Journal of Water Reuse and Desalination | 04.3 | 2014

A simulation impact evaluation of social-economic development on water resource use

Wenyi Wang, Weihua Zeng, Bo Yao and Jing Wei

ABSTRACT

Due to the fast growth of the economy and population, the water scarcity issue has aroused widespread critical concern. In fact, reasonable structure, adaptive patterns and effective regulation of the economy, society and water resources can bring a harmonious future. Therefore, the study of how to balance economic social growth and water resources is of great importance. A model of the water resource, society and economy system of the Tongzhou district was designed by Stella. The model established here attempts to analyze future trends in social-economic development and the impact of the economic and population growth on water use in the Tongzhou district under three scenarios. The results reveal that the water shortage is very serious. If the current trends persist, the existing water supply will not be able to meet the water demand in the future. Tongzhou district's water shortage will be 162.50 million m^3 in 2020 under the business-as-usual scenario. Therefore, it is necessary to develop unconventional water sources and improve the water-saving capacity of production and life to alleviate the water tensions. This research offers insight into larger questions regarding economic growth and water resource management in general.

Key words | scenario analysis, society and economy, Stella model, system dynamics, water resource, water shortage

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INTRODUCTION

The Tongzhou district is one of three new developmental towns in Beijing and has been one of the key components of 'New Beijing' progress (Xu *et al.* 2010). The district has convenient transportation, good infrastructure and cultural heritage, and it is intended to take on the excess population from the central urban area, the expansion of industry and other urban functions. Tongzhou district is low lying, known as 'the ends of nine rivers', and many rivers converge within the district (Zhang *et al.* 2010). However, with high economic growth and acute population aggravation, water consumption has recently multiplied to meet the needs of factories and the populace. There are conflicts between water demand and supply in this district, which have aroused concerns. Therefore, it is necessary to find a good way to achieve the sustainable development of water resource in the Tongzhou district.

System dynamic modeling is a methodology for studying complex feedback-loop systems with nonlinear and multi-variable characters introduced by Forrester in the early 1960s. Since then, the system dynamic model has been applied in many ways, such as in social-economic dynamics (Forrester 1969, 1971), urban dynamics (Meadows *et al.* 1973; Steiss 1974a, b), for analyzing city problems (Satsangi *et al.* 2003), business systems (Sterman 2000), agricultural systems (Qu & Barney 1998), for solid waste management (Karavezyris *et al.* 2002; Dyson & Chang 2005; Sufian & Bala 2007), eco-industrial systems (Audra & Potts 1998; Yang & Lay 2004; Fang *et al.* 2007; Guan *et al.* 2011; Zhan *et al.* 2012), ecological systems (Grant *et al.* 1997), global environmental development (Meadows *et al.* 2004) and environmental systems (Vizayakumar & Mohapatra 1992, 1993; Ford 1999).

doi: 10.2166/wrd.2014.050

In the field of social economy and water resource system research, system dynamics (SD) has been applied to model water resources for the San Juan Basin combining hydrology and economics (Ewers 2005), in water resource management (Winz *et al.* 2009; Bagheri *et al.* 2010), for the evaluation of temporary water transfers (Gastélum *et al.* 2010), to study the impact of water resources planning (Ho *et al.* 2005; Zhang *et al.* 2008) and in global modeling of water resources (Simonovic 2002). The intent of this paper is to analyze the future trends of the economic and water demand and supply in the Tongzhou district under three scenarios using an SD model in Stella and to determine the appropriate water balance approach in promoting harmonious advancement. The major originalities of this research are as follows:

- The SD model integrated water resource, society and economy sectors into one system by Stella.
- The whole economic structure was considered in the research, including the primary, secondary and tertiary sectors.
- The model analyzed future trends in social-economic development and the impact of the economic and population growth on water use under the business-as-usual scenario, the planning-oriented scenario and the sustainable development scenario.

STUDY AREA AND DATA SOURCES

Site description

The Tongzhou district is located in the southeast of Beijing city and the north end of the Jing-Hang Grand Canal. Tongzhou town, 20 km from Tiananmen Square, is the largest satellite county of Beijing. Tongzhou is approximately 37 km wide from east to west and approximately 48 km from north to south, and it is located between 39°36′ and 40°02′ north latitudes and between 116°32′ and 116°56′ east longitudes. It has an area of approximately 906 km^2, which makes up approximately 5 percent of Beijing's total territory and approximately 14 percent of Beijing's plain. According to the requirement of the Tongzhou Town Plan, the Tongzhou district is positioned as 'waterfront livable city' and 'an important base for Bohai Sea-Rim regional cooperation in Beijing'.

Data sources

The data include social and economic statistical data, water consumption data and water supply data. Social-economic data include primary sector, secondary sector, tertiary sector, population (rural and urban), natural growth rate and population migration rate, which were collected from the Tongzhou statistical yearbook (2000–2010), social-economic census in Tongzhou (2004), Tongzhou new town planning (2005–2020), industry development planning (2006–2010), population development and control planning (2006–2010), the 11th Five-Year Plan of social economy development of Tongzhou district and the Beijing city general plan (2004–2020). Water consumption data were acquired from the Tongzhou statistical yearbook (2000–2010), the integrated water resources planning of the Tongzhou district, the program for science and technology development of the Tongzhou district and the Beijing urban master plan. The water supply data were collected from the water resources protection and utilization planning, the Tongzhou new town planning (2005–2020) and the regional strategic environmental impact assessment of the Tongzhou district.

METHODS

Concept of SD

The SD models are built using four types of basic components: stock, flow, auxiliary variable and information connector. A stock represents a state variable that denotes an aspect of the system. A flow defines the rate of change of a stock. The auxiliary represents the rate of variable change. Information connectors link the auxiliary variables, flows and stocks. There is a group of nonlinear differential equations in the simulation model. The key equation is the state equation, which can be expressed as Equation (1)

$$X_i(t + \Delta t) = X_i(t) + f(X_i, R_i, A_i, C_i) \cdot \Delta t \quad (1)$$

where $X_i(t)$ is a vector of state variables, f() is a vector-valued function, R_i is a vector of flow variables, A_i is a vector of auxiliary variables, C_i is a vector of parameters, t is time, and Δt is the change in time.

Description of the model

The system is divided into two parts: the population and water sector and the economy and water sector.

Population and water sector

The population and water sector is an important part of the model. Water is the important material foundation for human subsistence and development, and water consumption is affected by population.

The structure of the population and water sector is shown in Figure 1(a). In the model, the total population is divided into two parts: the urban population and the rural population, which both consist of the resident population and the floating population. With increases in population size and living standards, water consumption is multiplied. Now, there is growing competition between the water needed for domestic use and the water needed for the ever-expanding industrial growth. The prediction of domestic water consumption plays an important role in the utilization of urban water resources.

Economy and water sector

In the economic and water sector, economic benefits are brought to the region with increased production activities. At the same time, greater water consumption is inevitable as the economy grows. Rapid industrialization is increasing Tongzhou's demand for more water, straining already depleted sources. A large amount of wastewater is produced in various processes in industries. An effective way to minimize water consumption is to design the wastewater reuse network to maximize the use of wastewater.

The structure of the economy and water sector is shown in Figure 1(b). In the model, the sector is divided into three modules, the primary sector, secondary sector and tertiary sector, in accordance with the social-economic statistical classification. The secondary sector includes industry and construction, which could be further divided into 15 industries in the design of the model structure: mining (I01), food processing (I02), textiles and garments (I03), wood furniture (I04), papermaking (I05), printing, culture and education (I06), petrochemicals (I07), pharmaceuticals and chemicals (I08), chemical fibers (I09), rubber and plastics (I10), non-metallics (I11), metal processing (I12), equipment manufacturing (I13), other manufacturing (I14) and electricity, gas and water production (I15).

The SD model

The model is written in Stella with a time step of 1 year, and a model run spans 10 years. The model illustrates the connections of the social economy and the water supply and demand, and can be used to show the isolated effects of individual variables. The main parts of the model, the stock-flow diagrams of the population module, the industry module (taking I01 as an example), primary sector module and tertiary sector module, are shown in Figure 2. The boundary of the Tongzhou SD model is the Tongzhou district in Beijing.

Model evaluation

Model calibration

The model is calibrated by testing parameter accuracy of historical fit using the correction coefficient (R), absolute relative error (ARE) and the mean absolute relative error (MARE) (Equations (2)–(4)) (Kiani & Ali Pourfakhraei 2010; Wei et al. 2012)

$$R = \frac{\sum_{t=1}^{n}(Y_t - \overline{Y_t})(\hat{Y}_t - \overline{\hat{Y}_t})}{\sqrt{\sum_{t=1}^{n}(Y_t - \overline{Y_t})^2 \sum_{t=1}^{n}(\hat{Y}_t - \overline{\hat{Y}_t})^2}} \quad (2)$$

where t is time, n is the number of samples, Y_t and $\hat{Y}_t$ represent the observed and simulated results, and $\hat{Y}_t$ and $\overline{\hat{Y}_t}$ represent the mean of the observed and simulated results.

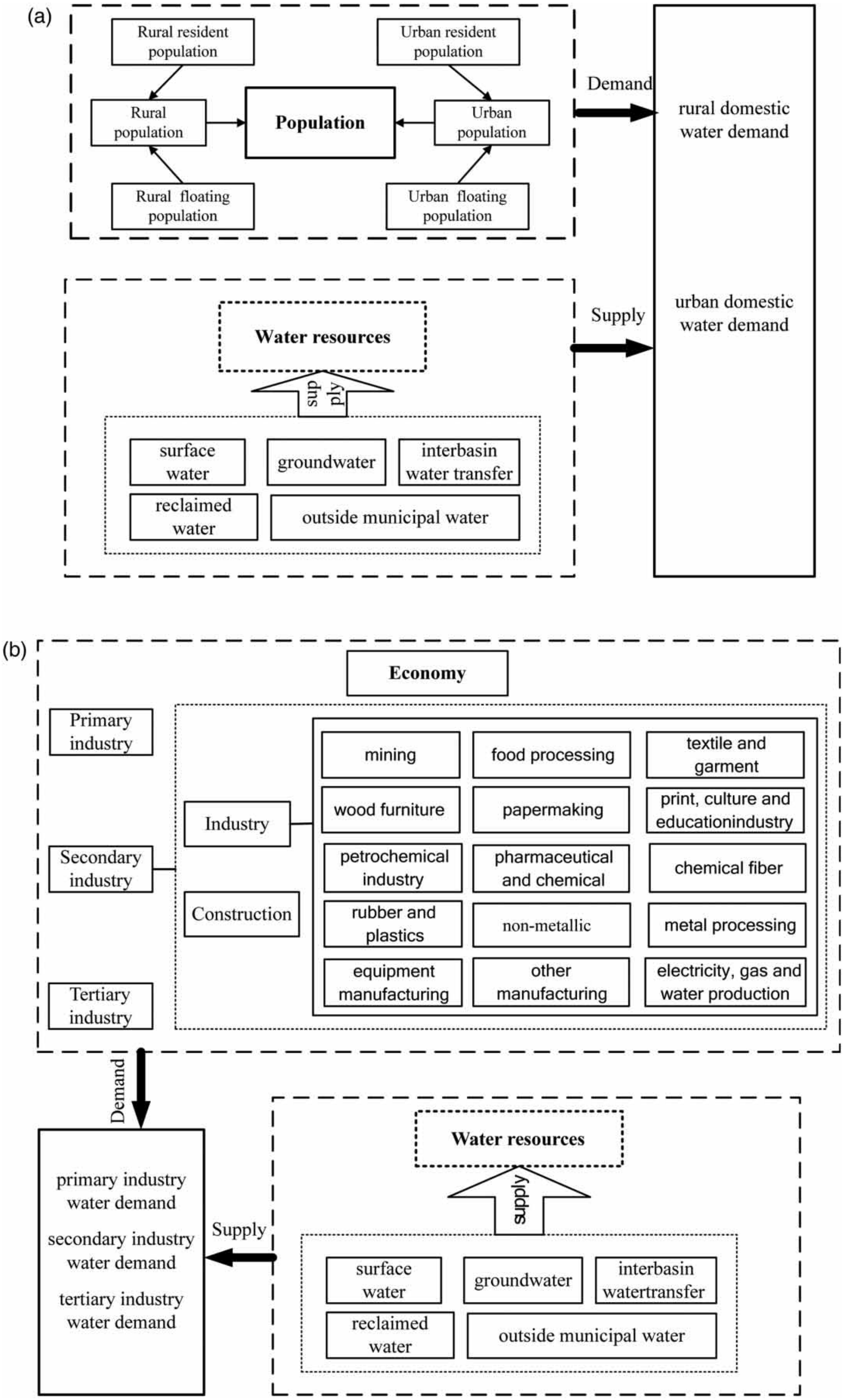

Figure 1 | The structure of the system: (a) the population and water sector and (b) the economy and water sector.

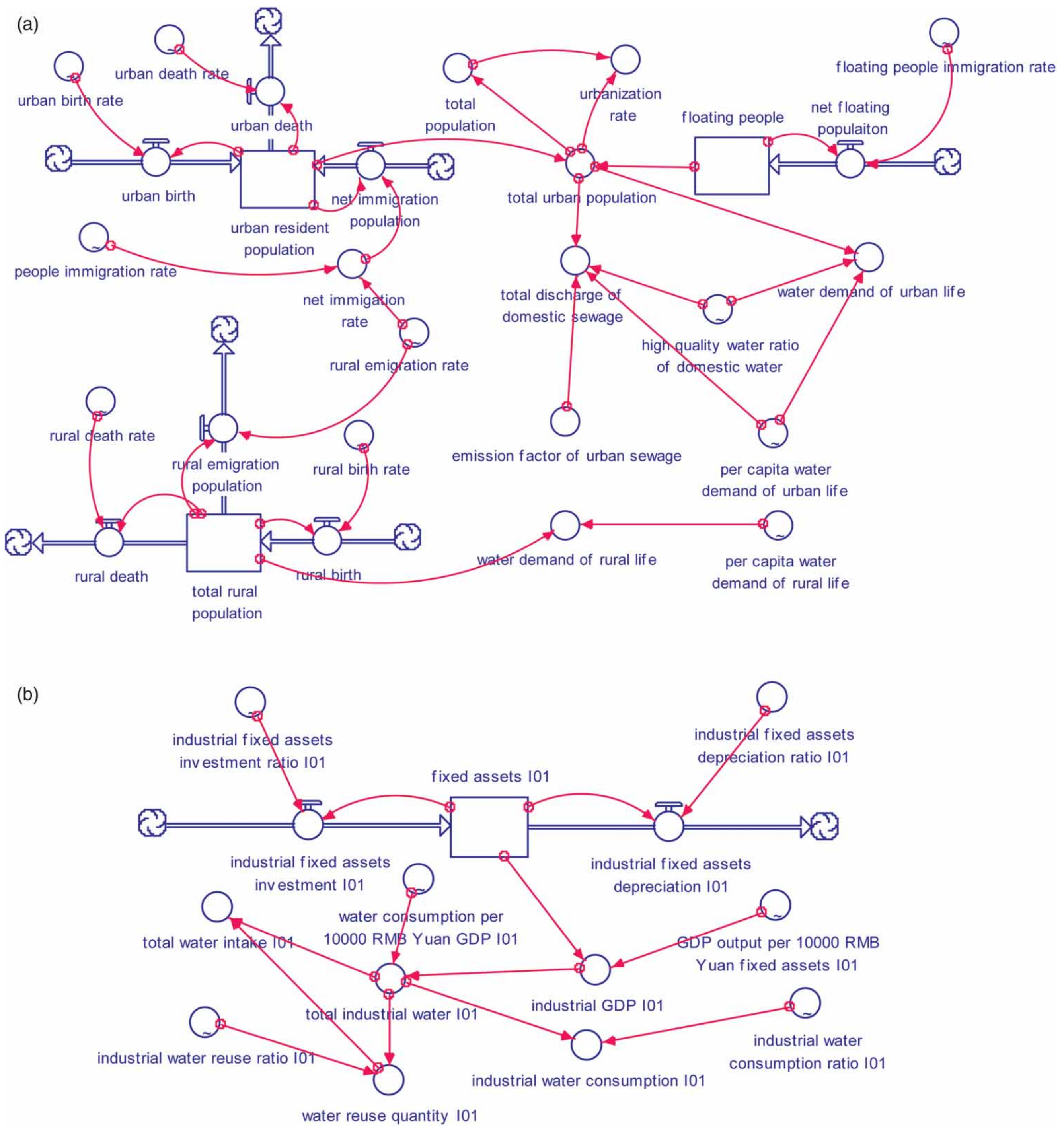

Figure 2 | The main parts of the system dynamic model, including modules of (a) population, (b) industry (I01), (c) the primary sector and (d) the tertiary sector (GDP = Gross Domestic Product). (*continued*)

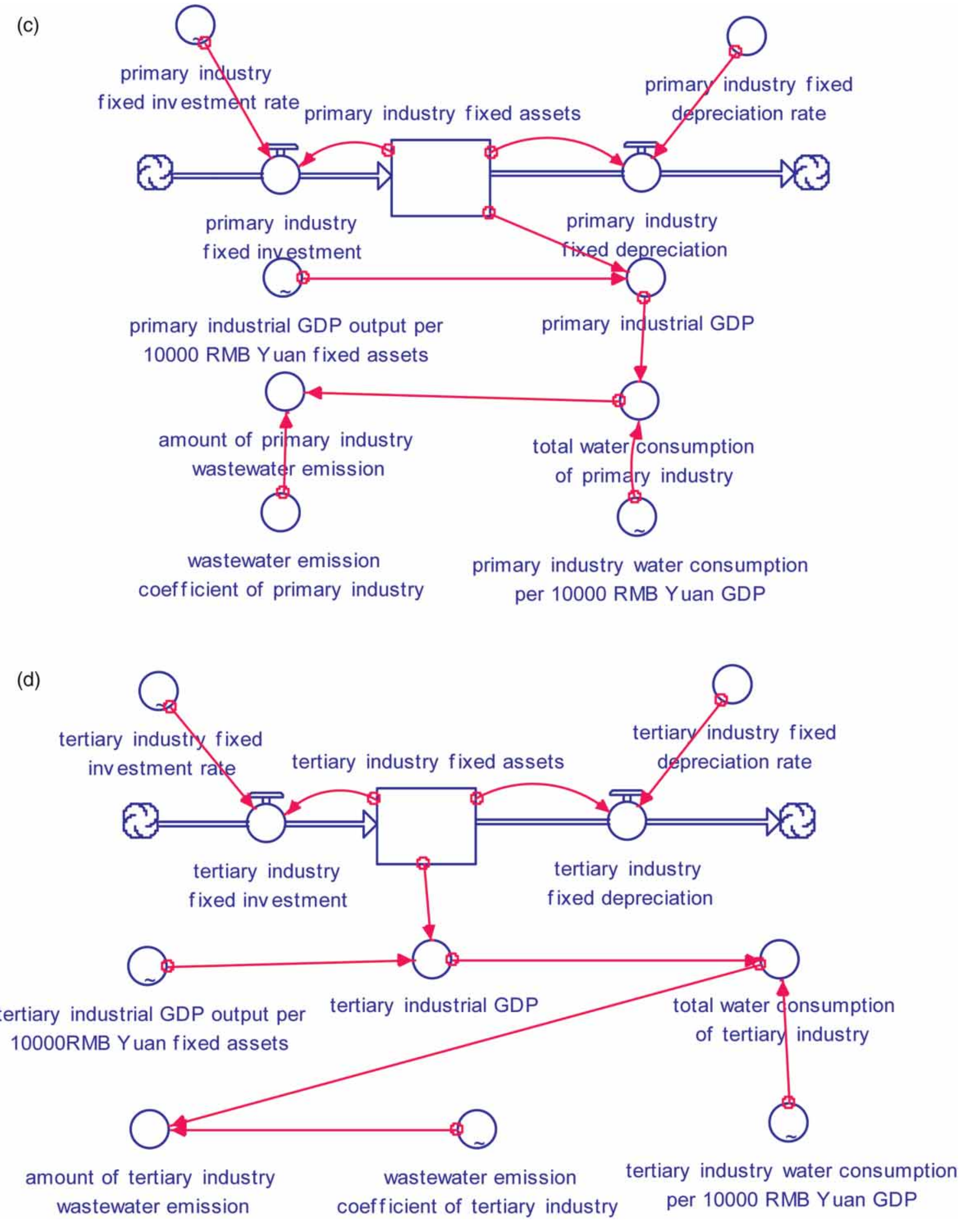

Figure 2 | Continued.

Model validation

Model validation is the comparison of the model results with the independent observations. ARE and MARE are also used for model performance validation (Kiani & Ali Pourfakhraei 2010; Wei *et al.* 2012)

$$\mathrm{ARE} = \left| \frac{(\hat{Y}_t - Y_t)}{Y_t} \right| \quad (3)$$

$$\text{MARE} = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{(\hat{Y}_t - Y_t)}{Y_t}\right| \quad (4)$$

Sensitivity analysis

The sensitivity analysis is conducted using the univariate method, which varies the value of one parameter at a time, while keeping the values of the other parameters constant. The sensitivity index can be calculated using the following equation (Equation (5)):

$$S_Y = \left|\frac{dY_t}{Y_t}\cdot\frac{X_t}{dX_t}\right| \quad (5)$$

where t is time; S_Y represents the sensitivity index of system state Y to parameter X; Y_t denotes the system state at time t; X_t is the value of the system parameter at time t; and dY_t and dX_t are the values for a change of system state Y and parameter X at time t, respectively.

The general sensitivity degree index is the degree of sensitivity of a parameter to the n stock variables ($Y_1, Y_2, \ldots, Y_n$) at time t, which is defined by Equation (6) (Qi & Chang 2011; Wei *et al*. 2012)

$$S = \frac{1}{n}\sum_{i=1}^{n} S_{Yi} \quad (6)$$

where S is the general sensitivity degree; n denotes the number of stock variables; and S_{Yi} is the sensitivity degree of the stock variable Y_i.

Scenario establishment

There are three scenarios: the business-as-usual scenario, planning-oriented scenario and sustainable development scenario.

Business-as-usual scenario

The business-as-usual scenario refers to the development of the society, economy and water demand in accordance with the current trend. The water supply depends on the actual water supply capacity without any adjustments.

Planning-oriented scenario

The planning-oriented scenario refers to the possible states of the society, economy and water resources under the constraints of the new town plan objectives. The planning-oriented scenario is designed to analyze the water demand when realizing the social economic goals of the Tongzhou district plan. The water supply capacity is the same as that in the business-as-usual scenario.

Sustainable development scenario

The sustainable development scenario is an idealized scenario, which is able to realize the economic objectives of the Tongzhou new town plan and to reduce the enormous water resource pressure brought by the economic and population growth through upgrading the water saving technology and the economic structure. The designs of the population size and the scale of the economy remain consistent with those in the planning-oriented scenario. In the sustainable development scenario, the new water sources of rainwater, floodwater, reclaimed water, municipal water from outside the area and water transfer from south to north are developed to increase the water supply.

RESULTS AND DISCUSSION

Model evaluation results

Calibration and validation results

The data series during the period of 2004–2010 is divided into two parts to conduct model calibration and validation, in which the first part from 2004 to 2008 is used for model calibration, and the rest is used for validation.

The correlation coefficient ($R = 0.93$) between the observed and simulated results is high through the calculation using Equation (2), and the MARE of 0.013 is small, as shown in Figure 3, which demonstrates that the model results corresponded well with the historical observations. The validation results are illustrated in Figure 4, in which the small ARE and MARE (0.019) indicate that the model reflected the behavior of the system very well.

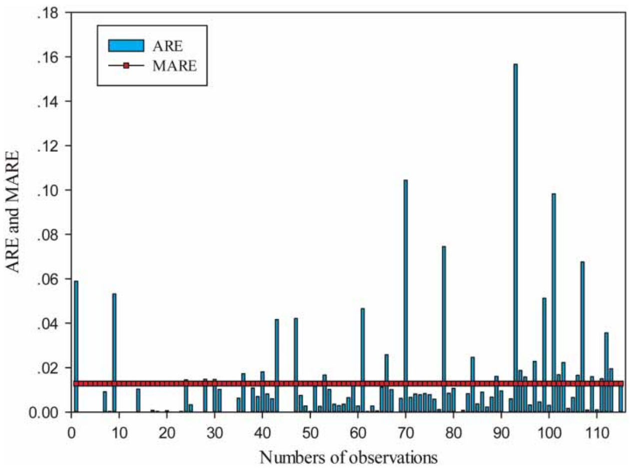

Figure 3 | Calibration results using ARE and MARE.

Sensitivity analysis

In the SD model, 41 parameters (Table 1) had high levels of uncertainty. The variations of the 41 parameters were set based on the likely ranges of the uncertainties of the respective parameters. The sensitivity analysis results are illustrated in Table 1.

The model showed that the sensitivity degrees of the industrial water reuse ratio (I02, I07, I08, I09, I10) and water consumption per 10,000 RMB Yuan GDP (I01, I02, I05, I07, I08, I09, I10, I11, I13, I14, I15) are very high. The system state is also sensitive to the parameters of water consumption per 10,000 RMB Yuan GDP (I03, I04, I06, I12, primary industry, tertiary industry and construction industry), the industrial water reuse ratio (I05, I11, I13, I14, I15), the per capita water demand of urban life and the per capita water demand of rural life. The sensitivity values imply that the simulation results can be significantly affected by the errors in the values of these parameters. The parameters of industrial water reuse ratio (I03, I04, I06, I12, I15), rural birth rate, urban birth rate, floating people immigration rate, people immigration rate, rural death rate and urban death rate are less sensitive, while the remaining parameters are not sensitive to the target system state.

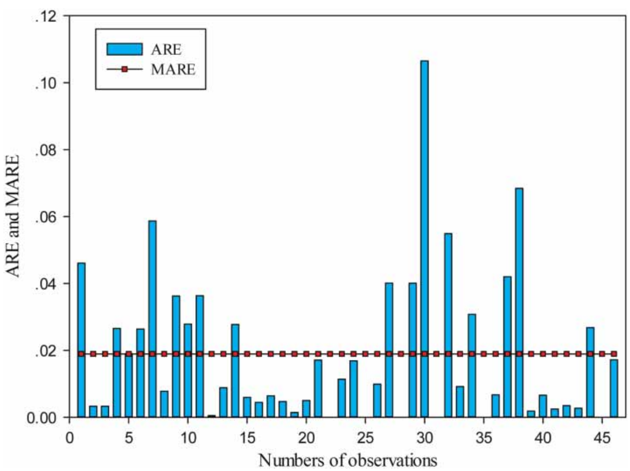

Figure 4 | Validation results using ARE and MARE.

Simulation results

Simulation results of the business-as-usual scenario

In the business-as-usual scenario, the economic strength is being upgraded constantly in the Tongzhou district; the primary sector has a steady growth, the secondary sector increases rapidly as a leading role, and the growth rate of the tertiary sector rises year by year. According to the forecast results shown in Figure 5(a), Tongzhou district's GDP will reach 65.55 billion (10^9) RMB Yuan in 2020, an increase of 99.8 percent compared to 2011. The output values of the three industries are 2.10 billion (10^9) RMB Yuan, 32.62 billion (10^9) RMB Yuan and 30.83 billion (10^9) RMB Yuan, and their proportions are 3 percent, 50 percent and 47 percent, respectively. However, the GDP should reach at least 120 billion (10^9) RMB Yuan according to the new town planning. Thus, it is difficult to meet the economic planning target under the business-as-usual scenario.

According to the forecast results shown in Figure 5(b), the total water demand of the Tongzhou district is increasing yearly in the business-as-usual scenario. The total water demand increases from 348.97 million m^3 in 2011 to 366.16 million m^3 in 2020, with an annual rate of increase of 0.5 percent. The primary industry is the main water-consuming sector, and it accounts for 65.5 percent of the water consumption in 2020. Although the agricultural water-saving potential is small in the Tongzhou district, the primary industrial water demand can be reduced by adjusting the planting structure, reducing field crop irrigation and increasing underground pipe irrigation. The water demand of the secondary industry is predicted to rise to 52.51 million m^3 in 2020. Tertiary industrial water use will

Table 1 | Sensitivity degrees resulting from the variations of input parameters

	S (%)						
Parameter	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Water consumption per 10,000 RMB Yuan GDP I01	222.24	227.82	233.80	240.22	247.15	254.61	262.74
Industrial water reuse ratio I01	122.22	127.81	133.79	140.21	147.13	154.60	162.74
Water consumption per 10,000 RMB Yuan GDP I02	153.91	158.12	162.84	168.16	174.09	180.76	188.35
Industrial water reuse ratio I02	512.99	527.04	542.80	560.42	580.28	602.48	627.77
Water consumption per 10,000 RMB Yuan GDP I03	133.38	134.93	136.60	138.39	140.26	142.24	133.38
Industrial water reuse ratio I03	33.34	34.91	36.57	38.36	40.19	42.23	33.34
Water consumption per 10,000 RMB Yuan GDP I04	125.00	126.58	128.28	130.12	132.12	134.27	136.61
Industrial water reuse ratio I04	25.00	26.58	28.29	30.13	32.12	34.27	36.62
Water consumption per 10,000 RMB Yuan GDP I05	181.86	187.24	193.10	199.59	206.84	214.83	223.83
Industrial water reuse ratio I05	81.83	87.21	93.09	99.58	106.80	114.82	123.81
Water consumption per 10,000 RMB Yuan GDP I06	111.11	112.11	113.20	114.41	115.75	117.27	118.92
Industrial water reuse ratio I06	11.11	12.11	13.20	14.41	15.74	17.23	18.87
Water consumption per 10,000 RMB Yuan GDP I07	400.00	414.95	431.12	448.97	468.62	490.24	400.00
Industrial water reuse ratio I07	300.00	314.95	331.24	349.09	368.72	390.42	300.00
Water consumption per 10,000 RMB Yuan GDP I08	400.02	412.41	425.68	440.03	455.48	472.33	490.55
Industrial water reuse ratio I08	299.97	312.37	325.61	339.93	355.39	372.28	390.52
Water consumption per 10,000 RMB Yuan GDP I09	285.72	293.91	302.71	312.20	322.46	333.48	345.47
Industrial water reuse ratio I09	185.72	193.91	202.71	212.20	222.46	233.59	245.71
Water consumption per 10,000 RMB Yuan GDP I10	390.64	400.04	409.88	420.31	431.42	443.10	455.49
Industrial water reuse ratio I10	290.62	299.98	309.83	320.26	331.37	343.03	355.48
Water consumption per 10,000 RMB Yuan GDP I11	166.66	170.07	173.72	177.65	182.04	186.49	191.50
Industrial water reuse ratio I11	66.65	70.05	73.69	77.61	81.95	86.47	91.45
Water consumption per 10,000 RMB Yuan GDP I12	111.12	112.64	114.36	116.36	118.68	121.41	124.61
Industrial water reuse ratio I12	11.11	12.61	14.34	16.35	18.68	21.39	24.59
Water consumption per 10,000 RMB Yuan GDP I13	208.38	214.53	221.23	228.60	236.65	245.54	255.35
Industrial water reuse ratio I13	108.35	114.51	121.20	128.57	136.61	145.51	155.34
Water consumption per 10,000 RMB Yuan GDP I14	208.31	209.46	210.62	211.79	212.96	214.19	215.41
Industrial water reuse ratio I14	108.33	109.47	110.62	111.79	112.98	114.19	115.42
Water consumption per 10,000 RMB Yuan GDP I15	199.94	210.51	222.80	237.39	254.94	276.34	303.03
Industrial water reuse ratio I15	100.00	110.53	122.84	137.42	154.94	176.35	203.07
Primary industry water need of 10,000 RMB Yuan GDP	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Tertiary industry water need of 10,000 RMB Yuan GDP	100.02	100.05	100.00	100.04	99.92	99.97	99.96
Construction industry water need of 10,000 RMB Yuan GDP	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Per capita water demand of urban life	100.03	100.03	100.03	100.01	100.03	100.02	100.02
Per capita water demand of rural life	100.03	100.00	100.02	100.01	100.05	100.07	100.05
Urban death rate	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Urban birth rate	0.66	0.85	1.21	1.11	1.99	2.14	2.40
Floating people immigration rate	0.11	0.91	2.08	3.49	4.98	6.27	7.51

(*continued*)

Table 1 | Continued

	S (%)						
Parameter	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
People immigration rate	0.11	3.68	7.67	12.36	17.49	22.78	28.38
Rural death rate	0.00	0.62	1.01	1.87	1.79	2.24	3.26
Rural birth rate	0.69	0.00	0.14	0.00	0.52	0.64	0.19

increase by 8.78 million m^3 between 2011 and 2020 and will reach 34.38 million m^3 in the Tongzhou district in 2020.

Figure 5(c) shows that the total domestic water consumption of the Tongzhou district has a very small increase in the next 10 years. Specifically, the water demand of urban life will rise to 28.89 million m^3 in 2020; however, the rural domestic water consumption will drop to 10.43 million m^3. Largely, this is because the urbanization process is accelerating, leading to a large number of people in the countryside moving to the city.

As Figures 5(d)–5(f) show, with the industrial GDP growth of the Tongzhou district, the water demands of most industries will increase in the next decade under the business-as-usual scenario. Among them, the metal processing industry (I12) is the largest water-consuming industry, with a projected water requirement of 12.3 million m^3 in 2020, accounting for 26.9 percent of the total industrial water need. The textile and garments industry (I03), food-processing industry (I02) and pharmaceutical and chemical industry (I08) are also heavy water consumers, and take up 16.7, 13.3 and 10.6 percent of the total industrial water demand in 2020, respectively. The mining industry (I01), petrochemical industry (I07) and chemical fiber industry (I09) need less water, and their water demands are 6.59, 37.94 and 36.65 thousand m^3 in 2020.

The water supply in the Tongzhou district is mainly from groundwater, in addition to a small amount of surface water. According to the strategic environmental assessment of the Tongzhou district (Yang *et al.* 2007), the yearly average total groundwater supply in the Tongzhou district is 213.27 million m^3. Because of over-reliance on groundwater and persistent drought years, the groundwater is over-exploited, and the water table has been falling over the last decade. To maintain the balance, the amount of groundwater extraction should not be greater than 195.66 million m^3. Due to the serious river pollution in the Tongzhou district, the available amount of surface water is only 8.0 million m^3 (Yang *et al.* 2007).

The total water supply of the Tongzhou district under the business-as-usual scenario is 203.66 million m^3. By contrast, the model projects that in 2020 Tongzhou will have a water shortage of 162.50 million m^3. The water shortage problem is prominent in the Tongzhou district. The social-economic development is severely constrained by water shortage. The contradiction between the supply and demand of water resources should be solved by opening up new sources and reducing water use.

Simulation results of the planning-oriented scenario

As shown in Figure 6(a), the GDP of the Tongzhou district will rise to 120.4 billion (10^9) RMB Yuan in 2020 under the planning-oriented scenario. The percentage of the tertiary sector will increase to 68.4 percent, while the percentage of the primary sector and the secondary sector will be reduced to 2.1 and 29.5 percent.

As shown in Figure 6(b), the total water demand of the Tongzhou district in the planning-oriented scenario is larger than that in the business-as-usual scenario. The total water requirement will be 395.23 million m^3 in 2020, which is an increase of 29.07 million m^3 compared with the business-as-usual scenario. Therefore, the rapid population and economic growth will place a great pressure on the water resource.

In the predicted results, the water consumption in the primary industry declines after 2017. This is mainly due to the decrease of the primary industry proportion, the adjustment of the planting structure, the reduction of the crop area, and the advancement of micro-irrigation technology. However, the primary industry will still be a major

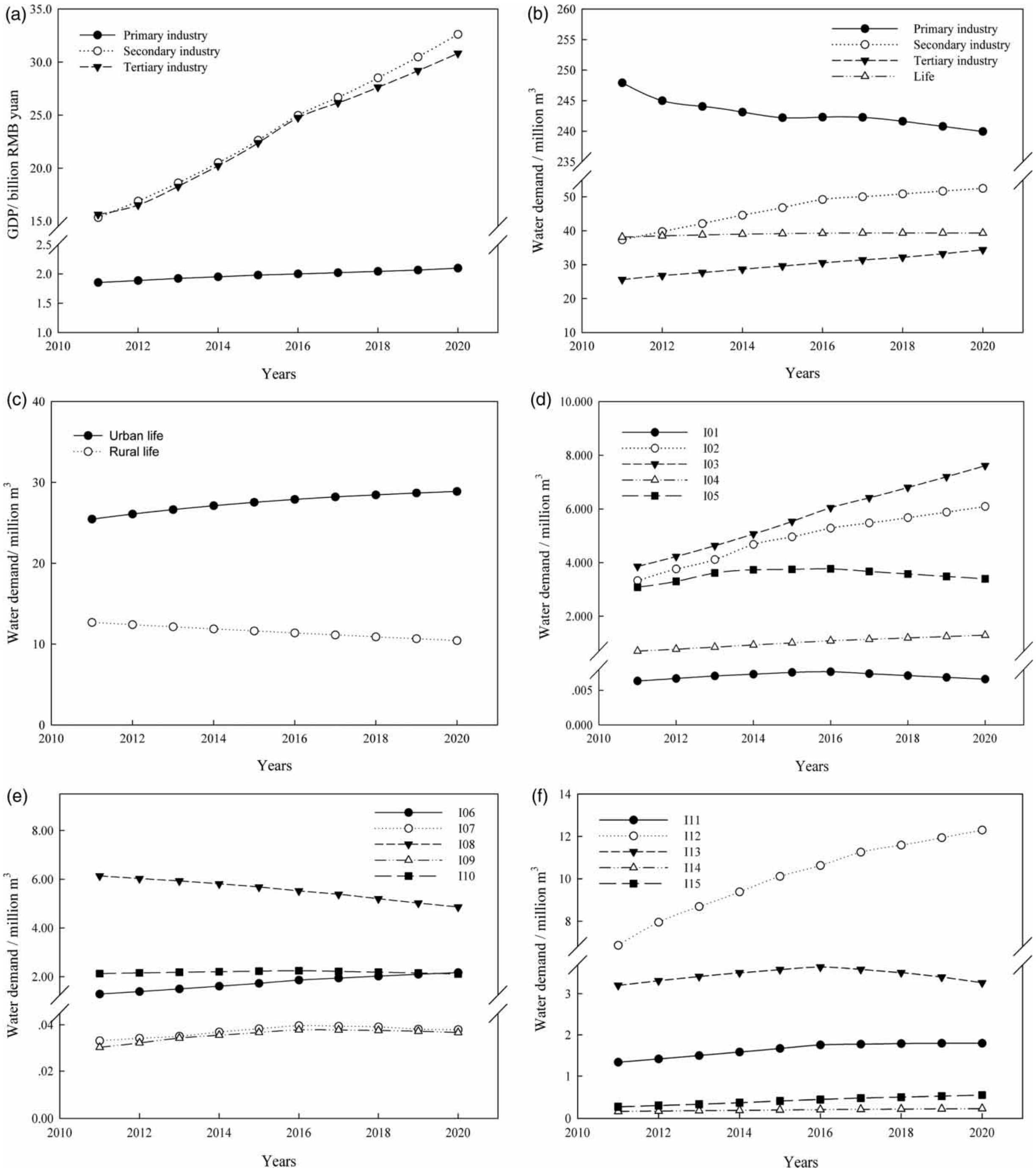

Figure 5 | Simulation results under the business-as-usual scenario. (a) Economy development (billion (10^9)), (b) water use for production and life, (c) water use for urban and rural life, (d) industrial water consumption (I01–I05), (e) industrial water consumption (I06–I10), and (f) industrial water consumption (I11–I15).

water-consumption sector, and the water demand will increase to 257.38 million m^3 in 2020, which will account for 65.12 percent of the total water demand in the Tongzhou district. On the one hand, that is determined by the agricultural production characteristics, but on the other hand, the agricultural water saving technology of the Tongzhou district has only been developed to a certain level, and the water-saving capacity is smaller relative to that of other industries.

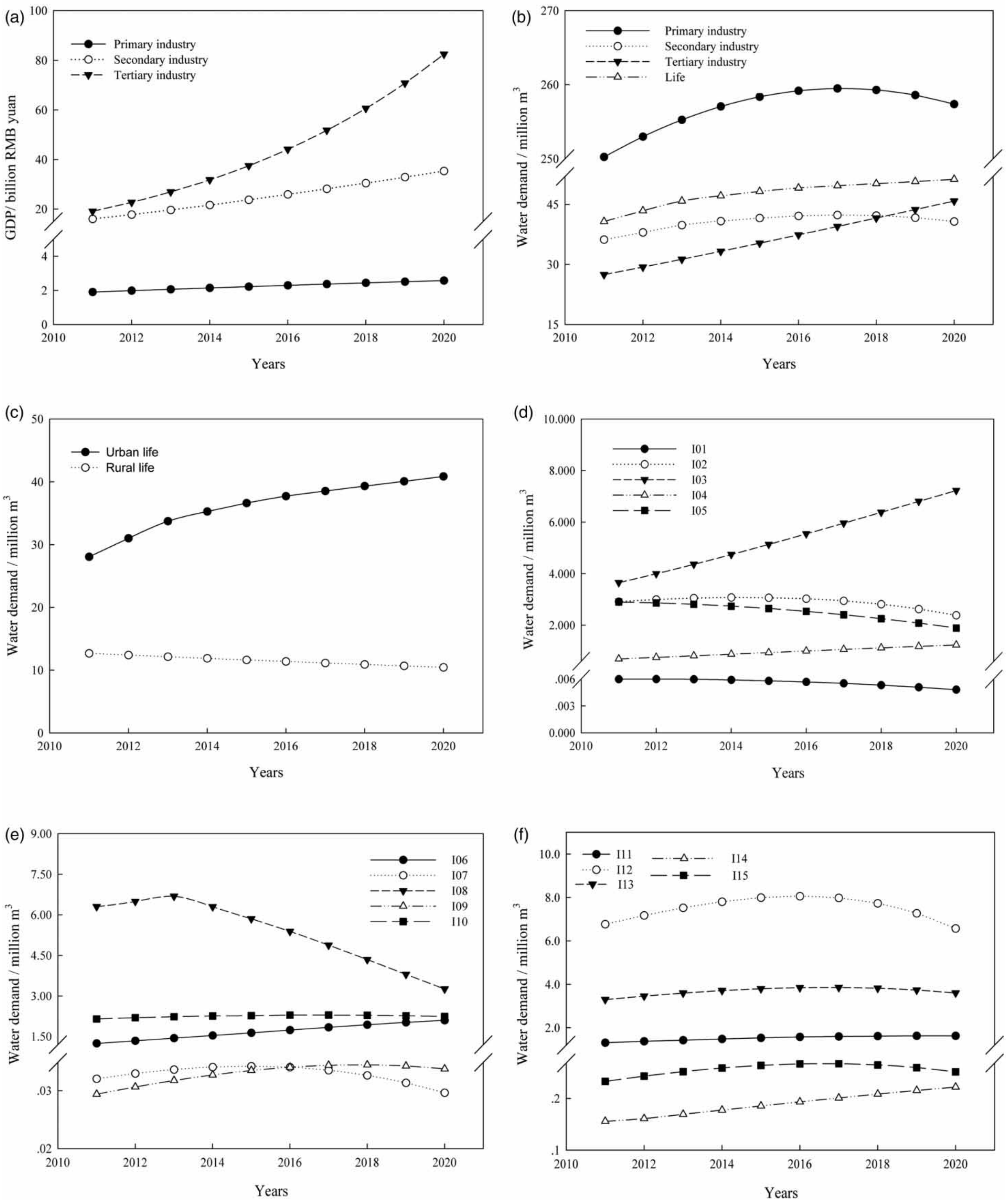

Figure 6 | Simulation results under the planning-oriented scenario. (a) Economy development (billion (10^9)), (b) water use for production and life, (c) water use for urban and rural life, (d) industrial water consumption (I01–I05), (e) industrial water consumption (I06–I10), and (f) industrial water consumption (I11–I15).

The water requirement of the tertiary sector is predicted to undergo a soaring increase to 45.83 million m^3 in 2020, which is 11.45 million m^3 more than that under the business-as-usual scenario. The total domestic water demand in 2020 under the planning-oriented scenario is 11.98 million m^3 more than that under the business-as-usual scenario. As Figure 6(c) shows, with the growth of population, the water uses of urban life and rural life will reach 40.86 and 10.44 million m^3 in 2020, respectively, which are 11.97 and 0.01 million m^3 more than in the business-as-usual scenario.

However, the water demand of the secondary sector will be 40.71 million m^3 in 2020, which is 11.78 million m^3 less than in the business-as-usual scenario. Although the textile and garments industry (I03), pharmaceutical and chemical industry (I08) and metal processing industry (I12) will have relatively high water consumption (Figures 6(d)–6(f)), the water demands of these three industries are only 7.23, 3.26 and 6.57 million m^3, respectively, which will decrease by 0.38, 1.60 and 5.72 million m^3 in 2020, compared with the business-as-usual scenario. These changes are due to improvements in water reuse capacity and the restriction and reduced development of high water-consuming industries, such as the pharmaceutical and chemical industries, papermaking industry and rubber and plastics industry. However, with the rapid growth of tertiary sector, the water demand for production will continue to increase in the next decade.

The results suggest that the increased water demand will further exacerbate the conflict between water supply and water demand in the planning-oriented scenario. The water shortage in 2020 is predicted to be 191.57 million m^3, which is a larger water supply-demand gap. The water shortage would seriously hamper the healthy development of the Tongzhou district.

Results of the sustainable development scenario simulation

The sustainable development scenario is an idealized scenario, which is intended to relieve the pressures of the population and economic growth on the water resource by upgrading water-saving technology and opening up new water sources.

The development of the economy and society in the sustainable development scenario remain consistent with that of the planning-oriented scenario. As shown in Figure 7(a), the GDP of the Tongzhou district will reach 120.41 billion (10^9) RMB Yuan in 2020, and the three industries' percentages will be 2, 30 and 68%. The regional economic strength will be greatly improved, and the tertiary sector will become the leading industry, which meets the new town planning objectives.

As shown in Figure 7(b), with the growing population and economy, the total demand on water resources in the Tongzhou district continues to increase, especially the water needs of the tertiary sector. The total water demand in 2020 will be 374.65 million m^3 under the sustainable development scenario, 20.58 million m^3 less than that under the planning-oriented scenario.

The water requirement of the primary sector reaches its peak around 2017 and then continues to decline. The agricultural water-saving capacity mainly depends on the adjustment of the planting structure and changes to the irrigation methods. Since the 1990s, water-saving irrigation technology has developed quickly in Tongzhou. Comprehensive water savings have basically been achieved, so the water-saving potential is small. The tertiary sector is developing rapidly and accounts for an increasing proportion of water use every year, so the water consumption is hardly reduced in the next decade. The water needs of the primary sector and the tertiary sector will be 257.38 and 45.83 million m^3, respectively, in 2020, which are the same as those in the planning-oriented scenario.

However, through adjusting industrial structures and inhibiting the development of high water consumption industries, industrial water consumption can be significantly reduced. The water demand of the secondary sector will be 26.48 million m^3 in 2020, 14.24 million m^3 less than in the planning-oriented scenario. The life water demand will be 44.96 million m^3 in 2020, which is 6.34 million m^3 less than in the planning-oriented scenario. As Figure 7(c) shows, the water use of urban life will be 34.52 million m^3 in 2020, 6.34 million m^3 less than in the planning-oriented scenario, and the water use of rural life is the same as in the planning-oriented scenario. The domestic water conservation is implemented by establishing the reclaimed water reuse sector in the district and promoting the use of water-saving equipment.

Through improving the production process and the water reuse rate, the water requirements of most industries are predicted to decrease in the future under the sustainable

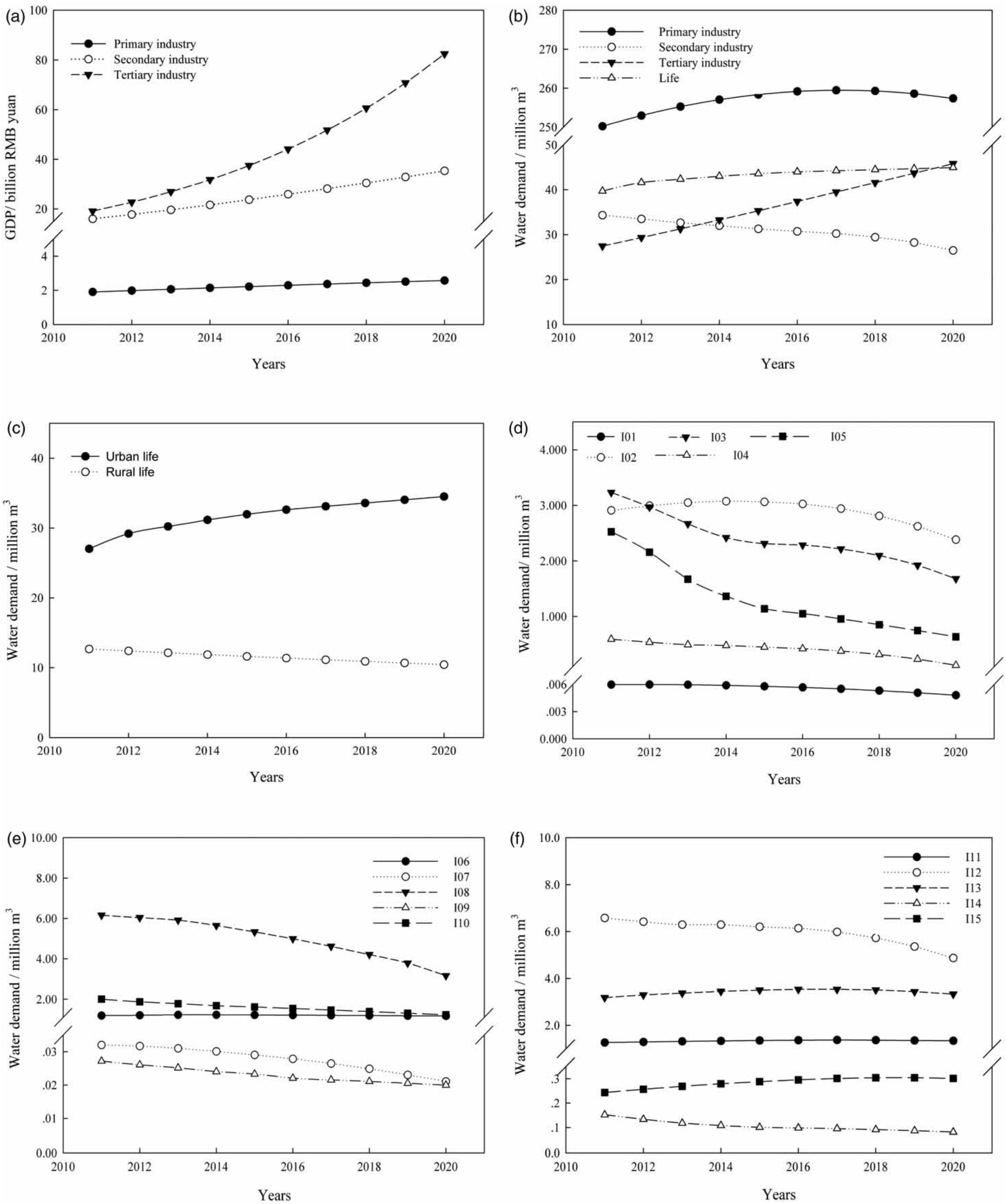

Figure 7 | Simulation results under the sustainable development scenario. (a) Economy development (billion (10^9)), (b) water use for production and life, (c) water use for urban and rural life, (d) industrial water consumption (I01–I05), (e) industrial water consumption (I06–I10), and (f) industrial water consumption (I11–I15).

development scenario. As shown in Figures 7(d)–7(f), the metal processing industry (I12) is the largest water consumption industry with a water requirement of only 4.87 million m^3 in 2020, which is 1.70 million m^3 less than in the planning-oriented scenario. The pharmaceutical and chemical industry (I08), equipment manufacturing industry (I13) and textile and garments industry (I03) are also heavier water consumers and will take up 15.5, 16.4 and 8.3 percent, respectively, of the total industrial water need in 2020. The water demands of the three industries will be 3.16, 3.33 and 1.68 million m^3 in 2020, which are drops of 0.10, 0.27 and 5.55 million m^3 compared with the planning-oriented scenario.

According to the predicted results, the water shortage in the Tongzhou district will be 170.99 million m^3 in 2020 in the sustainable development scenario. Because of the imbalance between water resource supply and demand, the people have to extract more and more groundwater. The groundwater is over-exploited currently, which poses a serious threat to the regional ecosystem.

To alleviate the water shortage situation in the Tongzhou district, new water sources should be accessed, including reclaimed water utilization, use of municipal water from outside the area and water transfer from south to north. According to the strategic environmental assessment of the Tongzhou district, if considering these new water sources, the amount of water available in the Tongzhou district will be 571.62 million m^3 in 2020 (Yang *et al.* 2007). Figure 8 shows the comparison of the available water supply under the three scenarios.

In contrast, Tongzhou district's water supply alternative solution can satisfy the water requirements of production and life. However, because half of the water supply is secondary recycled water, the water quality cannot meet the water standard of life, so the water of different qualities should be utilized by grades. The groundwater and municipal water are good quality water that should be given to users requiring high quality water as a priority, such as residential uses, municipal services and industrial production. The water qualities of rainwater and floodwater are not stable, so the rainwater and floodwater can be used in irrigation. The deep reclaimed water has better quality, so it can be used for municipal use, landscaping and cooling water for industry. The large amount of secondary reclaimed water has poor water quality, which can be used mainly for irrigation and river ecological restoration.

CONCLUSION

In this study, the SD model was established to predict the development of social economy and the impact of economic

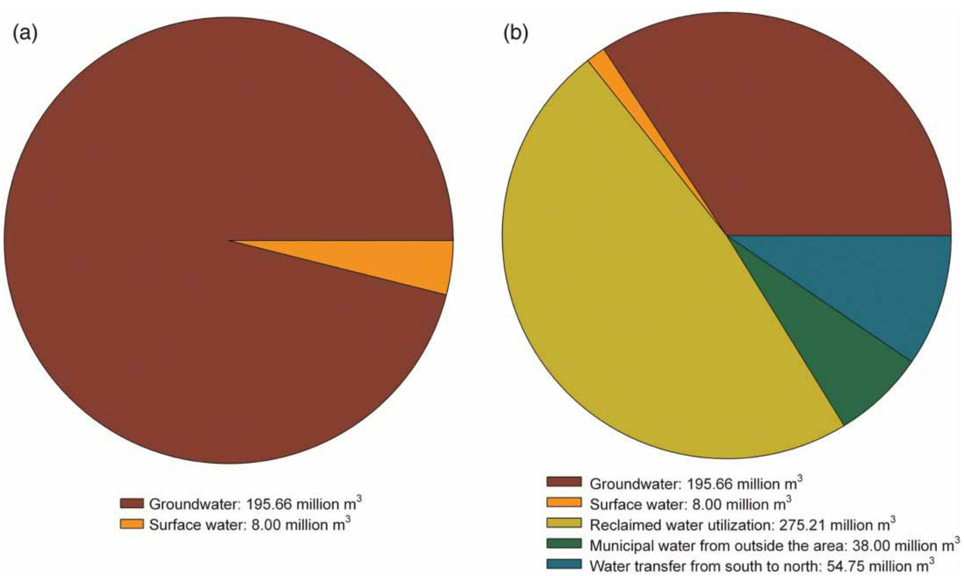

Figure 8 | Water supply under the three scenarios. (a) Water supply under the business-as-usual scenario and the planning-oriented scenario and (b) water supply under the sustainable development scenario.

and population growth on water consumption in the Tongzhou district under the three scenarios. The simulation results reveal the following. (1) Although it is impossible to achieve the economic objective of the Tongzhou new town plan under the business-as-usual scenario based on the simulation results, there will be a rapid economic increase, which will have a huge impact on water resources. In accordance with current trends, the water demand will exceed the water supply. (2) In the planning-oriented scenario, the social-economic objectives of the Tongzhou new town plan can be achieved through increased investment and structure adjustment. However, the realizations of the targets will be achieved at the expense of greater pressure on water resources. This will be mainly due to the rapid growth of the population and economy, increasing the water demand greatly. The water resource shortage will be the restrictive factor for local economy and society advancement. (3) Of the 15 industries, the textile and garments, pharmaceutical and chemicals and metal processing were the heaviest water consumers. It is necessary to develop recycled water technology and restrict the scales of high water-consuming industries appropriately. (4) Not only is it important to realize the district's economic and social goals, but it is also equally important to balance water resource supply and demand. To relieve the tension of water usage in the Tongzhou district, new water sources should be opened up, such as reclaimed water, municipal water from outside the area and water transfer from south to north. In the sustainable development scenario, through the two-way regulation of developing unconventional water sources and improving water-saving capacity of production and life, the conflict between water supply and demand in the Tongzhou district can be resolved. (5) The limitations of the study are as follows: it does not take into account the balances of demand and supply in economy, and does not consider the interactions among industries in contrast to input-output analysis and applied general equilibrium analysis.

ACKNOWLEDGEMENTS

This research was supported by the major science and technology programs of water pollution control and treatment, China (No. 2012ZX07102-002-05) and by the environmental protection public welfare projects for the research of technological contribution to pollution reduction and National Action Plan, China (No. 201209037).

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First received 4 November 2013; accepted in revised form 24 January 2014. Available online 25 February 2014