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An Integrating Approach for Conjunctive-Use Planning of Surface and Subsurface Water System

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Abstract This study proposes an integrated approach to assess the performance of a conjunctive-use surface and subsurface water system. System dynamics serves as the main framework of the proposed conjunctive-use model, simulating the interaction between surface and subsurface water and the impact of various conjunctive-use alternatives on the system as a whole. This study assumes natural groundwater recharge as a water source to the system, and estimates its volume using geographic information system (GIS) tools, a groundwater simulation model (MODFLOW), and a parameter identification model (UCODE). This study assesses various conjunctive-use alternatives and analyzes the frequency of water shortage to illustrate how the recharge rate affects water supply reliability under the conjunctive-use framework. Simulation results indicate that conjunctive-use with artificial recharge indeed reduces the frequency of extreme water shortages. Results also reveal that artificial recharge is necessary to maintain groundwater conservation without overusing river flow. Although this study focuses on southern Taiwan, the proposed concepts and procedure are applicable to other areas with a similar conjunctive-use framework.

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1 Introduction

Climate changes caused by global warming have made hydrological conditions increasingly unstable spatially and temporally (Simonovic and Li 2003). Because surface water resources are highly related to climate changes, global warming increases the risk of water deficits. However, groundwater provides a more stable water resource, and rich groundwater areas play a vital role in regional water resources (Tsur 1990). Therefore, the conjunctive use of surface and subsurface water can enhance the water supply reliability (Fisher et al. 1995). This study proposes an integrated approach to assess the performance of a surface and subsurface water conjunctive-use system.

Water distribution models can be developed using either an optimization or a simulation approach (Yeh 1985). This study uses a simulation approach, system dynamics, to assess water distribution system behavior. Following the recommendations of previous studies (Brito et al. 2006; Juckem et al. 2006; Lin and Anderson 2003; Szilagyi et al. 2005), this study uses Geographic Information System (GIS), MODFLOW and UCODE to estimate the interactions between surface and subsurface water resources. The objective of this study is to assess various conjunctive-use alternatives and evaluate water shortage risks using the proposed developed model.

System dynamics, initially developed by Jay W. Forrester, uses information feedback and mutual or recursive causalities to understand the dynamics of complex physical, biological, social, and other systems (Forrester 1961). A stock-flow diagram of system dynamics not only displays the system diagram, but also presents information linkages among components or variables. In other words, the stock-flow diagram simultaneously shows the structure of the problem and the internal process of the system. Therefore, using the system dynamics approach makes the modeling process transparent.

Many system dynamics studies on water resource management focus on the global policy results of large-scale systems. These studies use system dynamics to study long-term water resource planning and policy analysis (Simonovic and Fahmy 1999; Simonovic and Li 2003; Stave 2003; Xu et al. 2002). However, the tendency of current research is to model systems in detail, with more emphasis on quantitative results. Ahmad and Simonovic (2000) used system dynamics to study the impacts of a gated spillway on the flood management capacity of a reservoir. Sehlke and Jacobson (2005) applied system dynamics to the conjunctive-use analysis of surface and subsurface water. They used aquifer response curves to evaluate the effects of ground water pumping on surface water flows in the Bear River, a transboundary basin that includes portions of Idaho, Utah, and Wyoming. Yang et al. (2008) combined a system dynamics approach and impact analysis to evaluate water strategy systematically and quantitatively. They formulated an appropriate strategy that strikes a balance between mitigating water shortages and limit total financial costs. These studies clearly demonstrate that the system dynamics approach is well suited to investigating detailed operation rules and complex interactions among components.

2 Methodology

Figure 1 presents the framework of the proposed conjunctive-use model, where system dynamics integrates a groundwater recharge model into a conjunctive-use distribution system. The groundwater recharges are from natural recharges (including rainfall, river interaction, and boundary recharge) and artificial recharge (coming from non-used river flows). The natural recharges are estimated based on GIS, MODFLOW, and UCODE. The following sections describe these methods and tools in detail.

2.1 System Dynamics

System dynamics is a computer-aided approach to evaluating the interrelationships of components and activities within complex systems (Sehlke and Jacobson 2005). The use of causal loops and stock-flow diagrams make system dynamics unlike other approaches. These elements help describe how a seemingly simple system can display baffling nonlinearities.

System dynamics has four basic building components: stocks, flows, converters, and connectors. Stocks and flows mostly represent variables associated with physical quantities, such as reservoir storage or reservoir release, while converters represent additional variables, such as water demands, water treatment plant capacity, or water pipe capacity. Connectors connect the dependency relationships among stocks, flows, and converters.

Figure 2 shows the causal loop of a single node water distribution problem. This is a negative causal loop, which implies that the system state achieves a goal or desired state (Simonovic and Fahmy 1999). In other words, the loop indicates that operation behavior will trend towards a balance between supply and demand. The variables on the loop are endogenous variables that influence each other. Variables not on this loop are exogenous variables, which must be specified or estimated before endogenous variable computation.

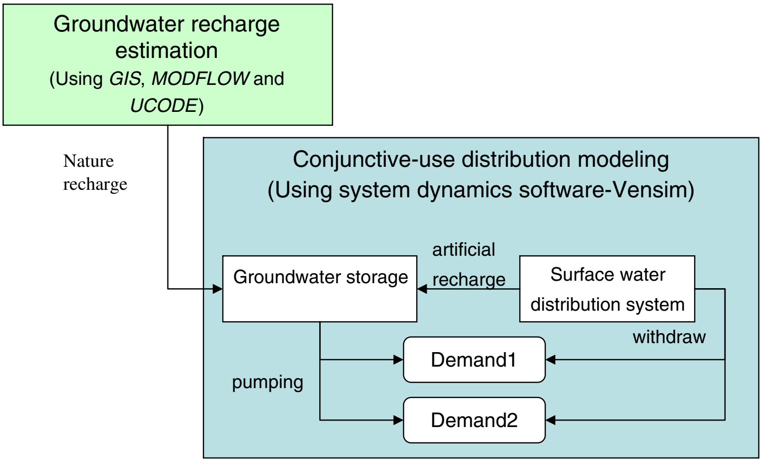

Fig. 1 The framework of conjunctive use modeling

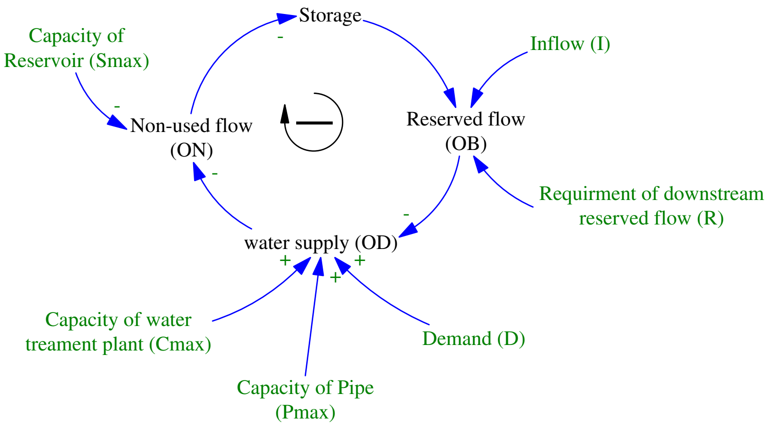

Fig. 2 The causal loop diagram of water distribution system (single node)

2.2 MODFLOW model

The modular three-dimensional groundwater flow model (MODFLOW) was developed by the United States Geological Survey (USGS) (Harbaugh and McDonald 1996). McDonald and Harbaugh (1988) were the first to document the MODFLOW model. The MODFLOW model is a physical finite-difference numerical flow model and a computer program developed by the USGS that numerically solves three-dimensional partial-differential equations for ground-water flow through a porous medium using a finite-difference method (Harbaugh and McDonald 1996). Before running MODFLOW, an analyst must discretize the study area into cells and assign parameters to them to simulate confined or unconfined flows and saturated flows in one, two, or three dimensions using the finite-difference techniques.

2.3 UCODE

This study uses UCODE, developed by USGS, to perform parameter optimization (Poeter and Hill 1998). UCODE is a computer code for the universal inverse model based on the nonlinear regression. UCODE minimizes a weighted least-squares objective function with respect to parameter values using the modified Gauss–Newton method or Conjugate-Direction Method. This study applies UCODE to solve an inverse problem in which the sink and source are the parameters to be identified.

3 Model Development for Study Case

3.1 Study Area Description

The study area covers the two metropolitan areas of Tainan and Kaoshing in Southern Taiwan. This area contains two major basins, the Kaopin River basin

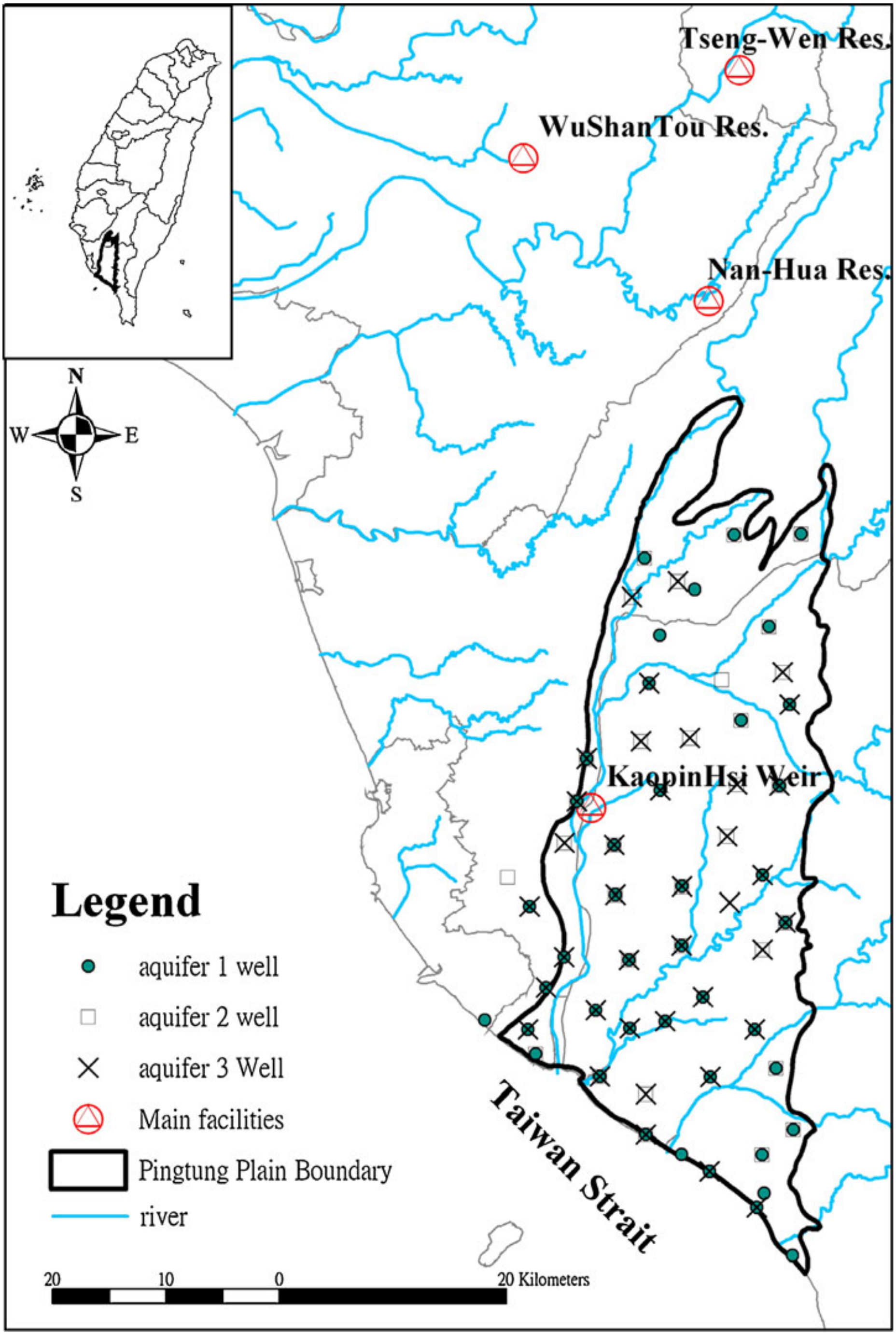

Fig. 3 The main facilities location of the study area

Table 1 The capacities and demands of the main facilities in the study area

Reservoir capacity (10^4 m^3)			The treatment capacity of Water treatment plant (10^4 m^3/day)			Demand (10^4 m^3/day)	
Nan-Hua Reservoir	Tseng-Wen Reservoir	Wu-Shan-Tou Reservoir	Pin-Tin water treatment plant	Nan-Hua water treatment plant	Wu-Shan-Tou and Tan-Tin water treatment plant	Tainan	Kaoshing
3,236.9	8,708	8,376	200	110	67	172.4	228.5

and the Tseng-Wen River basin. The main surface water facilities are the Nan-Hua Reservoir, the Tseng-Wen Reservoir, the Wu-Shan-Tou Reservoir, and the Kaopin-Hsi Weir. There are four main water treatment plants, the Pin-Tin water treatment plant, the Nan-Hua water treatment plant, the Wu-Shan-Tou water treatment plant, and the Tan-Tin water treatment plant.

The main groundwater resources come from the Pingtung Plain. At 1,140 km^2, the Pingtung Plain is the largest alluvial plain in Taiwan. The Central Mountain Range is the east boundary of the Pingtung Plain, while the northern and western boundaries of the plain are low hills of quaternary sediments. The southern boundary of the plain is the Taiwan Strait. Figure 3 depicts the study area's location, and Table 1 shows the main facilities described above. Figure 4 shows the water distribution system.

The groundwater system of the Pingtung Plain consists of one unconfined aquifer (Aquifer 1) and two confined aquifers (Aquifer 2, and Aquifer 3). The

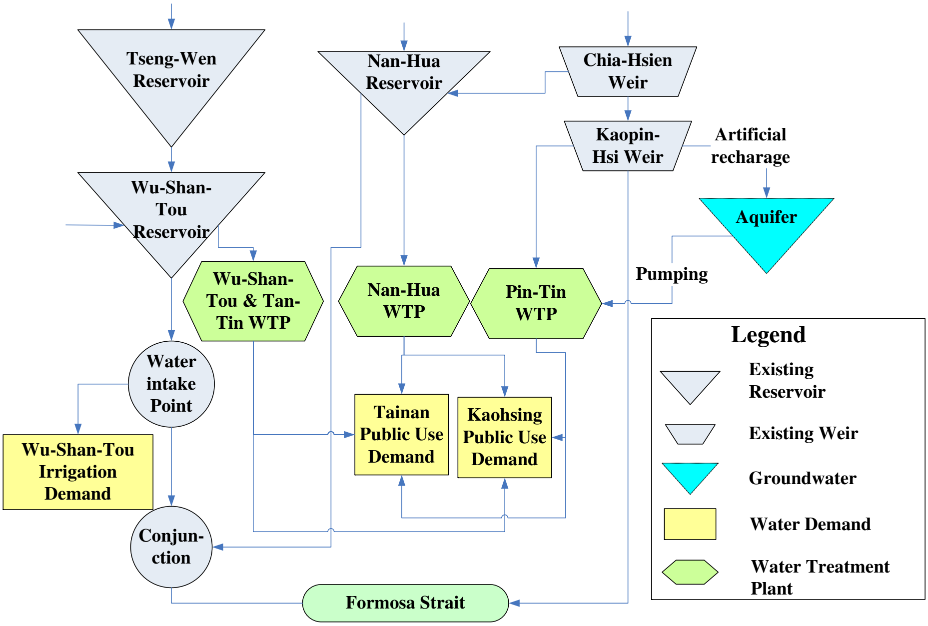

Fig. 4 Water distribution system of the study area

hydro-geological parameters such as hydraulic conductivity are adopted from the data of groundwater monitoring network. There are 41 monitoring wells at Aquifer 1, 35 monitoring wells at Aquifer 2, and 40 monitoring wells at Aquifer 3.

The basic operational concept of conjunctive use is to withdraw surface water before using groundwater to conserve groundwater and ensure efficient distribution. In this case, groundwater acts as the water supplement when the surface water supply cannot fulfill the demand for water.

The other operating rule of conjunctive use is to fulfill demand in sequence depending on water source availability. For example, when withdrawing water from the Kaopin River and aquifer, Kaoshing public use demand has a higher priority for fulfillment then Tainan public use demand. Further, when withdrawing water from reservoirs, Wu-Shan-Tou irrigation demand, Tainan public use demand, and Kaoshing public use demand should be fulfilled in sequence. The three reservoirs operate together as a multi-reservoir system and the water released from each reservoir is managed according to the index level method of storage balancing provided by the US army corps of engineers.

Additionally, conjunctive-use operation should be based on the operating curve of an equivalent reservoir. However, there is no operating curve for the conjunctive-use system. Therefore, this study applied the original reservoirs operating curve as the conjunctive-use rule guide. The original operating curve is based on the equivalent reservoir combining the Tseng-Wen Reservoir and the Wu-Shan-Tou Reservoir. The current operating curve divides this equivalent reservoir volume into five operating zones; inactive, low buffer, high buffer, conservation, and flood control zones (Fig. 5). Each zone has different criteria for decreasing target demand depending on how much water has been stored in the equivalent reservoir. The available storage of the equivalent reservoir is the sum of all inflows and the initial storage of each reservoir. The public use demand should be fulfilled 100%, 100%, 100%, and 80% when the available storage of the equivalent reservoir falls within the flood control zone, conservation zone, high buffer zone, or low buffer zone, respectively. The irrigation demand should be fulfilled 100%, 100%, 75%, and 50% when the available storage of the equivalent reservoir falls within the flood control zone, conservation zone, high buffer zone, or low buffer zone, respectively. Additionally, if the available storage falls within the flood control zone, the reservoir will operate in flood control mode and try to evacuate water as quickly as possible.

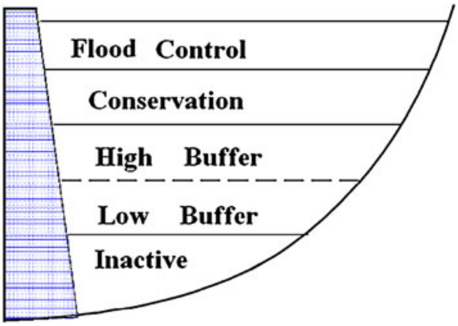

Fig. 5 Definition of reservoir operating zones for the equivalent reservoir of the Tseng-Wen Reservoir and the Wu-Shan-Tou Reservoir

3.2 Water Distribution Model Development

Because inflow data vary unevenly, reservoir releases are difficult to predict. Hence, this study develops a water distribution model and model results describe these release variations in depth. Figure 6 show the stock-flow diagram of water distribution for a single node.

The following equation describes variable quantification. First, define the reserved flow based on Eq. 1

$$OB_{k,t} = \min\left(\sum_{\mathrm{i}\subset \mathrm{L}} I_{i,t} + S_{k,t}, R_{k,t}\right) \tag{1}$$

where $\mathrm{OB}_{\mathrm{k,t}}$ is the reserved flow of node k at time t, $I_{i,t}$ represents the inflow to node k at time t, and $S_{k,t}$ denotes node k storage at time t. The first suffix of all variables denotes the node number; the second suffix represents the time step. L is the set of all inflows for node k. $\mathrm{R}_{\mathrm{k,t}}$ denotes the requirement of downstream reserved flow at node k and time t. For ensuring that the reserved flow can fulfill the ecological base streamflow after downstream, $\mathrm{R}_{\mathrm{k,t}}$ is setting as the summation of the ecological base streamflow and priority downstream water demands that should be fulfilled prior to fulfilling the water demands of node k. The ecological base streamflow is the minimum requirement for aquatic animal survival. Equation 2 defines $\mathrm{R}_{\mathrm{k,t}}$ as follows:

$$R_{k,t} = \sum_{i\subset M} DR_{i,t} + B_{k,t} \tag{2}$$

where $\mathrm{DR}_{\mathrm{i,t}}$ is the priority downstream water demand, and $\mathrm{B}_{\mathrm{k,t}}$ represents the ecological base streamflow at node k and time t. M denotes the set of all priority downstream water demands. The value of $\mathrm{B}_{\mathrm{k,t}}$ is estimated from the exceedance probability of a stream flow equal to 95%.

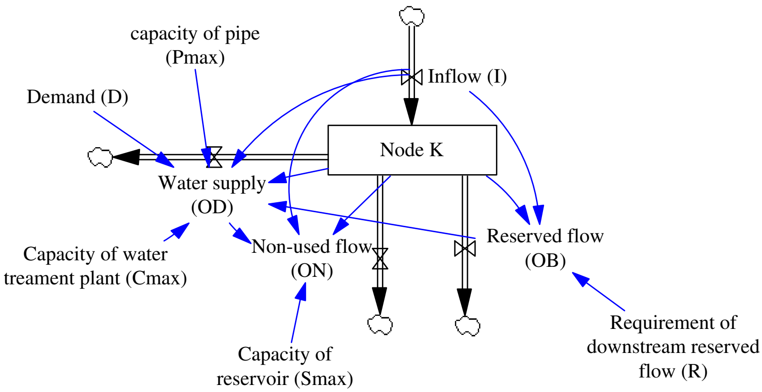

Fig. 6 The stock-flow diagram of water distribution system (single node)

Equation 3 illustrates the water supply:

$$OD_{K,t} = \min\left[\sum_{i\subset L}\left(I_{i,t}\right) + S_{k,t} - OB_{k,t}, \sum_{j\subset N}\left(D_{j,t}\right), C\mathrm{max}_k, P\mathrm{max}_k\right] \tag{3}$$

where $\mathrm{OD}_{\mathrm{k,t}}$ is the water supply from node k at time t, $\mathrm{D}_{\mathrm{j,t}}$ is the desired demand of node k at time t, N is the set of all demands of node k, $\mathrm{Cmax}_{\mathrm{k}}$ denotes the maximum water treatment plant capacity for node k, and $\mathrm{Pmax}_{\mathrm{k}}$ denotes the maximum pipe capacity for node k.

Equation 4 represents the unused flow of node k if node k is an impounding node. Alternately, Eq. 5 shows the unused flow if node k is a non-impounding node.

$$\begin{aligned} ON_{k,t} &= \sum_{K\subset L} I_{k,t} + S_{k,t} - OD_{k,t} - OB_{B,t} - S\mathrm{max}_k, \\ &\quad if \sum_{K\subset L} I_{k,t} + S_{k,t} - OD_{k,t} - OB_{k,t} > S\mathrm{max}_k \\ &= 0 \qquad\qquad\qquad\qquad\qquad\qquad , \\ &\quad if \sum_{K\subset L} I_{k,t} + S_{k,t} - OD_{k,t} - OB_{k,t} \le S\mathrm{max}_k \end{aligned} \tag{4}$$

$$ON_{k,t} = \sum_{K\subset L}\left(I_{k,t}\right) - OB_{K,t} - \sum OD_{k,t} \tag{5}$$

where $\mathrm{ON}_{\mathrm{k,t}}$ is the non-used flow of node k, and $\mathrm{Smax}_{\mathrm{k}}$ denotes the maximum storage capacity of node k.

The mass balance principle defines node k storage at the next time step (t + 1):

$$S_{k,t+1} = S_{k,t} + \sum_{i\subset L} I_{i,t} - \sum_{j\subset W} O_{j,t} \tag{6}$$

where $S_{k,t+1}$ denotes node k storage at time t + 1, $O_{j,t}$ is the outflow from node k at time t, which involves reserved flow, water supply, and non-used flow, and W is the set of all outflows draining from node k. If node k is a non-impounding node, $\mathrm{S}_{\mathrm{k,t}}$ and $\mathrm{S}_{\mathrm{k,t+1}}$ must equal zero.

It is possible to deduce the multi-nodes distribution system model based on the proposed procedure for the single node water distribution problem. Figure 7 shows the causal loop diagram of multi-nodes distribution system. The symbol definitions in this case are the same as mentioned above, and the number denotes the node number. The reserved flow (OB) and unused flow (ON) from the upstream node are the inflow of the downstream node.

The combined Groundwater storage levels and the remaining water treatment plant capacity determine the quantity of groundwater available. The groundwater

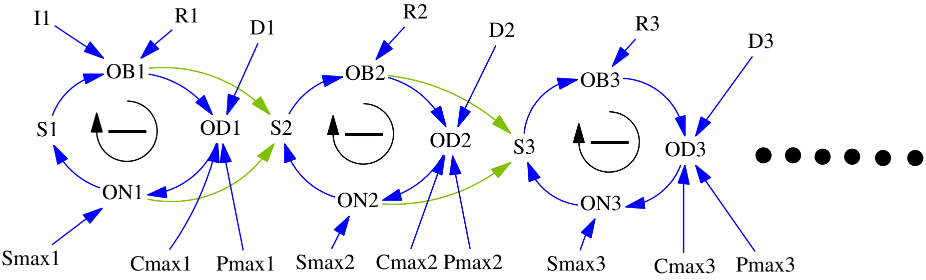

Fig. 7 The causal loop diagram of multi-nodes distribution system

storage level is the groundwater storage at time t minus the initial groundwater storage. Equation 7 denotes the groundwater supply:

$$\text{IF } i \subset G$$

$$\begin{aligned} ODW_{i,t} &= \min\left[GI_{i,t},\ D_{i,t} - \sum_{k\subset S} OD_{k,t},\ \mathrm{Cmax}_i,\ P\mathrm{max}_i\right] && ,\mathrm{GI}_{\mathrm{i,t}} > 0 \\ ODW_{i,t} &= 0 && ,\mathrm{GI}_{\mathrm{i,t}} \leq 0 \end{aligned} \tag{7}$$

where $\mathrm{ODW}_{\mathrm{i,t}}$ is the water supply from the groundwater node i at time t, $\mathrm{GI}_{\mathrm{i,t}}$ indicates the groundwater storage level variation, $\mathrm{D}_{\mathrm{i,t}}$ is the desired demand withdrawn from groundwater node i at time t, $\mathrm{OD}_{\mathrm{k,t}}$ is the water supply of the surface-water node k at time t, $\mathrm{Cmax}_{\mathrm{i}}$ denotes the maximum water treatment plant capacity for node i, and $\mathrm{Pmax}_{\mathrm{i}}$ denotes the maximum pipe capacity for node i. G means that the storage node belongs to groundwater, while S denotes the pipes connect surface water node with demand $\mathrm{D}_{\mathrm{i,t}}$.

3.3 Groundwater Recharge/discharge Estimation

Figure 8 illustrates the procedure of estimating the recharge and discharge of the groundwater system. A groundwater system typically includes into four types of recharge or discharge: area recharge from surface infiltration, river and groundwater interaction (recharge/discharge), recharge from the eastern boundary (Central Mountain Range), and area pumping. This study estimates the area recharge from surface infiltration using GIS tools, and determines the three other source and sink quantities by solving a parameter identification problem (inverse problems). The parameter identification problem in this study involves the famous finite different numerical model, MODFLOW (Harbaugh and McDonald 1996; McDonald and Harbaugh 1988), and a computer code for universal inverse modeling, UCODE (Hill 1998; Poeter and Hill 1998).

First, area recharge estimation requires GIS tools, a land use map, and soil type coverage. The land use map of Pingtung Plain used in this study originally had 95 land use types, which were reclassified into five classes according to the infiltration abilities of each type. Figure 9 shows the reclassified map with these five classes, including impermeable zones, river zones, paddy field zones, water body zones, and other permeable zones. Figure 8 shows the estimation process for these

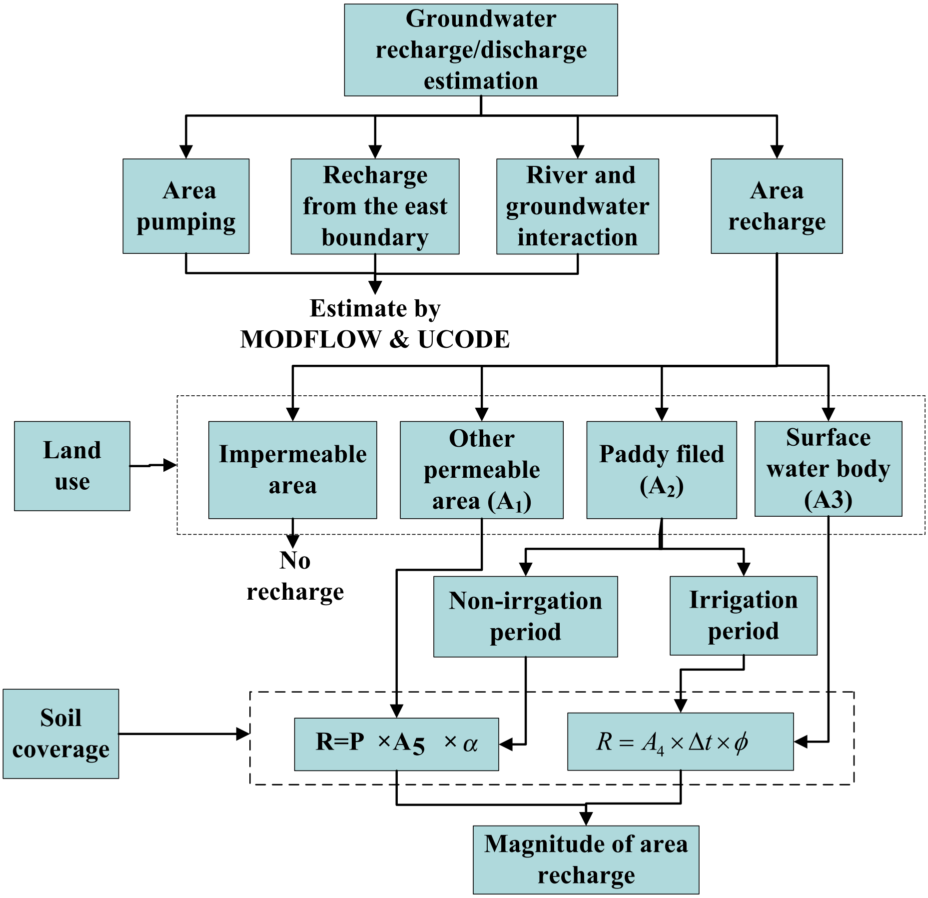

Fig. 8 Procedure for Groundwater recharges/discharge estimation

five classes. The recharge quantity of each land use class is based not only on its own recharge mechanism, but also according to its type of soil coverage. Because the interaction between river and groundwater is very complex, the parameter identification procedure determines the recharge quantity of river zones, as the next step illustrates. Due to the effects of man-made structures, the recharge quantity for impermeable zones is zero. The area values of the three other zones, paddy field zones, water body zones and other permeable zones, are A_1, A_2, and A_3, respectively. Two equations, Eqs. 8 and 9, determine the recharge quantities for different classes. Equation 8 is suitable for wet land, while Eq. 9 is for dry land. These equations can respectively estimate the quantities of water body zones and other permeable zones:

$$R = A_4 \times \Delta t \times \phi \tag{8}$$

where A_4 is total area of wet land. (L^2), Δt is time interval of each time step. (T),ϕ denotes the constant infiltration rate of saturated soil (L/T) varies according to soil coverage type.

$$R = P \times A_5 \times \alpha \tag{9}$$

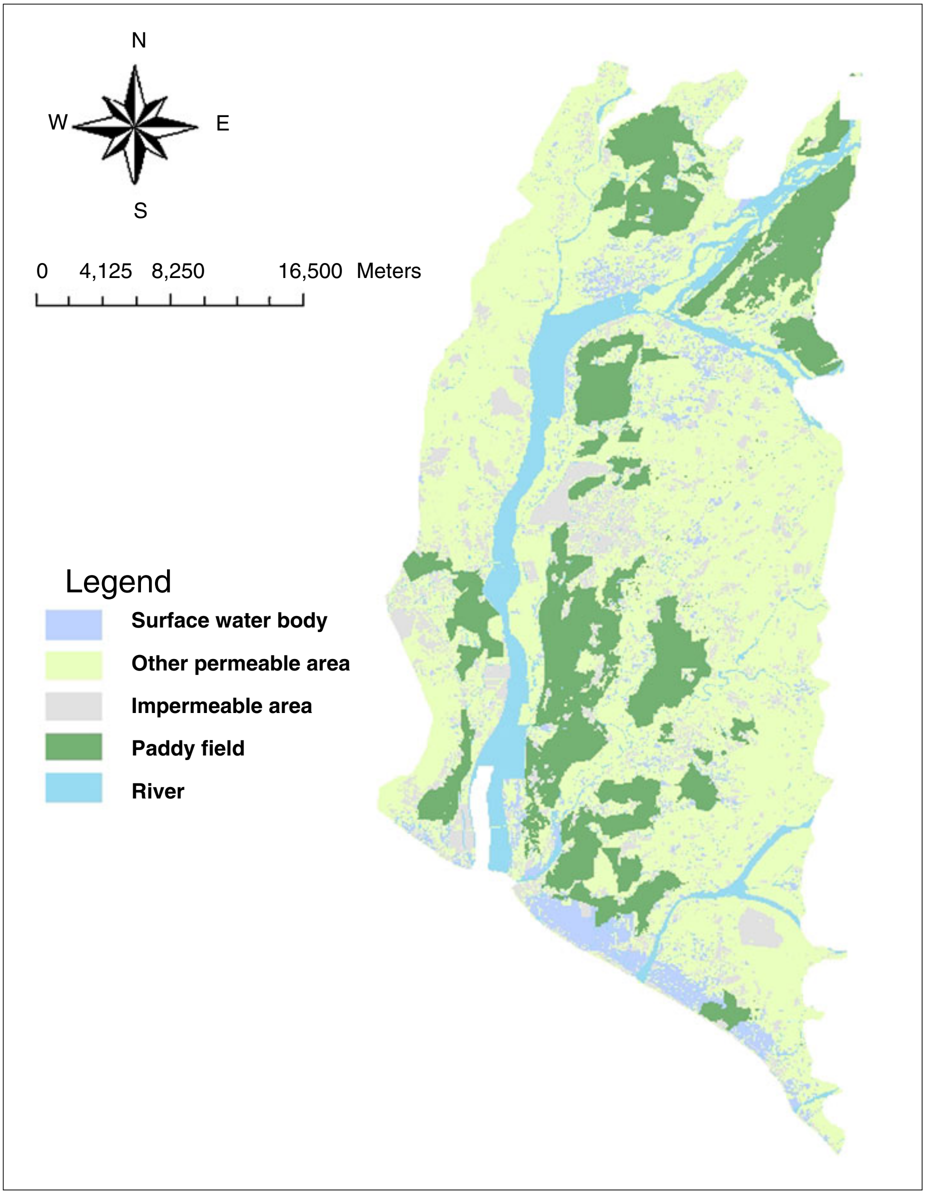

Fig. 9 Land-use diagram of Pingtung Plain

where P is total rainfall quantity in the time interval (L), A_5 is total area of dry land (L^2), α denotes rainfall recharge coefficient (non-dimensional), varies according to soil type.

In Eq. 8, the soil is saturated and the infiltration rate relies on the soil properties, ϕ. The symbol ϕ means the constant infiltration rate of saturated soil and its value are referred to the data of a previous study of the Hydrology Agency, Ministry of Water Resources of mainland China (Assessment of China Water Resources (Chinese)

1986). Because the paddy field zones during irrigation period store specific levels of water, the mechanism is the same as one on wet land. Therefore, the total area of wet land, A_4, equals the sum of A_1 and A_2 during irrigation periods, and A_2 during non-irrigation periods.

In Eq. 9, rainfall and soil water levels determine the recharge quantities. The value of α is taken from the study of the Hydrology Agency, Ministry of Water Resources of mainland China (Assessment of China Water Resources (Chinese) 1986). Because paddy field zones are dry during non-irrigation periods, this mechanism is as same as that of dry land. Therefore, the total area of dry land, A_5, is equals the sum of A_1 and A_3 during non-irrigation periods, and A_3 during irrigation periods. Summing the quantities of paddy field zones, water body zones and other permeable zones reveals the magnitude of area recharge.

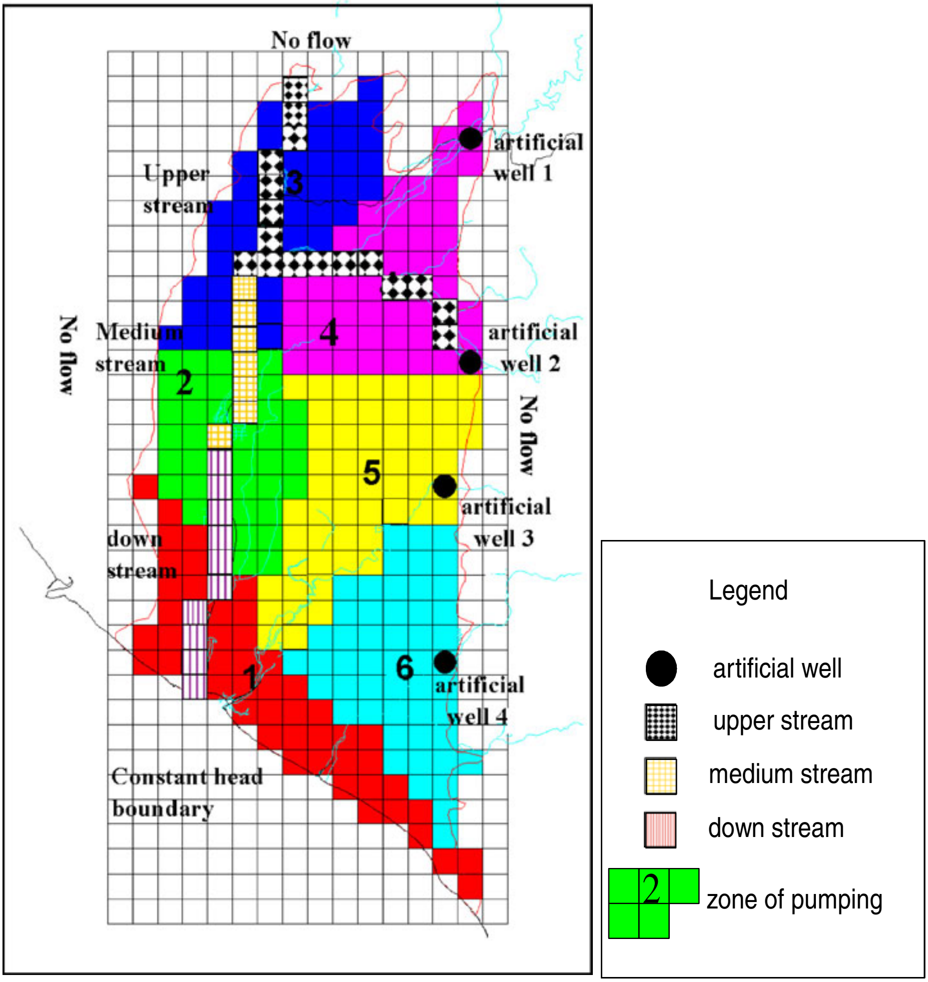

Fig. 10 Conceptual model of groundwater simulation for MODFLOW and UCODE

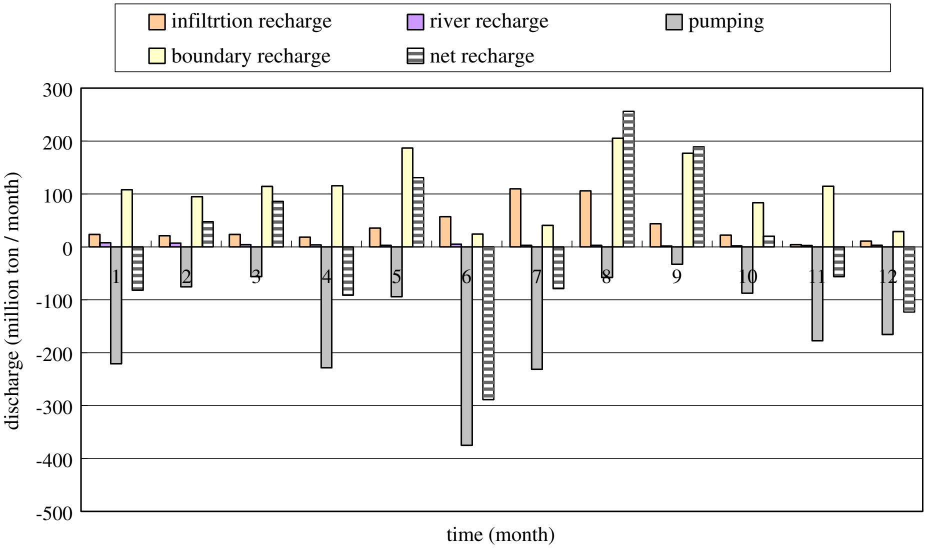

Fig. 11 Results of groundwater recharge/discharge estimation

Next, this study uses MODFLOW and UCODE to solve the inverse problem (the parameter identification). The purpose of the inverse problem is to estimate the other sink and source quantities of the groundwater system, such as area pumping, recharge from the eastern boundary, and interaction between river and groundwater. Owing to a lack of raw data, such as riverbed conductance, we used the well package, instead of river package, to simulate the interaction between river and groundwater. Figure 10 shows the Pingtung Plain divided into 316 cells with a size of 2.0 × 2.0 km each for MODFLOW modeling. The Zonation method then reduced parameter dimensions (Yeh 1986). Figure 10 shows that the area pumping includes six zones. River and groundwater interaction is only considered in the Kaoping River, dividing it into upper, middle, and downstream sections (Fig. 10). Applying the Zonation method, cells in the same river section or the same zone were simulated with the same pumping and injecting rates. Four 'artificial wells' that recharge the shallow aquifer at the boundary represent recharging at the eastern boundary, making it possible to implement the well package. The number of decision variables in the parameter identification procedure is 13, including quantities for six zones, three river sections, and four artificial wells.

Figure 11 shows the results of recharge and pumping estimation for the groundwater system at each month. This figure indicates that the net recharge is positive during February, March, May, August, September, and October. Figure 12 compares the groundwater table observations and simulations using contour lines. These results demonstrate a good fit between the simulated groundwater table and observed data.

4 Simulation Results

The proposed model investigates the performance of different conjunctive-use alternatives in southern Taiwan. This study uses two indicators, the shortage index (SI)

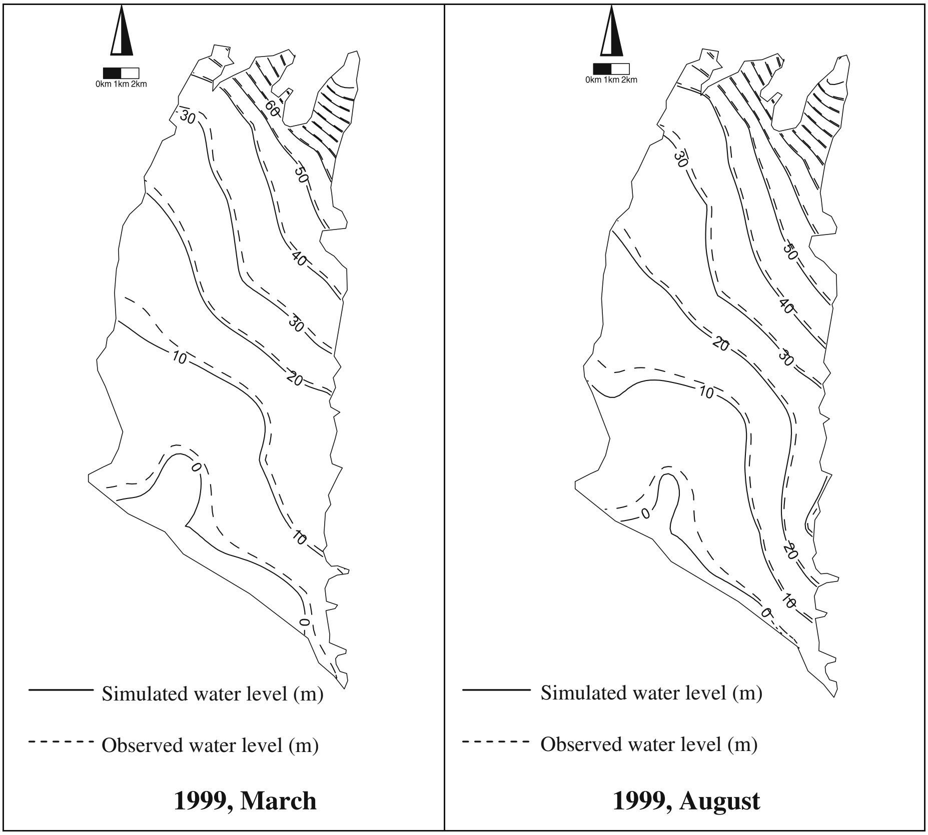

Fig. 12 Comparison of contour lines of groundwater level for simulation and observation

and the intensity of surface water use, to respectively indicate the water shortage severity and water resources depletion in Taiwan. The SI, proposed by US Army Corps of Engineers, represents water shortage impact in Taiwan. The SI is defined as

$$SI = \frac{100}{N} \sum_{i=1}^{N} \left(\frac{Sh_i}{T_i} \right)^2 \tag{10}$$

where N denotes number of periods, Sh_i is the water shortage volume during period I, and T_i represents the demand of the water use sector (agriculture or industry) during period i. Each period in this study is 10 days, which is commonly used in Taiwan when performing long-term studies for water resource planning.

The intensity of surface water use is the ratio of annual water used to annual river flow, and indicates the depletion of surface water resources in Taiwan. A high value of this indicator represents the overuse of surface water, and may have negative impacts on river environment sustainability.

Table 2 summarizes the results of different conjunctive-use alternatives. Case 0 is the base scenario that uses only surface water, while other cases use both surface and groundwater resources with different artificial recharge capacities. The

Table 2 Summaries of conjunctive-use operations with different artificial recharge capacities

Case	Conjunctive-use	Artificial recharge capacity 10^4 m^3/10 days	Average groundwater pumping (10^4 m^3/year)	Average artificial recharge (10^4 m^3/year)	Shortage index	Intensity of surface water use for the Kaopin River (%)	Intensity of surface water use for the Zengwen River (%)
Case 0	No	–	0	0	0.91	16.72	56.53
Case 1	Yes	0	527.35	0	0.84	16.72	56.53
Case 2	Yes	100	611.68	220.95	0.58	17.18	56.53
Case 3	Yes	200	832.16	441.42	0.3	17.65	56.53
Case 4	Yes	300	1,049.88	661.90	0.13	18.10	56.53

water shortage (indicated by the SI) decreases as the artificial recharge capacity increases. Because the only river on the Pingtung Plain is the Kaoping River, the artificial recharge only includes the unused flow of the Kaoping River. Hence, only the intensity of surface water use for the Kaoping River varies, while that for the Zengwen River is stationary.

Figure 13 indicates the variations of groundwater storage increment for various scenarios. These results indicate that all scenarios preserved the same average variations in last 8 years. Higher artificial recharge leads to higher final groundwater storage. Table 2 shows the average volume of groundwater used and artificial recharge.

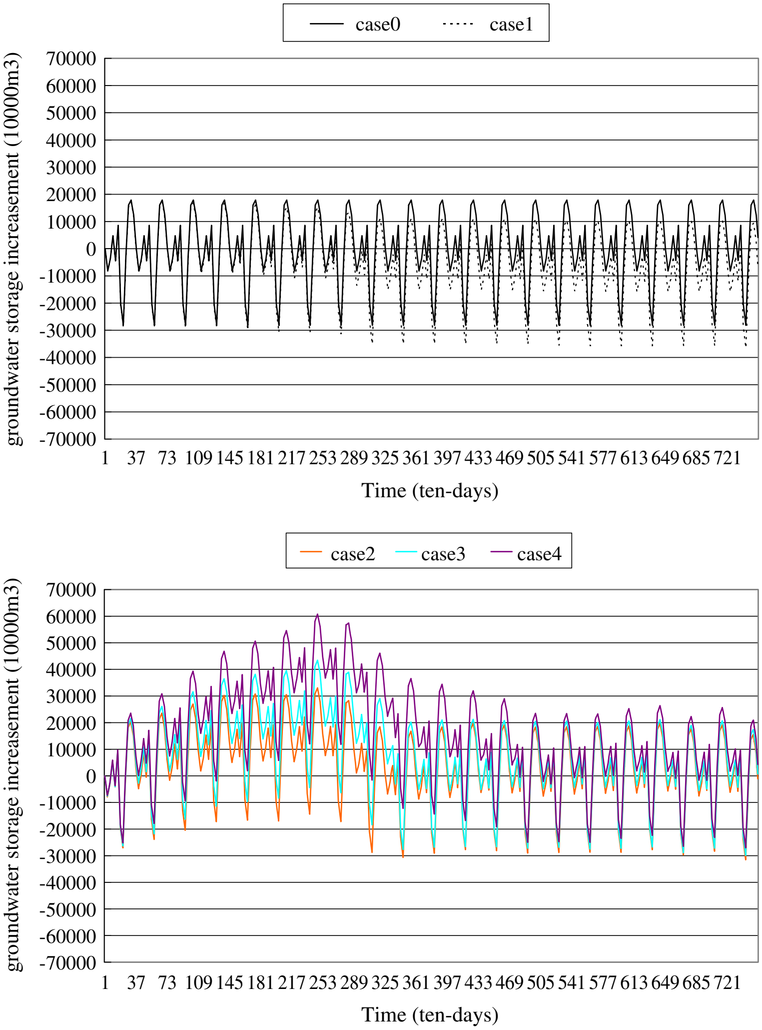

Fig. 13 Groundwater storage increment variations for various cases

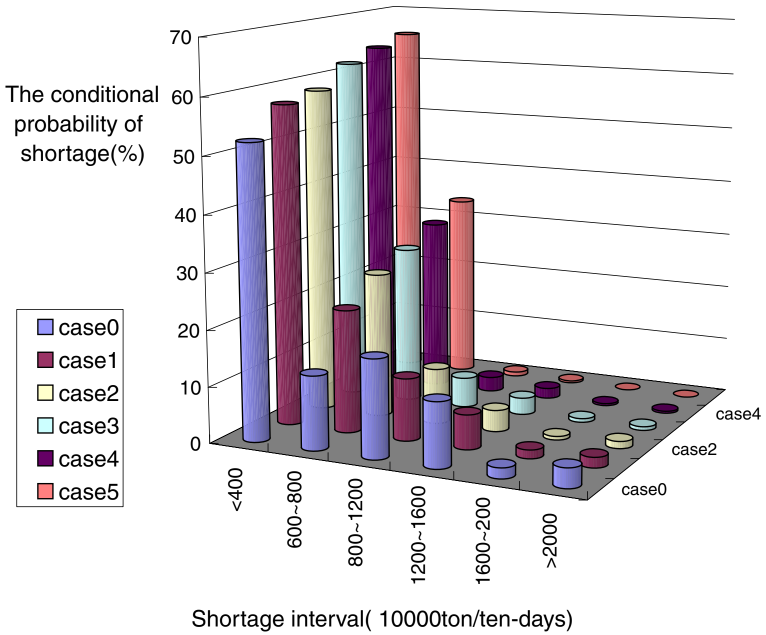

Fig. 14 Conditional probabilities of water shortage for all cases

Furthermore, the occurrence frequency analysis of water shortage illustrates how artificial recharge capacity affects water supply reliability under the conjunctive-use framework. The analysis in this study adopts the conditional probability expressed in Eq. 11:

$$P(SH_R|SH) = \frac{P(SH_R \cap SH)}{P(SH)} \tag{11}$$

where $P(SH_R|SH)$ indicates the probability of a specific amount (R) of water shortage based on the occurrence of a water deficit. $P(SH)$ represents the probability of a water deficit. $P(SH_R \cap SH)$ is the joint probability, indicating the probability of two events in conjunction. Figure 14 represents the histogram of the conditional probability of water shortage value for all cases with six intervals. This figure shows that water supply without conjunctive-use (case 0) has the highest conditional probability of large water shortages. As the artificial recharge capacity increased, the conditional probability of large water shortages decreased. Water system managers would rather incur a sequence of smaller shortages in water supply than one potential catastrophic shortage. Hence, this conditional probability diagram can provide useful information for decision makers to avoid extreme water shortages.

5 Conclusions

This study proposes a systematic procedure to assessing the performance of potential planning alternatives for reducing water shortage risks in a conjunctive-use water distribution system. The proposed procedure is based on system dynamics, groundwater model simulation, parameters identification, and GIS tools. This study uses the stock-flow diagram of system dynamics to explore the relationships among system components and provides a transparent framework for model development. Simulation results demonstrate that the proposed integrated approach is well suited for analyzing the performance and long-term effects of different water management alternatives.

The occurrence frequency analysis in this study also provides useful information for decision makers to avoid potential catastrophic shortage. These results indicate that as the artificial recharge capacity increased, the occurrence probability of extreme shortages decreased. These results also demonstrate that artificial recharge is necessary to maintain groundwater resource conservation without overusing river flow. Although this study focuses on southern Taiwan, the proposed concepts and procedures are applicable to other areas with a similar conjunctive-use framework.

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References

Ahmad S, Simonovic SP (2000) System dynamics modeling of reservoir operations for flood management. J Comput Civ Eng 14(3):190–198

Assessment of China Water Resources (Chinese) (1986) The hydrology agency. Ministry of Water Resources of the Mainland China

Brito MG, Costa CN, Almeida JA, Vendas D, Verdial PH (2006) Characterization of maximum infiltration areas using GIS tools. Eng Geol 85(1–2):14–18

Fisher A, Fullerton D, Hatch N, Reinelt P (1995) Alternatives for managing drought - a comparative cost-analysis. J Environ Econ Manage 29(3):304–320

Forrester JW (1961) Industrial dynamics. MIT, Cambridge

Harbaugh AW, McDonald MG (1996) User's Documentation for MODFLOW-96, an update to the U.S. Geological survey modular finite-difference ground-water flow model. U.S. Geological Survey, Virginia

Hill MC (1998) Methods and guidelines for effective model calibration. U.S. Geological Survey, Colorado

Juckem PF, Hunt RJ, Anderson MP (2006) Scale effects of hydrostratigraphy and recharge zonation on base flow. Ground Water 44(3):362–370

Lin YF, Anderson MP (2003) A digital procedure for ground water recharge and discharge pattern recognition and rate estimation. Ground Water 41(3):306–315

McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference ground-water flow model. US Geological Survey techniques of water-resources investigations, book 6 Ed

Poeter EP, Hill MC (1998) Documentation of UCODE, a computer code for universal inverse modeling. U.S. Geological Survey, Colorado

Sehlke G, Jacobson J (2005) System dynamics modeling of transboundary systems: the Bear River basin model. Ground Water 43(5):722–730

Simonovic SP, Fahmy H (1999) A new modeling approach for water resources policy analysis. Water Resour Res 35(1):295–304

Simonovic SP, Li LH (2003) Methodology for assessment of climate change impacts on large-scale flood protection system. J Water Resour Plan Manage—ASCE 129(5):361–371

Stave KA (2003) A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. J Environ Manag 67(4):303–313

Szilagyi J, Harvey FE, Ayers JF (2005) Regional estimation of total recharge to ground water in Nebraska. Ground Water 43(1):63–69

Tsur Y (1990) The stabilization role of groundwater when surface-water supplies are uncertain - the implications for groundwater development. Water Resour Res 26(5):811–818

Xu ZX, Takeuchi K, Ishidaira H, Zhang XW (2002) Sustainability analysis for yellow river water resources using the system dynamics approach. Water Resour Manage 16(3):239–261

Yang C, Chang L, Ho C (2008) Application of system dynamics with impact analysis to solve the problem of water shortages in Taiwan. Water Resour Manage 22(11):1561–1577

Yeh WWG (1985) Reservoir management and operations models—a state-of-the-art review. Water Resour Res 21(12):1797–1818

Yeh WWG (1986) Review of parameter-identification procedures in groundwater hydrology—the inverse problem. Water Resour Res 22(2):95–108