Water-Energy-Environment Nexus Modelling for Optimizing Water Loss Control Strategy and Interventions

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SUMMARY
Due to the increasing water-related challenges, water loss management has been given high priority by governments, water utilities, and other stakeholders in the water sector. General water loss management strategy, programs, and interventions are established by water utilities only considering outputs in the water sector. To overcome limitations, we developed the urban water Nexus model to assess and evaluate the synergies and trade-offs in the water, energy, and environment sectors. System dynamics modelling, a top-down modelling method based on causal mechanisms among the elements within a specific system, is adopted for the comprehensive analysis of multi-sectoral systems at a macro level. Based on the multi-scenario and multi-attribute analysis, the Nexus model can offer optimal water loss management interventions and provide the scientific basis for decision-making. Therefore, sustainable and systematic water loss management is possible through the generalized and holistic urban water-energy-environmental Nexus model.

KEYWORDS
System dynamics, Water-Energy-Environment Nexus, Water loss management

INTRODUCTION
The mounting water-related challenges such as climate change, water scarcity, rising water demand, and aging infrastructure place more pressure on urban water management. Especially, a high level of water losses in distribution networks is one of the significant concerns to water utilities, as it causes water wastage, technical burdens, water contamination, and revenue losses. Water utilities establish holistic, flexible, and customized water loss management strategies and programs to reduce the Non-Revenue Water (NRW). When water utilities select interventions in line with strategy, they always first set their sights on apparent losses caused by metering inaccuracy, data handling error, or unauthorized consumption rather than real losses. Although this approach can be accomplished with a low level of investment and an immediate payback, it has the disadvantage of considering only the water sector.

Water is widely used in other sectors, such as food and energy, and is an essential factor for basic livelihood and development. Water shortages and unequal allocation cause great problems not only in the water sector but also in other areas. The study of the Nexus has been identified as a helpful approach for quantifying and assessing the synergies and trade-offs between sectors (Weitz et al., 2014; Mohtar, 2016). Nexus also presents complex interdisciplinary relationships as feedback reflecting sector's characteristics; therefore, Nexus can be utilized efficiently in policymaking and resource management.

This study aims to suggest an appropriate water loss management strategy from a Nexus point of view. We built a Water-Energy-Environment (WEE) Nexus model for urban water system using System Dynamics (SD) and analyzed the resource consumption and transfer between water, energy, and environment sectors.

METHODS

Nexus analysis approach and scope

Even though some analysis frameworks and methodologies have been introduced to facilitate a better understanding of the Nexus, there is no universally accepted and applicable approach for all cases (Endo et al., 2015; Liu et al., 2017). Appropriate methods vary in response to the scale and research priorities of a specific nexus system. Various Nexus methods (e.g., questionnaire survey, ontology engineering, input-output analysis, benefit-cost analysis, life cycle assessment, SD modelling, agent-based modelling, integrated modelling, etc.) have been applied to systematically evaluate interlinkages of sectors or support the development of social and political water resource policies. Several researchers have noted the suitability of SD in urban water management because of the inextricably interconnected and intertwined cause-and-effect chains found in water systems; therefore, we adopted SD in this study.

The Nexus model can have various forms depending on the scope (sectors, spatial range, interconnectivity, mechanism, indicators, etc.). Defining system scopes and clarifying objectives before building the model is critical to goal-oriented analysis and decision making. In this study, the scope of the Nexus model was set up as shown in **Table 1.1**.

Table 1.1 The Scope for the Urban SD WEE Nexus Model

Items	Details
Sector	Water, energy, environment
Spatial scope	Urban level
Interconnectivity	Macroscopic
Mechanism	Internal impact analysis, One-way effect analysis: building a water-driven Nexus
Indicators	Water footprint, total energy use, carbon footprint

Model building and simulation

We considered the processes and causality in the urban water system of water intake, water conveyance, water treatment, water distribution, water use, sewer system, wastewater treatment, reuse, discharge based on the previous Nexus model (Shrestha et al., 2017; De Stercke et al., 2018). In addition to the general components of the urban water system, the process of high resource usage and movement were included as essential components. The main causal loop diagram of the WEE Nexus model is shown in **Figure 1.1**.

To derive the optimal water loss control strategy and to analyze resources movement between sectors according to three urban energy intensity (low, medium, high) and for water loss levels (low NRW, high NRW & low AL ratio, high NRW & medium AL ratio, high NRW & high AL ratio), we performed analysis based on 12 scenarios as shown in **Table 1.2**.

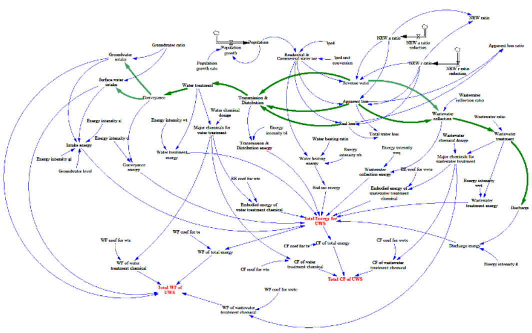

Figure 1.1 Causal Loop Diagram of WEE Nexus Model

Table 1.2 Simulation Scenario Matrix

Water losses Energy intensity	Low NRW	High NRW & Low AL	High NRW & Medium AL	High NRW & High AL
Low EI	S 1-0	S 1-1	S 1-2	S 1-3
Medium EI	S 2-0	S 2-1	S 2-2	S 2-3
High EI	S 3-0	S 3-1	S 3-2	S 3-3

RESULTS AND DISCUSSION

In the same energy intensity city, it is analyzed that water footprint, total energy use, and carbon footprint are high in the order of high NRW & Low AL (S 1-1, S 2-1, S 3-1), high NWR & medium AL (S 1-2, S 2-2, S 3-2), high NRW & high AL (S 1-3, S 2-3, S 3-3), and low NRW (S 1-0, S 2-0, S 3-0). Apparent losses occur in the situation where even though water utilities supply the water to the customer, they do not receive the payment. Therefore, the larger the apparent losses at the same water leakage rate, the fewer resources are lost from the Nexus perspective.

In the same leakage conditions, the water footprint, total energy use, and carbon footprint are the highest in high energy intensity cases (S 3-0, S 3-1, S 3-2, S 3-3). As the energy intensity increased, the water footprint tends to rise to some extent, and the total energy use increases rapidly compared to the water footprint. The carbon emission is also directly related to the total energy use; therefore, an increase in carbon footprint is similar to that of the total energy use.

S 3-1 is analyzed to identify resource use and transfer in the general urban water system. In water intake, water conveyance, water treatment, water distribution, water use, sewer system, wastewater treatment, and discharge process, water foot print are 1,641,147m^3 (87.21%), 131,170m^3 (6.97%), 33,120m^3 (1.76%), 32,793m^3 (1.74%), 27,054m^3 (1.44%), 0m^3 (0%), 16,245m^3 (0.86%), 322m^3 (0.02%), respectively. The direct water intake process accounted for 87.21% of the total water footprint, indicating that most of the water footprint occurred.

CONCLUSIONS

In this study, we built the WEE Nexus model for urban water management and derived optimal water loss management strategies based on the energy intensity and water losses. Firstly, even though reducing apparent losses is prioritized in the conventional economic-oriented water loss control program, handling real losses should be highly considered in the program from the Nexus perspective. Secondly, it was proved that each energy intensity of the urban water process has a significant impact on resource consumption and transfer. Therefore, it should be considered as an essential factor to be analyzed in advance. Lastly, sustainable, systematic, and feasible water loss management is expected through this generalized and holistic urban WEE Nexus model.

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