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Water demand forecasting under changing environment: a system dynamics approach

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Abstract A System Dynamics (SD) approach, focusing on water demand forecasting, was applied and developed based on the analysis of dynamic interactions among physical elements (natural runoff, groundwater recharge), environmental (water quality, ecosystem preservation) and socio-economic (population growth, water consumption, policy and management) aspects of water management elements in a regional water resources system. Through the analysis of multi-feedbacks and nonlinear interactions among system elements, a complex SD model was developed and applied in Tuwei River in the middle reaches of the Yellow River using water demand theory. The practical verification of the model shows that the relative error is small; therefore the model is reasonable structured to mimic the actual situation. Furthermore, total water demand of the whole basin can be also forecasted under the future changes of population, economic and climate scenario, and then propose the sustainable strategy for water demand management to achieve the goal of sustainable development in the whole basin.

Key words system dynamics; water demand forecasting; water management; climate change; Tuwei River

INTRODUCTION

Human needs for water resources continue to grow with increasing population and economic development in past years (Butler, 2006). Data shows that total water use in China has increased 5.6 times from 1949 to 2007; this caused serious water shortage problems in past years. The government pays more attention to increasing the water supply to meet the growing demand. As future water demand will be affected by many factors, how to accurate future projection for the supply and demand of water is essential for the adoption of suitable alternatives to cope with such concerns (Frederick, 1997; Wang Xiaojun, 2009, 2011).

Studies on climate change and water problems have usually focused on the supply side, nowadays, water supply in the future is commonly estimated using General Circulation Models that consider climate change such as global warming, as to demand side, water demand in the future is estimated by considering the increase of unit demand of water that accompanies population growth and economic development (Frederick, 1997; Zhang, 2008). However, more and more research showed that warmer temperatures and drier conditions due to climate change will further increase future water demand in many regions, and affect the potential supply. Where climate change is associated with increased aridity, it would directly affect water demand with respect to agricultural and domestic uses. For example, outdoor domestic water uses (e.g. gardening and lawn watering) and drinking-water demand tends to increase in warmer, drier conditions (Frederick, 1997). In some cases, technological, restrictions and management changes may sufficiently increase water use efficiency to address the increased demand. Management changes that work to reduce the demand for water will also be important. Warming of surface waters would have a direct impact on industrial operations by decreasing the efficiency of cooling systems, which could in turn reduce plant outputs. A new research program, performed by consulting firm Tetra Tech for the Natural Resources Defense Council (NRDC), revealed the effects of global warming on water supply and demand in the contiguous United States. More than 1100 counties were studied, and one-third of all counties in the lower 48 will face higher risks of water shortages by mid-century as a result of global warming. More than 400 of these counties will face extremely high risks of water shortages, so the critical question is how to provide adequate water supply to meet world population growth and economic development (NRDC, 2010).

In this paper, we forecast future water demands and study the relationship between the projected population growth and the predicted future water uses for different water sectors by using the System Dynamics (SD) approach, based on the analysis of dynamic interactions among physical elements (natural runoff, groundwater recharge), environmental elements (water quality, ecosystem preservation) and socio-economic aspects (population growth, water consumption, policy and management) of water management in the regional water resources system. Through the analysis of multi-feedbacks and nonlinear interactions among system elements, a complex SD model was developed and applied in Tuwei River in the middle reaches of Yellow River using water demand theory. The practical verification of the model shows that the relative error is small; therefore the model is reasonably structured to mimic the actual situation. Furthermore, total water demand of the whole basin can also be forecasted under the future changes of population, economic and climate scenario, and then propose the sustainable strategy of water demand management to achieve the goal of sustainable development in the whole basin.

SYSTEM DYNAMICS MODELLING ON CLIMATE CHANGE AND WATER DEMAND

System Dynamics modelling

System Dynamics (SD) is a methodology and computer simulation modeling technique for framing, understanding, and discussing complex issues and problems by creating qualitative and quantitative causal models, which capture the inter-relationships of the physical (e.g. water inflows, outflows) and behavioural (e.g. decision rules, perceptions) processes in the system (Wolstenholme, 1990). It was originally developed by Prof. Jay Forrester of the Massachusetts Institute of Technology to help corporate managers improve their understanding of industrial processes, and is currently being used throughout the complex problems for policy analysis and design by modelling the causal structure deriving the problematic behaviour (e.g. cause-effect interrelationships, feedback loops, delays, nonlinearity) (Sterman, 1994, 2000).

SD also widely applied in water resource management. SD was considered to be an appropriate method to illustrate the complex dynamics and analyse the relative implications of regulatory policies. It is possible to link physical (temperature and precipitation patters, flood and drought flows, groundwater recharge), environmental (water quality, ecosystem preservation and health) and socio-economic (population growth, water and land use, policy and management) aspects of river basin management (Ahmad, 2000; Karavezyris, 2002; Chien-Hwa Yu, 2003; Ahmad, 2004; Zhang Hailun, 2005; Elmahdi, 2007; Zhang, 2008, Wang Xiaojun, 2011). The other strength of system dynamics 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. The modelling can help the user gain insight into situations of dynamic complexity, and reveal causes of policy resistance. In a word, with SD, a good understanding of the behaviour of the entire river basin system could be derived of its components and its interconnections, eventually leading to better and more effective management.

Model description

System Dynamics Modelling (SDM) is a methodology for studying and managing complex feedback systems, typically used when formal analytical models do not exist, but system simulation can be developed by linking a number of feedback mechanisms. To demonstrate the importance of feedback relationships in determining the behaviour of complex water systems, our model provides a feedback representation, in Fig. 1, of four crucial sectors: the external environment system (population growth, economic development and climate change) water supply system (reservoir water supply, diversion water supply, pump water supply, groundwater supply), water demand system (production water demand, domestic water demand, ecological water demand), and water price system (resource price, engineering price and environment price) (Wang Xiaojun, 2011).

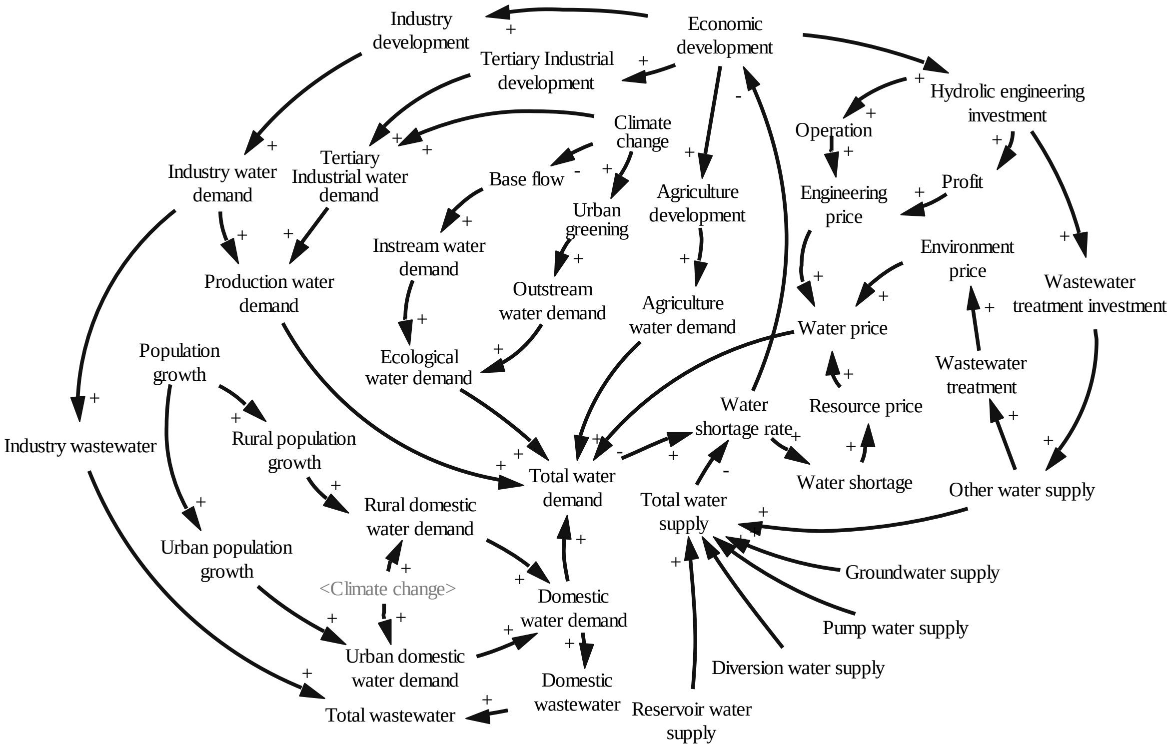

Fig. 1 The whole model feedback structure.

In Fig. 1, the positive or negative polarity associated with each arrow indicates the direction of change one model component imposes on the next. Positive relationships represent change in the same direction, where an increase/decrease in one sector causes an increase/decrease in the next sector, while negative relationships mean that change occurs in the opposite direction, so that an increase/decrease in one sector causes a decrease/increase in the next sector. The figure also presents the manner in which one model component influences the next. For example, with economic development, total water demand will increase, and this will accelerate the water shortage, and then will make the water manager focus on water supply side for essential water supply.

This paper focuses on the importance of feedbacks between these four sectors listed above; the linkage between them is the foundation for modelling. As there are many feedbacks loop between each element, we only present these five loops as an example:

L1: Economic Development→＋Industry Development→＋Industry Water Demand→＋Production Water Demand→＋Total Water Demand→＋Water Shortage Rate→－Economic Development.

L2: Economic Development→＋Agriculture Development→＋Agriculture Water Demand→＋Production Water Demand→＋Total Water Demand→＋Water Shortage Rate→－Economic Development.

L3: Population Growth→＋Urban Population Growth→＋Domestic Water Demand→＋Total Water Demand→＋Water Shortage Rate→＋Resource Price→＋Water Price→－Total Water Demand→－Water Shortage Rate→＋Economic Development.

L4: Climate Change→＋Tertiary Industry Development→＋Tertiary Industry Water Demand→＋Total Water Demand→＋Water Shortage Rate→－Water Supply→＋Water Price→－Total Water Demand→－Water Shortage Rate→＋Economic Development→＋Tertiary Industry Development.

L5: Climate Change→－Base Flow→＋Instream Water Demand→＋Ecological Water Demand→＋Total Water Demand→＋Water Shortage Rate→－Water Supply→＋Water

Price→－Total Water Demand→－Water Shortage Rate→＋Economic Development→＋Agriculture Development→＋Agriculture Water Demand→＋Production Water Demand→＋Total Water Demand→＋Water Shortage Rate→－Economic Development.

The equations and mathematical relationships between these sectors representing the feedback loops are also difficult. Here, we present population subsystem as an example (Fig. 2). Then the relationship between population growths can be written by the basic mathematical form of the Vensim modelling language (equations (1) and (2)).

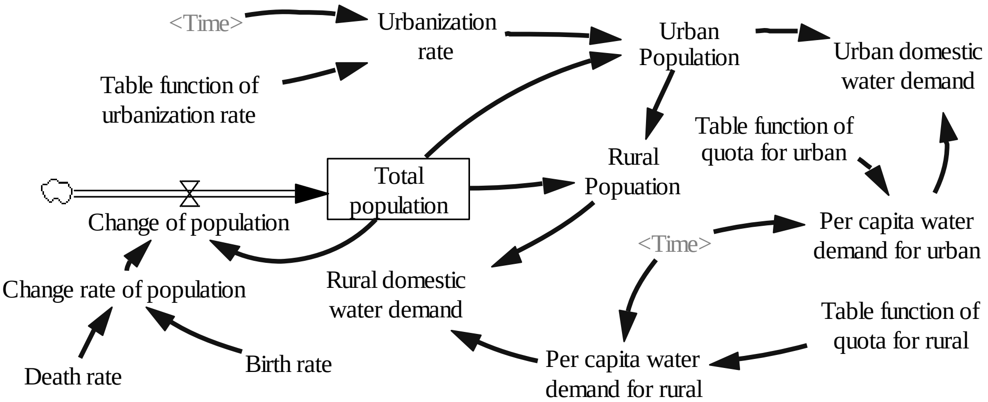

Fig. 2 Flow diagrams for population subsystem.

$$\begin{aligned}\frac{d}{dx}(Total\ population) &= (Change\ rate\ of\ \ population)\cdot Total\ population \\ &= (Birth\ rate - Death\ rate)\cdot Total\ population\end{aligned} \tag{1}$$

$$Total\ population = Urban\ population + Rural\ population \tag{2}$$

The water demand and population growth are linked through the following equations:

$$\begin{aligned} LW^{t} &= LuW^{t} + LrW^{t} \\ &= Pu^{t} \times LQu^{t} \times 365/1000 + \mathrm{Pr}^{t} \times LQr^{t} \times 365/1000 \end{aligned} \tag{3}$$

where, t is time, LW^t is the domestic water demand (10^4 m^3), which can be estimated by multiplying the projected population (10^4 p) with the projected per capita water consumption (l/p.d), and the methods is distinction for urban and rural area. As for urban population, urban water demand LuW^t is estimated by multiplying the urban population Pu^t (10^4 p) with the per capita water consumption for urban LQu^t (l/p.d), and for rural water demand LrW^t, it is estimated by multiplying the rural population Pr^t (10^4 p) with the per capita water consumption for rural LQr^t (l/p.d) (Zhang Hailun, 2005; Wang Xiaojun, 2011).

As to other sectors, they can also be written in the same way with equations, but one thing should mentioned, because there are so many parameters of the model, some of them are difficult to define, so we determine them through the experiences of researchers and comments of decision-makers, then with verification, we can use the model as a whole for the water resources planning and management (Zhang, 2008; Wang Xiaojun, 2011).

CASE STUDY

Study area

The model developed considers the Tuwei River as shown in Fig. 3. This small basin is located at latitude 38°10′–39°10′N and longitude 109°45′–110°35′ E, one of the regions suffering from serious soil erosion in the middle reaches of the Yellow River. The whole basin has a total drainage area of 3294 km^2. The annual average precipitation is about 380 mm, 75% of which is concentrated in June, July and August. The mean annual runoff is 3.79×10^8 m^3, equivalent to the mean runoff depth of 117 mm, the groundwater resources of the whole basin is 3.89×10^8 m^3, as the duplicative amount is 2.8×10^8 m^3, the gross mean annual potential of water resources is estimated at 4.88×10^8 m^3.

Fig. 3 Hydrological map of the Tuwei River basin.

Future scenarios for Tuwei River

The total population of Tuwei River was 23.13×10^4 in 2005, with most being in rural areas, so agriculture occupies an important place in the Tuwei River Watershed. With the population growth and industry development in the future, projections from Tuwei River water resources planning showed that the total population will increase to 26.60×10^4. In addition, with development of the chemistry industry, industrial output will also sharply increase to 58.90×10^8 Yuan; this will cause serious water shortage problems in the basin.

Also, historical time series records for the temperature and precipitation parameters from Gaojiachuan gauge stations showed that the temperature is always increasing in the whole basin.

Future climate change scenarios for the basin are based on the scenarios developed and studied by the National Climate Center for providing the data of their simulations by regional climate model. It provides a climate change database for three emissions scenarios, A1B, A2 and B1, respectively. In this case, we are using the temperature and precipitation parameters from the National Climate Center (Table 1).

Table 1 Future climate change scenarios for the Tuwei River.

Year	Temperature (°C)			Precipitation(mm)		
	B1	A2	A1B	B1	A2	A1B
2010	11.71	11.96	11.88	469	471	482
2020	12.11	12.03	11.87	457	487	437
2030	12.17	11.97	12.46	469	528	475

Water demand under the changing environment in Tuwei River

With the population growth, economic development and changing climate, total water demand of the Tuwei River will increase, and the results for the difference scenarios can be seen in Fig. 4.

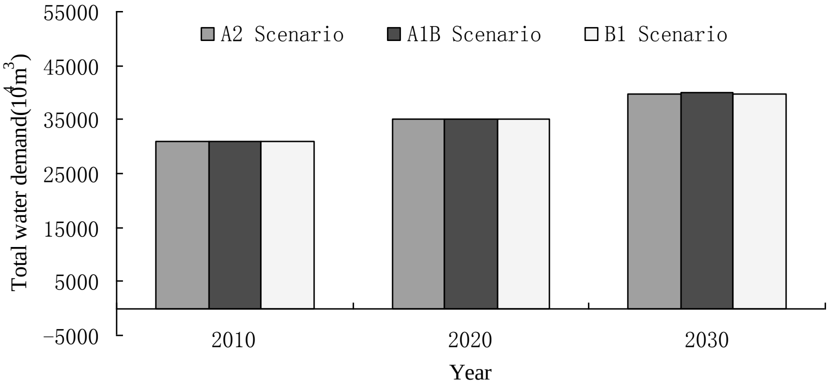

Fig. 4 Water demand under different climate scenarios.

From Fig. 4, we can see that under the A1B scenario, total water demand will be little higher than others because of the temperature increase. It can also be seen that with other scenarios B1 and A1B, the total water demand is 39 798 × 10^4 m^3 and 39 939 × 10^4 m^3, respectively. In 2030, this means with a temperature increase of 0.5°C, total water demand between them increasing to 141 × 10^4 m^3, which is nearly 3% of total water consumption of the whole basin in 2005. However, the increasing demand will lead to heavy stress on the supply side of this small watershed, and the situation should also be paid more attention in other large basins.

The future of water management for sustainability

The analysis shows that climate change will have significant impacts on total water demand of the whole basin. In 2030, if the temperature increases by 0.5°C, 141 × 10^4 m^3 of water will be difficult for the water managers to meet increasing demand because all of the available water of the river is already used; it would be difficult to find new sources.

As for new sources, there is no choice but to transfer water from the Yellow River, but the situation is that the Yellow River has dried up several times in recent years, so it is difficult to meet the growing demand. While water management and climate change adaptation plans will be essential to lessen the impacts, they cannot be expected to counter the effects of a warming climate. The water demand management as a new way for water management has been widely used all over the world, it aims to increase water efficiency through both wise use and reduction in use to reduce or to postpone the need to build more dams and drill more boreholes (Butler, 2006; Wang Xiaojun, 2009, 2011). Results show that water use efficiency greatly improved after the introduction of the water demand management programme. It is necessary for the Tuwei River to take water demand management measurements through a wide range of structural measures and non-structural measures due to the future changing climate.

CONCLUSIONS

This paper presents SD modelling for understanding and analysing the complex dynamics of climate change and water demand in the Tuwei River basin in northwest China. Simulation results show that with future changing climate the current management regime cannot maintain the socio-economic growth and ecological sustainability in the region. Instead, results indicate that a portfolio of demand management mechanisms and conservation measures is the most sustainable strategy for maintaining the economic and ecological status of the region.

Two considerations are noteworthy. First, with so many uncertainties in water demand under the future climate change, the paper only gives a new way of considering it; we propose this as an interesting point for future research. Second, water demand management as a new way for water management is widely used around the world, and the paper only suggested demand management as a way for solving water shortage problem in the basin; how to put this into practice should be a topic of further research.

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