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Innovative Applications of O.R.

System dynamics simulation model for assessing socio-economic impacts of different levels of environmental flow allocation in the Weihe River Basin, China

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ABSTRACT

This study develops a complex system dynamics model (SD) reflecting interactions between water resources, Environmental Flow (EF) and socio-economy using SD software package "Vensim PLE". The proposed model is employed to assess socio-economic impacts of different levels of EF allocation in the Weihe River Basin of China. Four alternative socio-economic growth patterns and four EF allocation schemes are designed to simulate those impacts. The results reveal that developed SD model performance well in reflecting the dynamic behavior of the system in the current study area. In the meanwhile, an optimal growth pattern considering both socio-economic growth and EF requirements are also found by comparing the different scenario simulation results.

1. Introduction

There is an increasing awareness and understanding of the importance of preserving some amount of water in a river to maintain the constant functions and services of the river system (Smakhtin et al., 2004; Tharme et al., 1998). The amount of water required to maintain the health of a river ecosystem is usually referred to as the 'Environmental Flow' (EF); however, there is no universally agreed definition of EF (IWMI, 2005). Tharme et al. (1998) defined environmental (or instream) flows as flows that are left in, or released into, a river system in order to maintain valued features of the ecosystem. Dyson et al. (2003) stated that an EF is the water regime provided within a river, wetland, or coastal zone to maintain ecosystems and their benefits. A variety of other alternative terms are used by different researchers, including 'minimum flows', 'environmental demand', 'instream flow requirements', and 'ecological acceptable flow regime', each describing a slightly different concept (IWMI, 2005; Song and Li, 2004). In general, a good EF definition is necessary in working out conceptual schemes to ensure that a river system remains environmentally, economically and socially healthy.

The problems of water scarcity and water quality, due to rapid socio-economic development (Vairavamoorthy et al., 2008; Wei et al., 2010) and climate change (Kashaigili et al., 2009), have become more serious in countries, resulting in an increase in water demand and reduction in EF. Allocating water resources efficiently, equally, and fairly for socio-economic development and a healthy river system has become one of the major concerns for sustainable development. Water resources, socio-economic development, and EF interact interdependently, and form a large system, which has complex, dynamic, diverse and nonlinear characteristics.

System dynamics (SDs) is a theory of system structure and an approach for representing such a complex system and analyzing its dynamic behavior (Forester, 1961). Comparing to the traditional methods, the SD simulation approach studies the dynamic, evolving, cause-effect interrelations, and information feedbacks that direct interactions in a system over time, and it does not require longitudinal (Panel and Time Series Cross-Section) data. SD is usually characterized as a "strategy and policy laboratory" and "socio-economic system laboratory" because it provides a tool to test the effects of various strategies and policies in a system, especially for socio-economic systems. In environmental and water resources management, SD has been applied to the following main fields: carrying capacity of water resources (Sun et al., 2007) and land resources (Chen et al., 1999); simulating problems in water use (Fedorovskiy et al., 2004); environmental impacts (Deaton and Winebrake, 2000); global modeling of water resources (Simonovic, 2002); interrelationships between environmental, ecological and economic resources (Costanza et al., 1998); reservoir operations (Ahmad and Simonovic, 2000); sustainable development (Xu et al., 2002); garbage disposal (Cai, 2006); water resources planning

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(Zhang et al., 2008); as well as water quality management (Rivera et al., 2006; Tangirala et al., 2003).

However, studies on the application of SD to simulate interrelations among socio-economic, water resources and EF (SEWEF) in a river basin have not been available in the literature. In order to fill this gap, a complex SEWEF system dynamic simulation model has been developed and employed for assessing socio-economic impacts of different levels of EF allocation in the Weihe River Basin in China. The main goals of the study include:

- Studying water availability-demand balances in the study area;
- analyzing water resources carrying capacity to socio-economic development;
- examining interrelations of water resources and socio-economic growth;
- demonstrating and evaluating impacts of various EF allocation alternatives on socio-economic development;
- investigating optimal and practical strategy to increase water carrying capacity in light of EF allocations, water availability and local socio-economic conditions.

2. Study area and data sources

2.1. Site description

The Weihe River basin in the Guanzhong region of Shaanxi Province was selected as our study area due to the serious conflicts between water use and EF allocation. The study area includes five municipalities – Baoji, Xianyang, Xi'an, Tongchuan and Wei'nan, and five main hydrological gages, namely Linjiacun, Weijiabao, Xianyang, Lintong and Huaxian (Fig. 1). The river is 818 km long with a watershed area of 1.36×10^5 km^2, the largest tributary of the Yellow River. It has 176 tributaries with a catchment area of over 100 km^2, among which 16 rivers have an annual runoff of over 1.0×10^8 m^3. The river is called the 'Mother River' of the Guanzhong region, which plays a great role in the development of West China and the health of the ecosystem of the Yellow River. However, since the late 1990s many parts of the river have lost their ecosystem functions, restricting as a consequence the sustainable development of the region socially and economically (Song and Li, 2004).

2.2. Data sources

Data sources include a literature review and a one-month site survey in April 2010. The main types of data include information on socio-economy (1999–2008), water resources and hydrology (1959–2000), water use (1995–2008), wastewater discharge and treatment (1999–2008), environment and ecology (1999–2008), as well as EF. Socio-economic data cover population (rural and urban), natural growth rates, industrial and agricultural gross domestic products, per capita disposable income of urban households, and per capita net income of rural households, irrigation areas, as well as consumer price index (CPI), which were collected from the Shaanxi Statistical Yearbooks (SXBS and SXITNBSC, 2000–2009) and the Xi'an Statistical Yearbook (XABS, 2008). Water resources and hydrological data, including surface water, ground water and river discharge, were collected mainly from previous studies (Song and Li, 2004; Wang et al., 2009) and different hydrological gages. Water use data, spanning rural and urban domestic daily water use, industrial water use, agricultural water use, the water consumption coefficients of these sectors, and the water saving ability of domestic and agricultural users were all collected from the Shaanxi Statistical Yearbooks (SXBS and SXITNBSC, 2000–2009), the site survey in 2004, and previous studies (Xing et al., 2006; Zhou, 2006). Wastewater discharge and treatment data include mainly domestic use and industrial waste water discharge, waste water treatment rates and reclaim rates taken from the Shaanxi Statistical Yearbooks (SXBS and SXITNBSC, 2000–2009). The environment and ecology data on urban green areas, and water and soil conservation areas are collected from the Shaanxi Statistical Yearbooks (SXBS and SXITNBSC, 2000–2009), and data on urban water surface areas, artificial water body areas, zonal vegetation areas and water quotas are taken from Wang et al. (2008). EF data on EF requirements were taken from the studies of Song and Li (2004).

3. Methods

3.1. Concept of SD

The basic building blocks of SD simulation are composed of four components: Stock ("state variable", "level", or "reservoir"), Flow ("Rate", "Control Variable" or "Processes"), Converter ("Auxiliary", or "Translation variable") and Connector (or "Information Arrow"). The SD simulation model consists of a set of nonlinear differential equations, such as level (or state) equations, flow equations, auxiliary equations, parameter equations, condition equations as well as initial value equations. Level equation is the core equation, which presents the dynamic behavior of a system, and it can be expressed as:

$$\frac{dX_i(t)}{dt} = f(X_i, R_i, A_i, C_i) \tag{1}$$

The differential equation can be expressed as follows:

$$X_i(t + \Delta t) = X_i(t) + f(X_i, R_i, A_i, C_i)^{*}\Delta t \tag{2}$$

where X_i(t) is a vector of state variables, f() is a vector-valued function, and 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 variable, Δt is time difference. The above equations are solved numerically by a simulation procedure such as Euler, and Runge–Kutta.

The state Eq. (2) expresses three time points – past, present and future, in which the present state is a summary of past states, and the difference between current and last period, and the future state is an expression of the present state plus the change during the variation time period. Thus it states the dynamic variations of a system over time.

3.2. SD simulation process

In general, SD modeling and simulation process can be summarized as: (1) defining simulation objectives, (2) determining the system boundary, (3) designing a user-interfaced graphical structure of the system, (4) developing stock-flow diagrams, (5) formulating the mathematical model, (6) calibrating and validating the model, and (7) implementing the model.

3.3. Nominal to real value transformation

The original time series data of economic values, including industrial and agricultural gross domestic product, per capita incomes of households, etc., are calculated at current prices, which contain inflation and subsequently are called *current*(*nominal*)*values*. In order to compare them, the *nominal values* of a series are usually transformed to *real*(*constant*) *values*, i.e. values calculated at constant prices in a reference year (Wei et al., 2010). The method of transformation of *nominal* to *real values* is expressed by the following equation:

$$VR_{t+n} = VB_t^{*}ID_{t+1}^{*}ID_{t+2}^{*}\ldots{}^{*}ID_{t+n}, \quad n = 1, 2, 3, \ldots, N \tag{3}$$

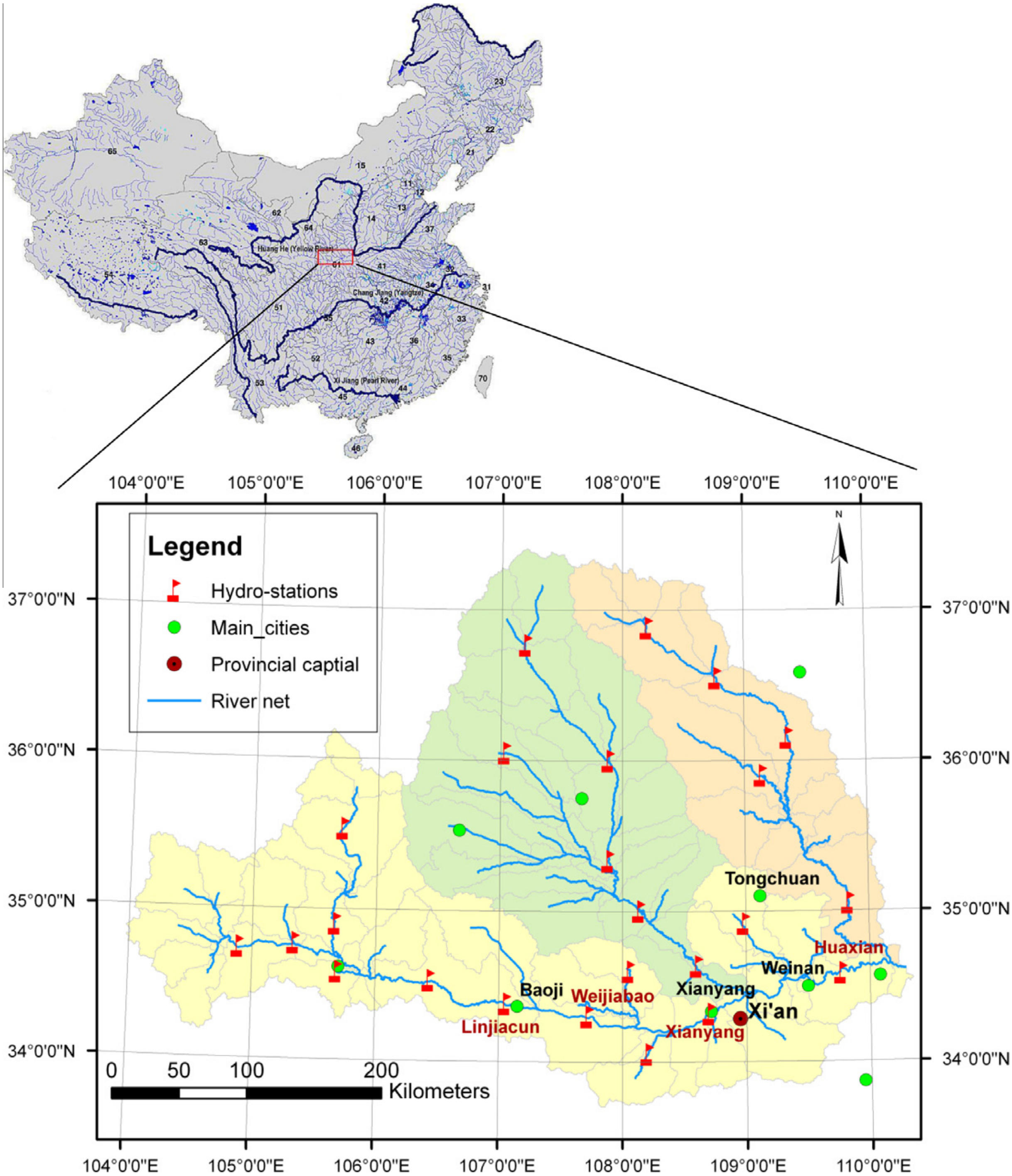

Fig. 1. Map of Weihe River basin.

where *t* stands for a time point (reference year), VR_{t+n} is the real (or comparative) value of a *nominal value*, VB_t is the starting value in the reference year; *ID* is a Price Index whose preceding year is 100, an indicator for inflation calculated by comparing a current value to its value in the preceding year.

3.4. A SD simulation model

A system dynamic simulation model, applied to assess the socio-economic impacts of different levels of environmental flow in the Weihe River, abbreviated as WeiheSD, is developed through identification of interactions among environment, socio-economy and resources. The boundary of WeiheSD is the Guanzhong area in Shaanxi Province. The model is formulated and simulated using a professional SD software package "Ventana simulation environment personal learning edition (Vensim PLE)". The simulation is run for a period from 1999 to 2050, where the strategic planning period is from 2010 to 2050 with 2008 as the base year, and the modeling time step is 1 year.

WeiheSD consists of nine sub-systems, i.e. population, industry, agriculture, water use/demand, wastewater and its treatment technology and policy, water resources, water balance, ecology and environment water demand, as well as EF requirements (Fig. 2). It includes 160 variables and parameters including seven level variables, 41 constants and 97 functions. The notations of all the variables, parameters and the functions in Vensim language used in this study are summarized in Appendix A.

3.5. Model evaluation

3.5.1. Model calibration

Parameters in the model include seven initial values, 16 table (lookup) functions and 41 constants. Three methods for parameter estimation are used in this study: (1) using the first-hand materials

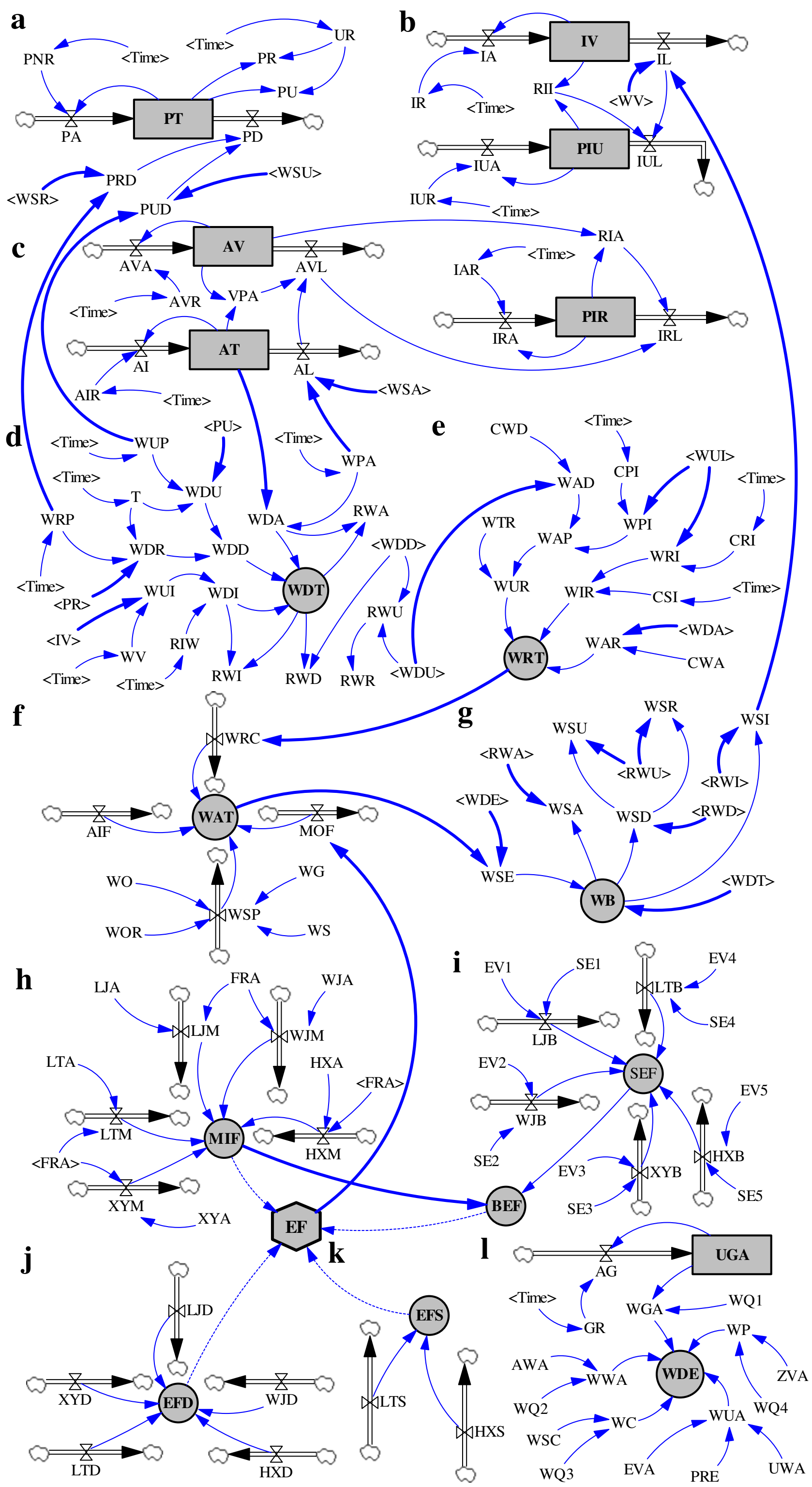

Fig. 2. A system dynamic stock-flow diagram representing the simulated system, including subsystems of (a) population, (b) industry, and (c) agriculture, (d) water use, (e) wastewater discharge and treatment, (f) water resources, (g) water shortage, (h) minimum EF, (i) basic EF, (j) EF for pollution purification, (k) EF for sediment transport, and (l) ecological water demand outside the rive channel; dash lines in figure presents four alternatives of EF allocation levels.

Table 1
Summary of the four EF allocation alternatives.

Code	EF allocation scheme	Description
A1	Minimum	Minimum instream flow for maintaining aquatic life, i.e. 10% of the multi-annual average measured river flow using Tennant method
A2	Basic	Instream flow required to keep a river balance, i.e. maintaining aquatic life, meet channel seepage and evaporation
A3	Pollution purification	Instream flow required for dilute pollutants to ensure the water body a sound functioning
A4	Sediment transport	Instream flow required to transport sediment in river channel to maintain a healthy watercourse

directly, (2) using secondary source materials (official data books and documents) and previous study results, and (3) by calculating the correlations between variables and ratios of two variables. We calibrated the model by testing parameter reality, and accuracy of historical fit using the Correction coefficient (R), Absolute Relative Error (ARE) and the Mean Absolute Relative Error (MARE) (Eqs. (4)–(6)).

$$R = \frac{\sum_{t=1}^{n}(Y_t - \overline{Y}_t)(\widehat{Y}_t - \overline{\widehat{Y}}_t)}{\sqrt{\sum_{t=1}^{n}(Y_t - \overline{Y}_t)^2 \sum_{t=1}^{n}(\widehat{Y}_t - \overline{\widehat{Y}}_t)^2}} \tag{4}$$

3.5.2. Model validation

Model validation is conducted through model structure test and model performance test over a range of conditions compared to the observed behavior of the target system. ARE and MARE are also employed for model performance validation.

$$ARE = \left|\frac{(\widehat{Y}_t - Y_t)}{Y_t}\right| \tag{5}$$

$$MARE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{(\widehat{Y}_t - Y_t)}{Y_t}\right| \tag{6}$$

where t is time unit, n is numbers of data, Y_t and $\widehat{Y}_t$ represent observed and simulated results, and $\overline{Y}_t$ and $\widehat{Y}$ represent the mean of the observed and simulated results.

3.5.3. Sensitivity analysis

We do the sensitivity analysis using the 'one-at-a-time' (or univariate) method by varying the value of one parameter at a time while keeping the values of other parameters constant. The sensitivity index can be calculated using the following equations:

$$S_Y = \left|\frac{dY_t}{Y_t} \cdot \frac{X_t}{dX_t}\right| \tag{7}$$

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

Table 2
Descriptions of the four growth patterns.

Code	Growth mode	Description
B1	Current	Business as usual, i.e. future policies, technology and growth rates all keep the current (base year) situations
B2	Lower	The future policies and technology are backward, and growth rates are very slow
B3	Middle	The future policies, technology and development are between B2 and B4
B4	Higher	The future policies and technology are progressing very sound and fast, and growth speeds are high

Table 3
Assumptions of the four growth modes.

Variables	B1	B2	B3	B4
Population natural birth rate (PNR) (‰)	4.4	1.0	2.5	4.0
Urbanization rate (RU) (%)	33	25	65	85
Industrial growth rate (IR) (%)	18	6.0	10	15
Increasing rate of per capita disposable income of urban household (IUR) (%)	6.0	4.0	9.0	12
Agriculture area increasing rate (AIR) (%)	−0.2	−0.3	−0.1	0
Agriculture GDP increasing rate (AVR) (%)	7.5	5.0	10	12
Increasing rate of IUR (IAR) (%)	6.0	4.0	9.0	12
Per capita urban domestic water use (WUP) (L)	142	160	120	100
Per capita rural domestic water use (WRP) (L)	65	55	85	95
Rate of industrial wastewater repeating use (RIW) (%)	86	76	94	98
Water use per unit of industrial value (WV) (m^3 10^{-4} yuan)	300	500	240	200
Water use per cultivated area (WPA) (m^3 mu^{-1})	120	140	100	90
Coefficient of industrial wastewater discharged into treatment plan (CPI)	0.009	0.02	0.002	0
Coefficient of industrial wastewater discharged into river (CRI)	0.09	0.2	0.05	0.03
Coefficient of meeting to standard of industrial wastewater discharged into river (CSI)	0.98	0.6	0.99	1.0
Wastewater plant treatment rate (WTR) (%)	65	45	85	95
Urban green area growth rate (GR) (%)	5.7	3.7	6.8	7.4
Artificial water area (AWA) (10^4 ha)	0.52	0.47	0.57	0.60
Water and soil conservation area (WSC) (10^4 ha)	61.3	55.2	73.6	79.7
Water demand of urban water surface area (WUA) (10^4 ha)	6700	6030	7370	7705
Zonal vegetation area (ZVA) (10^4 ha)	59.8	53.9	65.8	77.8

The general sensitivity degree index, i.e. the degree of sensitivity of a parameter to the n stock variables ($Y_1, Y_2, \ldots, Y_n$) at time t is defined by Eq. (8).

$$S = \frac{1}{n}\sum_{i=1}^{n} S_{Y_i} \tag{8}$$

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

3.6. Scenarios analysis

Four alternative EF allocations are considered with reference to the study results of Song and Li (2004), including minimum EF (A1), basic EF (A2), EF for pollution dilution (A3) and EF for sediment transport (A4) (Table 1). Five hydrological gauging stations, namely Linjiacun (LJ), Weijiabao (WJ), Xianyang (XY), Lintong (LT) and Huaxian (HX) from upper to lower stream, are selected to calculate A1, A2 and A3, while only the last two stations in the lower stream are chosen for A4 because a high sediment load is the main problem in the lower stream of the river. Regarding the system dynamics, four growth patterns are designed, namely current growth pattern (B1), lower growth pattern (B2), middle growth pattern (B3) and higher growth pattern (B4), and the descriptions and quantitative assumptions of the four modes are displayed in Tables 2 and 3. B1 is the base run scenario, which assumes that the existing pattern of human activities will be maintained in the future. B2, B3 and B4 are alternative planning designs focusing on future changes of the variables. The four EF allocation alternatives and four growth modes form a total of 16 scenarios.

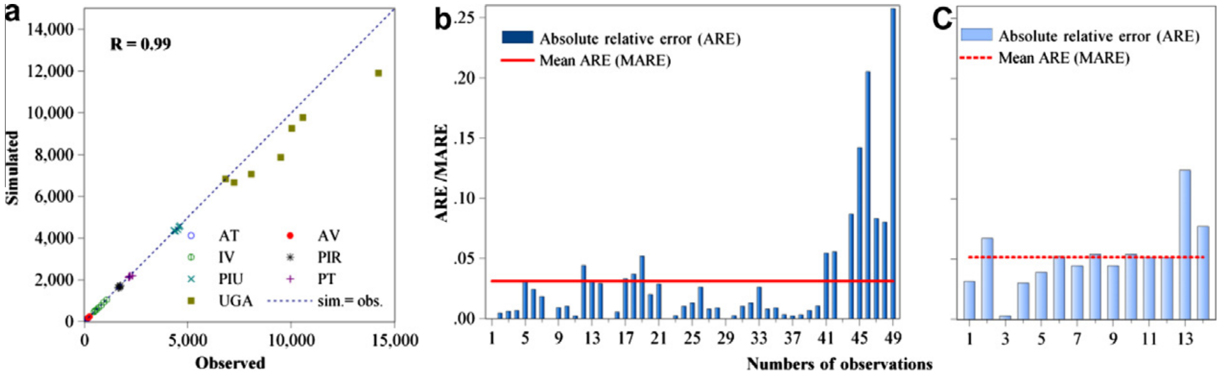

Fig. 3. Results of calibration and validation, (a) correlation coefficient (*R*) between simulated results and observed date, (b) calibration results using Absolute Relative Error (ARE) and Mean ARE (MARE), and (c) validation results using ARE and MARE.

4. Results and discussion

4.1. Model evaluation results

To conduct model calibration and validation, we divide the date series during the period of 1999–2008 into two parts. The first part from 1999 to 2006 is used for model calibration, and the rest for model validation. We select the seven stock variables for the quantitative analyses of calibration and validation results, including total population (PT), industrial GDP value (IV), total agricultural GDP value (AV) and cultivated area (AT), per capita annual disposable income of urban households (PIU), per capita annual net income of rural households (PIR) and Urban green area (UGA).

4.1.1. Calibration results

We conduct the model calibration through two steps: (1) testing if the parameters in the model are correspond to relevant descriptive and numerical knowledge of the real system; (2) diagnosing the accuracy of historical fit. The calibration process includes a series of simulations that are performed and repeated (trial-error-trial) by setting individual parameter values until no further significant improvement of the match between simulated outcomes and observed values. The final calibration results are illustrated in Fig. 3a and b, where the high correlation coefficient (*R* = 0.99) between observed and simulated results and the small MARE of 0.031 prove that the SD model results correspond well with the historical observations, although three AREs are larger than 0.1.

4.1.2. Validation results

We conduct a series of qualitative and quantitative tests for the validation. The qualitative test includes a system unit consistency test and a system structure test. The unit consistency test is automatically completed by the Vesnsim package. For the system structure test, we check if the model structure explains the real system reasonably well and if the model equations meet the physical laws. The quantitative tests validation is conducted by analyzing the model forecasting performances of the real system behaviors.

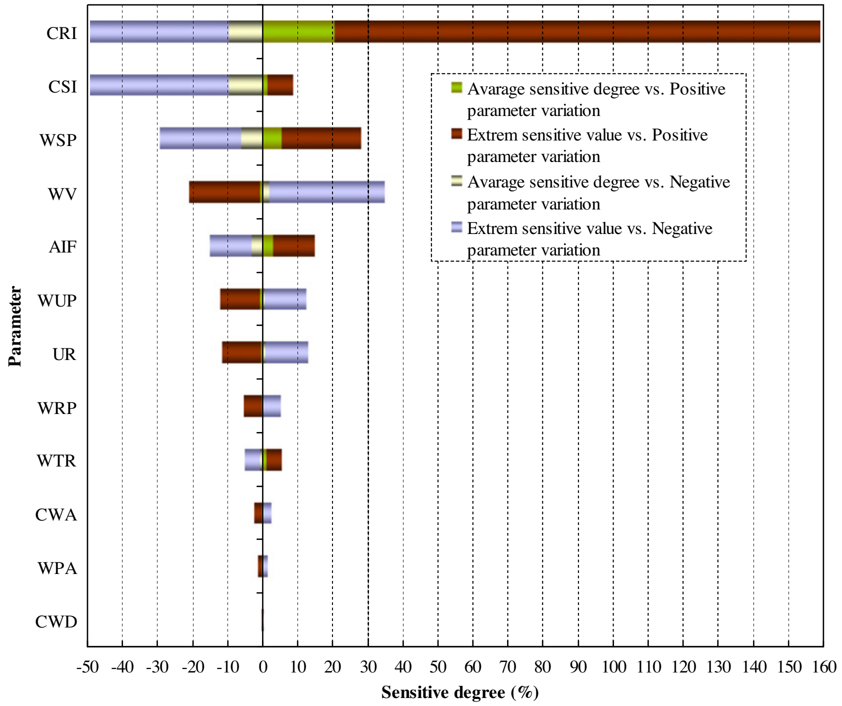

Fig. 4. A tornado diagram presenting the range of the output sensitive degrees resulting from the variations of input parameters.

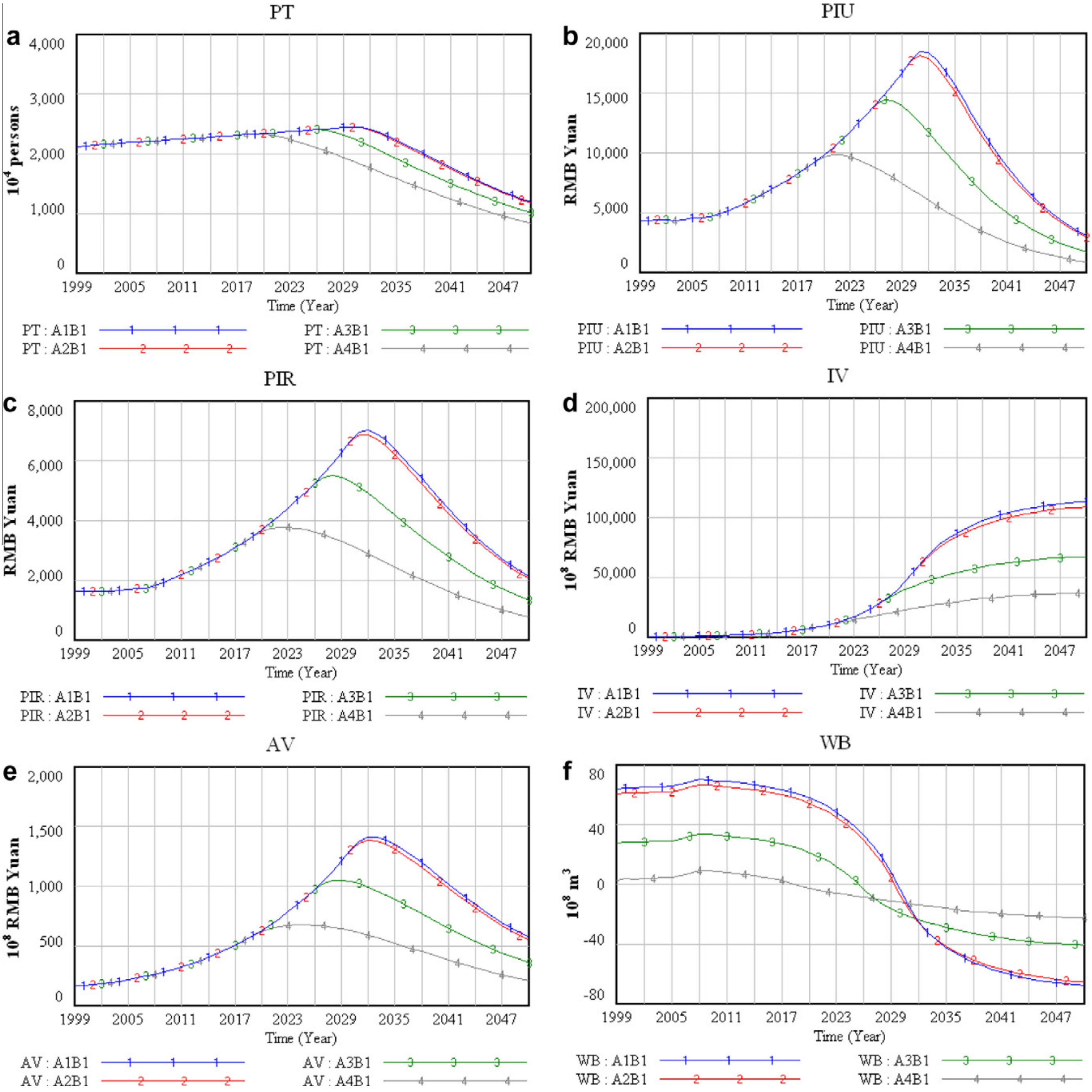

Fig. 5. The simulation results of base run scenarios under four EF allocation (A1B1, A2B1, A3B1, A4B1), (a) total population (PT), (b) Per capita disposable income of urban households (PIU), (c) Per capita net income of rural households (PIR), (d) industrial GDP, (e) agricultural GDP, and (f) water availability-demand balance of socio-economic sector.

The results are displayed in Fig. 3c, in which the smaller indices of APE ($\leqslant 0.12$) and MAPE (0.052) indicate that the model has a very good performance to reflect the behavior of the simulated system.

4.1.3. Sensitivity analysis

We selected 12 parameters which are likely to have high levels of uncertainty, including: the population urbanization rate (UR), urban and rural water use per day (WUP and WRP), water use per unit of cultivated area (WPA) and per unit of industrial value (WV), the water consumption coefficient of agriculture (CWA) and of urban domestics (CWDs), the waste water treatment rate (WTR), the coefficient of industrial waste water discharged into river (CRI), the coefficient of WRI meeting the national discharge standard (CSI), multi-annual mean inflow (AIF), and multi-annual mean self-produced water resources (WSP). The parameters of WUP, WRP, WPA and WV are varied by ±10%, CWA and CWD by ±15%, WTR, CRI and CSI by ±20%, UR by ±25%, and AIF, MOF and WSP by ±30%. The percentages are set based on the likely ranges of uncertainties of the respective parameters. The average percentage changes and extreme changes in the outputs in the socio-economic subsystems in response to changes in each of the 12 selected parameters are illustrated in Fig. 4. It can be seen that the degree of sensitivity is very high for CRI in terms of extreme and average percentages. The socio-economic system state is also sensitive to the parameters of CSI, WSP and WV in some years with reference to the extreme sensitivity degree values. However, these parameters are not sensitive to the general target system state in terms of their average degrees of sensitivity. The sensitivity values

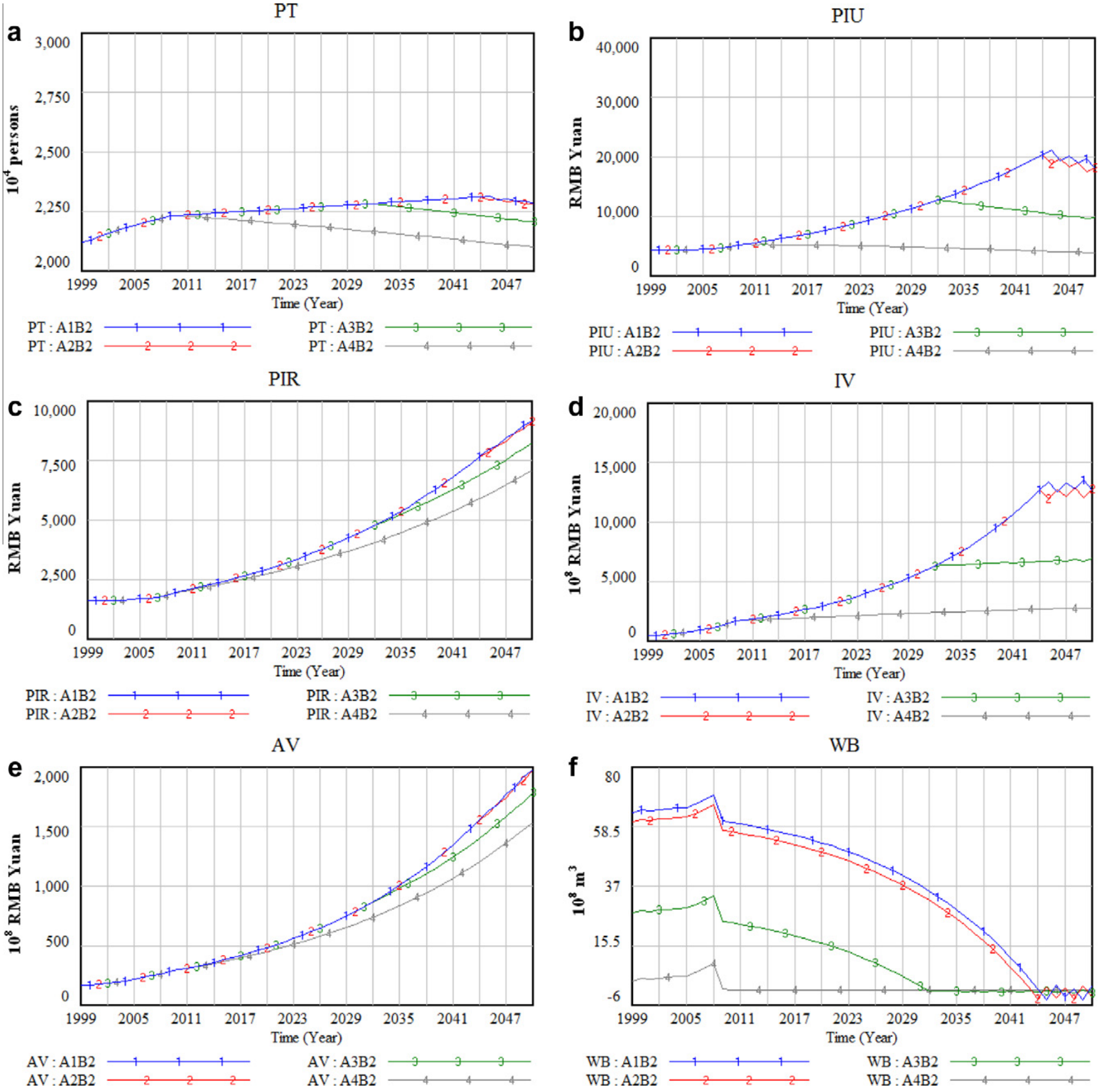

Fig. 6. The simulation results of low growth mode under four EF allocation (A1B2, A2B2, A3B2, A4B2), (a) total population (PT), (b) Per capita disposable income of urban households (PIU), (c) Per capita net income of rural households (PIR), (d) industrial GDP, (e) agricultural GDP, and (f) water availability-demand balance of socio-economic sector.

shown here imply that the simulation results can be significantly affected by the errors in the values of these parameters. The parameters of AIF, WUP and UR are less sensitive, while all the remaining parameters are not sensitive to target system state.

4.2. Simulation results

4.2.1. Quantity of EF under four allocation levels

The simulation results of four levels of EF allocation in the study area show that it requires an annual minimum EF of 7.2×10^8 m^3 to maintain aquatic life in the river (A1) and an annual basic EF of 10.6×10^8 m^3 to keep a river balance (A2), i.e. a sound aquatic life and river seepage and evaporation cycle. However, it requires an annual EF of 43.6×10^8 m^3 to dilute the river pollutant (A3), and requires even a large EF, 68.1×10^8 m^3 per year, for sediment transportation (A4).

4.2.2. Current growth pattern – B1

The simulation results of EF impacts under the current growth pattern (B1) are illustrated in Fig. 5. The results illustrate that under the four levels of EF allocation (A1, A2, A3 and A4), PT, PIU, PIR and AV exhibit an upward trend, and water capacity reaches the maximum and then decreases, and IV initially shows an upward trend and then moves slowly towards its maximum water capacity during the simulation period (Fig. 5a–e). This is mainly because the available water is rapidly decreased due to a large increase in water demand for socio-economic development, and the results illustrate that the study area will face a serious water shortage of

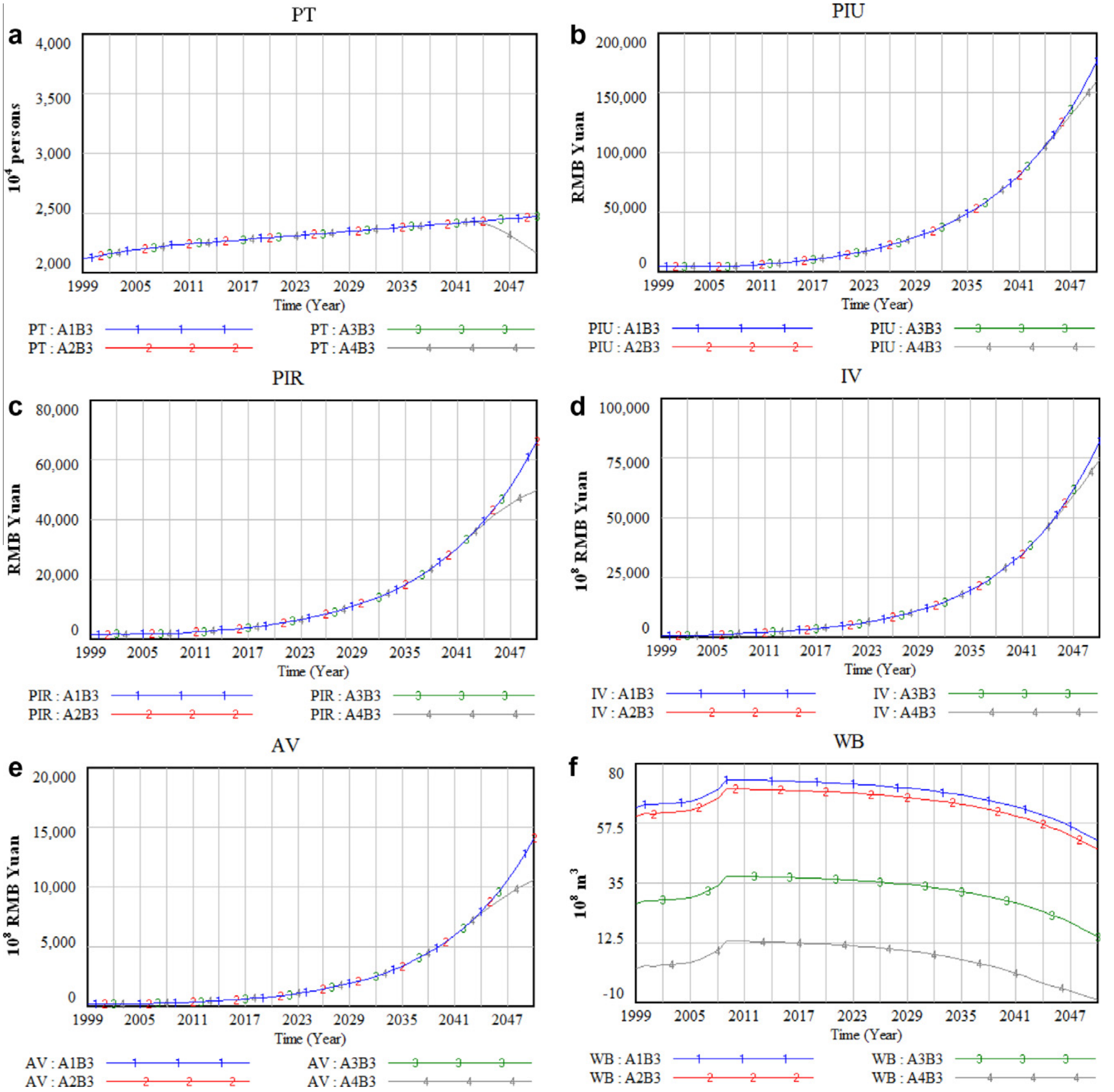

Fig. 7. The simulation results of the middle growth mode under four EF allocation (A1B3, A2B3, A3B3, A4B3), (a) total population (PT), (b) Per capita disposable income of urban households (PIU), (c) Per capita net income of rural households (PIR), (d) industrial GDP, (e) agricultural GDP, and (f) water availability-demand balance of socio-economic sector.

3.54×10^8 m^3 and 67.97×10^8 m^3, respectively in 2030 and 2050 under the current growth pattern (B1) and A1 (Fig. 5f). The results also demonstrate that EF impacts on socio-economic development become more severe with more water allocated to EF, where socio-economic growth decreases more rapidly. For example, PT, PIU, PIR and AV achieve their highest values of 2449.27×10^4 persons in 2030, 18,474.7 yuan in 2031, 7014.64 yuan in 2032, and 1413.76×10^8 yuan in 2032, respectively, under A1. In contrast, they reach the maximum of 2332.77×10^4 persons in 2019, 9817.9 yuan in 2021, 3771.88 yuan in 2023, and 676.542×10^8 yuan in 2025, respectively, under A4. With reference to IV, it reaches $113{,}421 \times 10^8$ yuan in 2050 under A1, while it is only $26{,}642.4 \times 10^8$ yuan in 2050 under A4.

4.2.3. Lower growth pattern – B2

In the lower growth pattern (B2), PT, PIU and IV exhibit similar behaviors but experience a delay in reaching their maximum as compared with those in the current growth mode (Fig. 6a,b, and d), while PIR and AV exhibit upward trends (Fig. 6c and e). The impacts of EF allocation on socio-economic growth are stronger as more water is allocated to EF (Fig. 6f); for example, TP reaches its maximum of 2312.91×10^4 persons in 2045 under A1, 2311.13×10^4 persons in 2044 under A2, 2283.58×10^4 persons in 2032 under A3, 2232.32×10^4 persons in 2010 under A4, respectively. The water shortage situation is greatly alleviated during the simulation period in this growth pattern under this pattern, but the lower growth rate

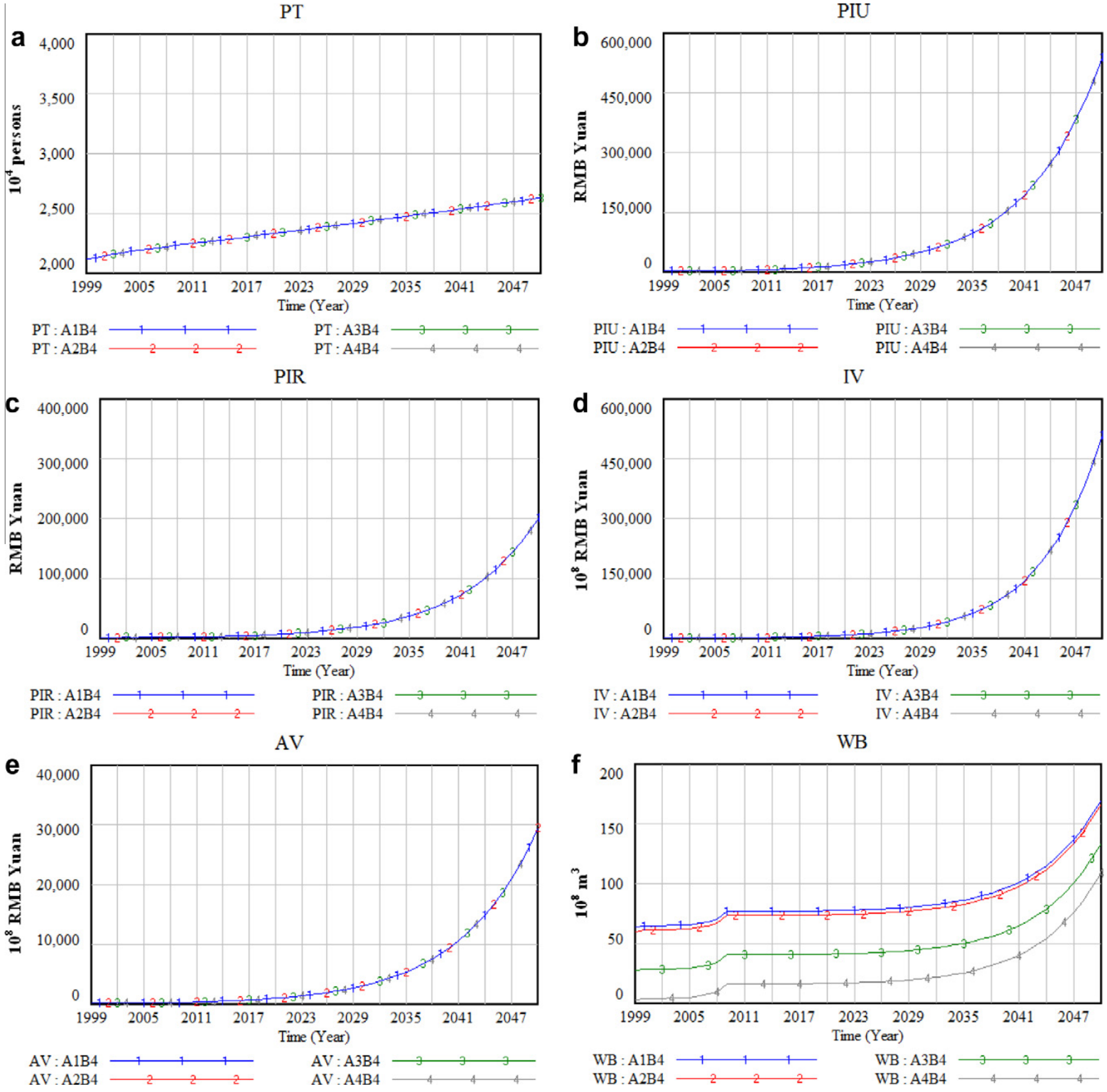

Fig. 8. The simulation results of the high growth mode under four EF allocation (A1B4, A2B4, A3B4, A4B4), (a) total population (PT), (b) Per capita disposable income of urban households (PIU), (c) Per capita net income of rural households (PIR), (d) industrial GDP, (e) agricultural GDP, and (f) water availability-demand balance of socio-economic sector.

will hinder socio-economic development itself. In addition, higher urban domestic and agricultural water use will put more pressure on water resources, and the higher wastewater discharges and lower treatment rates will increase polluted water discharges and hence increase EF requirements. Furthermore, the lower growth pattern also sacrifices the ecological environment.

4.2.4. Middle growth pattern – B3

We try to change the parameters by reducing slightly the current socio-economic growth rates and the current wastewater discharge but increasing current wastewater treatment and reclaiming rates. When we reach the middle growth model (B3), water is sufficient for socio-economic growth under the EF allocation levels of A1, A2 and A3. However, there will be water shortage when the EF for sediment (A4) is considered, and thus it exercises a negative socio-economic impact, especially on total population. Thus socio-economic growth keeps increasing under all four levels of EF allocation, except that TP will reach its maximum of 2424.86×10^4 persons in 2043 and then decreases under A4. During the simulation period, the socio-economic impacts of the first three levels of EF allocation (A1, A2, and A3) are nearly zero, and there are only slight impacts under the fourth EF allocation (A4) (Fig. 7). This is mainly because there is still sufficient water available for socio-economic development under EF allocations of A1, A2 and A3, although water demand-availability keeps decreasing. Under A4, however, water is sufficient for socio-economic development in the first few years, and then there are signs of water shortage in the remaining years.

4.2.5. Higher growth pattern – B4

When the variations arrive at the parameters in the higher growth pattern (B4), rural domestic water demand and ecological environmental water demand are increasing, but there is still sufficient water available to maintain a higher socio-economic growth rate even under the highest level of water allocation to EF (A4) (Fig. 8). Thus the four levels of EF allocation display no negative impacts on socio-economic growth. The main reason for this situation is because more of the recycling water can be used at lower wastewater discharge rates and higher wastewater treatment and reclaimed rates. Another reason is that more efficient water use in urban domestics and agriculture will reduce part of water required for socio-economic development.

4.2.6. Water shortage

The results from this study suggest that currently there is still more or less sufficient water to satisfy different levels of EF under the four growth patterns, although the water shortage will become a limiting factor in the future (Figs. 5f, 6f, 7f, and 8f). Our results seem to be contrary to the results in the literature in which most of the studies have suggested a water shortage to various degrees (Lei and Cao, 2002; Liu and Sun, 2006). A major reason for the differences is because many previous studies only considered the self-produced water resources in the area, i.e. WSP. The water availability we considered in this study included WSP, inflows and returned flows and recycling under the assumption that wastewater treatment reached the levels stated in the official statistics. However, in reality the wastewater treatment and reuse rates are generally much lower than those stated in the official statistics. This situation has been commonly recognized and is observed by the authors of this study during the field surveys. Hence, the E-flow may not be sufficient at the moment due to water scarcity caused by the low real treatment and recycling rates.

5. Conclusions

In this study we developed a system dynamic simulation model (SDSM) for supporting sustainable development on a river basin scale. The SDSM was utilized to simulate and analyze socio-economic impacts of four levels of EF allocation (A1, A2, A3, and A4) in the Weihe River Basin in China. The simulation results reveal that: (1) local water resources are not sufficient to maintain its current high socio-economic growth, and the negative impacts of EF allocation will be increased when EF allocation levels vary from A1 to A4; (2) when a lower socio-economic growth rate and less water used for the ecological environment are desiged, the water shortage situation will be eased, and the negative EF allocation impacts will be reduced; however, (3) a lower socio-economic growth rate will reduce the welfare of local people; and (4) Growth pattern 4 (B4) is the optimal combination in considering both socio-economic development and the environment, and it is the practical strategy to increase local water carrying capacity. B4 suggests that efficient use of water, lower wastewater discharge, high wastewater treatment and recycling rates are the main driving factors, and EF allocation shows lower or no negative impacts in such a growth mode. However, due to limited data, the model does not analyze how water prices will influence water supply and demand, and what impacts climate change will have on hydrology and water supply. We will therefore strive to improve the model by including those aspects.

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Appendix A

Summary of the information of the system parameters and expressions:

Entity	Description (unit)	Equations
Population subsystem		
PT	Total population (10^4 persons)	PT = INTEG (PN – PD, 2122.83)
PN	Net population added (10^4 persons)	PN = PT ∗ PNR
PD	Population died (10^4 persons)	PD = PRD + PUD
PR	Rural population (10^4 persons)	PR = PT ∗ (1 − RU)
PRD	Rural population died (10^4 persons)	PRD = IF THEN ELSE (WSR < 0,abs (RPR ∗ WSR), 0)
PU	Urban population (10^4 persons)	PU = PT ∗ RU
PUD	Urban population died (10^4 persons)	PUD = IF THEN ELSE (WSU < 0,abs (WSU ∗ UPR), 0)
RU	Population urbanization rate (%)	RU = WITH LOOKUP (Time, ([(1999, 0)(2008, 100)], (1999, 27), (2000, 28), (2001, 28), (2002, 29), (2003, 29), (2004, 29), (2005, 29), (2006, 31)))
PNR	Population natural growth rate (‰)	PNR = WITHLOOKUP (Time, ([(1999, 0)(2008, 10)], (1999, 3.9), (2000, 7.2), (2001, 5.9), (2002, 5.5), (2003, 5.2), (2004, 4.7), (2005, 4.5), (2006, 4.4)))
Industry subsystem		
IV	Industrial real GDP values (10^8 yuan)	IV = INTEG (IA-IL,412.94)
PIU	Per capita disposable income of urban households (10^8 yuan)	PIU = INTEG (IUA-IUL, 4336)
IA	Industrial value added (10^8 yuan)	IA = IV ∗ IR
IL	Industrial value lost (10^8 yuan)	IL = IF THEN ELSE (WSI < 0, abs (WSI ∗ WV), 0)
IUA	Income added (10^8 yuan)	IUA = PIU ∗ IUR
IUL	Income lost (10^8 yuan)	IUL = IL ∗ RII ∗ 10^8
RII	Ratio of PIU to IV	RII = PIU/10^8/IV
IUR	Increasing rate of PIU	IUR = WITH LOOKUP (Time, ([(1999, −0.8)-(2008, 10)], (2000, 0.3), (2001, 0.1), (2002, 0.7), (2003, 1.6), (2004, 2.9), (2005, 1.1), (2006, 1.2)))

(*continued*)

Industry subsystem		
IR	Industrial growth rate (%)	IR = WITH LOOKUP (Time, ([(1999, 0)-(2008, 20)], (2000, 12), (2001, 11), (2002, 16), (2003, 16), (2004, 18), (2005, 14), (2006, 15)))

Agriculture subsystem		
AT	Total cultivated field area (10^4 ha)	AT = INTEG (AI-AL, 168.667)
AV	Agricultural GDP value (10^8 yuan)	AV = INTEG (AVA-AVL, 164.83)
PIR	Per capita net income of rural households (yuan)	PIR = INTEG (IRA-IRL, 1628.6)
AI	Agriculture area increased (10^4 ha)	AI = AT ∗ AIR/100
AL	Irrigation area lost (10^4 ha)	AL = IF THEN ELSE (AWS > 0, 0, abs (10^4 ∗ AWS/WPA/15))
AVA	Agricultural value added (10^8 yuan)	AVA = AV ∗ AVR/100
AVL	Agricultural value lost (10^8 yuan)	AVL = AL ∗ VPA
IRA	Income added (Yuan)	IRA = IAR ∗ PIR/100
IRL	Income lost (Yuan)	IRL = AVL ∗ RIA ∗ 10^8
RIA	Ratio of PIR to AV	RIA = PIR/AV/10^8
VPA	Value produced per unit area (10^4 yuan ha^{-1})	VPA = AV/AT
AIR	Increasing rate of AI (%)	AIR = WITH LOOKUP (Time, ((2000, −2.7), (2001, −2.3), (2002, −3.2), (2003, −2.0), (2004, 0.28), (2005, −0.3), (2006, −0.9)))
AVR	Growth rate of AV (%)	AVR = WITH LOOKUP (Time, ([(1999, 0) – (2008, 10)], (2000, 4.3), (2001, 3.4), (2002, 3.3), (2003, 4.5), (2004, 8.9), (2005, 7.6), (2006, 7.3), (2007, 4.6), (2008, 7.5)))
IAR	Income increasing rate (%)	IAR = WITH LOOKUP (Time, ([(1999, −0.8) – (2008, 10)], (2000, 0.3), (2001, 0.1), (2002, −0.7), (2003, 1.6), (2004, 2.9), (2005, 1.1), (2006, 1.2)))

Water demand subsystem		
WDT	Total socio-economic water demand (10^8 m^3)	WDT = WDA + WDD + WDI
WDA	Agricultural water demand (10^8 m^3)	WDA = AT ∗ WPA ∗ 15/10^4
WDD	Domestic water demand (10^8 m^3)	WDD = WDR + WDU
WDI	Industrial water demand (10^8 m^3)	WDI = WUI ∗ (1-RIW/100)
WDR	Water demand of rural households (10^8 m^3)	WDR = PR ∗ WRP ∗ *T*/10^7
WDU	Water demand of urban households (10^8 m^3)	WDU = PU ∗ *T* ∗ WUP/10^7

(*continued*)

Water demand subsystem		
RWA	Ratio of agricultural water demand to WDT	RWA = WDA/WDT
RWD	Ratios of domestic water demand to WDT	RWD = WDD/WDT
RWI	Ratio of industrial water demand to WDT	RWI = WDI/WDT
RWU	Ratio of urban domestic water demand to WDT	RWU = WDU/WDD
RWR	Ratio of rural domestic water demand to WDT	RWR = 1-RWU
T	Time periods (days in year)	*T* = IF THEN ELSE (MODULO (Time, 4) = 0, 366, 365)
WUI	Industrial water use (10^8 m^3)	WUI = IV ∗ WV/104
RIW	Rate of industrial water repeating use (%)	RIW = WITH LOOKUP (Time, ([(1999, 0) – (2008, 100)], (2001, 83.0), (2002, 83.2), (2003, 82.6), (2004, 82.2), (2005, 82.3), (2006, 82.6), (2007, 83.5), (2008, 86.2)))
WUP	Per capita urban water use per day (*L*)	WUP = WITH LOOKUP (Time, ([(1999, 0) – (2008, 200)], (1999, 133), (2000, 153), (2001, 177), (2002, 188), (2003, 173), (2004, 158), (2005, 143), (2006, 125)))
WRP	Water demand per capita rural population per day (*L*)	WRP = WITH LOOKUP (Time, ([(1980, 0) – (2010, 80)], (1985, 45.4822), (1990, 39), (1995, 61), (2000, 63)))
WV	Water use per unit of industrial value (m^3 10^{-4} yuan)	WV = WITH LOOKUP (Time, ([(1999, 0) – (2008, 800)], (2001, 755), (2002, 669), (2003, 632), (2004, 578), (2005, 527), (2006, 407)))
WPA	Water use per cultivated area (m^3 mu^{-1})	WPA = WITH LOOKUP (Time, ([(1995, 0)–(2008, 400)], (1995, 137), (1999, 132), (2000, 125), (2005, 127)))

Subsystem of wastewater discharge and treatment		
WRT	Total recycling water (10^8 m^3)	WRT = WAR + WUR + WIR
WUR	Recycling water from urban wastewater treatment plant (10^8 m^3)	WUR = WAP ∗ WTR
WAD	Urban domestic wastewater discharge (10^8 tons)	WAD = WDU ∗ (1-CWD)
WAP	Wastewater in treatment plant (10^8 tons)	WAP = WAD + WPI
WAR	Returning water from agriculture (10^8 m^3)	WAR = WDA ∗ (1-CWA)
WIR	Recycling water from industry (10^8 m^3)	WIR = WRI ∗ CSI
WPI	Industry wastewater discharge into wastewater treatment plant (10^8 tons)	WPI = WUI ∗ CPI

(*continued on next page*)

(*continued*)

Subsystem of wastewater discharge and treatment

WRI	Industry wastewater discharge to river $(10^8$ tons)	WRI = WUI ∗ CRI
CWA	Agriculture water consumption coefficient	CWA = 0.65
CWD	Urban domestics water consumption coefficient	CWD = 0.55
WTR	Wastewater plant treatment rate (%)	WTR = 0.65
CPI	Coefficients of industrial wastewater discharged into treatment plan	CPI = WITH LOOKUP (Time, ([(1999, 0) – (2008, 0.1)], (2001, 0.003), (2002, 0.004), (2003, 0.003), (2005, 0.008), (2006, 0.009)))
CRI	Coefficient of industrial wastewater discharged into river	CRI = WITH LOOKUP (Time, ([(2001, 0.06) – (2008, 1)], (2001, 0.06), (2002, 0.06), (2003, 0.07), (2004, 0.07), (2005, 0.08), (2006, 0.08)))
CSI	Coefficient of WRI meeting to the discharge standard	CSI = WITH LOOKUP (Time, ([(1999, 0) – (2008, 1)], (1999, 0.62), (2000, 0.64), (2001, 0.80), (2002, 0.84), (2003, 0.88), (2004, 0.93), (2005, 0.94), (2006, 0.89)))

Water resources subsystem

WAT	Total available water resources $(10^8\ m^3)$	WAT = AIF + WRC + WSP-MOF
WSP	Annual mean self-produced water $(10^8\ m^3)$	WSP = WG + WS-WO-WTS
WRC	returning and recycling water from socio-economic development $(10^8\ m^3)$	WRC = WRT
MOF	Multi-annual minimum outflow $(10^8\ m^3)$	MOF = EF
WS	Surface water resources $(10^8\ m^3)$	WS = 60.392
AIF	Multi-annual mean inflow $(10^8\ m^3)$	AIF = 35.759
WTS	Water transferred from outside $(10^8\ m^3)$	WTS = 4.839
WG	Ground water resources $(10^8\ m^3)$	WG = 48.701
WO	Overlap of ground and surface water $(10^8\ m^3)$	WO = 35.532

Water shortage subsystem

WSE	Socio-economic water shortage $(10^8\ m^3)$	WSE = WAT-WDE
WB	Water availability-demand balance $(10^8\ m^3)$	WB = WSE-WDT
WSA	Agricultural water shortage $(10^8\ m^3)$	WSA = RWA ∗ WB
WSD	Domestic water shortage $(10^8\ m^3)$	WSD = RWD ∗ WB
WSI	Industrial water shortage $(10^8\ m^3)$	WSI = RWI ∗ WB
WSR	Rural domestic water shortage $(10^8\ m^3)$	WSR = WSD ∗ (1-RWU)
WSU	Urban domestic water shortage $(10^8\ m^3)$	WSU = WSD1 ∗ RWU

E-Flow requirement subsystem

EF	Environmental flow $(10^8\ m^3)$	EF = MIF, BEF, EFP, or EFS
MIF (A1)	Minimum instream flow for maintaining aquatic life $(10^8\ m^3)$	MIF = MAX (LJM, WJM, XYM, LTM, HXM)
LJM, WJM, XYM, LTM, HXM	Minimum instream flow for maintaining aquatic life in the five hydrological gauged stations $(10^8\ m^3)$	LJM = LJA ∗ FRA, WJM = WJA ∗ FRA, HXM = HXA ∗ FRA, XYM = XYA ∗ FRA, LTM = LTA ∗ FRA
LJA, WJA, XYA, HXA LTA	Multi-annual mean flows in the five hydrological gauged stations $(10^8\ m^3)$	LJA = 24.24, WJA = 29.87, HXA = 72.21, XYA = 44.74, LTA = 68.06
FRA	Fraction (%)	FRA = 10%
BEF (A2)	Basic instream flow for maintaining river balance $(10^8\ m^3)$	BEF = MIF + SEF
SE1, 2, 3, 4, 5	River channel seepage of the five hydrological gauged stations $(10^8\ m^3)$	SE1 = 0.80615, SE2 = 0.11385, SE3 = 1.73095 SE4 = 0.238325, SE5 = 0
SEF	River channel evaporation and seepage $(10^8\ m^3)$	SEF = HXB + LJB + LTB + WJB + XYB
LJB, WJB, XYB, HXB, LTB	Basic environmental flows for channel evaporation and seepage in the five hydrological gauged stations $(10^8\ m^3)$	LJB = EV1 + SI1, WJB = EV2 + SI2, XYB = EV3 + SI3, LTB = EV4 + SI4, HXB = EV5 + SI5
EV1, 2, 3, 4, 5	Evaporation of the five hydrological	EV1 = 0.067, EV2 = 0.152, EV3 = 0.079 EV4 = 0.130, EV5 = 0.111

(*continued*)

E-Flow requirement subsystem		
	gauged stations (10^8 m^3)	
EFD (A3)	Instream flow for pollution dilution (10^8 m^3)	EFP = MAX (LJP, WJP, XYP, LTP, HXP)
LJD, WJD, XYD, LTD, HXD	River flows for pollution dilution in the five hydrological gauged stations (10^8 m^3)	HXP = 29.04, LJP = 28.28, LTP = 29.03, WJP = 29.41, XYP = 43.55
EFS (A4)	Instream flow for sediment transport (10^8 m^3)	EFS = MAX (HXS, LTS)
LTS, HXS	River flows for sediment transport in LT and HX stations (10^8 m^3)	LTS = 59.43, HXS = 68.07

(*continued*)

Subsystem of ecological environmental water demand		
UGA	Urban green area (ha)	UGA = INTEG (AG, 7001)
AG	Urban green area added (ha)	AG = UGA ∗ GR
WDE	Water demand of ecology (10^8 m^3)	WDE = WC + WGA + WP + WUA + WWA
WC	Water for water and soil conservation (10^8 m^3)	WC = WQ4 ∗ WSC/10^4
WGA	Water demand of green area (10^8 m^3)	WGA = UGA ∗ WQ1/10^8
WP	Water demand of plant (ZVA)	WP = ZVA ∗ WQ5/104
WUA	Water demand of UWA (10^8 m^3)	WUA = UWA ∗ (EVA-PRE)/10^7
WWA	Water demand of AWA (10^8 m^3)	WWA = AWA ∗ WQ3/10^4
AWA	Artificial water area (10^4 ha)	AWA = 0.52
WSC	Water and soil conservation area (10^4 ha)	WSC = 61.31
UWA	Urban water surface area (ha)	UWA = 6700
ZVA	Zonal vegetation area (10^4 ha)	ZVA = 59.83
EVA	Evaporation of urban water surface (mm a^{-1})	EVA = 854.3
PRE	Mean precipitation (mm a^{-1})	PRE = 550.05
WQ1,2,3,4	Water quartos for UGA,AWA,WSC and ZVA, respectively (m^3 ha^{-1})	WQ1 = 2600, WQ2 = 304.25, WQ3 = 304.25, WQ4 = 150
GR	Urban green area increasing rate (%)	GR = WITH LOOKUP (Time, ([(1999, −4.0) – (2008, 100)], (1999, −2.4), (2001, 6.0), (2002, 11.4), (2003, 17.6), (2004, 5.7), (2005, 5.4), (2006, 34.6)))

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