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# A system dynamics based socio-hydrological model for agricultural wastewater reuse at the watershed scale

Hanseok Jeong[a], Jan Adamowski[b,*]

[a] Institute of Green Bio Science and Technology, Seoul National University, Gangwon 25354, Republic of Korea
[b] Department of Bioresource Engineering, McGill University, 21 111 Lakeshore Road, Sainte-Anne-de-Bellevue, QC, Canada

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ABSTRACT

The purpose of this study was to develop and verify a socio-hydrological model using system dynamics (SD), thereby combining a deterministic conceptual hydrological model and a social model incorporating population, land use, economics, technology, and policy dimensions. Applied to a central South Korean watershed where wastewater is reused for paddy irrigation, the present model was verified in terms of structure and behavior. Structural validity was confirmed when expected simulation sensitivity and consistency criteria were met during behavior sensitivity and extreme conditions tests. The model's behavioral validity in predicting hydrological processes including evapotranspiration, stream flow, and groundwater level, was also confirmed as the calibrated model performance during the validation period showed good agreement with those of the Soil and Water Assessment Tool (SWAT) model, validated for the study watershed, as well as observed groundwater levels. The values of Nash-Sutcliffe efficiency ($E_{NS}$), percent bias (PBIAS), and $R^2$ which compared model results with those of the SWAT model were 0.77, 3.0%, and 0.79, respectively, for the evapotranspiration, and 0.69, 1.4%, and 0.75, respectively, for the stream flow, while the generated and observed groundwater levels exhibited a linear relationship with an $R^2$ value of 0.70. The validated model indicated that urbanization within the study watershed could lead to increased stream flow and greater wastewater reuse. Instream flow regulation led to a decrease in stream flow tied to a lower base flow, and a decrease in social benefits associated with a decline in wastewater reuse. An assessment was made of the SD-based socio-hydrological model's usefulness when acting as an element of an integrated framework in providing a better understanding of small-scale socio-hydrological systems' interactions and the underlying causes of general trends and problems. SD-based socio-hydrological modeling was deemed a suitable decision-support framework for designing water resource policies contributing to successful integrated water resources management practice.

## 1. Introduction

To ensure that agricultural systems address the future challenges of global food security and environmental sustainability, present systems must be altered (Foley et al., 2011; Halbe et al., 2014; Kolinjivadi et al., 2014). Wastewater reuse for agriculture can provide a solution which addresses both challenges simultaneously, especially when water is scarce (Jang et al., 2010; Chavez et al., 2012; Jeong et al., 2014). Largely irrigated with wastewater, agricultural lands produce foods consumed worldwide (World Health Organization (WHO), 2006; Hamilton et al., 2007; Jimenez et al., 2010). Produced at a relatively constant rate, treated wastewater generated in Korea has abundant fertilizing agents and is widely used as irrigation water (Jang et al., 2012). This wastewater reuse is likely to increase over the coming decades (Jeong et al., 2016). However, public health issues and environmental concerns must be addressed for a safe and rational implementation of wastewater reuse in agricultural settings. Conducting long-term social and environmental assessments is vital to the implementation of successful and sustainable water resources policies. A modeling approach can aid in such assessments (Adamowski et al., 2010; Nalley et al., 2012; Nalley et al., 2013; Valipour, 2014a, 2015; Yaeger et al., 2014; Butler and Adamowski, 2015; Inam et al., 2015).

Successfully employed to predict the expected responses of hydrological systems to proposed water resource policies (Tuppad et al., 2010; Noory et al., 2011; Park and Roesner, 2012; Haidary et al., 2013; Rathinasamy et al., 2013; Belayneh et al., 2014), hydrological models have proven effective in physically interpreting natural phenomena. However, traditional hydrological models do not consider anthropogenic impacts on water cycle

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* Corresponding author.
*E-mail address:* jan.adamowski@mcgill.ca (J. Adamowski).

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dynamics (Wagener et al., 2010), thereby limiting their ability to fully mimic the response of hydrological systems to evolving circumstances. This has led to an event-oriented modeling approach based on linear thinking, largely ignoring interactions between system components. To develop sustainable water resource management strategies and achieve long-term water security for stakeholders and their environment, hydrological modeling must undergo a paradigm shift to provide predictions which consider whole system behavior (Wagener et al., 2010; Halbe et al., 2013; Straith et al., 2014; Valipour, 2014b).

The new field of socio-hydrology considers humans and their actions as an integral part of water cycle dynamics. Comprising three principal domains — historical (Wescoat, 2013; Zlinszky and Timar, 2013; Kandasamy et al., 2014; Liu et al., 2014), comparative (Chang et al., 2014), and process (Di Baldassarre et al., 2013; Elshafei et al., 2014; Viglione et al., 2014) — socio-hydrology attempts to describe the dynamics and co-evolution of coupled human-water systems. Whereas historical and comparative socio-hydrology are somewhat qualitative, process socio-hydrology represents the quantitative science required for modeling human-water systems and predicting possible future trends in their states. Therefore, process socio-hydrology can contribute to bringing about a paradigm shift in hydrologic modeling, allowing for a better understanding of how hydrological systems co-evolve with human activities.

Seeking to achieve greater insights into causal relationships within human-water systems, process socio-hydrology employs nonlinear, organic thinking (*i.e.*, systems thinking; Sivapalan et al., 2012). System dynamics (SD), a branch of systems thinking (Ford, 1999), was introduced by Forrester (1961) to support studies related to representing complex systems and analyzing their dynamic behavior (Hjorth and Bagheri, 2006). In a manner similar to other traditional hydrological models, the use of SD in hydrological modeling is focused on predictive simulations (Ahmad and Simonovic, 2004; Elshorbagy and Ormsbee, 2006; Ghashghaei et al., 2013). For example, Li and Simonovic (2002) established a conceptual hydrological model using SD to estimate snowmelt-derived flooding. Likewise, Khan et al. (2009) demonstrated the application of SD in simulating water balance in a rice paddy system, as well as surface-groundwater dynamic interactions in an irrigation area. Descriptive integrated modeling coupled with an SD approach has also served in multi-subsystem feedback modeling of water resources systems for strategic policy testing and selection (Simonovic et al., 1997; Simonovic and Fahmy, 1999; Guo et al., 2001; Stave, 2003; Madani and Marino, 2009; Ahmad and Prashar, 2010; Qi and Chang, 2011; Venkatesan et al., 2011). However, these applications have not included a detailed analysis of hydrological processes or focused on managing hydrological systems in such a manner as to implement integrated water resources management (IWRM) through a scenario-based approach. Towards these goals, Davies and Simonovic (2011) developed a SD-based integrated model incorporating the global climate system, carbon cycle, economy, population, land use, agriculture, novel versions of the hydrological cycle, global water use, and water quality to provide insights into the nature and structure of the connections between water resources and socio-economic and environmental change. Similarly, Wei et al. (2012) developed a complex SD model reflecting the interactions between water resources, environmental flow, and socio-economic factors. They assessed the socio-economic impacts caused by allocating different levels of environmental flow in China's Weihe River Basin. In the case of wastewater reuse issues, Venkatesan et al. (2011) used SD to evaluate the impacts on water quality and energy consumption of indirect and direct potable water reuse as water resources management options. Nasiri et al. (2013) created an SD model with different hypothetical levels of water reuse implementation in order to simulate and optimize the overall water system cost, accounting for future scenarios of population, economic growth and climate change. These studies mainly focused on evaluating the effects of water resources policies on a targeted system, whereas traditional hydrological modeling of wastewater reuse have focused on simulating the relevant hydrological process (Kim et al., 2008; Lee et al., 2010; Jeong et al., 2016).

Despite the number of studies on the subject of hydrological modeling and watershed management using SD, few SD modeling studies have sought to identify the interactions between physical hydrological processes and human activities within a process socio-hydrological framework. Such models could underpin the practice of IWRM through an enhanced understanding of coupled human and water systems dynamics (Sivapalan et al., 2012). The present study's objectives were therefore to: (i) develop a watershed-scale socio-hydrological model using SD to understand the ongoing processes and predict possible future trends for a central South Korean watershed which reuses wastewater for paddy irrigation, (ii) evaluate the resultant model for its structure and behavior through structural and behavioral validity tests, and (iii) employ the model to understand the impacts of urbanization and instream flow regulation on the socio-hydrological systems of the study watershed in order to implement sustainable wastewater reuse for agricultural purposes.

## 2. Socio-hydrological model

Based on a series of causal loops and model equations, a socio-hydrological model wherein agricultural water use served as the nexus of social and hydrological systems was developed (Fig. 1). This model can be classified as a semi-lumped hydrological model because the change in land use can be considered by using the infiltration ratio for the given land use type, while the watershed system is regarded as a single point in space without dimensions. As in other conceptual hydrological models, modeling the hydrological system was based on watershed-specific water balance equations. These included three main stock variables: stream flow volume, soil water volume, and groundwater volume, representing stream flow, interflow, and base flow, respectively. The social system accounted for changes in population, land use, economics, technology, and agricultural wastewater reuse policy. The resulting model simulates the demand for wastewater reuse, as influenced by policy and economic feasibility. Such a demand leads to irrigation capacity development for wastewater reuse, thereby bringing about changes to the entire hydrological system through the impacts of wastewater reuse on stream flow and the groundwater cycle. Changes in hydrological systems can also cause changes in the policy-making environment resulting in delayed changes in the overall socio-hydrological system. These feedback changes define a scenario leading to a balanced state at a specific point in time, along with the coevolution which occurs between social and hydrological systems.

### 2.1. Causal loop diagram

A conceptual modeling step, the causal loop diagram (e.g., Inam et al., 2015) was used in this study to describe the causal relationships and dynamics between social and hydrological systems related to agricultural wastewater reuse. Overall system dynamics are driven by either reinforcing ̈(+)̈or balancing ̈(−)̈feedback loops, where change in one variable feeds back to either reinforce or limit (*i.e.*, balance) the initial change.

The causal loop diagram developed for this study includes elements from the hydrological cycle, agricultural water supply, demand for reclaimed wastewater irrigation, and associated economic factors, along with changes in land use and