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ORIGINAL ARTICLE

Climate change and water resources management in Tuwei river basin of Northwest China

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Abstract Water resources are an integral part of the socio-economic-environmental system. Water resources have dynamic interactions with related social, economic and environmental elements, as well as regulatory factors that are characterized by non-linear and multi-loop feedbacks. In this paper, a complex System Dynamic (SD) model is used to study the relationship among population growth, economic development, climate change, management strategies and water resources, and identify the best management strategy to adapt with the changing environment in the Tuwei river basin of Northwest China. Three management alternatives viz. business as usual, water supply management and water demand management are studied under different climate change scenarios. Results indicate that water shortage rate in Tuwei river basin may increase up to 80 % by the year 2030 if current management practices are continued or the supply based management strategy is adopted. On the other hand, water demand management can keep the water shortage rate within a tolerable limit and therefore can be considered as the sustainable strategy for water resources management to maintain the economic growth and ecological status of the Tuwei river basin.

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1 Introduction

The primary challenge in water resources management is to balance water supply with the ever increasing demand. One option to balance supply and demand is to increase supply by augmenting the current water resources. This often involves large scale water resource projects such as the North–south Carrier in Botswana, the Great Man Made River in Libya, the Lesotho Highlands Water Project in South Africa and the National Water Carrier in Israel (Butler and Memon 2006; Rahm et al. 2006; Wheida and Verhoeven 2007). Though the supply enhancement projects can solve water shortage problems for time being, they are not enough to meet the increasing water demand caused by rapid economic development and population growth (Wang et al. 2011a, b, 2012). The development of society and intensive human activities has lead to extensive depletion of water sources throughout the world. Recently, water resource depletion has accelerated due to the large-scale population growth, urbanization, socioeconomic development and climate change (Butler and Memon 2006; WHO 2006; Wheida and Verhoeven 2007; Wang et al. 2008).

Researchers increasingly acknowledge that sustainable utilization of water resources is the most feasible way to achieve sustainability in water resources management in the context of changing environment (Stephenson 1999; Gumbo 2004; Wheida and Verhoeven 2007; Zou et al. 2011; Wang et al. 2012; Misra 2012). In South Africa and Middle East, two of the most water-challenged areas of the world, Water Demand Management (WDM) strategy have been applied in recent years. Results show that government expenditures have reduced and the performance of the water utility has improved (Butler and Memon 2006; Gumbo 2004; Wang et al. 2009). Case studies from other areas around the world also demonstrate predominant benefits of WDM including both lower costs and environmental protection (Wang et al. 2011a, 2012). Therefore, WDM can be considered as potentially the best solution to meet future demands which will increase in almost all over the world (Stephenson 1999; Butler and Memon 2006; Gumbo 2004; Wheida and Verhoeven 2007; Wang et al. 2009, 2011a).

Water management is a complex problem involving population, environment, economy and policy. One way to conceptualize water management policies is to build a computer simulation model (Stave 2003; Ahmad and Simonovic 2004; Le Bars and Le Grusse 2008). Models can be used to simulate complex reality and to test theories, whilst exploring their implications and contradictions. System Dynamics (SD) offers a new way of modeling complex systems and analyzing their dynamic behavior. Over the last decade, SD has been widely applied to water resources management on global, national and regional scales (Simonovic 1999, 2002; Ahmad and Simonovic 2004; Sehlke and Jacobson 2005; Amgad Elmahdi et al. 2007; Zhang et al. 2008). In the present study, a System Dynamic approach is proposed to understand the dynamics of the complex system of water resources management and analyze the relative implications of regulatory policies. The Tuwei river basin, a small basin in northwest China is considered as a case study. The economy of the Tuwei river basin rose greatly from 1980 to 2005. However, recently water shortage has become a serious problem which threatens to limit further economic growth.

The objective of this study is to apply system dynamics modeling approach to identify the best water resources management strategy in Tuwei river basin in the context of socioeconomic development, population growth and climate change. Three water resources management alternatives viz. the continuation of the current management practices, the supply side management practices, and the demand side management practices are considered under different climate change scenarios. It is expected that the study will help to understand the behavior of the Tuwei river basin system including its components and their interconnections in a time-compressed and systemic manner, and contribute to better and effective management of water resources.

2 Study area

The map of the Tuwei river basin is shown in Fig. 1. Tuwei is a small river basin with a total drainage area of 3,294 km^2 located in northwest China at latitude 38°10′ ~39°10′N and longitude 109°45′~110°35′ E. The annual average precipitation in the basin is approximately 380 mm. About 75 % of the total precipitation occurs in the months of June, July and August. The mean annual runoff of the basin is $379\times10^6 m^3$ which is equivalent to the mean runoff depth of 117 mm. The total groundwater resource of the basin is $280\times10^6 m^3$, while the gross mean annual potential of water resources is $488\times10^6 m^3$. The total population of Tuwei River was 1,166,000 in 2005. A major portion of the population lives in rural areas and directly or indirectly related to agriculture. With the industrial development in recent years, the whole basin is facing serious water shortage problem. The scarcity of water resources has handicapped the development of the basin.

3 Materials and methods

3.1 System dynamic modelling

A System Dynamic (SD) modelling approach takes a system-level view for analysing complex problems by modelling the causal structure derived from the problematic behaviour (e.g. cause-effect interrelationships, feedback loops, delays, and nonlinearity) (Sterman 2000). SD provides a rigorous methodology for conceptualizing, visualizing and communicating the future evolution of complex systems. It creates qualitative and quantitative causal models that capture the interrelationships of physical (e.g. water inflows, outflows) and behavioural (e.g. decision rules, perceptions) processes of a system (Forrester 1961; Wolstenholme 1990). Simulation of SD model yields systemic impacts of alternative policies in a time-compressed manner (Sterman 1994).

A SD model has five main phases consisting of problem articulation, model conceptualization, model formulation, model evaluation and policy analysis. Software tools like Stella, Dynamo, Vensim, Powersim, etc. are widely used for the development of SD simulation programs. These programs provide a set of graphical objects to represent the system structure and its underlying mathematical functions and code, which allow simulation models to be easily and quickly developed (Guo et al. 2001; Sun et al. 2002; Xu et al. 2002; Ahmad and Simonovic 2004; Elmahdi et al. 2007; Zhang et al. 2008). Strength of SD modeling lies in using mathematical models to formulate, test, and reformulate dynamic hypotheses of a real world problem, especially when social and physical interactions are present. Due to the mathematical analysis required it may be difficult to apply system dynamics at a very detailed level. Sometimes it is difficult to define the delay between two elements of a cause and

Fig. 1 Hydrological map of the Tuwei river basin showing watershed boundary and major hydrological features

effect relationship as well as to set the boundary of the system (Balyejusa 2006). However, system dynamics allows to look at the problems, incorporating interrelationships between important variables, and can help the user to gain insight into situations of dynamic complexity, and reveal causes of policy resistance.

System dynamics modeling has been widely applied in water resource management by linking the physical (temperature and precipitation patterns, flood and drought flows, ground water recharge), environmental (water quality, ecosystem preservation and health), and socio-economical (population growth, water and land use, policy and management) aspects of river basin management (Ahmed and Simovonic 2000; Guo et al. 2001; Karavezyris et al. 2002; Xu et al. 2002; Yu et al. 2003; Ahmad and Simonovic 2004; Fernández and Selma 2004; Zhang 2005; Hjorth and Bagheri 2006; Elmahdi et al. 2007; Zhang et al. 2008; Winz et al. 2009). In the recent years, SD modeling has been applied for water supply planning in the Han River basin of South Korea (Chung et al. 2010), sustainable utilization of regional water resources in Hubei Province of China (Dan and Wei-Shuai 2012), sustainable water resources management in the Eastern Snake Plain aquifer in the western United States (Ryu et al. 2012), urban water reuse planning in the Great Lakes region of Michigan (Nasiri et al. 2012) and modeling complex urban water systems of Tabriz in Iran (Zarghami and Akbariyeh 2012).

3.2 Data and sources

This study uses basin level data for various time periods. The data of annual precipitation, water supply and water demand are obtained from China Water Resources Bulletin. The data on population, GDP, etc. are derived from the Statistical Yearbook of China. Data of regional climate model simulations are obtained from National Climate Center of China.

3.3 Model description, formulation and testing

The conceptual model of the Tuwei river basin consists of several sectors representing the physical, environmental and socioeconomic activities that are relevant to the water resource management. These include climate change, population growth, economic development, water supply and water demand. The conceptual framework of these issues is shown in Fig. 2.

Based on the described conceptual framework, a causal loop diagram is used to capture the interactions between climate change, population growth, economic development, water supply and water demand as well as water investment in Tuwei river basin. The feedback structure is further developed to represent the influence factors for co-operation in more detail. The causal loop diagram is shown in Fig. 3, The fundamental feedback structure embodies six feedback loops. Each arrow in Fig. 3 indicates an influence of one element on another. This influence is considered as positive (+) if an initial change is amplified in the same direction as all components are traced through the loop, or negative (−) if an increase in one element causes a decrease in another (Karavezyris et al. 2002; Xu et al. 2002; Yu et al. 2003; Ahmad and Simonovic 2004; Zhang 2005; Elmahdi et al. 2007; Zhang et al. 2008). The hypotheses about these influences are based on literature studies as well as works previously carried out at our research unit.

Based on the conceptual dynamics framework and interactions outlined above, a SD model of the Tuwei river basin (TuweiSD) is developed using the software Vensim Personal Learning Edition. The TuweiSD model consists of 169 parameters that represent physical, environmental and socio-economic aspects of the basin. The strategic planning period ranges from 1980 to 2030.

The developed TuweiSD model is verified with the data of 2000–2005. Due to the large number of variables in the model, only total population (TP), Urban Population (UP), and Surface Water Supply (SWS) are examined for calibration purposes. Table 1 shows the prediction results for those variables; most of the variables have low relative errors, which indicate that the model closely predicts the actual situation.

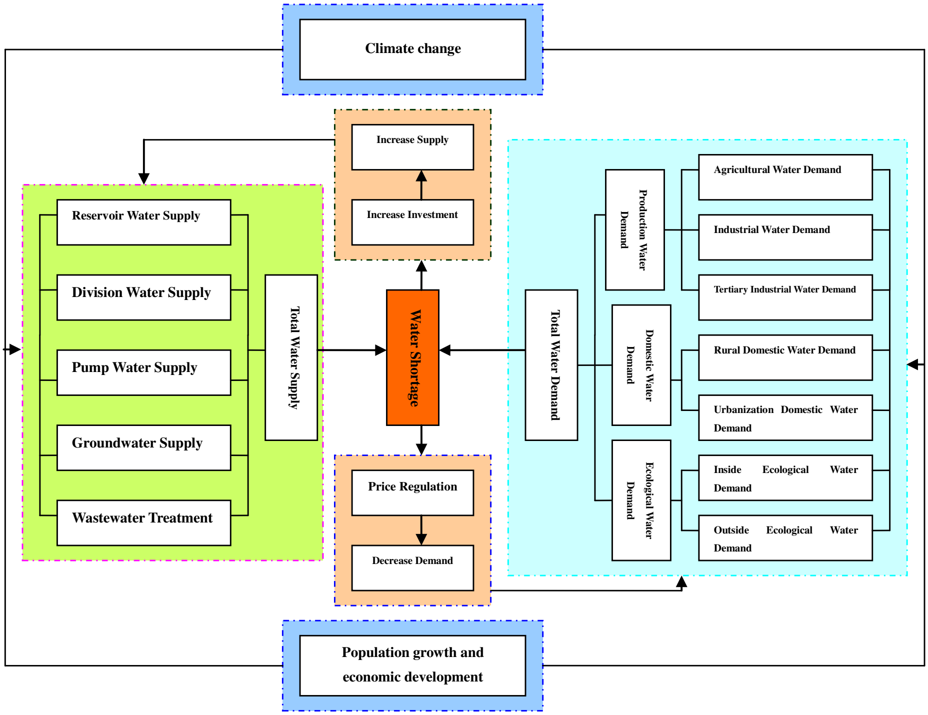

Fig. 2 Conceptual diagram of physical, environmental and socioeconomic aspects of water resources management

4 Results and discussion

Due to the economic development and population growth, water shortage problems in the Tuwei river basin are becoming increasingly severe. The climate models of Chinese National Climate Center predict that global warming will further exacerbate the situation. Figures 4 and 5 show the projected change in temperature and precipitation in the Tuwei river basin under three

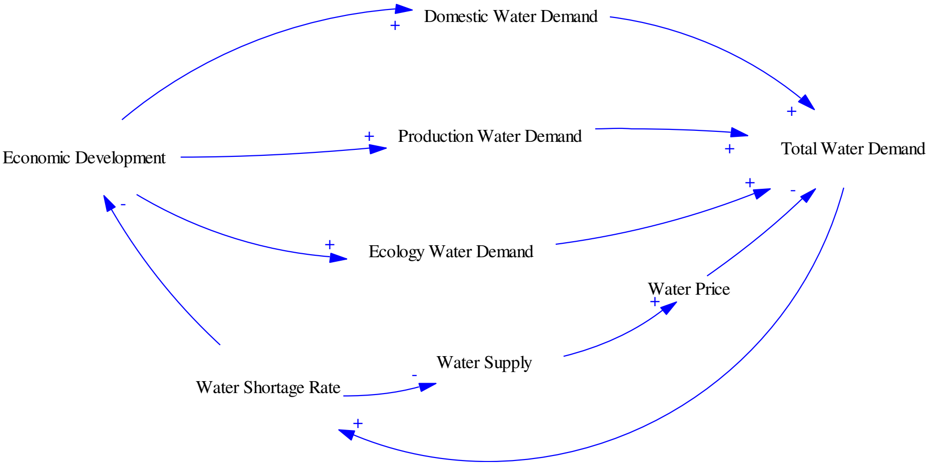

Fig. 3 Causal Loop Diagram of the basic SD model of Tuwei river basin

Table 1 Actual and simulated values of the main variables of Tuwei SD model

Variables	2000			2005		
	Actual	Simulated	Error	Actual	Simulated	Error
Total population (10^3 people)	225.3	213.3	−5.33	231.3	231.2	−0.04
Urban population (10^3 people)	17.7	16.9	−4.52	22.1	22.2	0.45
Surface water supply ($10^4 m^3$)	2666	2476	−7.13	2706	2558	−5.47

greenhouse gas emissions scenarios namely, B1, A1B and A2. The B1 scenario lies near the lower limit of projected changes in greenhouse gas emissions by different emissions, the A2 scenario lies near the upper limit of future greenhouse gas emissions, particularly beyond 2050, and the A1B scenarios which is a subset of the A1 scenario lies near the high end of the spectrum for future greenhouse gas emissions (IPCC 2001). Model predictions show that under a changing climate, temperatures will continue to increase whilst precipitation remain the same, if not decrease (Fig. 5) (Giorgi and Mearns 2002, 2003). This future change in climate may further negatively impact on the balance between supply and demand. It is therefore necessary for local water authorities to manage the water resources in an efficient manner.

As previously discussed, the three alternative water resources management methods are considered namely, (i) the continuation of the current management strategy or base run, (ii) the water supply management strategy, and (iii) the water demand management strategy. The simulation alternatives are attained through adjusting variables and parameters. The base run considers a steady management state based on the current management operation parameters and variables. The water supply management alternative focuses on increase the volume of water supply through system augmentation, such as Yellow river diversions in 2020 and increased ground water pumping. The water demand management pattern considers increased water prices, promotes water saving via education and incentives as methods to decrease water demand.

TuweiSD results under three alternative water resources management strategies are discussed below:

i) Base run: With the development of chemical energy industry, the economy of the Tuwei river basin has risen 40 times from 1980 to 2005, and water shortage has become a

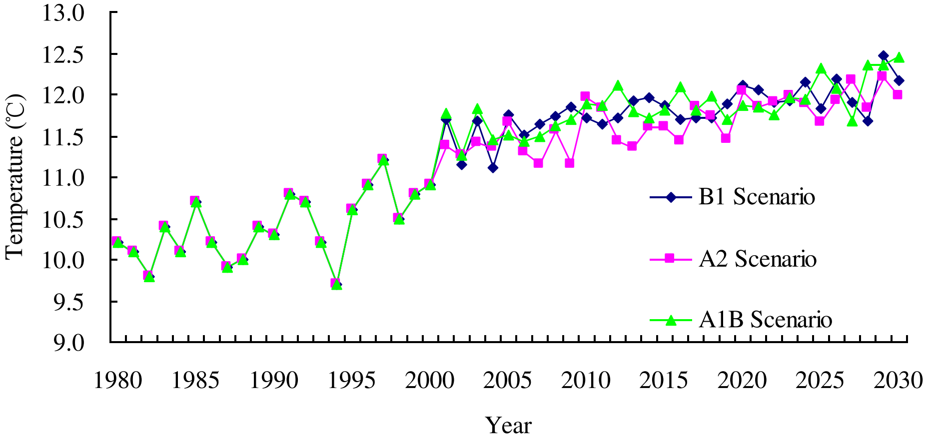

Fig. 4 Projected change of temperature in the Tuwei river basin

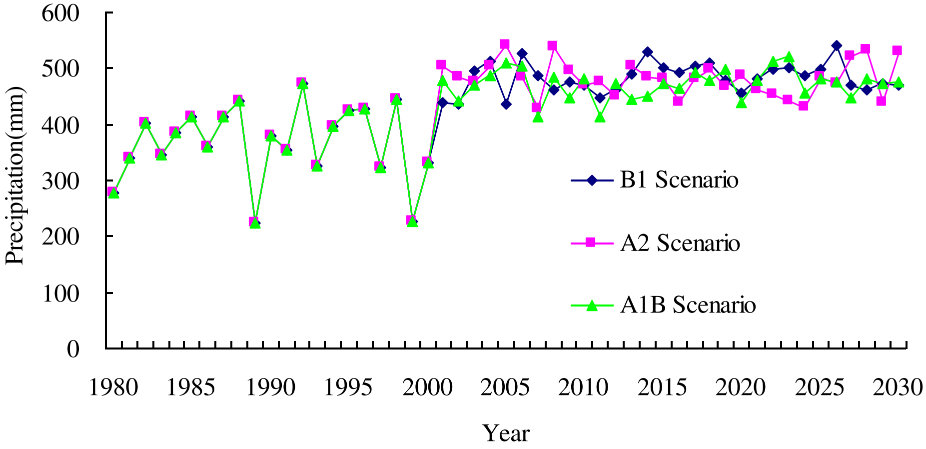

Fig. 5 Projected change of precipitation in the Tuwei river basin

serious problem which threatens to limit further economic growth. Figure 6 shows the results of the TuweiSD model analysis under the present management strategy. The figure shows that economic development will accelerate in the future, while the gap between supply and demand will be widened. Therefore, it is critical that a new method for water management should be adopted immediately to avoid stunting the region's economic growth and before water shortage become even more difficult to manage.

ii) Water supply management: Focusing on the economic development, this management alternative pays more attention to water supply, taking into consideration a water diversion from the Yellow River. According to the previous planning study, more than $133\times10^6 m^3$ of water in 2020 and $145\times10^6 m^3$ in 2030 will be transferred from the Yellow River (NWAFU 2008; SWEI 2005). However, recent depletion of water in Yellow River bas threatened the planned water transfer. The water transformation also have a high economic and social cost. Figure 7 shows the result of TuweiSD model under water supply management option. It can be seen from the figure that serious water shortage will occur despite the implementation of the Yellow River water transfer in 2020.

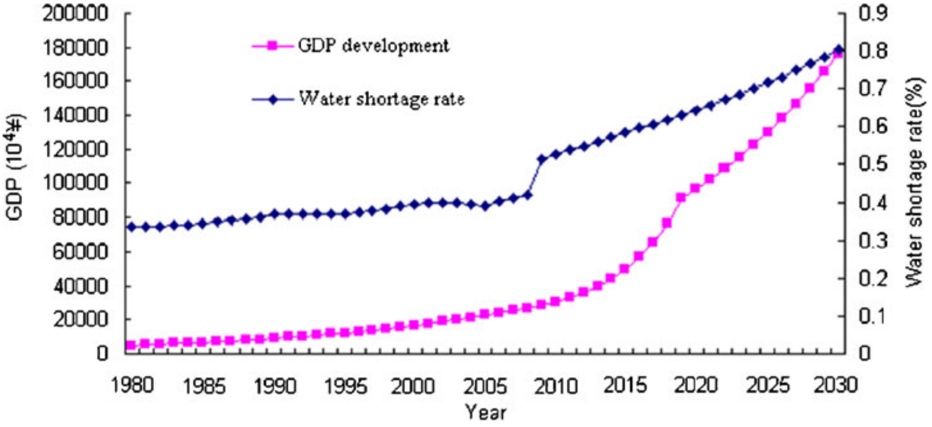

Fig. 6 Economic development and water shortage rate of the Tuwei river basin under business-as-usual condition

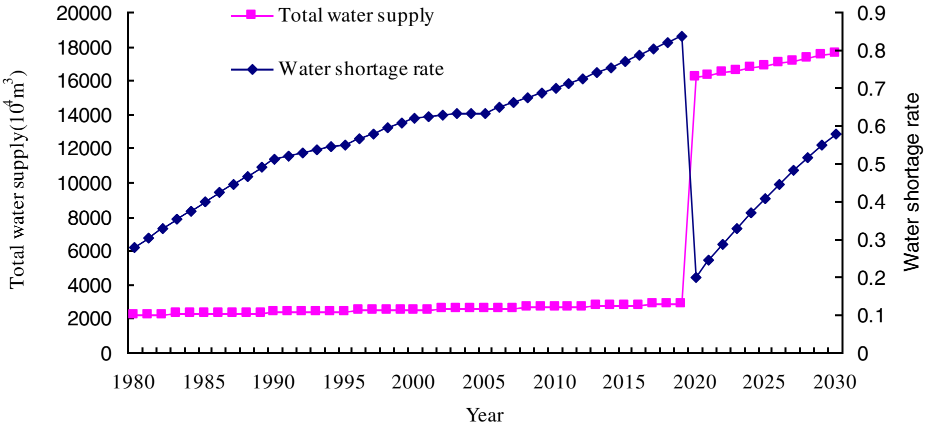

Fig. 7 Predicted water shortage rate versus total water supply under the water supply management alternative

Figure 8 gives economic development versus water shortage rate under the water supply management alternative. In the present study, water shortage rate is defined as the ratio of total water deficit to total water demand. The results of the SD model show that after the implementation of the Yellow River diversion, both the water shortage and the economic growth of the region will increase. However, water shortages will restrict economic growth and the cost of sourcing additional water will become higher and higher.

iii) Water demand management: In this water management strategy, the awareness of water-saving is increased through price control programs, the water market gradually matures, and the water price is used as a fundamental economic tool to influence demand. Furthermore, use of recycled water is modeled as a wastewater treatment plant commissioned in 2009. Figure 9 shows total water supply against the water shortage rate simulated by TuweiSD model under the water demand management alternative. The results predict that through a water saving regime, the water shortage rate will not increase as much compared to the base run and the water supply management alternatives. Figure 10 shows the economic development versus water shortage rate under

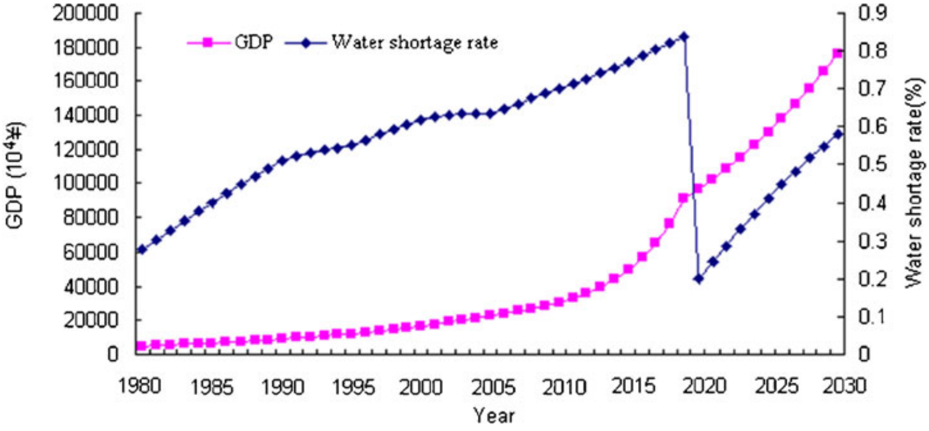

Fig. 8 Water shortage rate versus economic growth under water supply management alternative

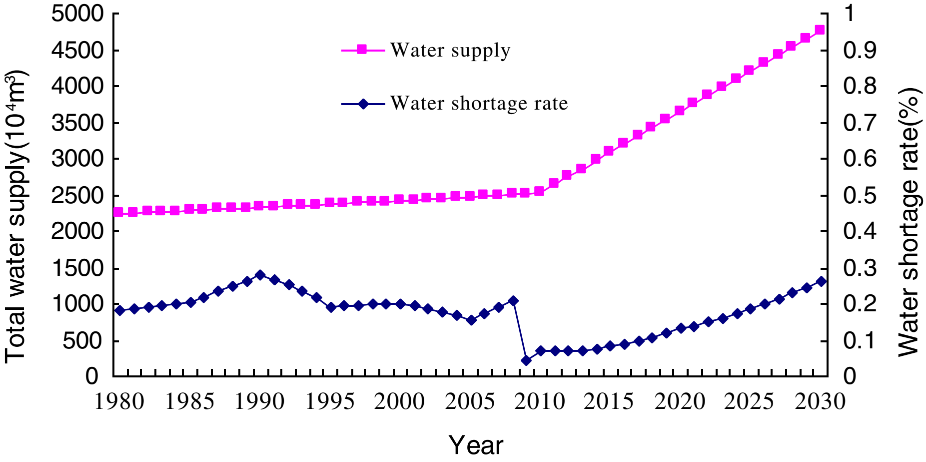

Fig. 9 Predicted water shortage rate versus total water supply under the water demand management alternative

the water demand management strategy. It can be seen from the figure that economic growth will continue to increase even with price increases.

Figure 11 shows the water demand under supply management and demand management strategies, and three emission scenarios introduced previously. Figure shows that the total water demand will be less under all climate change scenarios if water demand management strategy is adopted.

The different water resource management strategies have implications on water usage as well as on the economic and social development of Yuwei river basin. The water shortage rate will reach 65 % by 2020 and up to 80 % by 2030 under business-as-usual management strategy. On the other hand, under water supply management strategy, the water shortage will increase as high as 85 % in 2020 before the transfer of water from Yellow river. Transfer of water from Yellow River will reduce the water shortage rate to 18 % in 2010, but it will not able to solve the water shortage problem for a long run. At the end of 2030, the water shortage rate will increase to 59 % in the Yuwei river basin under the water supply management strategy. In

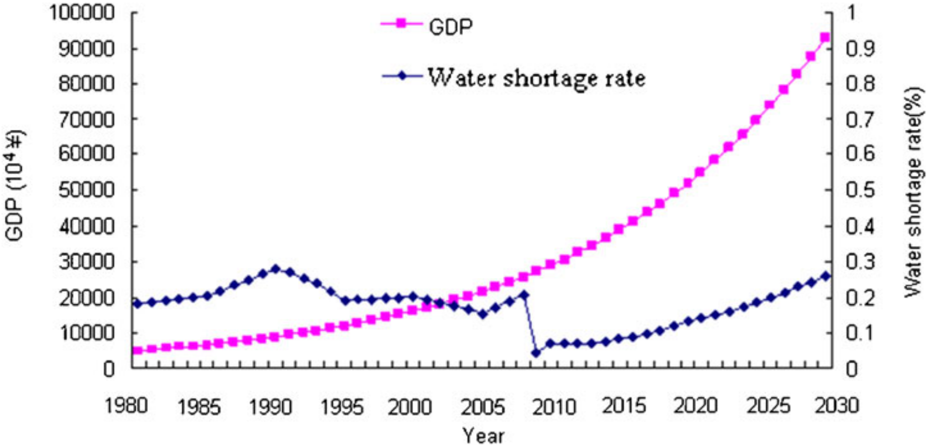

Fig. 10 Water shortage rate versus economic growth under water demand management alternative

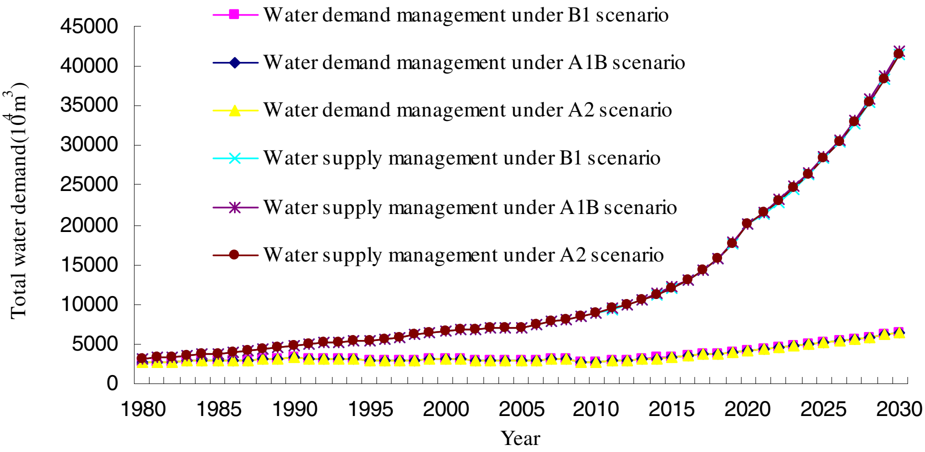

Fig. 11 Water demand under different management strategies and different climate scenarios

case of water demand management strategy, the water shortage rate will be relatively stabilized. It will increase only by 12 % between the years 2020 and 2030.

The supply enhancement by transferring water from Yellow River will cause a threat to ecological environment and water pollution. On the other hand, water demand management is limited and challenged by the industrial scale, and may affect the rate of economic growth. However, it will reduce the gap between water supply and demand. It is envisaged that the quantities of wastewater re-use will increase to provide additional supplies. Therefore, it can be remarked that though each of the three management systems have their own pros and cons, it is possible to achieve a better balance between water supply and demand if a water demand management option is adopted. Different water demand management options, such as water conservation, growing public water-saving awareness, improving efficiencies within the production process and agricultural consumption, controlling the consumer water price mechanism, etc. can help to achieve a better balance between water supply and demand to sustain the economic growth and socioeconomic development in the context of climate change.

5 Conclusions

This paper presents system dynamics modeling framework for understanding and analyzing the complex dynamics of water resources management of small watersheds. The SD modeling approach is applied in the Tuwei river basin located in southwest China to explore the best water resources management strategy. The SD model is developed by considering 169 interconnected physical, environmental and socio-economic parameters related to water resources management. Three management alternatives are considered, including the current management regime, a water supply management option and a water demand management option. The lesson learned from the present water resources management simulation can be summarized as below:

1) The current management regime as well as supply side water management strategy cannot maintain the socioeconomic growth and ecological sustainability.
2) Although additional infrastructure can cover the water deficit in the short period, but it cannot cope with the increasing water requirements, especially in the context of rapid economic development and climate change.

3) A portfolio of demand management mechanisms and conservation measures is the most sustainable strategy for maintaining the economic growth and ecological status.

Few considerations are noteworthy. The study assumed that economic development and population growth will follow the present projection which may not be true. Furthermore, obtained results based on climate model projections have uncertainty as there exists a large uncertainty in climate change model outputs. Therefore, the model should be regarded as a policy analysis tool that enables decision makers to explore and assess alternatives, rather than a predictive tool that generates accurate predictions of the resource future.

Climate change, economic development and population growth have made water supply very critical in many river basins of the world. As the system dynamic modeling approach can formulate dynamic hypotheses of a real world problem, especially when social and physical interactions are present, it can be used to explore the best water resources management strategy in the context of changing environment. Enhancement of water supply through system augmentation can coup the water scarcity for the time being, but to achieve sustainability in water resources management, demand management is the best alternative.

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