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Application of System Dynamics with Impact Analysis to Solve the Problem of Water Shortages in Taiwan

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Abstract The major two concerns for planning a successful water strategy in Taiwan are the modification of water shortages and a total financial cost, construction, and operating costs. Therefore, the purpose of this study is to formulate an appropriate strategy to seek a balance between mitigating water shortages and total financial cost. Accordingly, we propose a process for combining a system dynamics approach and impact analysis to evaluate water strategy systematically and quantitatively. Water shortages and total financial cost are referred to, as governments are responsible for the management of regional water resources. System dynamics is one approach that can help decision makers build a simulation model of a complex water supply system. The value of a water shortage and total cost to all possible planning strategies for future water demand can be obtained from system dynamics model simulation. The content of proposed impact analysis is used to design indexes that are able to indicate (1) the severity of a water shortage and (2) total financial cost. Examining the performance of proposed indexes, we can understand the interactive impact between these two objectives in every strategy and then select appropriate strategies. Finally, the effectiveness of the proposed methodology is verified by solving a problem of water shortage and total financial cost in central Taiwan.

Keywords System dynamics · Impact analysis · Water shortage · Water resources planning

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1 Introduction

The sustainability of water resources plays a critical role in the future economic development of Taiwan because the occurrence of water shortages may strongly affect high-tech investment. Therefore, effectively managing water supplies is an essential government task. The major two concerns in planning a successful water strategy in Taiwan are the modification of water shortage and a total financial cost, construction, and operating costs. The conventional system analysis approach to water resources problems has been to simulate, optimize, or choose a compromise alternative solution based on trade-offs between conflicting objectives. It is difficult to pinpoint the cause of water shortages and the interaction between parameters when referring only to 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 (feedback refers to the situation of X affecting Y, and Y in turn affecting X, perhaps through a chain of causes and effects) within the system, it is likely that problems might worsen over time. This is similar to the issue of long-term water shortages that can be illustrated as a problematic trend over time. Finding effective strategy interventions requires an understanding of the system structure. In order to solve a water shortage problem whose behavior is governed by feedback relationships and has a long-term time horizon, only a comprehensive study of

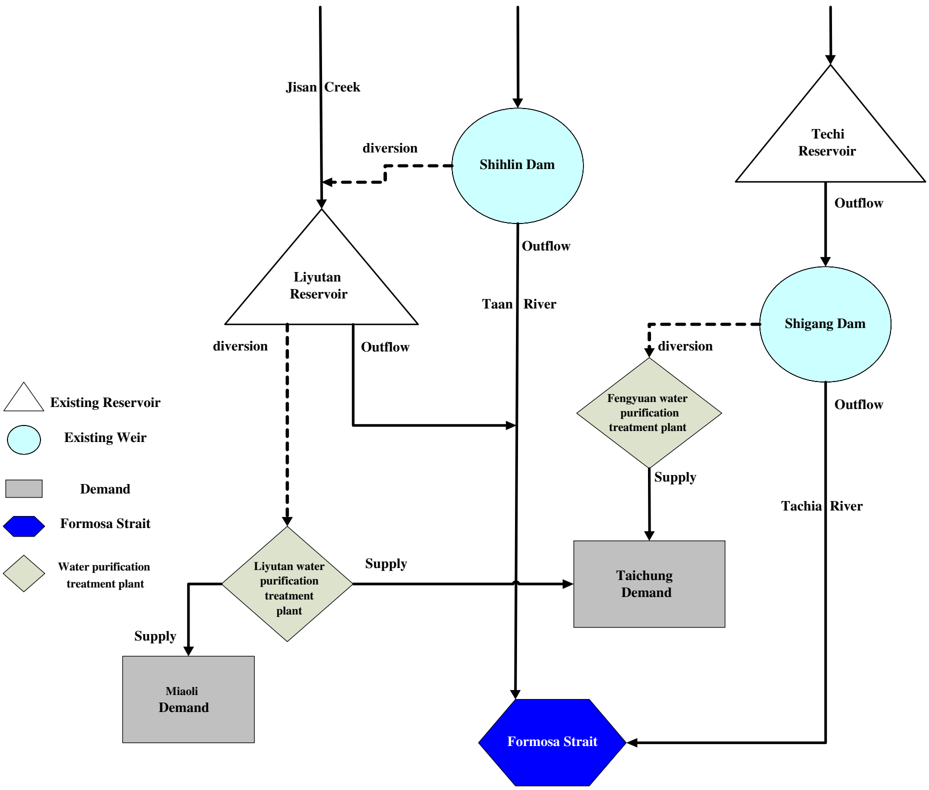


Fig. 1 System diagram of the study area

all the complexities involved, which means treating the system as a feedback system, will appropriate solutions be uncovered.

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. Recent applications of system dynamics approach in the field of water resources include the conjunctive use of surface water and ground water (Sehlke and Jacobson 2005), and long-term water resource planning and policy analysis (Simonovic and Fahmy 1997, 1999; Xu et al. 2002; Stave 2003).

A system dynamics model is proposed herein to simulate the work of water resources distribution in study area. After the completion of model simulation, the work of impact analysis is proceeding. The content of proposed impact analysis is used to design indexes that are able to indicate the severity of a water shortage and total financial cost. Examining the performance of proposed indexes, we can understand the interactive impact between these two objectives in every strategy and then select appropriate strategies. Therefore, the purpose of this study is to formulate an appropriate strategy to seek a balance between mitigating water shortages and total financial cost.

2 Methodology and Application

System thinking, the kernel of system dynamics, is a problem-solving concept that may clarify how to approach complex problems that affect or involve people and indicate the key feedback structures of the system. Establishing concepts is achieved by first defining a problem, describing the system, and drawing causal feedback loops. Then, a

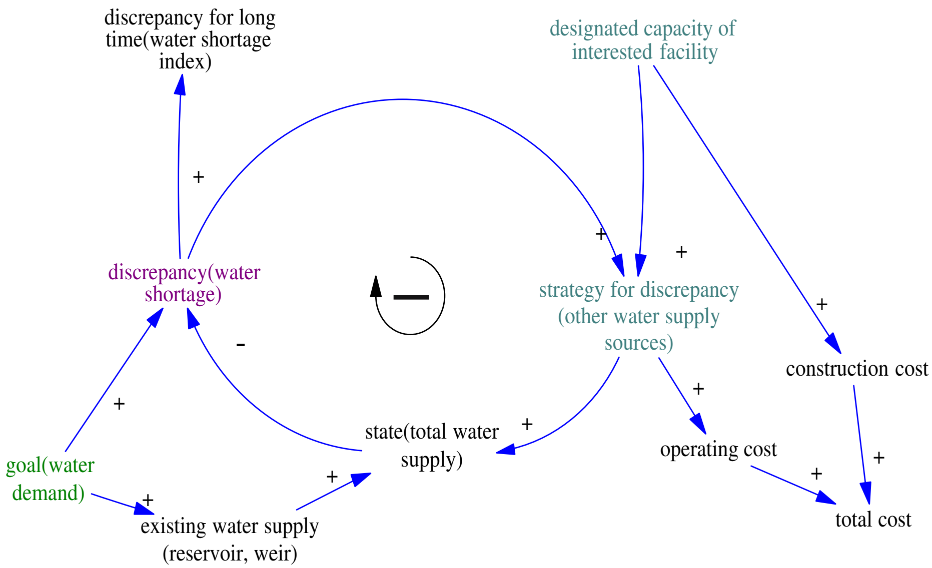


Fig. 2 Proposed causal feedback loop

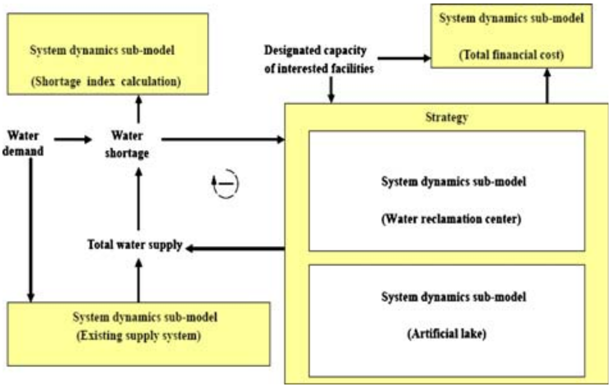


Fig. 3 System dynamics model of proposed causal feedback loop

system dynamics model can be designed and developed with four objects: stocks, flows, converters and connectors that refer to the above concept of problem solving. When the model structure has been validated via model confidence, it can be used to test strategy interventions on the problem. Finally, we can evaluate strategies with impact analysis and graph observation.

Demand for water in Taichung city has increased significantly in recent years owing to industrial growth and rising living standards. Therefore, planning appropriate strategies to avoid future water shortages is an essential government task. In light of this reason, Taichung city, located in central Taiwan, is our study area. Details of the proposed methodology are explained by a case study in Taichung city.

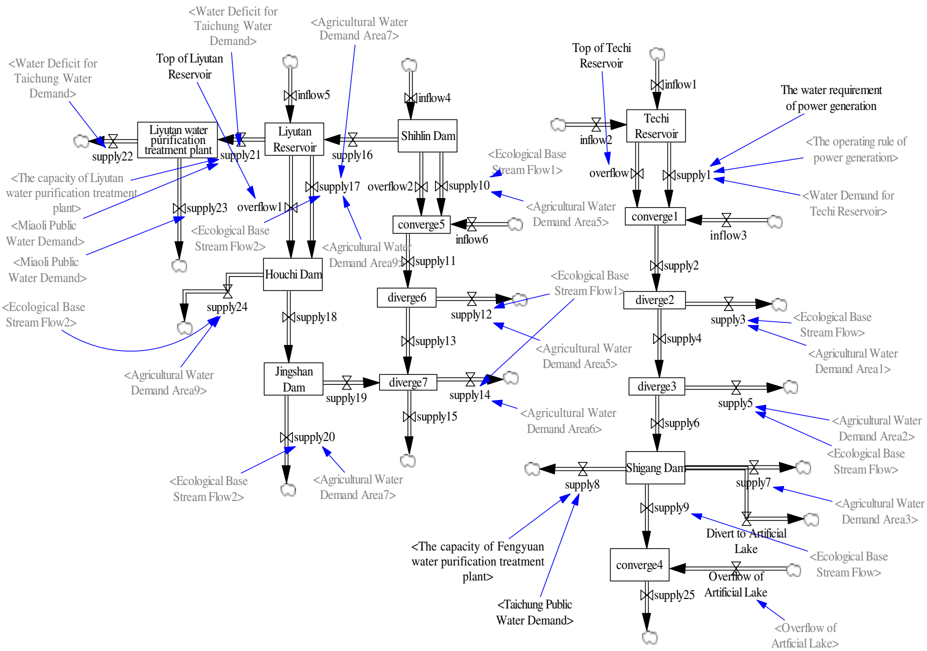


Fig. 4 Existing supply system dynamics model

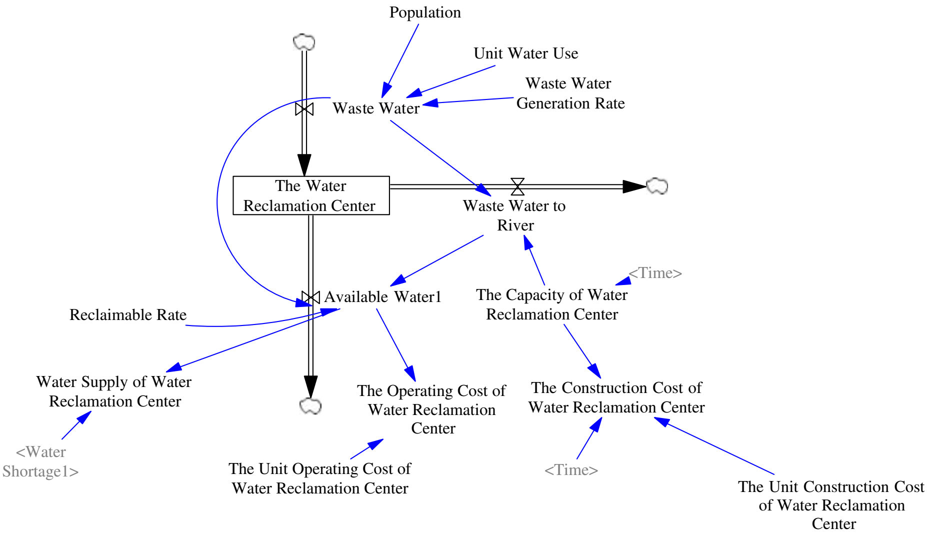


Fig. 5 Water reclamation center system dynamics model

2.1 Problem Definition

The shortage index (SI) developed by the US Army Corps of Engineers (Hsu 1995) is commonly adopted to reflect the scale of water deficit in Taiwan. The shortage index is defined as

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

Where N = number of periods; Sh_i = shortage volume during the period i; T_i = target demand during the period i and Σ is the summation of the indicated values for all periods. Ten days

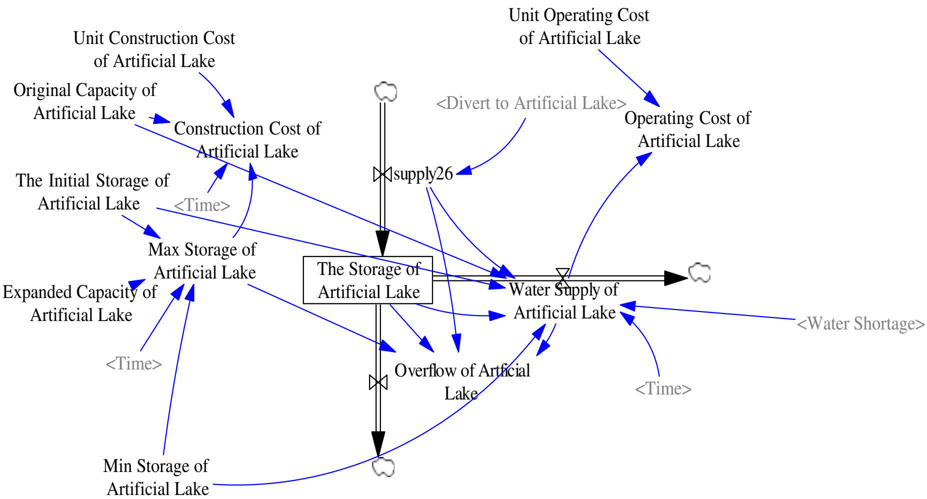


Fig. 6 Artificial lake system dynamics model

Table 1 The major objects of stock and flow in Tachia River

Major objects of stock and flow	Unit	Comment
Techi Reservoir	m^3	Water from the Techi Reservoir is mainly used for power generation, industrial use and domestic use
Inflow 1	m^3/10 days	Main flow in Tachia River
Inflow 2, 3	m^3/10 days	Tributary flow in Tachia River
Supply 1	m^3/10 days	The water supply of Techi Reservoir
Overflow	m^3/10 days	The overflow of Techi Reservoir
Converge 1	m^3	Merge with inflow 3; No storage, mass balance function present
Supply 2	m^3/10 days	The outflow of converge 1
Diverge 2	m^3	divide into supply 3 and supply 4
Supply 3	m^3/10 days	Supply to Agricultural Water Demand Area1
Supply 4	m^3/10 days	The outflow of diverge2; Requirement of Ecological Base Stream Flow needs to be met
Diverge 3	m^3	Divide into supply 5 and supply 6
Supply 5	m^3/10 days	Supply to Agricultural Water Demand Area2
Supply 6	m^3/10 days	The outflow of diverge3; Requirement of Ecological Base Stream Flow needs to be met
Shigang Dam	m^3	
Supply 7	m^3/10 days	Supply to Agricultural Water Demand Area3
Supply 8	m^3/10 days	Supply to Taichung Public Water Demand
Divert to artificial lake	m^3/10 days	The inflow of artificial lake
Supply 9	m^3/10 days	The outflow of Shigang Dam; Requirement of Ecological Base Stream Flow needs to be met
Converge 4	m^3	Merge with Overflow of Artificial Lake; No storage, mass balance function present
Overflow of Artificial Lake	m^3/10 days	The overflow of artificial lake
Supply 25	m^3/10 days	Flow into Formosa Strait

are taken as a period in our case study because 10-day intervals are normally used to simulate the performance of potential design alternatives for a long-term water resources planning in Taiwan.

The 2005 Water Resources Agency report indicated that the shortage index in Taichung city for 2002–2029 is 1, with a target public water demand of 1,638 m^3/10 days. Public water demand consists of water for industrial and domestic use, and is a proxy of regional economic growth. A shortage index value of one is acceptable to the Water Resources Agency. However, in order to be realistic, it is necessary to consider the shortage index when facing the target public water demand of 2,097 m^3/10 days because of the regional high economic growth. The value of shortage index is equal to 5.98 for the public water demand of 2,097 m^3/10 days. This value is significantly differs from the standard of SI=1–1.5. Therefore, how to plan suitable strategies to maintain a stable water supply for the target public water demand of 2,097 m^3/10 days is the foremost concern of this study. If all suggested strategies are implemented simultaneously, the problem of water shortage can be modified significantly. However, the financial impact of strategies must be assessed to enhance implementation feasibility. Consequently, another concerned problem in this study is the total financial cost, construction, and operating costs of all proposed strategies.

Table 2 The major objects of stock and flow in Taan River

Major objects of stock and flow	Unit	Comment
Shihlin Dam	m^3	
Inflow 4	m^3/10 days	Main flow in Taan River
Supply 16	m^3/10 days	Divert water to Liyutan Reservoir from Shihlin Dam
Supply 10	m^3/10 days	The reservation of discharge for Ecological Base Stream Flow1 and Agricultural Water Demand Area 5
Overflow 2	m^3/10 days	The overflow of Shihlin Dam
Inflow 6	m^3/10 days	Tributary flow in Taan River
Converge 5	m^3	Merge with inflow 6; No storage, mass balance function present
Supply 11	m^3/10 days	The outflow of converge 5
Diverge 6	m^3	Divide into supply 12 and supply 13
Supply 12	m^3/10 days	Supply to agricultural water demand area 5
Supply 13	m^3/10 days	The outflow of diverge 6; Requirement of ecological base stream flow 1 needs to be met
Diverge 7	m^3	Divide into supply 12 and supply 13
Supply 14	m^3/10 days	Supply to agricultural water demand area 6
Supply 15	m^3/10 days	Flow into Formosa Strait
Inflow 5	m^3/10 days	Main flow in Jisan Creek
Liyutan Reservoir	m^3	Supplies water for domestic, industrial and agricultural use in both the Taichung and Miaoli regions
Supply 21	m^3/10 days	Divert water to Liyutan water purification treatment plant from Liyutan Reservoir
Supply 17	m^3/10 days	Requirement of ecological base stream flow 2 needs to be met and agricultural water demand areas 7 and 9
Overflow1	m^3/10 days	The overflow of Liyutan Reservoir
Houchi Dam	m^3	
Supply 24	m^3/10 days	Supply to agricultural water demand area 9
Supply 6	m^3/10 days	The outflow of Houchi Dam; requirement of ecological base stream flow 2 needs to be met
Jingshan Dam	m^3	
Supply 20	m^3/10 days	Supply to agricultural water demand area 7
Supply 19	m^3/10 days	Divert the water to Taan River from Jingshan Dam
Liyutan water purification treatment plant	m^3	Divide into supply 22 and supply 23
Supply 22	m^3/10 days	Make up water deficit for Taichung water demand
Supply 23	m^3/10 days	Satisfy Miaoli public water demand

2.2 System Description

Located in central Taiwan, the study region covers two major watersheds: Tachia River and Taan River, and one metropolitan area, Taichung city. The utilization of water resources in the Tachia River is very intensive. 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. Water is mainly used for

Table 3 The major objects of stock and flow in Water reclamation center

Major objects of stock and flow	Unit	Comment
Waste water	m^3/10 days	The inflow of waste water at Futian water reclamation; waste water = unit water use × population × waste water generation rate
The Futian water reclamation center	m^3/10 days	The Futian water reclamation center is the most important water reuse facility in central Taiwan. The Futian water reclamation center has a water supply of 87.5 m^3/10 days, located at the downtown of Taichung
Available water	m^3/10 days	Available water is the quantity of reuse water which supplies to water deficit for Taichung water demand. The "waste water to river" and "reclaimable rate" affect strongly the scale of available water
Waste water to river	m^3/10 days	The overflow of waste water into a river at the Futian water reclamation center is decided by the capacity of center

power generation, industrial use and domestic use. Fengyuan water purification treatment plant is downstream Techi Reservoir and Shigang Dam. It is also a public water supply source to Taichung located along the Tachia River. Another water source is Taan River near the Tachia River. The important water resource facilities along the 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 for domestic, industrial and agricultural use in the region, which includes both Taichung and Miaoli. Liyutan water purification treatment plant, also a public water supply source, is located downstream Liyutan Reservoir and Shihlin Dam. As depicted in Fig. 1, Taichung's public water supply is obtained from Fengyuan water purification treatment plant and Liyutan water purification treatment plant.

Besides the capacity expansion of existing water purification treatment plants (Fengyuan and Liyutan) the establishment of an artificial lake and water reclamation center is also proposed according to government research reports (Water Resources Agency 2003, 2005a) to meet future public water demand in Taichung city. In order to replenish groundwater, provide public water, and to assist the infiltration rate, artificial lakes have been in operation for many years around the world. The artificial lake is a relatively new concept in Taiwan, so the Water Resources Agency has suggested a Taichung artificial lake be made, with an effective storage capacity of 28.39×10^6 m^3, located downstream Shigang Dam. In addition, improving water recycling and reuse is an important goal for water sustainability to the Taiwan Water Resources Agency. The agency is pushing for several works to encourage the

Table 4 The major objects of stock and flow in artificial lake

Major objects of stock and flow	Unit	Comment
Supply 26	m^3/10 days	The inflow of artificial lake. It is equal to the object of "divert to artificial lake" in Table 1
The storage of artificial lake	m^3	Taichung artificial lake with an effective storage capacity of 28.39×10^6 m^3, located downstream Shigang Dam
Water supply of artificial lake	m^3/10 days	Satisfy water deficit for Taichung water demand
Overflow of artificial lake	m^3/10 days	The overflow of artificial lake

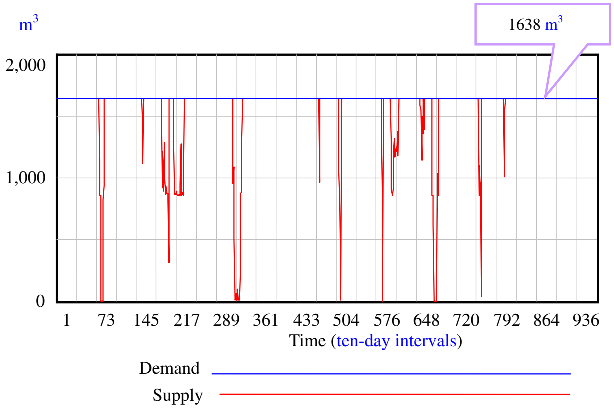


Fig. 7 The process of fulfilling the water demand of 1,638 m^3/10 days over time

recycling, reuse, and renewal (3Rs) of water. The Futian water reclamation center, with a water supply of 87.5 m^3/10 days located in downtown Taichung, is the most important water reuse facility in central Taiwan. Our proposed new facilities are the Taichung artificial lake and Futian water reclamation center.

2.3 Causal Feedback Loop

A causal feedback loop diagram facilitates an understanding of the impact dynamics and feedback to our concerned system. "Causal" refers to a cause-and-effect relationship. "+" on an arrow connecting two variables indicates the variable at the tail of the arrow causes a change in the variable at the head of the arrow in the same direction. "−" indicates a change in the opposite direction. The word "feedback loop" refers to a closed chain of cause-and-effect; a change in one variable among the loop feeds back to reinforce or slow down the initial change. There are two types of feedback loops. One is called positive, indicated by a "+" sign in parenthesis, if it contains an even number of negative causal links. The other is called negative, indicated by a "−" sign in parenthesis, if it contains an odd number of negative causal links. Positive feedback loops generate growth, amplify deviations, and reinforce change. Negative feedback loops seek balance, equilibrium, and stasis. Also, negative feedback loops act to bring the state of the system to approach a goal or desired

Fig. 8 The process of fulfilling the water demand of 2,097 m^3/10 days over time

Table 5 The classification of problem severity for each index

Definition of severity levels	Shortage index (SI)	Total cost
No (N)	<1.4	<NT$50 billion
Medium (M)	1.4<SI<2	NT$50 billion<total cost <NT$60 billion
Serious (H)	>2	>NT$60 billion

state (Sterman 2000). In light of those descriptions, the thinking of negative feedback loops is adopted in this study because the purpose of this study is to provide appropriate water supply strategies to meet future target public water demand.

The concept of our proposed causal feedback loop 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 or new facilities, future water demand, water shortages, shortage indexes, construction costs, operating costs referred to in the above concept, the causal feedback loop diagram can be built. The major variables affecting supply and demand and their connections are shown in Fig. 2. From Fig. 2, the first supply is the existing reservoirs and dams in Tachia River and Taan River. If the water supply of existing reservoirs and dams cannot meet the demand, there will be a water shortage and other facilities must be drawn upon. When the water shortage increases, the water supply from other facilities will increase. This will cause the total supply to rise, while the gap between demand and supply narrows. This process takes place in each simulated time step. The sign at the center of the loop based on the above thinking indicates that it is a negative feedback loop. The water supply changes in response to external sources, but also in response to changes in water shortages through the simulation of this mechanism, which anticipates changes in supply over time. Accordingly, this feedback loop represents the mechanism of water resources management in every time step.

2.4 Model Development

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 represent 'how things are,' with accumulations serving as resources. Flows, representing 'how things are going', are used to represent components whose values are measured as rates. Converters convey inputs into outputs. They can represent information or material quantities. Connectors link stocks to converters, stocks to flow regulators, and converters to other converters. They do not take on numerical values, they are transmitting them (Xu et al. 2002). Figures 3, 4, 5, 6 display the system dynamics model in this study. In these figures, the rectangles are stocks that graphically represent the volume of water

Table 6 The capacity setting of strategies

Strategies	The capacity setting of strategies
Taichung artificial lake	28.39×10^{6} m^3
Futian water reclamation center	87.5 m^3/10 days
Fengyuan and Liyutan water purification treatment plants	Fengyuan 1,300 m^3/10 days Liyutan 1,100 m^3/10 days

Table 7 The results of scenario for single strategy

Strategy	SI	Problem of water shortage	Total cost (NT$ billion)	Problem of total cost
Fengyuan and Liyutan water purification treatment plants	1.52	M	47.72	N
Futian water reclamation center	4.93	H	0.18	N
Taichung artificial lake	1.62	M	33.77	N

present within a dam, reservoir, artificial lake, and water reclamation center. The formulation of stock is shown in Eq. 2.

$$S_{t+1} = S_t + I_t - O_t \tag{2}$$

Where, S_{t+1} and S_t denote the storage of water supply facilities (dam, reservoir, artificial lake, and water reclamation center) at time $t+1$ and t respectively; I_t represents the amounts of inflow of water supply facilities at time t; O_t are the amounts of outflow of water supply facilities at time t.

The above-mentioned inflow and outflow of water supply facilities are belong to the object of flows. The converters are the rules controlling the stocks and flows in the model. A detailed description of stock and flow for our proposed water supply facilities is provided in Tables 1, 2, 3, 4.

2.5 Model Simulation

Our model was developed using the Vensim DSS Version 5.3 development tool (Ventana Systems Inc., Harvard, Massachusetts.) The sources of data or parameters for illustration are cited from several papers and websites related to water resources planning in Taiwan (Water Resources Agency 2003, 2005b; Hsu 1995). In these references, 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

Table 8 The results of scenario for combined strategy

Combined strategy	SI	Problem of water shortage	Total cost (NT$ billion)	Problem of total cost
Futian water reclamation center + Taichung artificial lake	1.37	N	30.77	N
Fengyuan and Liyutan water purification treatment plants + Futian water reclamation center	1.40	N	47.90	N
Fengyuan and Liyutan water purification treatment plants + Taichung artificial lake	1.11	N	51.23	M
Fengyuan and Liyutan water purification treatment plants + Futian water reclamation center + Taichung artificial lake	1.01	N	51.27	M

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 ine period, and the total number of periods is 972 (equal to 27 years; 2002–2029).

2.6 Model Confidence

The Water Resources Agency set the value of shortage index at 1 for 2002–2029 to meet target demand of 1,638 m^3/10 days for the moderate regional economic growth scenario. Its simulation includes a simplified assumption, assuming future inflow (2002–2029) to the system will be the same as previous historical inflow (1974–2001). With the same inflow and demand data, the value of shortage index is equal to 0.99 in our simulation by system dynamics model under no strategy. Figure 7 demonstrates that the water supply process intended to fulfill water demand of 1,638 m^3/10 days over time. Moreover, we calculate the value of shortage index when facing the target demand of 2,097 m^3/10 days for the high regional economic growth scenario and also obtain the value of 5.98. This indicates a very serious water shortage under the high regional economic growth. Figure 8 demonstrates that the water supply process to fulfill water demand of 2,097 m^3/ 10 days over time.

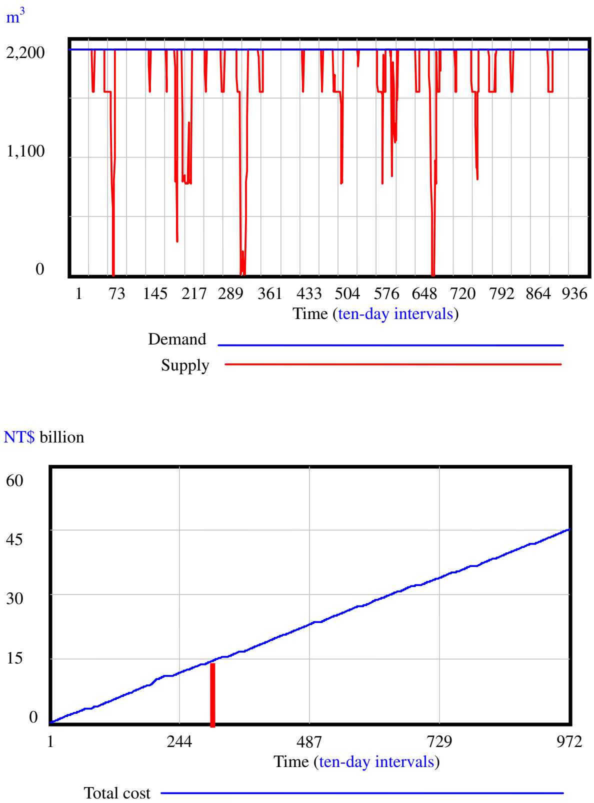
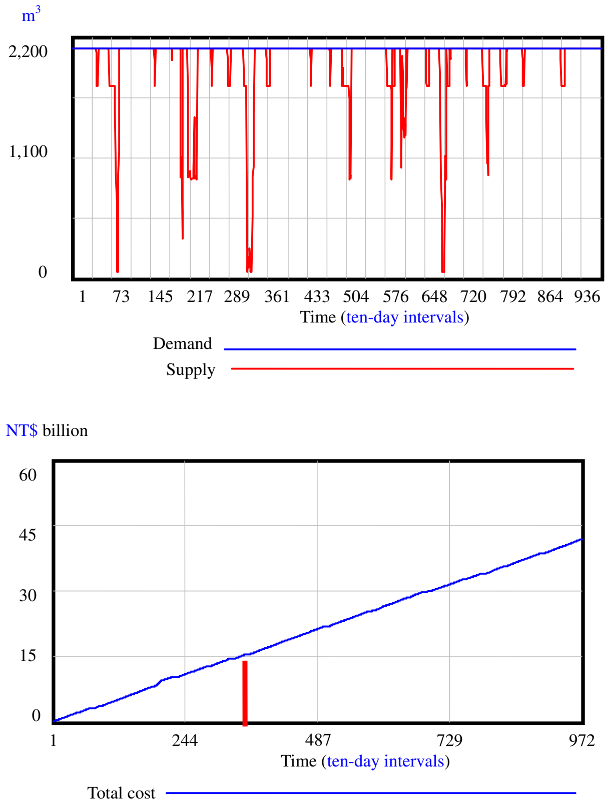


Fig. 9 The change of water shortage and total cost by time for combined strategy

Fig. 10 The change of water shortage and total cost by time for combined strategy 2



2.7 Impact Analysis

After the completion of model simulation, the values of water shortage and total financial cost of every scenario can be calculated and then evaluated using impact analysis. The content of proposed impact analysis is used to design indexes that are able to indicate the severity of a water shortage and total cost. Examining the performance of proposed indexes, we can understand the interactive impact between these two objectives in every strategy and then select appropriate strategies. 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. From Table 5, we can describe the interactive impact of these two problems when adopting various strategies and evaluate strategies under different considerations.

2.8 Scenario Results

The capacity setting of proposed strategies is shown in Table 6. There are two kinds of scenario simulation in this study: one is using a single strategy and another using a combined strategy.

1. Single strategy scenario First, we simulate under a single strategy establishment according to the concept of proposed causal feedback loops.

Table 9 The classification of problem severity for each index (including intensity of surface water use)

Definition of severity levels	Shortage index (SI)	Total cost	The intensity of surface water use
No (N)	≤1.4	≤NT$50 billion	≤0.5
Medium (M)	1.4<SI≤2	NT$50 billion<total cost≤NT$60 billion	0.5<The intensity of surface water≤0.62
Serious (H)	>2	>NT$60 billion	>0.62

Table 7 displays that the water shortage was significantly improved when the strategy of expanding the capacity of existing or new facilities is applied. Moreover, although the artificial lake and water purification treatment plant strategies are significant improvements in the performance of the water shortage index, SI values are still bigger than 1.4. It is clearly evident that a single strategy is not able to fulfill target demand even though total cost is not relatively lower.

2. Combined strategy scenario Table 8 shows the results of the combined strategy scenario, presenting two feasible strategies (combined strategies 1 and 2) which satisfy our goal. Although these two combined strategies are acceptable for our proposed definition, there will be consequences if we ignore water supply changes or accumulated total cost over time. Therefore, we draw the water shortage change and accumulated total cost over time according to acceptable strategies shown in Figs. 9 and 10. Through paired comparison, it is concluded that combined strategy 2 will avoid no water to be distributed in the water supply area in case of water shortage. Therefore, a rotation of the water supply within the area is possible. If the cost is NT$15 billion, the time to reach the target in combined strategy 1 is 2,500 days, and in combined strategy 2 almost 2,800 days. This information of time delay is useful for budget planning. In conclusion, these graphs are able to assist the government in formulating more appropriate decisions following impact analysis.

Table 10 The results of scenario analysis for the single strategy (including the intensity of surface water use)

Strategy	SI	Problem of water shortage	Total cost (NT$ billion)	Problem of total cost	The intensity of surface water	Problem of overuse
Fengyuan and Liyutan water purification treatment plants	1.52	M	47.72	N	0.51	M
Futian water reclamation center	4.93	H	0.18	N	0.44	N
Taichung artificial lake	1.62	M	33.77	N	0.64	H

Table 11 The results of scenario analysis for the combined strategy (including the intensity of surface water use)

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

2.9 Further Scenario Results

Although the objectives of water shortage and total financial cost are the most important concerns for Water Resources Agency, other objectives based on the existing variables of our system can be considered. For illustration, the intensity of surface water use is defined as the ratio of the total volume of annual water used to the total volume of annual river flow in Taiwan.

$$\begin{aligned}\text{Intensity of surface water use } (\%) = \text{Total volume of annual surface water used}/\\ \text{Total volume of annual available surface water}) \times 100\%\end{aligned} \tag{3}$$

This indicator 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 (Water Resources Agency 2005c). For example, there may be no enough river flow to dilute the discharged pollutants and strongly impact the river's ecology. The Water Resources Agency's report in 2004 suggested a criterion for the intensity of surface water use in the study area. 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). Accordingly, the Table 5 is modified as Table 9.

Table 12 The results of considering climate change for feasible solution (combined 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

The results of the scenarios analysis are showed in Tables 10 and 11. From Tables 10 and 11, only the combined strategy 2 can satisfy our goal. Due to the water resources of artificial lake is also from surface water, the intensity of surface water use is high in combined strategy 1 even though the value of SI and total financial cost are low comparing with the result of last scenario.

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. However, since this research is a quantitative study, to include the issue of climate change into this study, it is required to quantify the concept of climate change. 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. Therefore, to address the climate change in detail can not avoid a lot of discussion and will shift the focus of this paper. Hence, to address this issue without get too much detail into that, a sensitivity of the change of inflow to the considered indexes for combined strategy 2 was added in Table 12.

From Table 12, 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 12 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.

3 Conclusions

In this study, we propose a causal feedback loop corresponding to the concept of water resources management to solve a water shortage problem. Through the modeling of this loop a system dynamics model can be developed. After model confidence, the model can be used to test the effect of strategy interventions on the problem. Moreover, we cannot ignore the financial cost of strategy intervention because the government's budget is limited. According to total financial cost, the performance of strategies that involve capacity expansion of existing or new facilities can be evaluated. Therefore, the major purpose of our study is to formulate an appropriate strategy to seek a balance between mitigating water shortage and controlling cost. The major work of proposed impact analysis is to design indexes that are able to evaluate the situation. Examining the performance of proposed indexes, we can understand the interactive impact between these two objectives in every strategy and then select appropriate strategies. Even though these appropriate strategies can be accepted by decision makers, they must also take into consideration the factor of time. Therefore, variation of indexes under each strategy with respect to time is graphed to provide more useful information.

References

Forrester JW (1961) Industrial dynamics. Productivity Press, Cambridge, Massachusetts

Hsu S-K (1995) Shortage indices for water-resources planning in Taiwan. J Water Resour Plan Manage 121 (2):119–131

Sehlke G, Jacobson J (2005) System dynamics modeling of trans-boundary systems: the Bear River basin model. Ground Water 43(5):722–730

Simonovic SP, Fahmy H (1997) The use of object-oriented modeling for water resources planning in Egypt. Water Resour Manag 11:243–261

Simonovic SP, Fahmy H (1999) A new modeling approach for water resources policy analysis. Water Resour Res 35(1):295–304 (January)
Stave KA (2003) A system dynamics model to facilitate public understanding of water management options in Las Vegas. J Environ Manag 67:303–313
Sterman J (2000) Business dynamics: systems thinking and modeling for a complex world. McGraw-Hill, Boston, p 982
Water Resources Agency (2003) The potential evaluation of Futian water reclamation center. Taiwan. (In Chinese)
Water Resources Agency (2004) The assessment and computation of the indicators on sustainable development of water resources in Taiwan. Taipei, Taiwan. (In Chinese)
Water Resources Agency (2005a) The master plan of diversified water resources development in Taiwan. (In Chinese)
Water Resources Agency (2005b) The conjunctive use of water resources for Tachia and Taan river in Taiwan. (In Chinese)
Water Resources Agency (2005c) Chinese–English guidebook on the indicators of water resources sustainable development in Taiwan 2005. (In Chinese)
Water Resources Planning Commission (2005) The planning of Taichung Artificial Lake in Taiwan. (In Chinese)
Xu ZX, Takeuchi K, Ishidaira H, Zhang XW (2002) Sustainability analysis for yellow river water resources using the system dynamics approach. Water Resour Manag 16:239–261