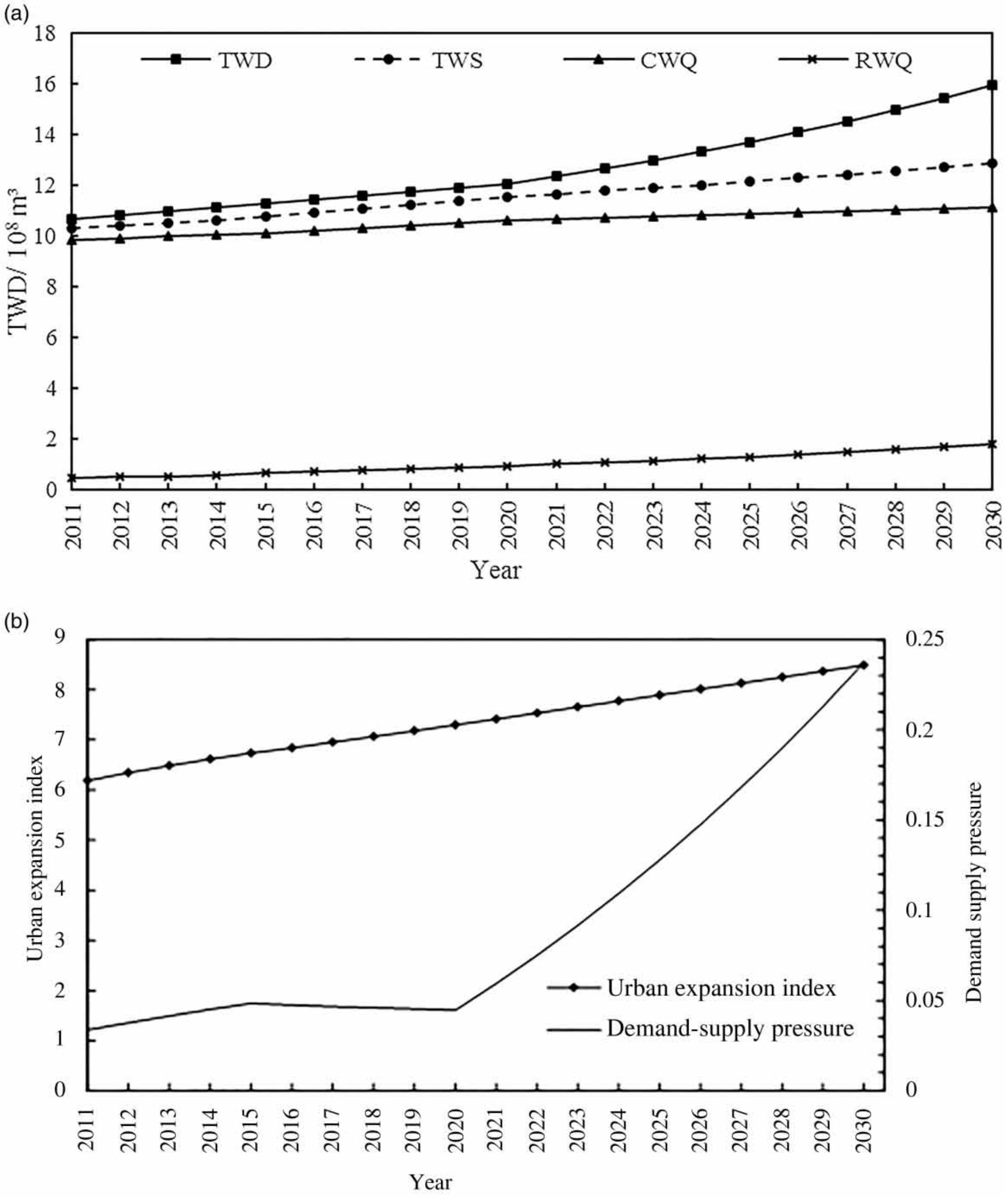

Figure 6 | Relationship between the urban expansion index and pressure of water supply and demand from 2011 to 2030. (a) The prediction of TWD in Urumqi. (b) The prediction about pressure of water supply and demand in Urumqi.

Assessment of water resource security under different scenes of urban expansion

We analyzed the impact of urban development on the urban water resources system to find a sustainable method for water resource use, according to the actual situation of Urumqi and other authors' experience (Feng *et al.* 2008; Cheng 2010). In this study the base year was 2006, the first target year was 2015, and long-term target years were 2020 and 2030. To find a sustainable method for water resource use, four scenarios of urban expansion were set up based on the sensitive variables.

Design of the urban expansion scenes

Scheme 1 (present development scenario): this scenario is also known as the trend-based scenario by assuming that the development policies and system structure do not change much in the forecasting period. The constant parameters are the same as in the model calibration stage, while the table-valued parameters are hypothesized with a moderate trend. The parameters are based on the analyzed data of Urumqi.

Scheme 2 (economic priority scenario): emphasize the importance of economic growth and improve the growth rate of each industry and optimize industrial structure. The economic parameters are referenced by the level of developed countries in the same period.

Scheme 3 (water-saving scenario): the aim of this scenario is to improve the efficiency of water and increase the source of water supply. The parameters of water-use efficiency are referenced by the level of developed countries in the same period.

Scheme 4 (harmonize scenario): this scenario is also known as a sustainable development scenario by emphasizing economic development and the protection of water resources at the same time. The parameters are referenced economic priority scenario and water-saving scenario.

Regarding the domestic and foreign information in these parameters, we obtained the values of 18 sensitive parameters (Table 6).

Change of water resource security under different scenarios of urban expansion

The change of WD and demand–supply pressure index under different scenarios of urban expansion was simulated (Table 7).

Table 7 shows that there is a different status with different development scenarios. Under the present development scenario, the total required water is projected to reach 15.92×10^8 m^3 in 2030. The gap between supply and demand is 3.05×10^8 m^3. Under the economic priority

Table 6 | Schemes design by changing parameters

	Scheme 1			**Scheme 2**			**Scheme 3**			**Scheme 4**		
Variables	**2015**	**2020**	**2030**	**2015**	**2020**	**2030**	**2015**	**2020**	**2030**	**2015**	**2020**	**2030**
RUROIA	36	38	40	36	38	40	39.6	41.8	44	39.6	41.8	44
IWUP	35	30	25	35	30	25	31.5	27	22.5	31.5	27	22.5
TIWUP	2.75	2.5	2.3	2.75	2.5	2.3	2.48	2.25	2.07	2.48	2.25	2.07
AIQ	650	580	500	650	580	500	585	522	450	585	522	450
POPI	1.2	1	1	1	1	1	1.2	1	1	1	1	1
POSI	45.3	40	29	40.77	36	26.1	45.3	40	29	40.77	36	26.1
POTI	53.5	59	70	58.23	63	72.9	53.5	59	70	58.23	63	72.9
GROPIGDP	4.17	10.23	10.23	4.59	11.25	11.25	4.17	10.23	10.23	4	10	10
GROSIGDP	6.28	4.25	4.25	6.91	4.68	4.68	6.28	4.25	4.25	6	4	4
GROTIGDP	11.94	12.72	12.72	13.14	13.99	13.99	11.94	12.72	12.72	14	15	15
RORWU	30	35	40	30	35	40	30	35	40	33	38.5	44
DSDC	53.25	53.25	53.25	53.25	53.25	53.25	55	55	55	55	55	55
IWEC	58.68	58.68	58.68	58.68	58.68	58.68	60	60	60	60	60	60
TIWWEC	53.33	53.33	53.33	53.33	53.33	53.33	56	56	56	56	56	56
IQ	30	30	30	30	30	30	30	30	30	33	33	33
SFWQ	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.81	0.81	0.81
UDWQ	156.9	156.9	156.9	172.59	172.59	172.59	141.21	141.21	141.21	141.21	141.21	141.21
RDWQ	69.3	69.3	69.3	76.23	76.23	76.23	62.37	62.37	62.37	62.37	62.37	62.37

Table 7 | Simulation results of major variables under different scenarios of urban expansion

	Scheme 1		**Scheme 2**		**Scheme 3**		**Scheme 4**	
Variables	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**
TP	377.77	596.76	377.77	596.59	378.02	597.67	378.07	597.63
GDP	3,154.93	7,964.00	3,391.05	9,620.60	3,158.48	7,986.49	3,435.16	10,173.10
TWD	12.05	15.92	12.19	17.08	10.88	14.44	10.91	14.59
PIWD	5.47	4.79	5.47	4.79	4.92	4.31	4.92	4.31
SIWD	3.79	5.77	3.66	6.28	3.98	8.18	3.34	5.97
TIWD	0.47	1.28	0.53	1.61	0.42	1.16	0.49	1.54
DWD	2.01	3.26	2.21	3.58	1.81	2.93	1.81	2.93
EWD	0.32	0.83	0.32	0.82	0.32	0.83	0.36	0.92
TWS	11.53	12.87	11.57	13.08	11.43	12.68	11.52	13.04
RWQ	0.94	1.78	0.98	1.99	0.84	1.59	0.93	1.95
SOSAD	0.52	3.05	0.63	4.00	−0.55	1.76	−0.61	1.54
DSP	0.04	0.24	0.05	0.31	0.04	0.14	−0.05	0.13
TAOS	1.75	2.67	1.82	2.99	1.57	2.59	1.49	2.49
IS	1:40:59	1:29:70	1:36:63	1:26.1:72.9	1:40:59	1:29:70	1:36:63	1:26.1:72.9

scenario, the total required water is increased further. The gap between supply and demand becomes larger than the first scenario. Under the water-saving scenario, the water-use pressure decreases to a certain extent, but the sewage (2.59×10^8 m^3) is a problem. In contrast, the harmonize scenario would have a high GDP of $10{,}173.1 \times 10^8$ Yuan, a small difference between demand and supply of 1.54×10^8 m^3 and a low sewage discharge of 2.39×10^8 m^3. Thus, the harmonize scenario with minimal consumption of water resources has the highest GDP and water-use efficiency. The effect of water shortage and pollution level on the social and economic development is also lower than in the other three development scenarios. This would be the best scheme of water resource development and utilization in Urumqi city.

Selection of urban expansion scenario based on water resources security

Figure 7 shows that the demand–supply pressure swiftly increases with urban expansion. The order of demand–supply pressure is the following: economic priority scenario > present development scenario > water-saving scenario > harmonize scenario. The order of urban expansion level is the following: economic priority scenario > harmonize scenario > water-saving scenario > present development scenario. From a water resource security perspective, the harmonize scenario is the best choice for the development of Urumqi. To achieve the goal, the main parameters would have to reach a new standard, i.e. the water-use quota for living, irrigation quota, water-use quota for industry and the service industry. The ratio of industrial structure would optimize to 1:26.1:72.9 for three industries. Reducing the sewage and increasing the reuse proportion of wastewater are also very important to relieve the stress of water shortage.

CONCLUSIONS

Through simulating the water resource security under different development scenarios using the SD model, the result shows that the WD increases with urban expansion. The water shortage has become more and more serious in Urumqi and has begun to restrict the development of the city.

Regarding water use, the largest demand is water consumption due to agriculture, followed by industry. However, the industrial water exceeds the agricultural water after 2027 with economic development.

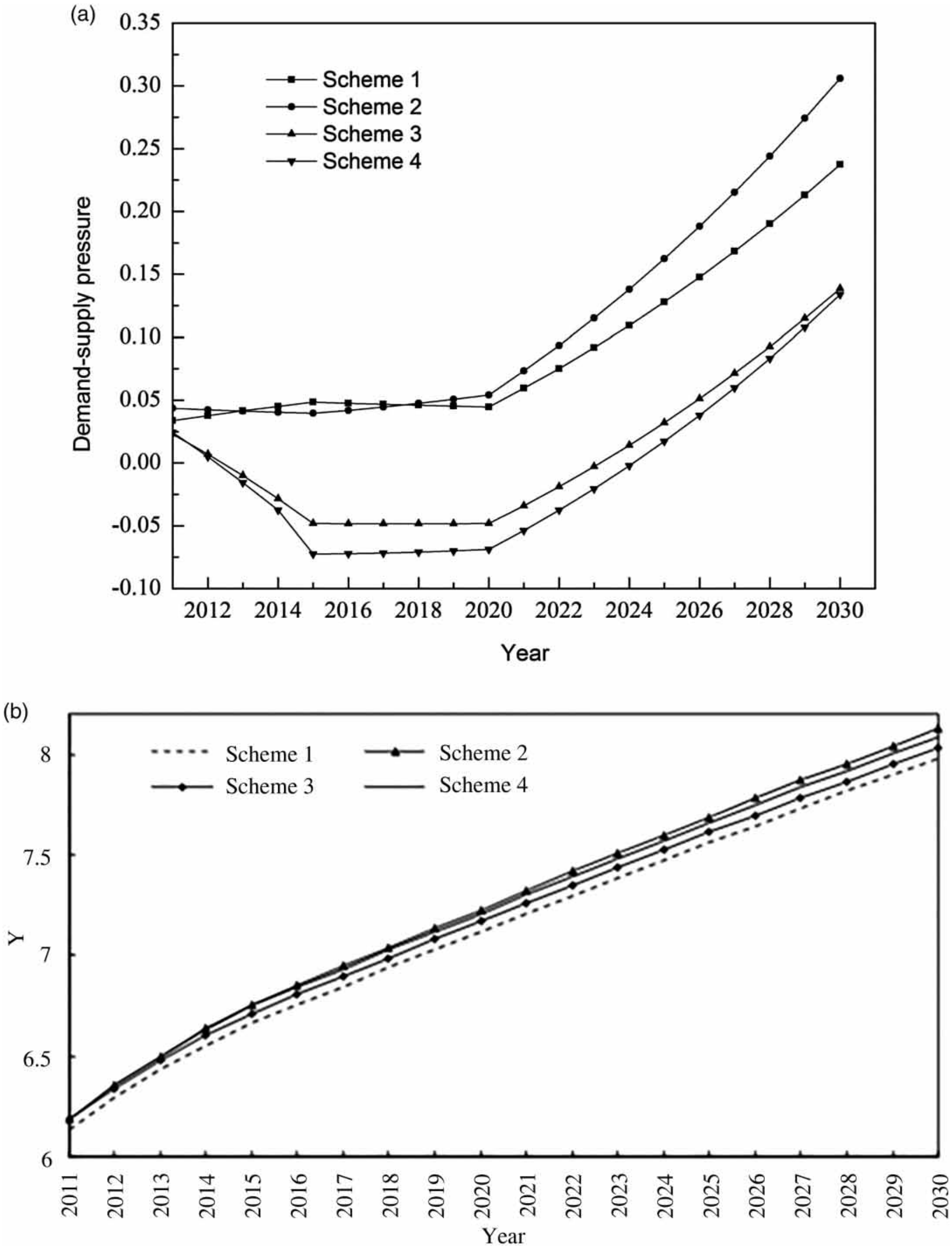

Figure 7 | Results of urban expansion in different schemes simulated by urban water resources SD model. (a) Simulation of demand–supply pressure in different schemes. (b) Simulation of urban expansion index (*Y*) in different schemes.

The harmonize scenario is the best choice for the development of Urumqi. There is great influence of urban expansion on the future water resource security in Urumqi. The demand–supply pressure swiftly increases with urban expansion. The order of demand–supply pressure is the following: economic priority scenario > present development scenario > water-saving scenario > harmonize scenario. The order of urban expansion level is the following: economic priority scenario > harmonize scenario > water-saving scenario > present development scenario.

The contradiction between supply and demand of water resources in Urumqi city is very prominent. To keep water resources safe, scenarios planning to realize the economic, living and environmental goals are essential.

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REFERENCES

Ahmad, S. & Simonovic, S. P. 2000 System dynamics modeling of reservoir operations for flood management. *Journal of Computing in Civil Engineering* **14**, 190–198.

Ahmad, S. & Simonovic, P. 2004 Slobodan. Spatial system dynamics: new approach for simulation of water resources systems. *Computing in Civil Engineering* **18**, 331–340.

Al-Otaibi, A. & Abdel-Jawad, M. 2007 Water security for Kuwait. *Desalination* **214**, 299–305.

Bogardi, J. J., Dudgeon, D., Lawford, R., Flinkerbusch, E., Meyn, A., Pahl-Wostl, C., Vielhauer, K. & Vörösmarty, C. 2012 Water security for a planet under pressure: interconnected challenges of a changing world call for sustainable solutions. *Current Opinion in Environmental Sustainability* **4**, 35–43.

Camagni, R., Gibelli, M. C. & Rigamonti, P. 2002 Urban mobility and urban form: the social and environmental costs of different patterns of urban expansion. *Ecological Economics* **40**, 199–216.

Chen, J., Xia, L. & Wang, H. 2011 Research on Urban Water Security Evaluation Based on Technique for Order Preference by Similarity to Ideal Solution Model. In: *Modeling Risk Management for Resources and Environment in China* (Y. Zhou & D. D. Wu, eds). Springer, Berlin, pp. 341–348.

Cheng, L. I. 2010 System dynamics model of Suzhou water resources carrying capacity and its application. *Water Science and Engineering* **3** (2), 144–155.

Cook, C. & Bakker, K. 2012 Water security: debating an emerging paradigm. *Global Environmental Change* **22**, 94–102.

Danielson, L. E. 1979 An analysis of residential demand for water using micro time-series data. *Water Resources Research* **15**, 763–767.

Deng, X., Huang, J., Rozelle, S. & Uchida, E. 2008 Growth, population and industrialization, and urban land expansion of China. *Journal of Urban Economics* **63**, 96–115.

Falkenmark, M. & Widstrand, C. 1992 Population and water resources: a delicate balance. *Population Bulletin* **47**, 1–36.

Feng, L. H., Zhang, X. C. & Luo, G. Y. 2008 Application of system dynamics in analyzing the carrying capacity of water resources in Yiwu City, China. *Mathematics and Computers in Simulation* **79**, 269–278.

Fletcher, E. 1998 The use of system dynamics as a decision support tool for the management of surface water resources. *First International Conference on New Information Technologies for Decision Making in Civil Engineering*, pp. 909–920.

Forrester, J. W., Mass, N. J. & Ryan, C. J. 1976 The system dynamics national model: understanding socio-economic behavior and policy alternatives. *Technological Forecasting and Social Change* **9**, 51–68.

Guo, H. C., Liu, L., Huang, G. H., Fuller, G. A., Zou, R. & Yin, Y. Y. 2001 A system dynamics approach for regional environmental planning and management: a study for the Lake Erhai Basin. *Journal of Environmental Management* **61**, 93–111.

Han, Y., Ruan, B. & Xie, J. 2003 Multi-objective and multilevel fuzzy optimization model and its application in water security evaluation. *Resources Science* **25**, 37–42.

Hunter, C. 1998 Perceptions of the sustainable city and implications for fresh water resources management. *International Journal of Environment and Pollution* **10**, 84–103.

Jaber, J. O. & Mohsen, M. S. 2001 Evaluation of non-conventional water resources supply in Jordan. *Desalination* **136**, 83–92.

Ji, X. B., Kang, E. S., Chen, R. S., Zhao, W. Z., Xiao, S. C. & Jin, B. W. 2006 Analysis of water resources supply and demand and security of water resources development in irrigation regions of the middle reaches of the Heihe River Basin, Northwest China. *Agricultural Sciences in China* **5**, 130–140.

Keyes, A. M. & Palmer, R. N. 1993 The role of object oriented simulation models in the drought preparedness studies. *Water Management in the '90s: A Time for Innovation*. ASCE, New York, pp. 479–482.

Li, L. & Simonovic, S. 2002 System dynamics model for predicting floods from snowmelt in North American prairie watersheds. *Hydrological Processes* **16**, 2645–2666.

McDonald, R. I. 2008 Global urbanization: can ecologists identify a sustainable way forward? *Frontiers in Ecology and the Environment* **6**, 99–104.

Mohapatra, P. K., Mandal, P. & Bora, M. C. 1994 *Introduction to System Dynamics Modeling*. University of Nevada Press, Reno pp. 132–156.

Motohashi, Y. & Nishi, S. 1991 Prediction of end-stage renal disease patient population in Japan by system dynamics model. *International Journal of Epidemiology* **20**, 1032–1036.

Niemczynowicz, J. 1999 Urban hydrology and water management–present and future challenges. *Urban Water* **1**, 1–14.

Palmer, M. A., Bemhard, E. S., Chomesky, E. A., Collins, S. L., Dobson, A. P., Duke, C. S., Gold, B. J., Jacobson, R., Kingsland, S., Kranz, R., Mappin, M. J., Martinez, M. L., Micheil, F., Morse, J. L., Pace, M. L., Pascual, M., Palumbi, S., Reichman, O. J., Townsend, A. & Tumer, M. G. 2004 *Ecological science and sustainability for a crowded planet*. Report from the Ecological Society of America, Ecological Visions Committee, USA, pp. 17–26.

Peters, N. E. & Meybeck, M. 2000 Water quality degradation effects on freshwater availability: impacts of human activities. *Water International* **25**, 185–193.

Rijsberman, M. A. & Van De Ven, F. H. 2000 Different approaches to assessment of design and management of sustainable urban water systems. *Environmental Impact Assessment Review* **20**, 333–345.

Shi, Y. & Qu, Y. 1992 *Carrying Capacity of Water Resources in Urumqi River Basin and its Rational Utilization*. Science Press, Beijing, pp. 128–139.

Shiflet, A. & Shiflet, G. 2011 *System Dynamics Tool: Vensim PLE Tutorial 1. Introduction to Computational Science: Modeling and Simulation for the Sciences*. Whitney Darrow, Princeton, pp. 12–43.

Simonovic, S. P. & Fahmy, H. 1999 A new modeling approach for water resources policy analysis. *Water Resources Research* **35**, 295–304.

Sterman, J. D. 2000 *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin/McGraw-Hill, Boston, 19.

Sun, C. Z. & Chi, K. X. 2008 Establishment and application of the assessment model for water resources safety in Dalian. *Journal of Safety and Environment* **1**, 33.

Vennix, J. A. 1996 *Group model building: Facilitating team learning using system dynamics*. Wiley, Chichester.

Vörösmarty, C. J., Green, P., Salisbury, J. & Lammers, R. B. 2000 Global water resources: vulnerability from climate change and population growth. *Science* **289**, 284–288.

Xia, J. & Zhu, Y. Z. 2002 The measurement of water resources security: a study and challenge on water resources carrying capacity. *Journal of Natural Resources* **3**, 262–269.

Yeh, W. W. G. 1985 Reservoir management and operations models: a state of the art review. *Water Resources Research* **21**, 1797–1818.

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