EVALUATION OF WATER STRATEGIES FOR WATER SHORTAGE CONSIDERING CLIMATE CHANGE BY SYSTEM DYNAMICS

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ABSTRACT

The demand for water at the central part of Taiwan has increased significantly in recent years owing to the development of Central Taiwan Science Park (CTSP) and increasing living standards. Therefore, appropriate planning is urgent strategies to avoid water shortage in the future. The major indexes for planning a successful water strategy in Taiwan are water shortages index, a total financial cost (consist of construction and operating cost) and intensity of surface water use. Therefore, the purpose of this study is to formulate an appropriate strategy to seek a balance among mitigating water shortages, total financial cost, and intensity of surface water use using a system dynamics approach. Besides, we design several scenarios of model simulation under different inflow decreasing rate to understand the impact of climate change for our water supply system. Finally, the effectiveness of the proposed methodology is verified by solving a problem of water shortage in central Taiwan.

Key Words: Water shortage, System dynamics, Water supply

INTRODUCTION

The conventional system approach to water problems has been to simulate, optimize, or choose a compromise alternative solution based on trade-offs between conflicting objectives. It is not easy to understand the cause and the chain reaction of policy decisions only by the outcomes of simulation models or a compromise alternative solution based on trade-offs between conflicting objectives from optimization techniques. Furthermore, if dynamic behavior arises from feedback within the system, it is likely that the problems might worsen through time. This is similar to the issue of water shortage that can be represented as a problematic trend over time and finding effective strategy interventions usually requires understanding of the system structure. System dynamics is one approach that can help decision makers to realize the structure and characteristics of a complex system. This approach, initially developed by Jay W. Forrester (Forrester 1961), uses a perspective based on information feedback and mutual or recursive causality to understand the dynamics of complex physical, biological, social, and other systems. The work of concept establishment is implemented through the procedures of problem definition, system description and causal

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feedback loop drawing. Problem definition is to find one or more key variables whose behavior over time defines the problem. Describing the system means identifying the system structure that appears to be generating the problematic trend. A causal feedback loop diagram provides an understanding of the nature of the impact dynamics and feedback. It shows the technique to portray the information feedback in a system. Then a system dynamics model (also called stock-flow diagram) can be designed and developed with four objects: stocks, flows, converters and connectors that refer to the above concept of problem solving. Finally, simulating the system dynamics model shows the effect of the system structure on strategy interventions.

The demand for water at the central part of Taiwan has increased significantly in recent years owing to the development of Central Taiwan Science Park (CTSP) and increasing living standards. Therefore, appropriate planning is urgent strategies to avoid water shortage in the future. Consequently, in order to solve the water shortage problem whose behavior is governed by feedback relationships and has a long-term time horizon, only the study of the whole system as a feedback system will lead to find appropriate solutions.

On the other hands, the impact of the climate change to the environment and human being is well known to be one of the most challenge issues, and it definitely worth the effort to study that. Since most of the climate change study are in large or global scale, to quantify the climate change in the study area still requires a lot of research work. Hence, to address this issue without get too much detail into that, a sensitivity of the change of inflow. From above, we design several scenarios of model simulation under different inflow decreasing rate to understand the impact of climate change for our water supply system. Finally, the effectiveness of the proposed methodology is verified by solving a problem of water shortage in central Taiwan.

APPLICATION

Located in central Taiwan, the study region covers two major watersheds, Tachia River and Taan River, and one metropolitan area, Taichung. Tachia River is a main river in central Taiwan. The utilization of water resources in the Tachia River is very intensive and the basin is the main source for water supply, power generation and irrigation in the Taichung area. Important water resource facilities along the River include Techi Reservoir with an effective storage capacity of 169.19×10^6 m^3 and Shigang Dam with an effective storage capacity of 750×10^3 m^3. Major usages of water are for power generation, industrial use and domestic use. Fengyuan water purification treatment plant is located downstream from the Techi Reservoir, and Shigang Dam on Tachia River is also a source of public water supply to Taichung. Another water source is Taan River near the Tachia River. The important water resource facilities along the Taan River include Liyutan Reservoir with an effective storage capacity of 122.78×10^6 m^3 and Shihlin Dam with an effective storage capacity of 1.15×10^6 m^3. They serve to provide water supply for domestic, industrial and agricultural uses in the region including Taichung and Miaoli. Liyutan water purification treatment plant is located downstream from the Liyutan Reservoir and Shihlin Dam and is also a public water supply source (Water Resources Agency, 2005). As depicted in Figure 1, public water supply of Taichung is obtained from Fengyuan water purification treatment plant and Liyutan water purification treatment plant.

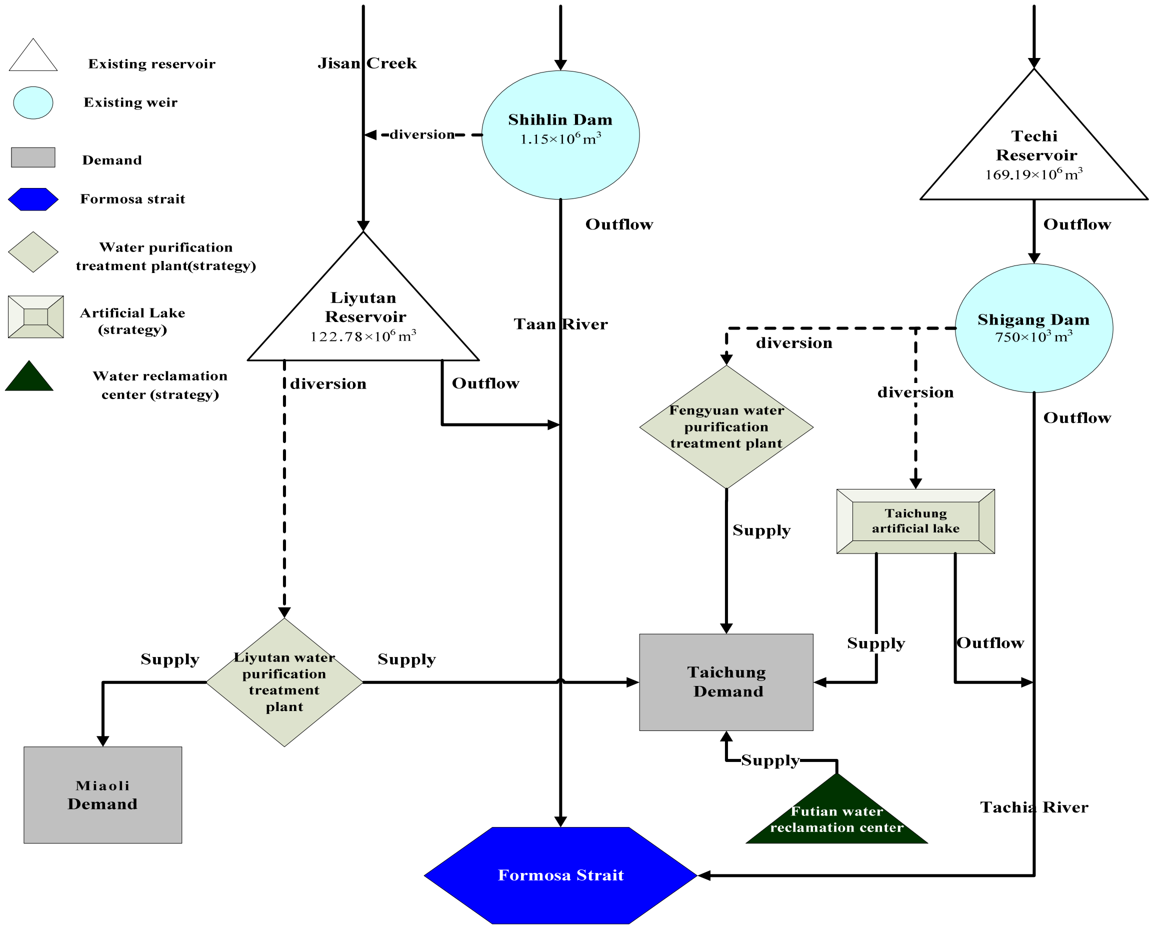

Fig. 1 System diagram of the study area

The system dynamics simulation tool adopted in this investigation contains objects for denoting the system structure of concept building: stocks, flows, converters and connectors. Stocks (name) represent 'how things are,' with accumulations serving as resources. Flows, which represent 'how things are going', are used to represent components whose values are measured as rates. The symbol represents an inflow and an outflow. It is easy to present the topology relation among the components in a water supply system by these two objects. Figures 2 display the system dynamics model in this study. In this figure, the rectangles are stocks that graphically represent the volume of water present within a dam, reservoir, artificial lake, and water reclamation center. The concept of our proposed model is as follows. The state of system is compared to the goal. If there is a discrepancy between the goal and actual outcome, corrective action is initiated to bring the state closer to the goal. Considering existing facilities, future water demand, water shortages, shortage index, the intensity of surface water, strategies (strategies in this paper are combination of Fengyuan and Liyutan water purification treatment plants, Futian water reclamation center, and Taichung artificial lake), total cost, the model can be built. Besides, the construction cost coefficients of Futian water reclamation center is 0.73 NT\$/m^3, with 1.0 NT\$/m^3 for the water purification treatment plant and 223.67 NT\$/m^3 for Taichung's artificial lake. The coefficients for the operating costs of Futian water reclamation center, Taichung artificial lake and water purification treatment plant are 0.36 NT\$/m^3, 10.96 NT\$/m^3 and 11.03 NT\$/m^3 respectively. Ten-day intervals are in a period, and the total simulated number of periods is 972 (equal to twenty-seven years; 2002-2029).

The shortage index (SI) developed by the U.S. Army Corps of Engineers is commonly adopted to reflect the scale of water deficit in Taiwan. The shortage index is defined as Eq. (1).

$$SI = \frac{100}{N} \sum_{i=1}^{N} \left(\frac{Sh_i}{T_i} \right)^2 \qquad (1)$$

Where N = number of periods; Sh_i = shortage volume during the period i ; Ti = target demand during the period i and $\sum$ is the summation of the indicated values for all periods.

The intensity of surface water, defined as Eq. (2), reflects the status of the water resources depleted by human due to diverse water demands. A high value of the indicator indicates that the river's water resources is overused and may have a negative impact on the sustainability of river environment as a whole.

Intensity of surface water use (%) = (Total volume of annual surface water used/Total volume of annual available surface water) × 100% (2)

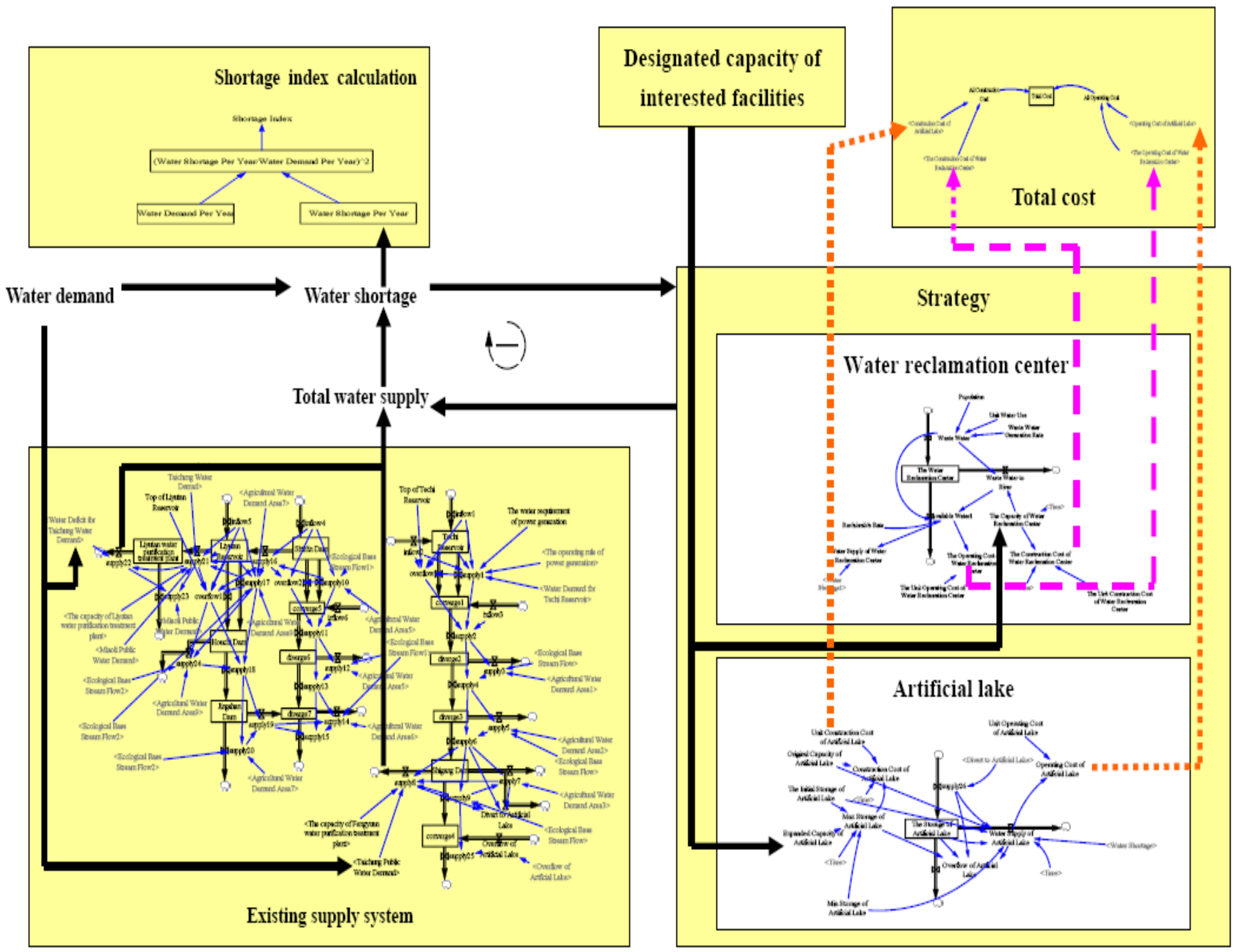

Fig. 2 System dynamics model of proposed causal feedback loop

In addition, an interface of decision supporting by Vensim was developed. This interface, as shown in Figure 3, includes slider bars for changing input values of a variety of strategies and output graphs that represent the status of the problems concerned.

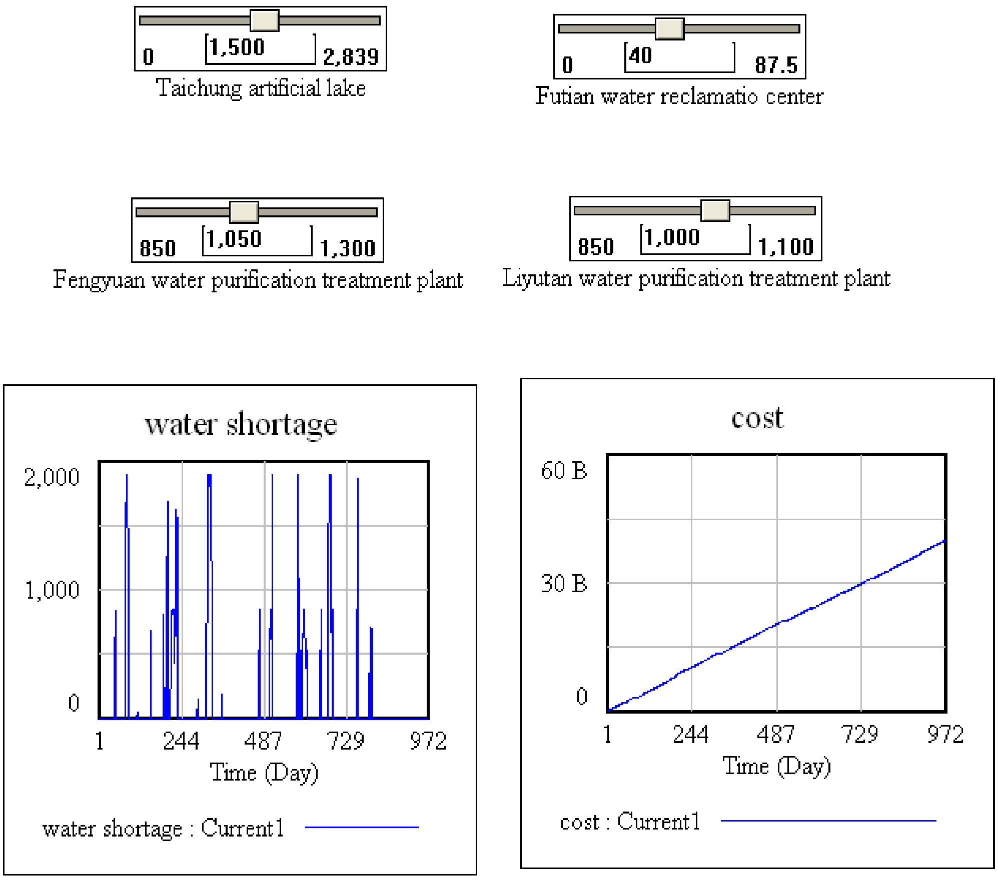

Fig. 3 The interface of decision supporting by Vensim

RESULT

In this case, if the SI is below 1.4, it reflects the water shortage problem is slight ("N") and same with the total cost below NT$50 billion. If the SI is over 2, it reflects the problem of water shortage is serious ("H") and same with the net benefit is over NT$60 billion. If the SI ranges between 1.4 and 2, it reflects the water shortage problem is medium ("M") and same with the net benefit ranges between NT$50 billion and NT$60 billion. For the intensity of surface water use over 0.62, the overuse of the river's water resource is serious ("H"). If the intensity of surface water use ranges between 0.5 and 0.62, it reflects the severity overuse problem is medium ("M"). If the intensity of surface water use is below 0.5, it reflects no overuse problem ("N").

The results of the scenarios analysis are showed in Table 1 and 2. From table 1, only the strategy 2 can satisfy our goal. To understand the impact of climate change for our water supply system, a sensitivity of the change of inflow to the considered indexes for strategy 2 was in Table 2. From table 2, the problem of water shortage is serious if the inflow decreasing rate is larger than 10%. Although the total cost still keeps low, the overuse of surface water increases gradually. Table 2 shows that we may still have enough money to reduce the water shortage, but increasing the water withdraw from the river is not a good alternative since the increasing intensity surface water use.

Table 1 The results of scenario analysis for the strategy

Strategy	SI	Problem of water shortage	Total cost (NT$ billion)	Problem of total cost	The intensity of surface water	Problem of overuse
1.Futian water reclamation center＋Taichung artificial lake	1.37	N	30.77	N	0.64	H
2.Fengyuan and Liyutan water purification treatment plants＋Futian water reclamation center	1.40	N	47.90	N	0.50	N
3.Fengyuan and Liyutan water purification treatment plants＋Taichung artificial lake	1.11	N	51.23	M	0.65	H
4.Fengyuan and Liyutan water purification treatment plants＋Futian water reclamation center ＋Taichung artificial lake	1.01	N	51.27	M	0.65	H

Table 2 The results of considering climate change for feasible solution (strategy 2)

Climate change factor	SI	Problem of water shortage	Total cost (NT$ billion)	Problem of total cost	The intensity of surface water	Problem of overuse
Original inflow	1.40	N	47.90	N	0.50	N
Inflow decrease 10%	2.42	H	44.10	N	0.55	M
Inflow decrease 20%	4.23	H	38.00	N	0.60	M
Inflow decrease 30%	7.34	H	33.17	N	0.65	H

CONCLUSIONS

We have demonstrated that system dynamics can quickly evaluate trends and cause-effect relationships in large-scale river basins and easily integrate interdisciplinary data, information, and criteria to support the better management decisions. Moreover, examining the performance of proposed indexes, we can understand the interactive impact among these objectives in every strategy and then select appropriate strategies.

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