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A System Dynamics Model for the Simulation of the Management of a Water Supply System

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Abstract. In this paper, a System Dynamics (SD) computer simulation model has been developed in this paper to aid the efficient management of water supply systems. To develop the SD computer model the conceptual framework for the working mechanism of water supply systems was established and, then, the causal feedback loop relationships among the components of the systems management including the management of water pipes were identified. Data from a water supply service in South Korea was used as a case study to validate the model structures. Some important indicators of the system under study were analyzed via management scenario simulations including development of an alternate water source. The principles of establishing the causal relationships used in the SD computer modeling are also expected to work as a prototype for modeling other water supply systems' management problems.

Keywords: Computer Model, Management, Simulation, System Dynamics, Water Supply.

1. Introduction

Due to the nature of water as public goods, many water supply services globally have been confronted with various problems, such as difficulties in the efficient operation of their systems, problems with management structure, and a lack of competence in the technical skills of the personnel. The water supply services in South Korea have also faced these problems and suffered from inefficient operation and poor finance.

Therefore, it is considered that understanding the components of the working mechanism of the systems, as well as the correlations between them, is essential to appropriately analyze the problems associated with water supply systems and establish policies that are appropriate for the problems of interest. A very useful and efficient methodology suited for modeling such multiple component systems, where these components influence each other, is the System Dynamics (SD).

In this paper, a SD computer simulation model has been developed in this paper to aid the efficient management of water supply systems. To develop the SD computer model the conceptual framework for the working mechanism of water supply systems was established and, then, the causal feedback loop relationships among the components of the systems management including the management of water pipes were identified.

Data from a water supply service in South Korea was used as a case study to validate the model structures. Some important indicators of the system under study were analyzed via management scenario simulations, with sensitivity analyses conducted on some major indicators of the case study system to illustrate the developed SD model able to facilitate the identification of policy leverage for achieving a

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specific management objective for a water supply system. The model was also used to assess the effects of developing and providing an alternate water source on the management of the water supply system in the case study area.

2. The System Dynamics Methodology

The System Dynamics Methodology is a simulation methodology based on systems theory. It deals with the interpretation of the dynamic nature of systems in which information and material feedbacks are present. The characteristics of systemic approaches adopted in the systems theory were well presented by Beard [1] in which 14 systemic ideas were provided, with each idea explained in terms of the associated philosophical concepts. The methodology can facilitate understanding of a system by extracting structures essential to its working mechanisms, and, based on an analysis of feedback structures inherent to the system, lead to development of efficient management strategies.

After Forrester [2] introduced the concept of SD to model systems with complex feedback structures, the applications of SD methodology have found many applications including the management of water supply service management. Grigg and Bryson [3] were the first to develop an SD model for the water supply system in Fort Collins, Colorado, which focused on controlling the price of water while meeting the water demand of the growing population. Lee et al. [4] presented an SD model, to model the dynamic nature of the water revenue ratio, supplying population and financial status of water supply businesses, and mainly analyzed the effects of transparency of operational and managerial status of a case water supply system. Lee et al. [5] modified the model of Lee et al. [4] to more comprehensively analyze managerial conditions of a case water supply system. A comprehensive review on the applications of SD methodology for water resource management problems can be found in Winz *et al*. [6].

Computer simulation models that are developed based on a system dynamics methodology are composed of four basic components: stocks, flows, converters, and interrelations among them, which are graphically represented as arrows and mathematically modeled as the finite difference equations. The value of each component is calculated at each *delta time* (*DT*) for a specified simulation time period defined in a model, starting at the initial values of the stocks, and based on the functional relations among components. Computer simulation experiments using a system dynamics methodology are realized using object-oriented modeling software such as Vensim, Powersim Studio, AnyLogic, STELLA, etc. Fig. 1 provides an example of a system dynamics computer model that shows a causal feedback loop diagram of a reservoir system with outflows and the corresponding stock-and-flow representation of the model using STELLA.

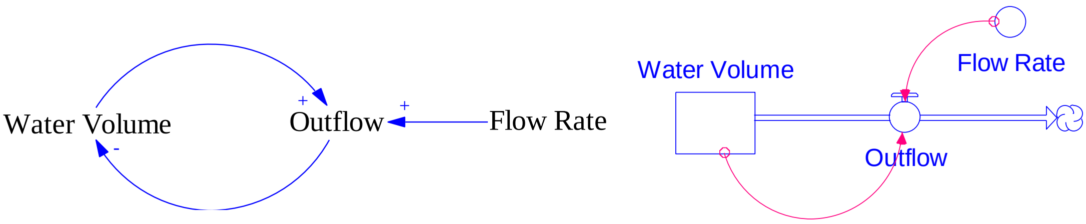

Fig. 1. A causal diagram and the corresponding stock-and-flow model using STELLA.

The plus ('+') sign in Fig. 1 implies that an effect is changed in the same direction as the cause. In other words, the plus sign indicates a situation in which an effect is increased when its cause is increased and vice versa. The minus sign ('-') represents the opposite, a situation in which the difference of the effects in the current and the previous time step is decreased when the cause is increased and vice versa. The finite difference equations generated by STELLA for the example model are shown in Table 1.

Table 1: Finite difference equations for the example model.

STOCKS	OUTFLOWS
Water_Volume(t) = Water_Volume(t-dt)+(-Out_Flow) $\times$ *dt*	*Out_Flow = Water_Volume* $\times$ *Flow_Rate*
INITIAL VALUE: *Water_Volume* = 50 [m^3]	*Flow_Rate* = 0.1 [m^3/hr/m^3]

3. The Causal Relationships of the Working Mechanism of Water Supply Systems Management

The goal of establishing the underlying causal relationships in water supply systems management was to identify key drivers of managerial action and the corresponding consequences of action. As a result, the fundamental working mechanism of a water supply system was established conceptually, in relation to the causal relationship between each component of the mechanism. A causal feedback loop diagram for water supply systems was developed based on the conceptual framework that was established to generally represent the working mechanism of water supply systems management. Fig. 2 shows the causal feedback loop relationships among the components of the systems management identified in this study.

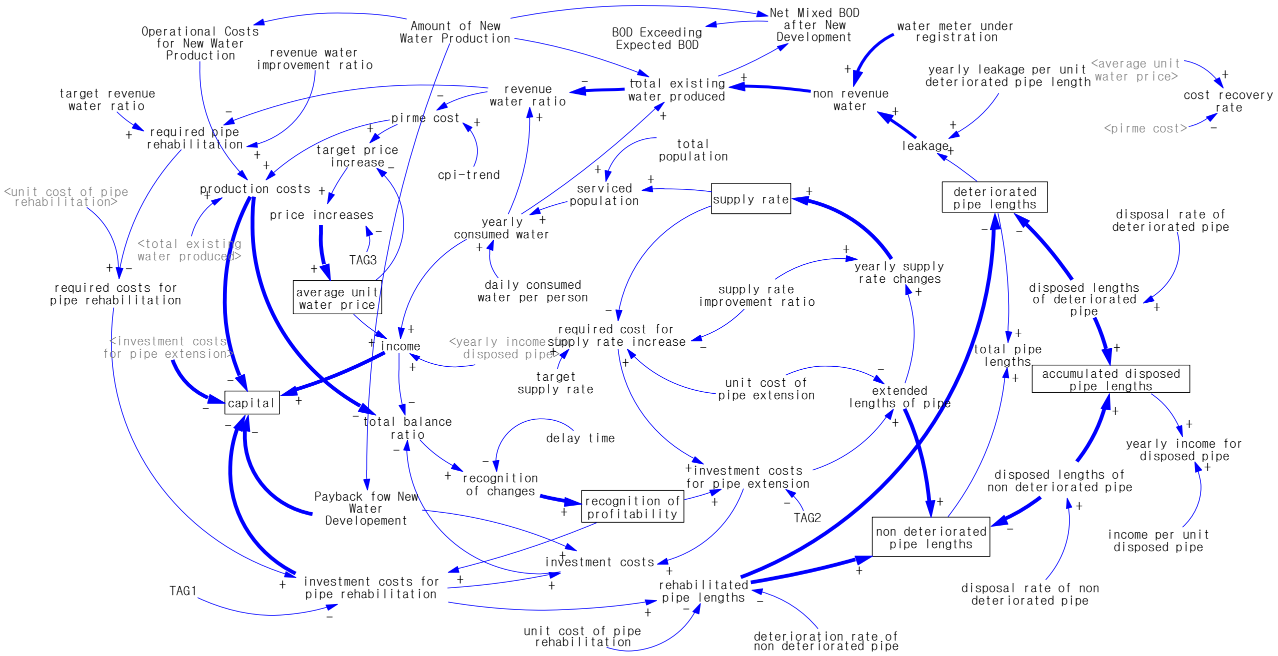

Fig. 2. The causal feedback loop relationships among the components of water supply systems management.

Three main ‘Managerial Indicators’, that are ‘(water) supply ratio [dimensionless]’, ‘revenue water ratio [dimensionless]’ and ‘water price [the Korean currency 1,000 won or 0.7 Euro/m^3]’, were utilized in establishing the causal relationships. ‘(Water) Supply ratio [dimensionless]’ represents the portion of population that has access to a water supply system and has the value between 0 and 1. ‘Revenue water ratio’ represents the ratio of amount of billed(or consumed) water to total amount of produced water and also has the value between 0 and 1. The causal relationships developed in this paper identified the fundamental working mechanisms of water supply systems operation and management in which the efforts to reduce the differences between ‘supply ratio’ and ‘target supply ratio’, ‘revenue water ratio’ and ‘target revenue water ratio’, and ‘water price’ and ‘target price increase’ trigger the working mechanisms of water supply systems.

4. Description of the Developed SD Computer Simulation Model

A SD computer simulation model was developed based on the causal feedback loops shown in Fig. 2. The model was composed of four sub-models: a water supply sub-model, pipe maintenance sub-model, water supply business, and alternate water source sub-model. Fig. 3 shows the stock and flow diagram of the computer model constructed using STELLA.

The water supply sub-model modelled the changes in the ‘supply ratio’ due to population changes and pipeline extension, as well as the long-term changes in the ‘total (volume of) water produced (per year) [m^3/yr]’, which are affected by the changes in ‘leakage’ due to pipe deterioration. In the pipe maintenance sub-model, the conditions of pipes were defined as ‘deteriorated pipes [km]’, ‘non-deteriorated pipes [km]’ and ‘disposed-of pipes [km]’. In the water supply business finance sub-model, the indicators able to represent the financial status of a water supply system were modelled, and included the ‘income’, ‘production costs’, ‘investment costs for pipe rehabilitation’ and ‘investment costs for pipe extension’.

The management scenarios for the case study system were created for the period between 2008 and 2030 by creating different sets of values for some of the exogenous variables to predict the status of the system under optimistic, basic and pessimistic managerial conditions.

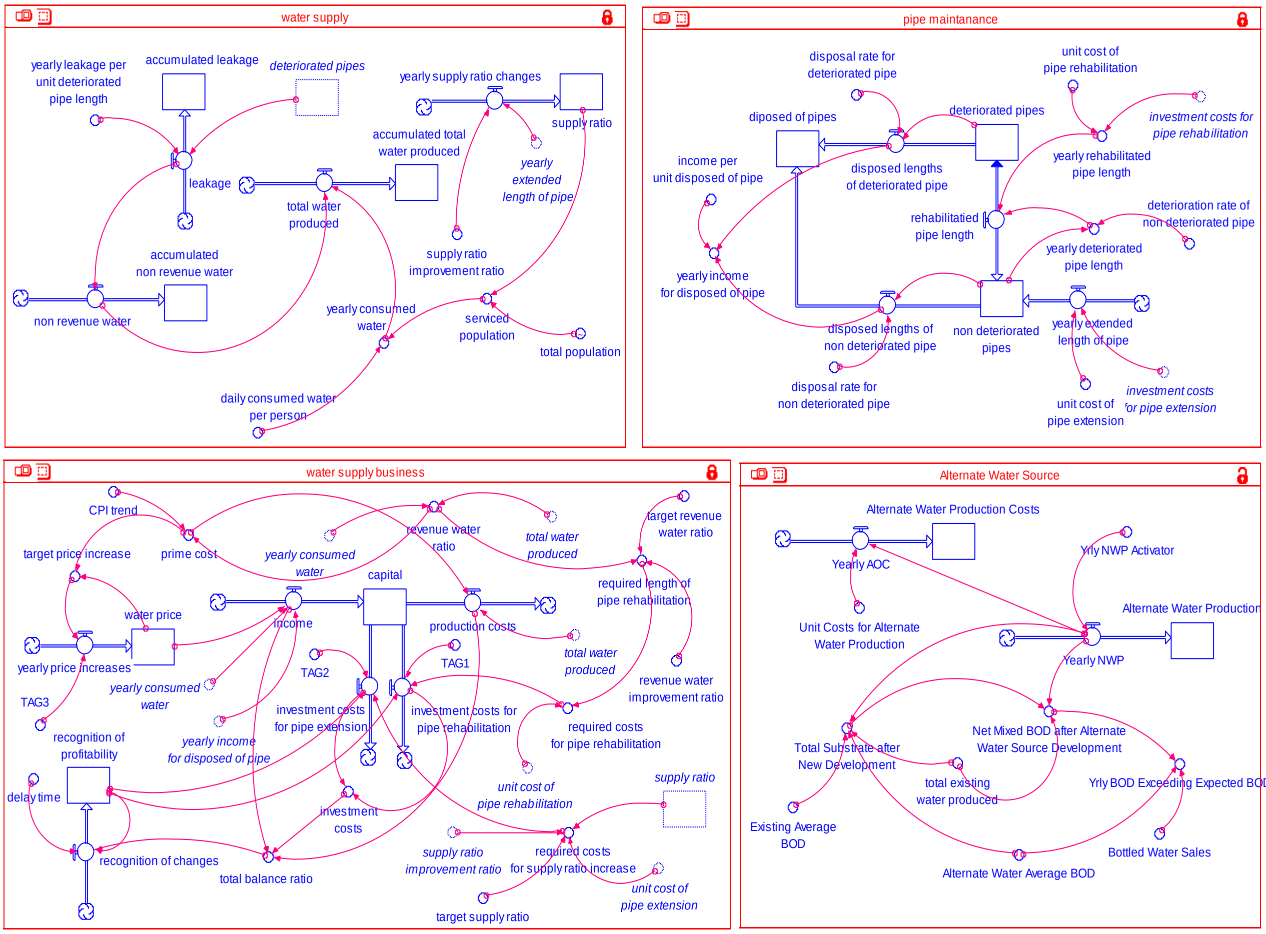

Fig. 3. The stock and flow diagram of the SD computer simulation model.

The optimistic scenario was created to simulate a managerial condition that will improve the financial status of the system compared to the basic scenario, while the pessimistic scenario was designed to simulate the opposite managerial condition to the optimistic scenario. As an example of the management scenario simulations Fig. 4 to shows the results for the ‘revenue water ratio’ which shows the expected range of the variations of the index during 2008 and 2030 for the assumed management scenarios.

5. Conclusions

In this paper, an SD computer simulation model was presented based on the causal feedback relationships. Especially, the key factors and their interrelationships associated with the management of water pipes were identified and modelled based on the SD modelling principles. An example of the modelled causal feedback relations is the causal feedback loop, which includes ‘income’, ‘investment costs for pipe rehabilitation’, ‘rehabilitated pipe length’, ‘yearly deteriorated pipe length’, ‘leakage’, ‘non-revenue water’, ‘total water produced’, ‘revenue water ratio’, ‘prime cost’ and ‘water price’.

The aim of the model calibration in this study was to simulate the reported data as closely as possible. The historical data reported in Busan Water Supply Authority [7] were used to calibrate and verify the constructed computer model. Comparisons between the simulated results and historical data of the variables in the model during the calibration showed that the constructed model reasonably simulated the historical trends of the case study system.

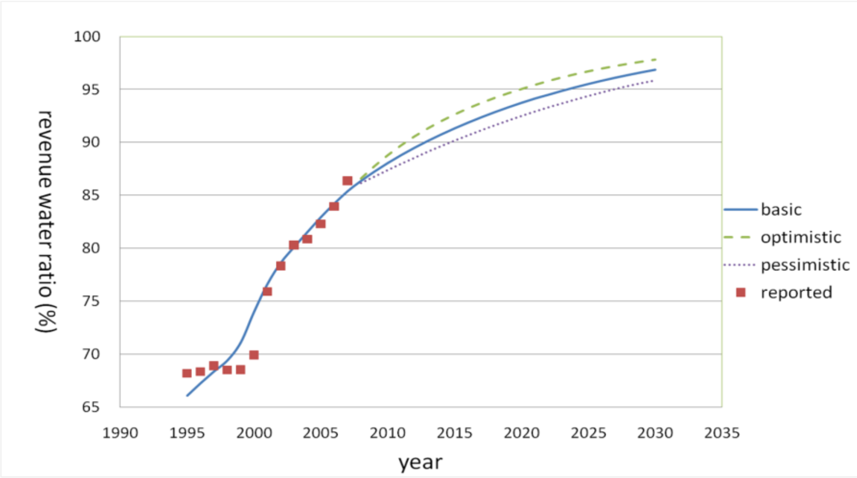

Fig. 4. Management scenario simulation results for the revenue water ratio

The analyses conducted on the model simulation results were based on assumed management scenarios, and showed that the 'supply ratio' and 'cost recovery ratio' of the system were predicted to reach a state of dynamic equilibrium under the basic scenario after around 2015. The relevant data in Busan Water Supply Authority [8] further ascertained this phenomenon. However, the 'revenue water ratio' and 'total balance ratio' were predicted to continuously improve under any of the assumed scenarios. Meanwhile, the pipes in the system were found to be in a deteriorating stage, even under the assumed optimistic scenario. Therefore, major investments for pipe rehabilitation greater than those assumed with the optimistic scenario may need to be implemented to reduce the amount of deteriorated pipes in the system. The major indicators of the management of the water supply system were also simulated for the case of alternate water source development. The results showed that there will be a slight increase in the 'supply ratio' and a maximum of 250 km of deteriorated pipes in the system compared to the case of 'no-development'. The principles of establishing the causal relationships used in the SD computer modeling are also expected to work as a prototype for modeling other water supply systems' management problems.

6. Acknowledgements

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7. References

[1] A.N. Beard. Some Ideas on a Systemic Approach. *Civil* Engineering *and Environmental Systems*. 1999, **16** (3), 197-209.

[2] J.W. Forrester. Industrial dynamics—a major breakthrough for decision makers. *Harvard Business Review*. 1958, **36**(4): 37–66.

[3] N.S. Grigg, and M.C. Bryson. Interactive simulation for water system dynamics. *Journal of Urban Planning Division*, 1975, **101** (1), 77–92.

[4] S. Lee, H. Kim, and H. Park. Analyzing Effects of Transparency on a Water Business Case Using System Dynamics. *Journal of the Korean Society of Water and Wastewater*. 2006, **20**(4): 605-616. (in Korean)

[5] S. Lee, H. Park, and H. Park. Application of System Dynamics Methodology for Comprehensive Analysis of the Water Business System. *Journal of the Korean Society of Water and Wastewater*, 2007, **21** (1), 65-73. (in Korean)

[6] I. Winz, G. Brierley, and S. Trowsdale. The use of system dynamics simulation in water resources management, *Water Resources Management*. 2009, **23**(7): 1301-1323.

[7] Busan Water Supply Authority, *2008 Statistics on Water Supply Services*. Busan: Republic of Korea, 2009.

[8] Busan Water Supply Authority, *2012 Statistics on Water Supply Services*. Busan: Republic of Korea, 2013.