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Application of system dynamics approach in surface and groundwater and farm system for water crisis management

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ABSTRACT: The interaction among various water cycle components consists of complex, non-linear and bidirectional (interdependent) biophysical processes which can be interpreted using feedback loops in a system dynamics environment. Application of system dynamics approach is demonstrated with two case studies using a specialized modeling tool; Vensim. The first case study simulates the water balance in a rice field system on a daily basis under aerobic conditions with provision of supplemental irrigation. Physically based conceptual water balance model was developed and then implement using Vensim to simulate the percolation, actual evapotranspiration, surface runoff, and capillary rise. The second case study simulates surface-groundwater dynamic interactions in an irrigation area. The modeled system encompasses dynamically linked processes including seepage from the river, evaporation from shallow water table, groundwater storage and lateral flow from upland to lowland. The model can be applied to simulate responses of different irrigation management scenarios to develop strategies to improve water use efficiency and groundwater salinity. The presented example applications of SD approach conclude that it helps investigate and simulate complex water system processes.

Keywords**:** *System dynamics, complex systems modeling, water balance, surface-groundwater interaction, Vensim.*

INTRODUCTION

System dynamics (SD) is the theory of system structures and a set of tools for representing complex systems and analyzing their dynamic behavior (Forrester, 1961) . The most important feature of this approach is to elucidate endogenous structure of the system under study, to see how different elements of the system actually relate to one another, and to experiment with changing relations within the considered system when different decisions are included. In SD, the relation between structure and behavior is based on the concept of information feedback and control (Simonovic, 2000). Moreover, causal loop diagrams represent major feedback mechanisms, which reinforce (positive feedback loop) or counteract (negative feedback loop) a given change in a system variable (Sterman, 2000).

The SD approach is an appropriate technique for simulating complex problems in integrated water resources. The inherent flexibility and transparency is particularly helpful for the development of simulation models for complex water resource systems with subjective variables and parameters. The flexibility allows the application of hierarchical decomposition in the model development and the transparency raises the possibility of practitioners' involvement in the model development, increasing their confidence on model operation and its outputs (Simonovic, 2000). Compared with the conventional simulation or optimization models, the system dynamics approach is more beneficial for indicating how different changes of basic elements affect dynamics of the system. It is therefore particularly useful for representing complex systems with strong influences from social or economic elements (Xu *et al.,* 2002). Recent applications of SD approach in the field of water resources include long-term water resource planning and policy analysis (Simonovic and Fahmy, 1999), reservoir operation (Ahmad and Simonovic, 2000), salinization of irrigated lands (Saysel and Barlas, 2001), and simulation of the hydraulic dynamics in a hydropower plants system (Caballero *et al.,* 2004).

The SD tool, Vensim (Ventana Systems, 2004) provides a fully integrated simulation system to conceptualize, document, simulate, analyze, and optimize models of dynamic systems. Vensim provides a simple and flexible way of building simulation models from causal loop or stock and flow diagrams. Khan *et al.* (2005) provided an overview of system approaches in water management and developed a SD version of the BHIWA (Basin Wide Holistic Integrated Water Assessment) model using the Vensim environment.

Two case studies on application of SD approach in water resources management are presented briefly using the Vensim environment to illustrate this exciting way of developing policy and management models.

Case Study of Rice Bay Water Balance Simulation

In irrigated aerobic rice systems, rice is grows in non-flooded and non-saturated soil using supplemental irrigation. Aerobic rice is suitable for water-scarce environments, and can stand being periodically flooded (Yang *et al.* 2005). Accurate estimation of different water balance components in a cropped field is essential to achieve effective use of limited irrigation water (Agrawal *et al.,* 2004).

In this case study a field soil water balance model was developed for non-ponded "aerobic rice" in North China Plain where aerobic rice has been grown since late 1990's as a supplementary-irrigated upland crop to cope with water scarcity. An attempt was made to develop a dynamic model for addressing soil water balance associated with hydrological processes.

The conceptual model is presented first, and then, based on the hydraulic processes occurring in an aerobic rice field, the general components of the water balance are outlined. The hydrodynamics are analyzed from the feedback relations among the components. The dynamic model formulated based on mathematical equations and implemented using Vensim simulated interactions among various water balance components including actual evapotranspiration, percolation, surface runoff, and capillary rise in the field on a daily basis. Finally, the model parameters were validated with the experimental field data from Huibei Irrigation Experiment Station, Kaifeng, China.

Conceptual Model

Schematically, the root zone can be conceptualized as a box (Figure 1) in which the water content (expressed as the crop root zone fraction) fluctuates over time. Rainfall, irrigation and capillary rise of groundwater towards the root zone add water to the root zone and decrease the root zone depletion. Soil evaporation, crop transpiration, surface runoff and percolation losses remove water from the root zone and increase the depletion (Allen *et al.,* 1998).

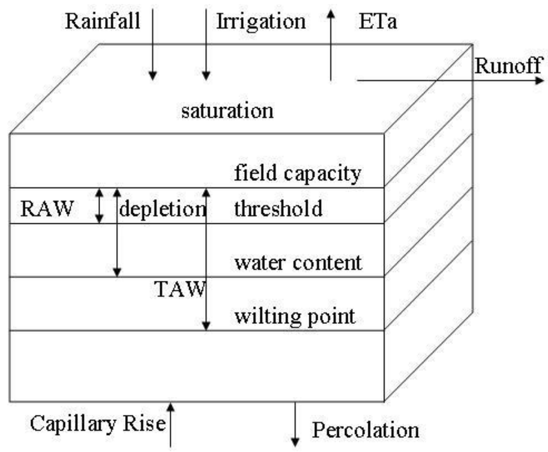

Fig. 1. Conceptual model of soil water balance (Allen *et al.,* 1998)

The System Dynamics Model

The first negative feedback loop in Figure 2 (causal loop diagrams are called that because each link has a causal interpretation) represents the interaction between actual evapotranspiration "ETa" and soil water storage: the larger the ETa, the less the water storage, then the less the soil water content and soil moisture coefficient "ks", which in turn decreases ETa, completing the negative loop.

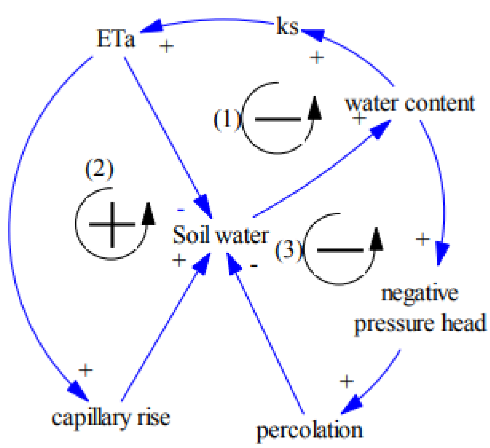

Fig. 2. Causal loop diagram for the dynamic soil water system

The second feedback loop represents the interaction between ETa and capillary rise: the larger the ETa, the larger the capillary rise, then the larger the soil water content and ks, which in turn increases ETa, completing the positive loop. The third feedback loop represents the interaction between soil water storage and percolation: the larger the storage, the larger the water content, then the larger the negative pressure head and percolation, which in turn decreases soil water storage, completing the negative loop. From this analysis it can be postulated that system dynamics is a suitable approach for modeling hydrological processes that are non-linear and occur in feedback form. The structure of dynamic soil water balance model as implemented using Vensim is shown in Figure 3.

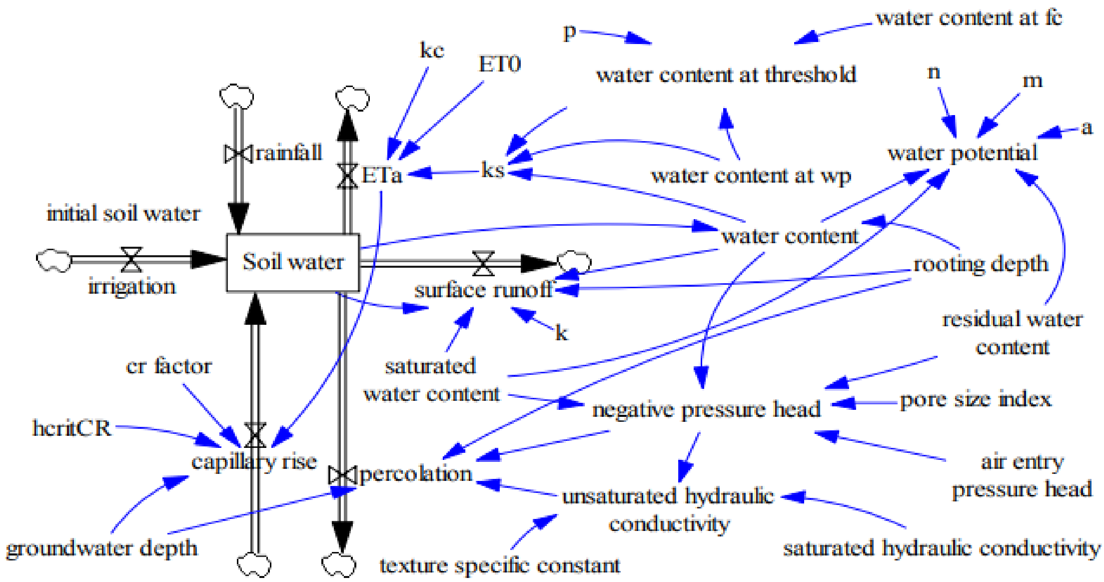

Fig. 3. The stock-flow structure of the dynamic soil water balance model

Validation of Dynamic Model

In the field experiment conducted in 2003, the supplemental irrigation was applied when soil water tension reached at -30 Kpa (Treatment 1) and -70 Kpa (Treatment 2). The results collected from the field experiments were used to validate the model. Figure 4 shows the daily variation of the observed values of variables for the experimental field, along with the simulated values. The Figures show that in most of the cases, observed and simulated values followed the same trend.

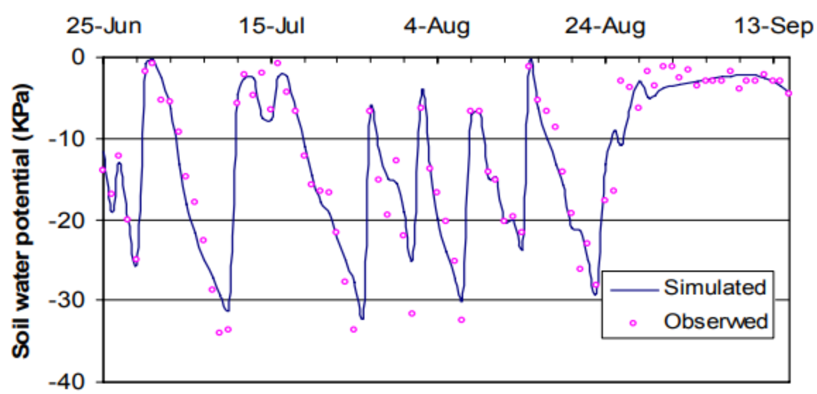

Fig. 4. Simulated and observed soil water potential for Treatment 1

Case Study of Surface-Groundwater Interaction Near a Canal

Groundwater table control is an important issue of water resources use and sustainable management of irrigation systems. During the 1950's several irrigation systems were developed in the lower Yellow River Basin, China. However, water diversion from the river was stopped from 1962 due to severe secondary salinization caused by shallow groundwater tables. In 1970's, conjunctive use of surface and ground water was adopted in these irrigation systems to manage recharge and soil salinity. In this case study, a dynamic model of surface-groundwater interactions was developed and validated with indirect structure test for Liuyuankou Irrigation System (LIS). The dynamic complexity of the system arises because: 1) components of the system interact with one another, 2) it is governed by feedback; 3) it is non-linear and counterintuitive (cause and effect are distant in time and space). Therefore, analytical solution of the model is complicated; therefore the conceptual model is implemented using the system dynamic tool, Vensim.

The LIS is located in south of the Yellow River in Kaifeng county and encompasses an area of about 40,724ha. Principal sources of recharge to groundwater are rainfall, irrigation (including seepage from canals) and seepage from the Yellow River. The Longhai Railway Line divides LIS into two parts. There is more recharge (seepage from the river and canals and more rice irrigation) and less groundwater abstraction above the railway line (ARL). As well as topography of the area gently sloping from northwest down to southeast, groundwater table in ARL is higher than that below railway line (BRL), which results in a lateral groundwater flow from ARL to BRL. Land use in the study area is mostly irrigated agriculture (rice in ARL in wet season and dry crops within whole LIS in dry season), and rural residential or urban development.

When groundwater depth is larger than 2m, evapotranspiration is not significant and salinization rarely occurs (Zhu *et al.,* 2002). The lifting capacity of most commonly used pumps in the LIS is around 10m. If groundwater depth is kept less than 10m, cost of groundwater abstraction is reduced and groundwater is available for sustainable use. Therefore, the key to sustainable irrigation water management in LIS is to maintain the groundwater depth between 2~10m.

Conceptual Model

The LIS is conceptualized into a two-box model to estimate the overall behavior of the system in time and space. The first box covers the ARL of the LIS, and the second the BRL (Figure 5).

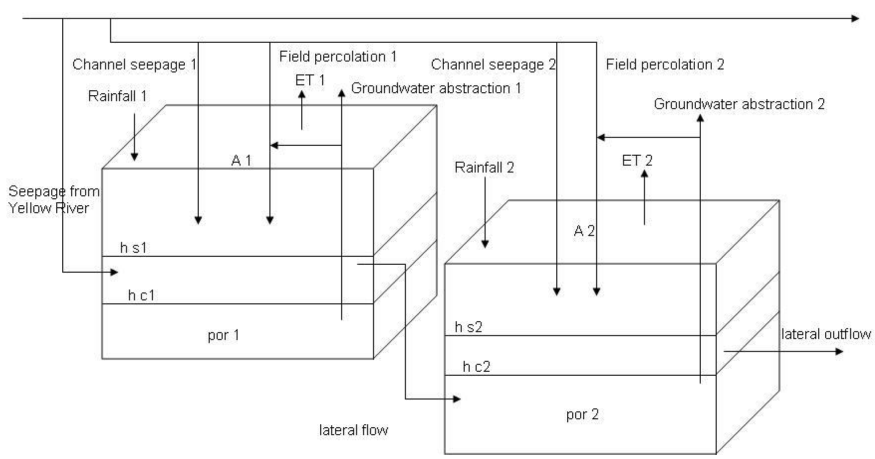

Fig. 5. The conceptual model of surface-groundwater interaction in LIS

The System Dynamics Model

The groundwater storage in upper part aquifer is controlled by three negative feedback loops that involve seepage from the Yellow River, evapotranspiration and lateral flow from upper part to the lower part. The first negative feedback loop in Figure 6 represents seepage from the river: the larger the seepage, the larger the groundwater storage in the upper aquifer, and then the higher the groundwater level, which in turn decreases the seepage from the river, completing the negative or balancing loop. The second negative feedback loop represents evapotranspiration: the larger evapotranspiration, the lesser the groundwater storage in the upper aquifer, and then the lower the groundwater level, which in turn decreases evapotranspiration, completing the negative loop. The third feedback loop represents lateral flow between the two parts: the larger the lateral flow, then lesser the groundwater storage in the upper part aquifer, and then the lower the groundwater level, which in turn decreases lateral flow, completing the negative loop. Similarly, the groundwater storage in lower part aquifer is also controlled by three negative feedback loops representing lateral flow, evapotranspiration and lateral outflow as shown in Figure 6.

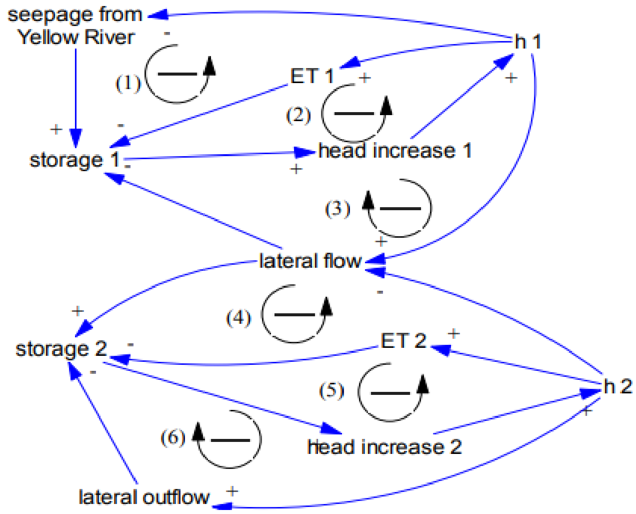

Fig. 6. Causal loop diagram for the dynamic groundwater model

Validation of Dynamic Model

The purpose of a system dynamics study is to evaluate policy alternatives in order to improve the system behavior; therefore the main criterion of model validity becomes 'structure' validity, the validity of the set of relations used in the model, as compared with the real processes. The validity of the 'behavior' is also important, but it is different in two ways: first, behavior validity is meaningful only after the structural validity is established ('right behavior for the right reasons' principle); second, a point-by-point match between the model behavior and the real behavior is not as important as it is in forecast modeling. What is more important in system dynamics method is that the model produces the major 'dynamic patterns' of concern (such as exponential growth, collapse, asymptotic growth, S shaped growth, damping or expanding oscillations, etc). Indirect structure testing is a commonly used way of testing validity of the model structure, and the two most powerful and practical indirect structure tests are extreme-condition and behavior sensitivity tests (Barlas, 1996; Sterman, 2000). In this section, the application of indirect structure tests to the model is illustrated.

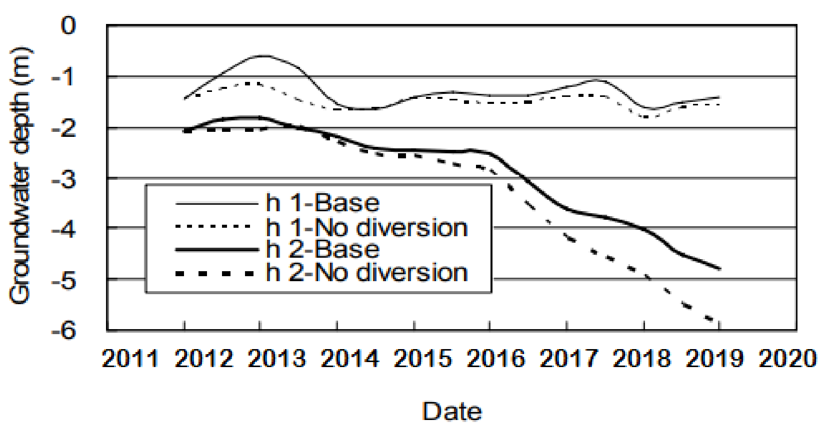

Fig. 7. System behavior when no irrigation water is diverted from Yellow River

Figure 7 illustrates the ‘extreme’ behavior of the system (h1 is groundwater depth ARL and h2 is groundwater depth BRL) under no irrigation water diversion from the Yellow River scenario. The results of the ‘extreme condition’ run are compared with those of the base run. The results show that when recharge from diverted water decreases, the discharge simultaneously decreases and seepage from the Yellow River increases, and groundwater depths in upper part become slightly higher. While for the lower part, lateral flow is the main recharge source, and when it decreases, with other variables remaining almost constant; the groundwater depth significantly increases which is consistent with Yang (2017). Similarly the ‘extreme’ behavior of the system when no groundwater water is abstracted in the lowlands was also found consistent with the observations.

Conclusions

The first case study demonstrates the process of conceptualization of physical interactions among various components of the water balance for aerobic rice system with supplementary irrigation and then implementation using a dynamic system simulation tool. The validation of the dynamic model against field data showed that the application of system dynamics technique proved to be an efficient approach for the simulation of a complex water resource system. The developed framework is also useful to analyze future scenarios for irrigation management of aerobic rice.

In the second case study, a surface-groundwater interaction model of the LIS is developed. The analytical solution of the model is complicated and therefore conceptual model is implemented using Vensim. The structure of the dynamic model was fully validated against real processes. The purpose of this model is not to predict what the groundwater levels will be in each month for the next 20 years. The intention is to reveal under what conditions and policies the groundwater heads would continue to rise or decrease, if and when they reach harmful levels, if and how they can be controlled.

The interaction among various water cycle components consists of complex, non-linear and bidirectional (interdependent) relationships. The case studies presented in this paper support the applicability of system dynamics approach to simulate such complex interactions.

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