A system dynamics computer model to assess the effects of developing an alternate water source on the water supply systems management

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Abstract

The purpose of developing alternate water sources is to secure water sources of sufficient quantity and high quality due to water quality and/or quantity problems of an existing water source and, thereby, raise the level of consumer satisfaction. Considering the enormous costs and the effects to the consumers and operation of water supply enterprises, a technique to support long term management of water supply systems is needed. In this paper a System Dynamics computer simulation model was developed to evaluate the effects of alternate water source development. The System Dynamics model was used for the simulation of the effects of the alternate water source development project in Busan, South Korea.

Keywords: alternate water source; computer model; 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.

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The purpose of developing alternate water sources is to secure water sources of sufficient quantity and high quality due to water quality and/or quantity problems of an existing water source and, thereby, raise the level of consumer satisfaction. In South Korea seven inter-regional water supply systems are planned to be constructed by 2017 with a budget of US $1.5 billion. Considering the enormous costs and the effects to the consumers and operation of water supply enterprises, a technique to support long term management of water supply systems including the period of before and after alternate water source development is needed.

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. In this paper a SD computer simulation model was developed to evaluate the effects of alternate water source development by improving the system dynamics model by [1]. The SD model was used for the simulation of the effects of the alternate water source development project in Busan, South Korea, which is to develop the riverbank water storage in Nak-Dong River as an alternate water source.

2. The Method

The System Dynamics Methodology developed by [2] 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 [3] 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.

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 modelled 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 modelling software such as Vensim, Powersim Studio, AnyLogic, STELLA, etc. Figure 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.](image-url)
3. The Developed System Dynamics Model

Figure 2 shows the stock and flow diagram of the computer model constructed using STELLA. The model is composed of four sub-models: a water supply sub-model, pipe maintenance sub-model, water supply business, and alternate water source sub-model. 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 simulation period used for the model was from year 1999 to 2058.

Fig. 2. The stock and flow diagram of the SD computer simulation model.
Table 1 ~ Table 4 show the initial values of the stock variables and the values or trend equations of the exogenous variables used for the developed Water Supply Sector, Pipe Maintenance Sector, Water Supply Business Finance Sector and Alternate Water Source Sector SD model. The initial values were obtained from [4] and the values or trend equations of the exogenous variables were established based on the statistics reported in [4].

Table 1. Stock and exogenous variables of the Water Supply Sector

| Variable Type | Variable Name                        | Initial Value/Function of Time | Unit   |
|---------------|--------------------------------------|--------------------------------|--------|
| Stock         | Supply rate                          | 0.981                          | -      |
|               | Accumulated leakage                  | 81,378,000                     | m³     |
|               | Accumulated metering under registration | 75,982,000                     | m³     |
|               | Accumulated Non-revenue water        | 79,323,000                     | m³     |
|               | Accumulated total water produced     | 526,154,210                    | m³     |
| Converter     | Daily consumed water (volume) per person | 254.96                         | ℓ/-capita·day |
|               | Supply rate improvement ratio        | 1.75E-7·ln(time)+6.622E-6      | (1/yr)/km |
|               | Yearly leakage per unit deteriorated pipe length | 27985·e^{-0.10×time}           | (W/yr)/km |

Table 2. Stock and exogenous variables of the Pipe Maintenance Sector

| Variable Type | Variable Name                        | Initial Value/Function of Time | Unit   |
|---------------|--------------------------------------|--------------------------------|--------|
| Stock         | Non-deteriorated lengths             | 5504.2                         | km     |
|               | Deteriorated lengths                 | 2963.8                         | km     |
|               | Accumulated disposed pipe            | 84.68                          | km     |
| Converter     | Unit cost of pipe rehabilitation     | 53548·time^{0.524}             | 1,000 Won/km |
|               | Deterioration rate of non-deteriorated pipe | If time ≤ 5 then 0.075 else 0.03 | 1/year |
|               | Unit cost of service expansion       | 8176.47·ln(time)+113965.34     | 1,000 Won/km |
|               | Disposal rate of non-deteriorated pipe | If time ≤ 5 then 0.07 else if time > 13 then 0.010 else 0.004 | 1/year |
|               | Disposal rate of deteriorated pipe   | If time ≤ 5 then 0.03 else 0.01 | 1/year |
|               | Income per unit disposed pipe        | 200                            | 1,000 Won/km |

Table 3. Stock and exogenous variables of the Water Supply Business Finance Sector

| Variable Type | Variable Name                        | Initial Value/Function of Time | Unit   |
|---------------|--------------------------------------|--------------------------------|--------|
| Stock         | Capital                              | 212,918,197                    | 1,000 Won |
|               | Average unit water price             | 0.4754                         | 1,000 Won/m³ |
|               | Recognition of profitability         | 0.4                            | -      |
| Converter     | TAG 3                                | 17                             | Year   |
|               | Prime cost                           | 0.018·time+0.603               | 1,000 Won/m³ |
|               | Delay time                           | 1                              | Year   |
|               | Target revenue water ratio           | 1                              | -      |
|               | Revenue water improvement ratio      | 5451.66                        | km/%   |
|               | TAG 2                                | 4.5                            | Year   |
|               | Unit Payback Price                   | 0.223                          | 1,000 Won/m³ |
|               | Target service ratio                 | 1                              | -      |
### Table 4. Stock and exogenous variables of the Alternate Water Source Sector

| Variable Type | Variable Name                              | Initial Value/Function of Time          | Unit        |
|---------------|--------------------------------------------|----------------------------------------|-------------|
| Stock         | Alternate Water Production Costs           | 0                                      | 1,000 Won   |
|               | Alternate Water Production                | 0                                      | m³           |
| Converter     | Existing Average BOD                       | -256.20·ln(time)+2635.62               | mg/m³       |
|               | Unit Costs for Alternate Water Production | 0.0491                                 | 1,000 Won/m³|
|               | Alternate Water Average BOD                | 1000                                   | mg/m³       |
|               | Bottled Water Sales                        | if time ≤ 5 then -6077.2·time² + 53225·time + 54555 else 101425·ln(time) - 5971 | m³/yr       |

### 4. The Results of the Model Simulations

The results of the simulation were compared to the case of ‘No Alternate Water Source Development’. During the simulation period the water supply rate was estimated to be slightly higher than the case of ‘No Alternate Water Source Development’. The water revenue rate was close to the case of the ‘No Alternate Water Source Development’ scenario. The water rate was expected to become about half of that of the ‘No Alternate Water Source Development’ case from year 2041. These model simulations results are shown in Figure 3 ~ Figure 5.

The curves with the designation of ‘1’ and ‘2’ in Figure 3 ~ Figure 4 represent the model simulation results for the case of ‘Alternate Water Source Development’ and ‘No Alternate Water Source Development’, respectively. If the alternate water source is developed, the supply rate is expected to be increased slightly more than the case of ‘No Alternate Water Source Development’ as shown in Figure 3 due to the low total water production costs in the case of alternate water development and alternate water development costs. This results from the structure of the model in which the water production costs at the water treatment plant is reduced due to the reduction of total volume of water treated as much as the volume of the alternate water source developed. Since the reduction of the total costs for water treatment is less than the payment for the alternate water source development to the K-Water, the causal structure of the model inevitably leads to the improved budget balance ratio and subsequently increased pipe network expansion, which is the main cause of the supply rate increase.

The length of deteriorated pipes in Busan, as shown in Figure 4, for the case of ‘Alternate Water Source Development’ is predicted to be about 250 km less than the case of ‘No Alternate Water Source Development’ in year 2040. This is due to the causal structure of the model in which the budget balance ratio gets improved for the case of ‘Alternate Water Source Development’ and the investment for pipe maintenance is increased subsequently due to the improved budget balance ratio.

Figure 5 shows the results of the various simulation scenarios regarding the water rate in Busan. The curve number ‘1’ represents the expected changes in the water rate for the case of ‘No Alternate Water Source Development’, 2’ the case of ‘Alternate Water Source Development’ with the reduction of water production in the existing water treatment facility in Busan as much as the volume of the developed alternate water source production, ‘3’ the case of ‘Alternate Water Source Development’ with the reduction of water production in the existing water treatment facility in Busan as much as 50% of the volume of the developed alternate water source production, ‘4’ the case of ‘Alternate Water Source Development’ without any reduction of water production in the existing water treatment facility in Busan, respectively.
Fig. 3. Simulation results of the supply rate.

Fig. 4. Simulation results of the deteriorated pipe length.
5. Conclusions

In this paper, an SD computer simulation model was presented to predict the long-term effects of developing an alternate water source at Nak-Dong river bank storage in Busan, South Korea based on the causal feedback relationships inherent in water supply systems management. The model simulation results indicated that major water supply systems management index such as the water supply rate and revenue water ratio will be improved over the simulation periods of 60 years from year 1999.

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 [5] were used to calibrate and verify the constructed computer model. The calibration process also took into account expert opinions of managerial personnel of the case study system. During calibration, a comparison of the simulated results and historical data of the model variables showed that the constructed model reasonably simulated the historical trends of the case study system.

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. Through the scenario analyses illustrated in this paper, the SD model developed for water supply systems was shown to be sufficient in identification of policy leverage, leading to efficient water supply system management; the model could also be utilized to determine long-term effects of policy change on the status of a water supply system. The principles associated with establishing the causal relationships used in the SD computer modeling and the sensitivity analysis methods for exogenous variables used for identifying policy leverages are also expected to work as prototypical methods for modeling and solving the management problems of other water supply systems.

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