System Dynamics Modeling of the Conjunctive-Use of Surface and Subsurface Water

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Abstract

The conjunctive use of surface and subsurface water is used commonly for offering stable supplies in water resources management. Conventionally, the process of supply distribution model development can be classified as simulation method, describing system behaviors and operating rules directly, and optimization method, describing system behaviors by constraint equation and imitating operating rules by objective function. Owing to the allocation is spatial dependency and operating rules is temporal dependency, many researches prefer to construct conjunctive use models by “optimization method” then by “simulation method”. However, subject to the selected optimal methodology, such as linear programming or dynamic programming, modelers need to hypothesize or simplify the system. Hence, this study provides a powerful object oriented simulation modeling, system dynamics, alternative to optimization method for representing complex systems and analyzing their dynamics behavior. In system dynamics, the relation between structure and behavior is based on the concept of stock-flow diagrams. The process of model development, combining program flowchart with spatial system configuration, provokes modeler can build model easily. In this study, we also consider system expansion such as increasing new supply sources, and capacity expansion such as water treatment plant. We attempt to demonstrate this approach is a suitable methodology for constructing the complex

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water resources modeling.

Keyword: supply distribution, operating rule, system dynamics, system expansion, capacity expansion

Introduction

The frequency of extreme hydrologic event, such as drought or flood, has increased significantly recently owing to the effect of climatic change. Therefore, providing an efficient water resources management to avoid the disaster in future is urgent. Conventionally, water resources planning resolution need prepared system diagram to conceive topological position and flowchart to understand operation procedure simultaneously. However, the relation between system diagram and flowchart is implied in designer’s mind. That resulted in the solving conception can’t be understood easily and debugging is more difficult. Owing to complex water resources planning problem heavily rely on systems thinking, which is defined as the ability to generate understanding through engaging in the mental mode-based process of construction, comparison and resolution (Nandalal and Simonovic, 2003), this study proposes an approach, system dynamics, to integrate flowchart and topological position into the stock-flow diagrams.

The system dynamics, initially developed by Jay W. Forrester (Forrester 1961), uses a perspective based on information feedback and mutual or recursive causality to understand the dynamics of complex physical, biological, social, and other systems. Recent applications of system dynamics approach in the field of water resources include the conjunctive use of surface water and ground water (Sehlke and Jacobson, 2005), and long-term water resource planning and policy analysis (Simonovic et al., 1997; Simonov and Fahmy, 1999; XU et al., 2002; Stave et al., 2003). There has been a tendency to model small-scale systems in greater detail with more emphasis on quantitative results (Fletcher 1998). However most system dynamics researches in water resource management focus on global reaction with implementing a policy result in they simplified the real system mechanism, such as neglect reservoir operating rule with time or water treatment plant ability limited of turbidity. Hence this study tried to expound how to construct a model incorporating horizon and profundity. Owing to the continuity of mass is both an important concept for water distribution system and system dynamics, water distribution problems are well suited for application of system dynamics solution techniques (Simonovic, 2003).

Methodology

This research integrates water distribution and management into a dynamic model. System dynamics is a computer-aided approach to evaluate the interrelationships of components and activities within complex systems (Gerald, 2005). The most important
feature of this approach is to elucidate the endogenous structure of the system under study, to see how the different elements of the system actually relate to one another, and to experiment with changing relations within the system when different decisions are included. In system dynamics, the relation between structure and behavior is based on the concept of stock-flow diagrams, describing the system material flow and information communication simultaneously, has four basic building blocks: stocks, flows, converters and connectors. (Tangirala et al., 2003) (see Fig. 1).

Model Development

The conceptual framework of conjunctive use modeling is presented in Fig. 2. We apply rainfall and GIS data to estimate the natural recharges and calibrating it by Modflow model. We hypothesize the Groundwater capacity is infinite that can store whole natural recharge at any time and setting the initial capacity for zero. The restriction of pumping discharge is subject to both storage of groundwater and shortage of surface supplying (including reservoir supplying and artificial-lake supplying). The further description is represented following.

Architecture of water distribution model

The procedure of constructing stock-flow diagrams of water distribution model is represented by fig 3. First, we need prepare system diagram to conceive topological position between hydrologic structures and rivers. The water distribution system consisted of nodes, represented the hydrologic structures, and links, represented rivers or pipes. The relations with system components must conform to the mass balance. We can divide nodes into impounding nodes which is denoted stock, such as reservoirs, artificial-lakes and groundwater, and non-impounding nodes which is denoted auxiliary, such as water treatment plants and weirs. The mass balance equation of nodes can be represented as follow:

\[
S_{k,t+1} = S_{k,t} + \sum_{k \in L} I_{k,t} - \sum_{k \in L} O_{k,t} \quad \text{.................(1)}
\]

Where \( S \) denotes storage of node \( k \); \( I \) represents inflow into node \( k \); \( O \) is outflow from node \( k \); the first suffix of all variable denotes node number; the second suffix represents time. \( L \) is a set of all links filling or draining node. If the node belongs to non-impounding node, \( S_{k,t} \) and \( S_{k,t+1} \) must equal to zero.

The water distribution modeling must be constructed from upstream to downstream in sequent. Hence, the inflow data can be got from observation or from estimated outflows by upstream node. If the node denotes groundwater aquifer, the inflow data can get from natural recharge estimated by GIS data or from artificial recharge got by reservoir overflow. Furthermore, we can divide outflow into three parts, river yield, supply yield and overflow (figure 4). The river yield can be represented as equation (2).
\[ OB_{k,t} = \min(\sum_{k \in L} I_{k,t} + S_{k,t}, R_{k,t}) \]  \hspace{1cm} (2)

Where \( OB_{k,t} \) is river yield of node \( k \). \( R_{k,t} \) denotes downstream water right of node \( k \).

The downstream water right includes instream flow and high priority water supply for important demand. It can be represented as following:

\[ R_{k,t} = \sum_{i \in M} D_{i,t} + B_{k,t} \]  \hspace{1cm} (3)

Where \( R_{k,t} \) is downstream water right of node \( k \). \( D_{i,t} \) is the demand which should be fulfilled in high priority. \( B_{k,t} \) represents instream flow. \( M \) denoted a set of all higher priority demands than other demands of node \( k \). Because reservoir has individual operating rule, the value of \( D_{i,t} \) is determined by storage of reservoirs with time. The value of \( B_{k,t} \) relates to observation of inflow. We set the value of \( B_{k,t} \) equal to the flow yield which Occurrence Probability is 95%.

The supply yield can be represented as equation (4).

\[ OD_{k,t} = \min(\sum_{k \in L} I_{k,t} + S_{k,t} - OB_{k,t}, D_{k,t}, C_{\text{max}}) \]  \hspace{1cm} (4)

Where \( OD_{k,t} \) is supply yield of node \( k \). \( D_{k,t} \) is the demand withdrawn from node \( k \). \( C_{\text{max}} \) denotes the processing capacity of water treatment plant.

The final part of outflow, overflow, can be determined as equation (5) if the node belongs to impound node or as equation (6) if the node belongs to non-impound node.

\[
O_{k,t} = \begin{cases} 
\sum_{k \in L} (I_{k,t} + S_{k,t} - OD_{k,t} - OB_{k,t}) > SMAX_{k,t}, \sum_{k \in L} (I_{k,t} + S_{k,t} - OD_{k,t} - OB_{k,t} - SMAX_{k,t,0}) & (5) \\
\sum_{k \in L} (I_{k,t}) - OB_{K,t} \cdot \sum OD_{k,t} & (6)
\end{cases}
\]

Where \( O_{k,t} \) is overflow of node \( k \). \( SMAX_{k,t} \) denotes the max capacity of node \( k \).

- **Infiltration estimation**

In our study, the surface recharge was estimated by considering land use, soil texture and precipitation. The origins of surface recharge are divided into two kind, one is precipitation; other is caused by storage of water, like pond and lake.

Originally, there are layer total 95 types of attribute of land use. Then, the 95 types of land use were classified into 5 types; include water body, impermeable zone, paddy field, river, dry farmland and other permeable zone, according to characteristics of recharge mechanic. The approach of Infiltration estimation is demonstrated in figure 5.

First, the fishponds, lakes, reservoirs and other zones which store water in long term are belonged to water body. Because the surface soil under water body are always saturated, the infiltration rate of is closed to infiltration rate of saturation soil, and it could be a constant. The formulation of infiltration estimation for water body is
follow as,
\[ R = A \times T \times \phi \] ................................................................. (7)

Where:

A : area ( L^2 )

T : time ( T )

\( \phi \) : infiltration rate of saturated soil ( L/T ), is assign according to the soil texture.

Second, because the recharge of dry farmland and other permeable zone is relational to precipitation. The infiltration is estimated by follow formulation,
\[ R = P \times A \times \alpha \] ................................................................. (8)

Where:

P : precipitation ( L )

A : area ( L^2 )

\( \alpha \) : precipitation recharge coefficient ( non-dimension ),is assign according to the soil texture and precipitation.

Third, about the paddy field, at irrigation period, the recharge mechanic is similar to water body, the estimation of infiltration of paddy field is follow the equation(7). At non-irrigation period, the equation (8) is used to estimate infiltration of paddy field.

Finally, because of lock of the raw data of river and the complex mechanic of exchange between river and groundwater, it is difficult to estimate the recharge from river to groundwater by only considering precipitation and soil texture. Therefore, in our study, a proposed approach was used to estimate the recharge included exchange between river and groundwater. The proposed approach is introduced in follow section.

**Case study**

The applicability of the proposed approach is demonstrated with an application to water resources management in southern Taiwan. The study region covers two metropolitan areas, Tainan and Kaohsing. The original water sources of these areas were came from Nanhua Reservoir and Kaopin River Weir. Owing to the development of Tainan Science Park, there will be more and more demand for industry use. Hence, the government proposes new water sources policies for assisting in water supply of Tainan and Kaohsing. Pumping from aquifer and withdraw from artificial lake were famous and feasible strategies. The System
The diagram of the study basin can be displayed as figure 7. Among the hydrologic constructions, the processing capacity of Nanhua WTP and Pintin WTP was 80*10^4 ton/day and 150*10^4 ton/day individually. An effective storage capacity of Nanhua Reservoir was 149.46×10^6 m^3. Furthermore, we hypothesize Tseng-Wen Reservoir and Wu-Shan-Tou Reservoir provide stable water (80*10^4 ton/day) for Tainan. The proposed methodology is demonstrated to find facilities with appropriate capacities and operation procedures to satisfy the future demands in 2021. Figure 8 displays the system dynamics model in this study. The conjunctive-use should obey priority instruction, supplying from Kaopin River Weir first, from reservoirs second and from groundwater finally. Moreover, this study involves risk analysis of production postponed.

When the model structure has been validated, it can be used to test the effect of strategy interventions on the problem, by studying the model structure to find policy levers, then simulating the effect of those changes. The strategies of interest are the planning capacity and the beginning operation data of artificial lake or pumping machine. We settle two index, shortage index (SI) and average shortage rate(risk), to reflect the water deficit.

The model was simulated using Vensim PLE version 5.3 software. Fig.9 displays the shortage rate of base scenario increasing significantly after eighth year. That means the problems of water shortage is serious under no strategy when facing future demand (the SI get up to 9.847 and the risk reach 28.87%). Fig. 10 shows the effect when the construction of pumping well or artificial lake has been postponed. Generalize a conclusion that higher pumping rate has steeper slope with beginning operation date. In other words, variation of delay time has more serious inflection in large pumping rate. We also discovered the shortage behavior resulted from artificial lake was similar to resulted from pumping rate.

Furthermore, we also investigate the reaction of compound strategies with building artificial lake or pumping from aquifer. The black line in Fig. 11 displays the reaction when excavating pumping wells have been postponed under artificial lake has functioned at the outset. Owing to the shortage problem of base scenario increasing significantly after eighth year, less surplus water can be stored in artificial lake causes decreasing water supply. Thereby, the beginning operation data of pumping should be before eighth period to alleviate shortage risk. The dotted line in Fig. 11 shows the response when building artificial lake has been postponed under pumping has functioned at the outset. Whereas groundwater resources provide confident supply referred to seldom influenced from climate variation, constructing artificial lake delay has fewer shortage risk than excavating pumping wells postponed.
Conclusions

This study uses a perspective based on information feedback and mutual or recursive causality to understand the dynamics of complex systems. Basing on basic building blocks: stocks, flows, converters and connectors, we subdivide the flow (outflow) into three part, river yield, supply yield and overflow, for facilitating designer to construct conjunctive-use model. In this study we also discuss the postponed affection of excavating pumping well or constructing artificial lake. He simulation results reveal that the shortage problems are not serious before eighth year and the shortage problem of compound strategies hasn’t significant aggravation when beginning operation data before eighth year. Therefore, advantageous strategies for raising funds and reducing shortage problem are either construction of artificial lake and pumping well should be accomplished and another should be done at eighth year. The results reveal that the proposed methodology effectively for systematically and quantitatively evaluating water strategy. The proposed methodology can assist decision-makers in discovering the win-win strategy.

References


Figure 6: The conceptual model of study area for UCODE

Figure 7: Water distribution system diagram of the study basin

Figure 9: Average shortage rate of base scenario each year

Figure 10: Result of risk analysis about production postponed

Figure 11: Risk analysis about production postponed of compound strategies
Fig. 8 System dynamics model of the study area