Simulation of Urban Ecological Water Demand Using Multi-objective System Dynamic Model

Jing Du, Ling Xu, Shuo Wang, and Fenglin Yang

Abstract—**Water crisis has become the critical point in limiting cities' economical and social development nowadays. With the sharply increasing conflict of supply and demand of water resources, the prediction of ecological water demand is becoming an important part in urban water resource management. Thus, based on the overview of theories and methods for the calculation of urban ecological water demand, this paper introduces a multi-objective system dynamic model which combines system dynamic model with multi-ecosystem theory to simulate urban ecological water demand, with Dalian City, China as a case study. It is demonstrated that the proposed model can be an applicable and flexible method and it also provides an alternative approach for sustainable urban water utilization which can reconcile the conflict between urbanization process and water resource restraints.**

Index Terms—**Dalian City, multi-objective system dynamic mode, urban ecological water demand simulation, water sustainable utilization**

I. Introduction

Nowadays, aquatic ecological systems are suffering from not only water resource restraints but also multifunctional, intensive, and improper use of freshwater resources [1]. Thus, it is necessary to allocate a certain amount of water demand for sustainable development. People, however, usually only focus on the water resource demand of industry and lives, ignoring the ecological water demand (EWD). Simulation of EWD can be an effective means for water resources management, but it always gets unexpected results because of lack of data and simulation method limitation itself. The EWD concept, which portrays the ecological function as a fundamental aspect of water resources allocation with priorities can date back to 1940s. Now, there are a variety of definitions of EWD, and in a broad sense it refers to the water needed in maintaining the water balance of the earth biological, geographical, and ecological systems [2], while in a narrow sense, it refers to the water consumed in the stabilization and the protection of aquatic ecosystem, and the construction of artificial systems [3].

So far, models for EWD simulations, which are almost related to macroscopic water circulation and water balance, have largely been developed on the basis of hydrological and hydraulic calculations for river ecosystems, and the computational methods used are quite mature. For example, the Tennant method [4], the Wetted Perimeter method [5], the R2CROSS method [6], and in-stream flow incremental methodology (IFIM) [7]. Commonly used techniques are complex from the Tennant, which requires steam flow records alone, to IFIM, which explicitly accounts for the habitat requirements of individual species life-stages and physical characteristics of the stream [8]. Other methods such as R2CROSS and Wetted Perimeter which rely on in-stream conditions may be useful in further refining estimates of water availability. However, application of R2CROSS is somewhat subjective while the Wetted Perimeter method has no explicit representation of aquatic habitat.

Different from river ecosystems, environmental challenges faced by cities are more complex. Rapid economic growth, decentralization, privatization, and related socio-cultural changes are leading to the emergence of a complex decision making environment. New concepts and approaches are needed to find constructive solutions to water resource allocation issues in urban ecosystem. In recent years, the availability of data and tools in urban water demand forecasting field has increased dramatically, and because of it holistic analyses are conducted, which previously were difficult to accomplish. Tian et al. [9] forecasted domestic urban water demand by combining partial least squares regression and the grey model. Zou et al. [10] used second approach to combine the forecasting values from regression analysis model and from time series model. Wang et al. [11] proposed a combined forecasting method flexible enough to meet varying water consumption. However, urban ecological water demand (UEWD) which means the least water amount required to maintain the structure and the function of urban ecosystem was ignored in these simulation processes in which the water demand of industry and lives is largely focused on. This study sets out to test the usefulness of a multi-objective system dynamic (MOSD) model in this regard, particularly in simulating scenarios of UEWD, through an application to Dalian city, China.

II. Model and Studied Area

A. Generalities and Presentation of the MOSD Model

System dynamic model (SD model) [12] is an approach to understanding the behavior of complex systems. The basis of the method is the recognition that the structure of any system-circular, interlocking, sometimes time-delayed relationships among its components-is often just as important in determining its behavior as the individual components themselves. It deals with internal feedback loops and time delays that affect the behavior of the entire system. Thus, it can be flexibly applied in simulation of

Manuscript received September 9, 2010. This work was supported by the National Natural Science Foundation of China (No. 40801228), and the Fund of Water Pollution Control and Management Projects in the Eleventh Five-Year Plan of Chinese Government (No. 2009ZX07526-006).

Jing Du, Ling Xu, Shuo Wang and Fenglin Yang* are with Key Laboratory of Industrial Ecology and Environmental Engineering, MOE, Dalian University of Technology, China (corresponding author to provide phone:86-411-84706328;fax:86-411-84708083; e-mail: yangfl@dlut.edu.cn)

UEWD in urban complex ecosystem and its feedback loop elements can help describe how even seemingly simple systems display baffling nonlinearity.

The MOSD model was developed by combining system dynamic model which was proposed by Jay Forrester with multi-objective theory taking into account economic, social, and eco-environmental objectives. It operates at a simultaneous step on the basic principle of urban social-economic-natural complex ecosystem. Each branch systems are represented in terms of their various indicators of resources, costs, benefits and impacts.

B. Description Of The Studied Area

On the east coast of Eurasia and the southern tip of Liaodong peninsular in northeast China, Dalian stretches from 120º58' to 123º31' east longitude and 38º43' to 40º10' north latitude, with the Yellow Sea on the east, Bohai Sea on the west, facing the Shandong peninsular across the sea on the south and backed up by the vast Northeast Plain on the north. Dalian is the marine gateway of northeast China. There are mainly two large river systems, the Yellow Sea system and the Bohai Sea system. The large rivers which flow into the Yellow Sea are Biliu River, Yingna River, Zhuanghe River, Xiezi River, Dasha River, Dengsha River, Qingshui River, and Malan River, etc. while the main rivers which flow into the Bohai Sea are Fuzhou River, Li Guancun River, San Shilipu River. Among them, the largest one is Biliu River, the source river of cross-valley water diversion. In addition, there are more than 200 small rivers. The total amount of fresh water resource is 3.786 billion cubic meters, among which 3.42 billion cubic meters of water is ground water, 88.4 million cubic meters of water is underground water and 58 million cubic meters of water is shared by them both. The distribution of water resource in studied area is shown in fig.1.

Permanent population of Dalian at the end of the year 2009 totaled 6.17 million. The total registered population based on households was 584.8 thousand, with a net increase of 14 thousand over the previous year, of which the non-farming population was 357.8 million, accounting for 61.2 percent. The immigrant population from other provinces and cities was 69 thousand, for which mechanical growth was the dominant factor. The population birth rate and death rate was 6.73 and 5.56 respectively, with the population of newborn 39 thousand, and population natural growth rate at 1.17; gender ratio at birth was within the normal range. The rate of birth was in compliance with policies at 99.94 percent, the comprehensive contraceptive rate was 82.97 percent and the deferred marriage rate was 89.72 percent.

Comprehensive economic strength continued to improve. Preliminary estimation indicated that Dalian's GDP in 2008 grew to 385.82 billion yuan, representing a 16.5 percent increase over the previous year calculated at constant prices. Of the total, the added value of primary industry was 28.91 billion yuan, up by 8.1 percent; that of secondary industry 199.39 billion yuan, up by 19.6 percent; tertiary industry 157.52 billion yuan, up by 14.4 percent. The proportion of three industries was 7.5:51.7:40.8 and the ratios of their contributions to economic growth were 3.6 percent, 58.3 percent and 38.1 percent respectively. If calculated according to the average permanent population, the per capita GDP of Dalian was 63,198 yuan, equivalent to USD 9,099 converted at the average exchange rate of 2008.

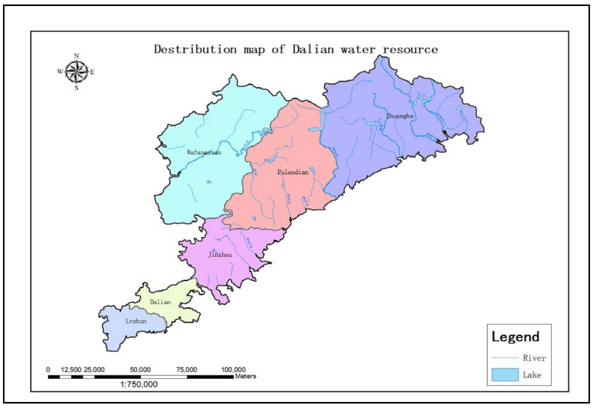

Figure 1. Distribution map of Dalian water resource

C. Setting Up The Mosd Model For Dalian City

The first step, focusing on the model purpose-the simulation of UEWD of Dalian city and defining the model boundary involves selecting components necessary to generate the behavior of interest as set by the model purpose, and then identify key variables. In our MOSD model, branch systems are defined as social system, environmental system and economic system and key parameters for branch systems are population for social system, green area water consumption for eco-environmental system and GDP for economic system respectively. The key parameters are influenced by corresponding variables, for example, the variables of population parameter in MOSD model are set as population reduce and population increase represented by death rate, immigrant output rate and birth rate, immigrant input rate as historical reference modes. Then, the final step in conceptualization is deciding on the basic mechanisms (feedback loops) of the urban social-economic-natural complex ecosystem. Fig. 2 shows the final MOSD model for Dalian city UEWD simulation. Use STELLA 9 (Isee Technology Inc.) software to build up this simulation Model.

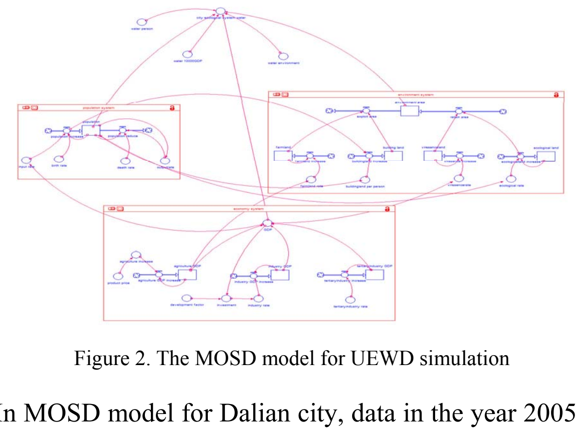

Figure 2. The MOSD model for UEWD simulation

In MOSD model for Dalian city, data in the year 2005 are defined as reference data, while those in the year 2006~2008 are test data. Related data are obtained from statistical annual and water resource investigation bulletin of Dalian City. (TABLEI,TABLE II)

TABLE I. DEMOGRAPHIC DATA OF DALIAN CITY IN 2005

Administrative Divisions	Population
Dalian City	5720810
Zhongshan district	351648
Xigang district	308252
Sha Heko district	652638
Gan Jingzi district	654655
Lu Shunkou district	207619
Jinzhou district	702294
Changhai county	74303
Wa Fangdian city	1025805
Pu Landian city	824974
Zhuanghe city	918622

TABLE II. WATER RESOURCES DATA OF DALIAN CITY FROM 2005 TO 2008

Year	water consumption per capita (m^3)	water consumption per ten-thousand-yuan GDP (m^3)	Total water consumption (billion m^3)
2005	205	51	1.158
2006	200	45	1.145
2007	212	39	1.226
2008	223	34	1.302

Input data into the MOSD model for UEWD simulation, the trend of population, GDP and Green area from 2005 to 2013 is forecasted as shown in the fig. 3, fig.4, fig.5.

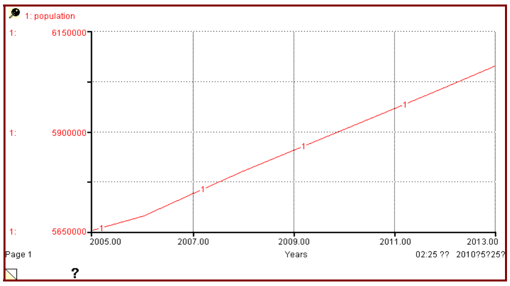

Figure 3. Population prediction curve of Dalian city until 2013

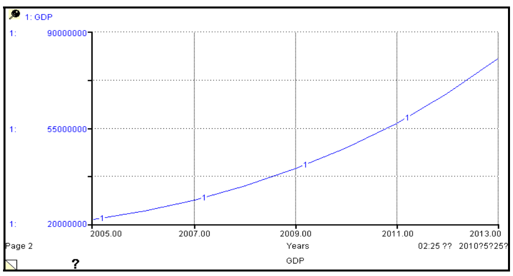

Figure 4. GDP prediction curve of Dalian city until 2013

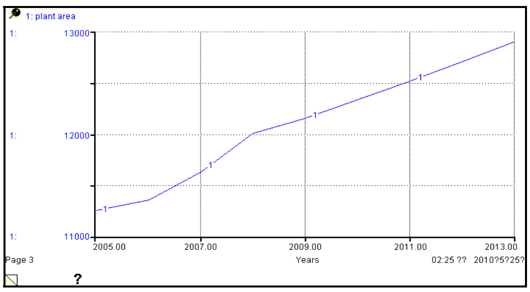

Figure 5 Green area prediction curve of Dalian city until 2013

III. RESULT AND DISCUSSION

A. Actual And Forecast Data Comparison

By comparing the actual data with forecast data from 2005 to 2008, the preliminary result shows that actual UEWD and forecast data are almost the same in the year 2005 and 2006, and actual data are a little bit greater than forecast UEWD data in the year 2007 and 2008 but the error of simulation is within the range of allowance (fig.6).

B. Scenario Analysis

According to calculated data, it can be forecasted that the registered population will reach 6.06 million, GDP will be above 800 billion yuan, and water consumption will exceed 2.47 billion cubic meters which is obviously more than Dalian water resource carrying capacity by the end of the year 2013. As a result, socio-economic development mode and water resource utilization system should be correspondingly changed as Dalian already being a water deficient urban area.

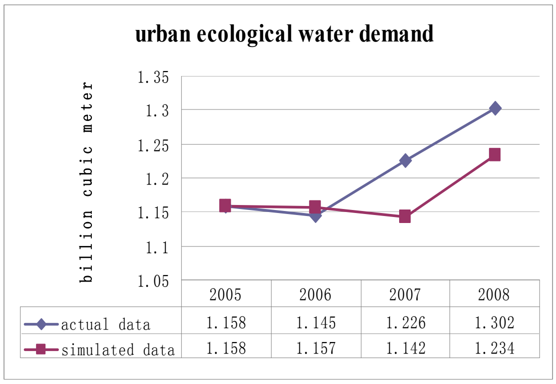

Figure 6. Actual and simulated data comparison of UEWD

Change variables in different parameters by different policies as follows to simulate UEWD again:

1) Population parameter: Keep birth rate of population balanced growth, and strict restrict immigration input to reduce mechanical growth rate of population simultaneously. Reduce the immigration input rate from 0.014 (2008) to 0.010 as a target. (scenario 1)
2) Economic parameter: Mitigate the rate of economic development by reducing GDP growth rate from 17% (2008) to 12%. (scenario 2)
3) Environment parameter: Strengthen rational water consumption consciousness, and restrict water consumption per capita and water consumption per ten-thousand-yuan GDP. Reduce water consumption per capita to 200 cubic meters and water consumption per ten-thousand-yuan GDP to 25 cubic meters. (scenario 3)

The trends of UEWD under three different policies can be clearly seen from the calculation results, which are shown in fig.7, fig.8, fig.9. There is no obvious change of UEWD with the application of population control policy. When using the control policy of economic development, with the decline in GDP growth rate, the UEWD takes on descending trend, but also for economic development speed. When adopting environmental policy which restricts water consumption per capita and water consumption per ten-thousand-yuan GDP, UEWD is declining sharply, while there is no great impact to urban development at the same time. The simulation result of the scenario 3 can be concluded in table III. According to table III, the registered will reach 6.06 million, GDP will be exceed 800 billion yuan, and total UEWD will be controlled in 1.73 billion cubic meters, reducing about 0.7 billion cubic meters water demand compared with original forecast data. Thus, policy of water resource sustainable utilization in cities through advocacy, technology and other means to reduce water consumption per capita and water consumption per ten-thousand-yuan GDP can be the best choice for water deficient urban areas such as Dalian city.

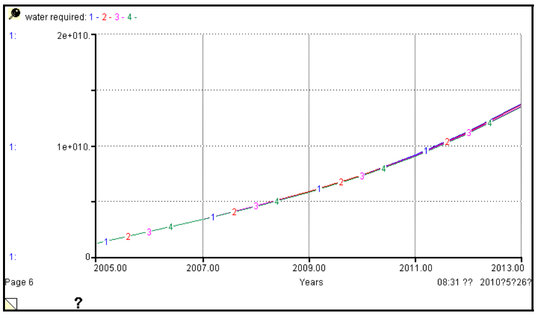

Figure 7. UEWD simulation under Scenario 1

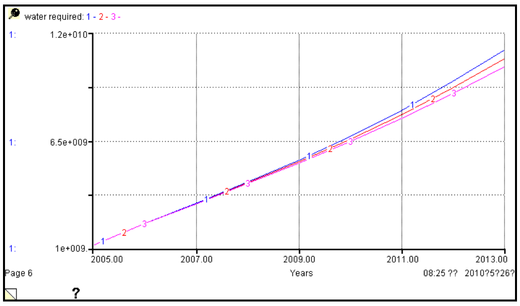

Figure 8. UEWD simulation under Scenario 2

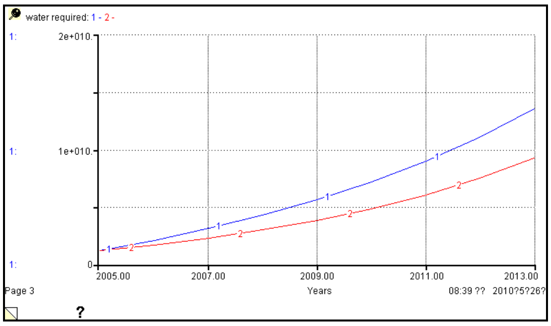

Figure 9. UEWD simulation under Scenario 3

TABLE III. THE SIMULATION RESULT OF SCENARIO 3

Year	**Population**	**GDP (billion yuan)**	**UEWD (billion m^3)**
2009	5852380	400.6961016	0.846
2010	5904174	476.4276648	1.015
2011	5956426	566.4724934	1.215
2012	6009140	673.8357947	1.45
2013	6062321	800.8340599	1.728

IV. CONCLUSION

Since water crisis has become more serious in the last few decades, a UEWD simulation model which combines system dynamic model with multi-objective theory taking into account economic, social, and eco-environmental objectives is proposed. According to the forecast data, it can be concluded that the MOSD model operates well and it is applicable and flexible. Three more UEWD data are simulated under three different scenarios by changing certain variables and according to the results, policy of water resource sustainable utilization in cities can be the best choice for water deficient urban areas rather than another two policies. Moreover, further study is required to quantity the objective that directly reflects the parameters and the proposed model and solution method can be introduced into a geographic information system (GIS) to set up a visual management information system for urban water management.

REFERENCES

[1] A. Schneiders, C. Wils, R. Verheyen, The use of ecological information in the selection of quality objectives for river conservation and restoration in Flanders (Belgium), Aquatic Ecosystem Health and Management, vol. 2, 1999, pp. 137–154.

[2] X.L. Su, S.Z Kang, Concept of Ecological Water Requirement and its Estimation Method, *Advances in Water Science*, vol. 14, Issue. 6, 2003, pp. 740-744.

[3] Y.M. Wang, X.D. Zhou, Research Development of Ecological Water Demand for Watershed, *Journal of Soil and Water Conservation*, vol. 16, Issue. 6, 2002, pp. 142-144.

[4] D.L. Tennant, Instream flow regimens for fish, wildlife, recreation and related environmental resources, *Fisheries* 1, 1976, pp. 6–10.

[5] J. O'Keeffe, D.A. Hughes, R. Tharme, Linking ecological responses to altered flows, for use in environmental flow assessments: the Flow Stressor-Response method, *Verhandlungen Internationale Vereinigung Limnologie,* vol.28, 2002, pp. 84–92.

[6] M.P. Mosely, The effect of changing discharge on channel morphology and instream uses and in Ohau River, New Zealand, *Water Resources Researches*, vol.18, 1982, pp. 800–812.

[7] J. H. Cho, S. K. Seok, H. S. Ryong, A river water quality management model for optimizing regional wastewater treatment using a genetic algorithm, *Journal of Environmental Management*, vol.73, Issue.3, 2004, pp. 229–242.

[8] A.H. Arthington, S.E. Bunn, N.L. Poff, R.J. Naiman, The challenge of providing environmental flow rules to sustain river systems, *Ecological Applications*, vol. 16, Issue. 4, 2006, pp. 1311–1318.

[9] Y.M. Tian, Y. Wang, H.Y. Chi, Urban domestic water demand forecasting by combining partial least squares regression and grey model, *Journal of Tianjin University*, vol.37, Issue. 4, 2004, pp. 322–325.

[10] G.Y. Zou, H.F. Wang, D.W. Wang, Urban water consumption forecast based on neural network model, *Information and Control*, vol. 33, Issue. 3, 2004, pp. 364–368.

[11] X.L. Wang, Y.F. Sun, L.G. Song, C. S. Meid, An eco-environmental water demand based model for optimising water resources using hybrid genetic simulated annealing algorithms, Part I. Model development, *Journal of Environmental Management*, Vol, 90, Issue. 8, June 2009, pp. 2628-2635

[12] J. Forrester, Industrial Dynamics--A Major Breakthrough for Decision Makers, *Havard Business Review*, vol.36, Issue.4, 1958, pp.37-66